# Hydropower VISION

## A New Chapter for America's 1st Renewable Electricity Source

U.S. DEPARTMENT OF ENERGY


VISION

Man did not weave the web of life, he is merely a strand in it. Whatever he does to the web, he does to himself. All things share the same breath—the beast, the tree, the man... the air shares its spirit with all the life it supports. Take only memories, leave nothing but footprints.

ARY

—Chief Seattle

U.S. DEPARTMENT OF ENERGY

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# FROM THE DIRECTOR

America's first renewable electricity source, hydropower, has been providing flexible, low-cost, and low-emission renewable energy for more than 100 years. In addition to producing electricity, many of today's hydropower facilities provide flood control, irrigation, water supply, and recreational opportunities. Hydropower deployment also delivers public health and environmental benefits—reduced greenhouse gas emissions, reduced air pollutant emissions, and reduced water consumption—and is facilitating the integration of increased levels of variable generation, such as wind and solar in various regions of our country.

The *Hydropower Vision* looks toward the future of the nation's hydropower sector, highlighting how hydropower can continue to be a substantial part of meeting the challenge to produce clean, affordable, and secure energy in the 21st century. With a goal of developing a cohesive long-term future for the benefit of the entire U.S. hydropower community, this landmark report analyzes a range of growth scenarios and establishes an objective roadmap of actions the hydropower industry, research community, and others can take to achieve higher levels of hydropower deployment within a sustainable national energy mix.

The *Hydropower Vision* represents a significant and extensive collaboration of the Energy Department, and experts from more than 150 organizations—including equipment industry associations; manufacturers; environmental organizations; federal, state, and local government agencies; utilities; developers; independent power producers; research institutions and laboratories; and more. To the more than 300 diverse individuals who supported this massive effort with their time and expertise, I express my sincerest gratitude. Their work helped ensure that the *Hydropower Vision* achieves not only breadth, but also depth in its approach to defining the future of this vital renewable energy resource.

The *Hydropower Vision* highlights the great potential of untapped hydropower resources across the United States, finding that U.S. hydropower could grow from 101 gigawatts (GW) of combined generating and storage capacity to nearly 150 GW by 2050—with more than 50% of this growth realized by 2030. Growth under this scenario would result from a combination of 13 GW of new hydropower generation capacity (upgrades to existing plants, adding power at existing dams and canals, and limited development of new stream-reaches), and 36 GW of new pumped storage capacity. Between 2017 and 2050, hydropower could save $209 billion in avoided damages from greenhouse gas emissions, $58 billion from avoided healthcare costs and economic damages due to air pollution, and 30 trillion gallons of water, equivalent to roughly 45 million Olympic-size swimming pools.

The factors that led to the hydropower industry's historical growth over the past century are different than the opportunities and challenges facing the industry today. Continued evolution, including transformative technical innovations able to meet the co-objectives of environmental sustainability and low-carbon energy, will be critical to enabling hydropower growth. The *Hydropower Vision* will help the nation usher in a new era for hydropower—one that ensures that America's first renewable electricity source maintains its place in our nation's 21st-century energy system.

José Zayas
Director, Wind and Water Power Technologies Office
U.S. Department of Energy

# Acronyms

| | |
|---|---|
| **AP2** | Air Pollution Emissions Experiments and Policy Analysis Model (formerly APEEP) |
| **BAA** | balancing authority area |
| **BAU** | Business as Usual or Business-as-Usual |
| **BPA** | Bonneville Power Administration |
| **Btu** | British thermal unit |
| **CAISO** | California Independent System Operator |
| **$CO_2$** | carbon dioxide |
| **CPP** | Clean Power Plan (EPA) |
| **DOE** | U.S. Department of Energy |
| **DOI** | U.S. Department of the Interior |
| **EIA** | U.S. Energy Information Administration |
| **EPA** | U.S. Environmental Protection Agency |
| **EROI** | energy return on investment |
| **FERC** | Federal Energy Regulatory Commission |
| **FPA** | Federal Power Act |
| **GDP** | gross domestic product |
| **GHG** | greenhouse gas(es) |
| **GW** | gigawatt(s) |
| **GWh** | gigawatt-hour(s) |
| **ILP** | Integrated Licensing Process (Federal Energy Regulatory Commission) |
| **IOU** | investor-owned utility |
| **IPP** | independent power producer |
| **ISO** | independent system operator |
| **ITC** | investment tax credit |
| **IWG** | Interagency Working Group (on Social Cost of Carbon) |
| **LIHI** | Low Impact Hydropower Institute |
| **kW** | kilowatt(s) |

| | |
|---|---|
| **kWh** | kilowatt hour(s) |
| **MISO** | Midcontinent Independent System Operator |
| **MW** | megawatt(s) |
| **MWh** | megawatt-hour(s) |
| **NEPA** | National Environmental Policy Act |
| **NERC** | North American Electric Reliability Corporation |
| **NG** | natural gas (CH4) |
| **$NO_x$** | nitrogen oxides |
| **NPD** | non-powered dams |
| **NREL** | National Renewable Energy Laboratory |
| **NSD** | new stream-reach development |
| **O&M** | operations and maintenance |
| **ORNL** | Oak Ridge National Laboratory |
| **$PM_{2.5}$** | Particles less than 2.5 micrometers in diameter, referred to as “fine” particles. |
| **PMA** | Power Marketing Administration (Federal) |
| **PPA** | power purchase agreement |
| **PSH** | pumped storage hydropower |
| **PTC** | production tax credit |
| **PV** | photovoltaic (solar) |
| **REC** | renewable energy credit or renewable energy certificate |
| **ReEDS** | Regional Energy Deployment System (ReEDS Model) |
| **RPS** | renewable portfolio standard |
| **RTO** | regional transmission organization |
| **SCC** | social cost of carbon |
| **$SO_2$** | sulfur dioxide |
| **TVA** | Tennessee Valley Authority |
| **TWh** | terawatt-hour(s); trillion kWh |
| **VG** | variable generation (or variable generation resources) |

# OVERVIEW

# Overview: The *Hydropower Vision*

**The U.S. Department of Energy's (DOE's) Wind and Water Power Technologies Office has led a first-of-its-kind comprehensive analysis to evaluate future pathways for low-carbon, renewable hydropower (hydropower generation and pumped storage) in the United States, focused on continued technical evolution, increased energy market value, and environmental sustainability.**

**Undertaken through a broad-based collaborative effort, the *Hydropower Vision* initiative had four principal objectives:**

- Characterize the current state of hydropower in the United States, including trends, opportunities, and challenges;
- Identify ways for hydropower to maintain and expand its contributions to the electricity and water management needs of the nation from the present through 2030 and 2050;
- Examine critical environmental and social factors to assess how existing hydropower operations and potential new projects can minimize adverse effects, reduce carbon emissions from electricity generation, and contribute to stewardship of waterways and watersheds; and
- Develop a roadmap identifying stakeholder actions that could support responsible ongoing operations and potential expansion of hydropower facilities.

**The *Hydropower Vision* analysis finds that U.S. hydropower could grow from 101 gigawatts (GW) of capacity to nearly 150 GW by 2050. Growth under this modeled scenario would result from a combination of 13 GW of new hydropower generation capacity (upgrades to existing plants, adding power at existing dams and canals, and limited development of new stream-reaches), and 36 GW of new pumped storage capacity. If this level of growth is achieved, benefits such as a savings of $209 billion from avoided greenhouse gas (GHG) emissions could be realized, of which $185 billion would be attributable to operation of the existing hydropower fleet. Transformative technical innovations able to meet the co-objectives of environmental sustainability and low-carbon energy will be critical to enabling additional hydropower growth beyond these levels.**

**The *Hydropower Vision* report specifically does not evaluate or recommend new policy actions but instead analyzes the feasibility and certain benefits and costs of various credible scenarios, all of which could inform policy decisions at the federal, state, tribal, and local levels.**

## *The Hydropower Vision Framework*

The *Hydropower Vision* report is based on three equally important foundational principles, or "pillars," arrived at through extensive stakeholder input. These pillars are critical to ensuring the integrity of the research, modeling, and analysis in the *Hydropower Vision:*

**Optimization: Optimize the value and power generation contribution of the existing hydropower fleet within the nation's energy mix to benefit national and regional economies, maintain critical national infrastructure, and improve energy security.**

**Growth: Explore the feasibility of credible long-term deployment scenarios for responsible growth of hydropower capacity and energy production.**

**Sustainability: Ensure that hydropower's contributions toward meeting the nation's energy needs are consistent with the objectives of environmental stewardship and water use management.**

*Hydropower Vision:* Responsibly operate, optimize, and develop hydropower in a manner that maximizes opportunities for low-cost, low-carbon renewable energy production, economic stimulation, and environmental stewardship to provide long-term benefits for the nation.

## *Hydropower Vision Insights*

Applying these foundational principles to both the quantitative and qualitative analyses in the *Hydropower Vision* led to several key insights regarding the role of existing and future hydropower in the U.S. power sector:

- Existing hydropower facilities have high value within the U.S. energy sector, providing low-cost, low-carbon, renewable energy as well as flexible grid support services.
- Hydropower has significant near-term potential to increase its contribution to the nation's clean generation portfolio via economically and environmentally sustainable growth through optimized use of existing infrastructure.
- Meeting the long-term potential for growth at potential sites that are not developed for hydropower is contingent upon continued commitment to innovative technologies and strategies to increase economic competitiveness while meeting the need for environmental sustainability.
- Significant potential exists for new pumped storage hydropower to meet grid flexibility needs and support increased integration of variable generation resources, such as wind and solar.
- The economic and societal benefits of both existing and potential new hydropower, as quantified in this report, are substantial and include job creation, cost savings in avoided mortality and economic damages from air pollutants, and avoided GHG emissions.

**Hydropower has provided a cumulative 10% of U.S. electricity generation over the past 65 years (1950–2015), and 85% of cumulative U.S. renewable power generation over the same time period.**

## *Study Summary*

DOE's approach to characterizing key aspects of hydropower and assessing future potential had two major components: data gathering and computational analysis. More than 300 experts from over 150 organizations and agencies participated as task force members and reviewers in documenting the opportunities, challenges, and technical and market aspects of the industry. These experts also contributed cost data and input on methods and assumptions used in the computational analysis.

DOE's national laboratories used national-scale electric sector capacity expansion modeling to simulate the cost of construction and operation of generation and transmission capacity to meet electricity demand and other power system requirements on a competitive basis with other generation sources over discrete study periods—2017, through 2030, and through 2050. These modeling methods were used to evaluate a range of possible future outcomes for hydropower deployment based on resource availability, technical innovation, economic factors, market forces, and potential environmental effects. The modeling analysis assumed policy as legislated as of December 31, 2015, including the U.S. Environmental Protection Agency's *Carbon Pollution Standards for Existing Power Plants* (Clean Power Plan).[O1]

In addition to modeling future outcomes of new deployment, the future contributions of the existing hydropower fleet were evaluated. As of the end of 2015, the U.S. hydropower generation fleet included 2,198 active power plants with a total capacity of 79.6 GW and 42 pumped storage hydropower (PSH) plants totaling 21.6 GW, for a total installed capacity of 101 GW. PSH comprised the majority (97%) of the utility-scale electricity storage in the United States at the end of 2015.

O1. Though the Supreme Court issued a stay of the Clean Power Plan (CPP) in February 2016, the CPP is treated as law in all scenarios. The CPP is modeled using mass-based goals for all states with national trading of allowances available. Although states can ultimately choose rate- or mass-based compliance and will not necessarily trade with all other states, a nationally traded mass-based compliance mechanism is viewed as a reasonable reference case for the purpose of exploring hydropower deployment under a range of electricity system scenarios.

## *Analysis Overview*

For the report, four categories of hydropower projects were evaluated:

1. Existing hydropower plants that can be upgraded and optimized for increased generation and environmental performance;
2. New power plants at existing non-powered dams (NPDs) and other water conveyance infrastructures such as irrigation canals;
3. New and existing PSH facilities and upgrades; and
4. New stream-reach development (NSD).

Due to the limits of the quantitative economic modeling framework used, potential capacity additions from canals; from upgrades to existing pumped storage facilities; and in Alaska and Hawaii are only discussed qualitatively throughout the report.

More than 50 hydropower deployment scenarios were modeled to assess the relative influence of specific variables on hydropower growth in the competitive energy marketplace. The factors that most influenced the modeling results were: (1) technology innovation to reduce cost; (2) improvement of market lending conditions by valuing the long asset life of hydropower facilities; and (3) the concurrent influence of several environmental considerations. These factors and others were combined in a final set of four scenarios. This set of scenarios was used to quantify potential long-term hydropower growth and a range of potential benefits from specific metrics, such as GHG reduction, when compared to a baseline scenario representing no new unannounced hydropower development. Growth in hydropower generation capacity in the various scenarios was added to current installed capacity to establish a range of potential total capacity.

## *Results: Overall Positive Benefit for the Nation*

**The *Hydropower Vision* analysis found that—under a credible modeled scenario in which technology advancement lowers capital and operating costs, innovative market mechanisms increase revenue and lower financing costs, and a combination of environmental considerations are taken into account—U.S. hydropower including PSH could grow from 101 GW of capacity in 2015 to 150 GW by 2050. Growth potential is tied to a complex set of variables, and changes in these variables over long periods of time are difficult to predict. Modeling results therefore serve primarily as a basis for identifying the key factors and drivers likely to influence future trends and outcomes, and should not be interpreted as DOE projections or targets.**

### Benefits—Existing and New Capacity, 2017–2050[a,b,c]

| | Economic Investment | Greenhouse Gases | Air Pollution | Water | Jobs |
|---|---|---|---|---|---|
| **Existing Fleet and New Capacity Additions Combined (149.5 GW)** | $148 billion in cumulative economic investment[d]<br>$110 billion for hydropower generation and $38 billion for PSH | Cumulative GHG emissions reduced by 5,600,000,000 metric tons $CO_2$-equivalent, saving $209 billion in avoided global damages | $58 billion savings in avoided mortality, morbidity, and economic damages from cumulative reduction in emissions of $SO_2$, $NO_X$, and $PM_{2.5}$<br>6,700–16,200 premature deaths avoided | Cumulative 30 trillion gallons of water withdrawals avoided for the electric power sector | Over 195,000 hydropower-related gross jobs spread across the nation in 2050 |

a. Cumulative benefits are reported on a Net Present Value basis ($2015) for the period of 2017 through 2050.

b. Estimates reported reflect central values within a range of estimates as compared to the *baseline scenario* with no new hydropower.

c. Existing fleet includes new projects and plant retirements announced as of the end of 2015; new development reflects the modeled scenario titled *Advanced Technology, Low Cost Finance, and Combined Environmental Considerations.*

d. Capital investment and annual operating expenses, 2017–2050.

Selected benefits and impacts from the existing hydropower fleet and from new deployment, 2017–2050

Near-term growth of hydropower generation (through 2030), estimated as 9.4 GW under this scenario, is driven primarily from upgrades of existing hydropower facilities (5.6 GW) and powering non-powered dams (3.6 GW). Long-term growth of 3.4 GW between 2030 and 2050 includes 1.7 GW of NSD, for a total of 12.8 GW of new growth by 2050. The analysis also concluded that potential exists to increase new stream-reach development beyond this level; however, this development is unlikely to occur without significant, transformational innovation in technology and development approaches that can lower costs and meet environmental sustainability requirements.

Under a range of scenarios, PSH can increase in both the near term (to 2030), where 16.2 GW are added, and in the longer term (to 2050), where an additional 19.3 GW are deployed, for a total of 35.5 GW by 2050. This growth is driven primarily by modeled growth in other variable renewable generation sources, such as wind and solar, and by the inherent flexibility of pumped storage and its ability to provide needed operating reserves and other essential grid reliability services. With increased PSH deployment under *Advanced Technology* and *Low Cost Finance* modeling assumptions, PSH provides more operating reserves (52%) than any other technology by 2050.

**The *Hydropower Vision* modeled capacity of 150 GW by 2050 yields a scenario under which a combined $209 billion savings from avoided global damages from GHG emissions is possible, including $185 billion in savings from the existing hydropower fleet being operated through 2050. The figure below provides an itemized quantification of selected benefits realized by both the existing fleet and new growth between 2017 and 2050.**

## Roadmap for Key Stakeholder Actions

The *Hydropower Vision* roadmap outlines potential actions, in a non-prescriptive manner, for consideration by all stakeholder sectors. Within the five topical action areas listed below, 21 subcategories include 64 actions developed in conjunction with task forces representing a wide range of stakeholder perspectives. The defined roadmap action areas are:

1. ***Technology Advancement*** to advance development of innovative technologies and system design concepts needed to reduce costs and improve both power production efficiencies and environmental performance;
2. ***Sustainable Development and Operation*** to further integrated approaches that incorporate the principles, metrics, and methodologies required to balance environmental, social, and economic factors;
3. ***Enhanced Revenue and Market Structures*** that appropriately compensate and incentivize new and existing hydropower, given the numerous energy production and grid support services it provides;
4. ***Regulatory Process Optimization*** by increasing access to shared data, making information on relevant scientific advances available, and furthering other means of enhancing process efficiency and reducing risks and costs; and
5. ***Enhanced Collaboration, Education, and Outreach*** including dissemination of best practices for maintaining, operating, and constructing facilities; and developing curricula for vocational and university programs to train new hydropower professionals.

## Risks of Inaction

While the hydropower industry is mature in terms of established facilities and technologies, many actions and efforts remain critical to further advancement of U.S. domestic hydropower as a key future energy source. Continued technology development is needed to increase efficiency, improve sustainability, and reduce costs. Improvement in the way markets value grid reliability services, air quality and reduced GHG emissions, and long asset lifetimes can increase revenues.

The lack of well-informed, coordinated actions such as those identified in the roadmap reduces the likelihood that potential benefits to the nation will be realized. Failure to address business risks associated with hydropower development costs and development timelines could mean that opportunities for new deployment will not be realized. As detailed in the roadmap, engagement with the public, regulators, and other stakeholders is needed to address environmental considerations effectively. Continued research and analysis on energy policy and hydropower costs, benefits, and impacts are important to provide accurate information to policymakers and for public discourse.

Finally, regularly revisiting the *Hydropower Vision* roadmap and updating priorities across stakeholder groups and disciplines are essential steps to ensuring coordinated pathways toward a robust and sustainable hydropower future.

## Conclusions

One of the greatest challenges for the United States in the 21st century is ensuring the availability of low-carbon, affordable, and secure energy. Hydropower has been and can continue to be a substantial contributor toward meeting that challenge. Although the hydropower industry exhibited significant growth over the past century, the factors that led to its historical growth rates are different than the contemporary opportunities and challenges the industry is facing.

The hydropower industry has increasingly responded to the needs for technical advancement and environmental protection. Continued efforts to lower costs, increase efficiencies, and incorporate the principles of environmental sustainability through technical innovation are likely to determine the scale at which hydropower contributes to the energy mix of the future.

Increasing hydropower can simultaneously deliver an array of benefits to the nation that address issues of national concern, including air quality, GHG emissions, public health, economic development, energy diversity, grid reliability, and energy and water security. Based on the benefit and cost quantifications of the *Hydropower Vision,* the overall value of these types of long-term social benefits can be substantive.

# EXECUTIVE SUMMARY

# ES.1 Developing a *Hydropower Vision*

**Hydropower has provided clean, affordable, reliable, and renewable electricity in the United States for more than a century.** Building on hydropower's historical significance, and to inform the continued technical evolution, energy market value, and environmental performance of the industry, the U.S. Department of Energy's (DOE's) Wind and Water Power Technologies Office has led a first-of-its-kind comprehensive analysis focused on a set of potential pathways for the environmentally sustainable expansion of hydropower (hydropower generation and pumped storage) in the United States.[1,2]

**The *Hydropower Vision* analysis finds that U.S. hydropower could grow from 101 gigawatts (GW) of capacity to nearly 150 GW by 2050. Growth under this modeled scenario would result from a combination of 13 GW of new hydropower generation capacity (upgrades to existing plants, adding power at existing dams and canals, and limited development of new stream-reaches), and 36 GW of new pumped storage capacity. If this level of growth is achieved, benefits such as a savings of $209 billion from avoided greenhouse gas (GHG) emissions could be realized, of which $185 billion would be attributable to operation of the existing hydropower fleet. With this deployment level, more than 35 million average U.S. homes could be powered by hydropower in 2050.**

**Transformative technical innovations able to meet the co-objectives of environmental sustainability and low-carbon energy will be critical to enabling additional hydropower growth beyond these levels.**

Formulated through a broad-based collaborative effort of many stakeholders, the *Hydropower Vision* initiative was undertaken to realize four primary goals:

1. Document the history and existing state of hydropower in the United States, including key technical advancements, societal benefits, industry trends, and opportunities to facilitate sustainable development and operations;
2. Identify potential pathways for hydropower to maintain and expand its contributions to the electricity and water management needs of the nation from the present (2017) through 2030 and 2050, including supporting the growth of other renewable energy technologies, reducing carbon emissions, improving air quality, reducing water used for thermal cooling in the power sector, and fostering economic development and job growth;
3. Examine critical environmental and social factors to assess how existing hydropower operations and potential new projects can be operated and delivered to minimize adverse effects and contribute to responsible stewardship of waterways and watersheds to realize the highest benefit; and
4. Develop a roadmap identifying sets of stakeholder actions that could support continued responsible planning, operation, and expansion of hydropower facilities.

1. Hydropower as discussed in this report includes new or conventional technologies that use diverted or impounded water to create hydraulic head to power turbines, and pumped storage hydropower facilities in which stored water is released to generate electricity and then pumped back during periods of excess generation to replenish a reservoir. Throughout this report, the term "hydropower" generally encompasses all categories of hydropower. If a distinction needs to be made, the term "hydropower generation" distinguishes other types of projects from "pumped storage hydropower," or "PSH".
2. This report does not address marine (wave, current, and tidal) and river hydrokinetic technologies, as marine and hydrokinetic technologies are defined by Congress as separate and distinct from hydropower (Energy Policy Act of 2005. Public Law No: 109-58. 42 U.S.C. § 931 (a)(2)(D) Hydropower and 42 U.S.C. § 931 (a)(2)(E)(i) Miscellaneous Projects. *https://www.congress.gov/109/plaws/publ58/PLAW-109publ58.pdf*).

**The *Hydropower Vision* report resulted from DOE's collaboration with more than 300 experts from over 150 hydropower industry companies, environmental organizations, state and federal governmental agencies, academic institutions, electric power system operators, research institutions, and other stakeholder groups.** Collectively, these participants were instrumental in documenting the state of the industry and identifying future opportunities for growth, as well as pinpointing challenges that need to be addressed to ensure that hydropower continues to evolve and contribute value to the nation for decades to come.

***Hydropower Vision:*** **Responsibly operate, optimize, and develop hydropower in a manner that maximizes opportunities for low-cost, low-carbon renewable energy production, economic stimulation, and environmental stewardship to provide long-term benefits for the nation.**

**For purposes of the *Hydropower Vision*, sustainable hydropower projects are those that are sited, designed, constructed, and operated to meet or optimize social, environmental, and economic objectives at multiple geographic scales (i.e., national, regional, basin, site).** While hydropower development has, in some cases, had adverse effects on river systems and the species that depend upon them, hydropower offers many benefits and continues to make advances in environmental performance. Accordingly, the *Hydropower Vision* sets increasing expectations for new hydropower development under which environmental gains are maintained and the trend of improvement continues. Sustainable hydropower fits into the water-energy system by ensuring that the ability to meet energy needs is balanced with the functions of other water management missions in the present as well as into the years ahead. In some cases, dam removal and site restoration may be part of meeting the sustainability objective.

## ES.1.1 *Hydropower Vision* Framework

**The *Hydropower Vision* aims to document a set of pathways to responsibly operate, optimize, and develop hydropower in a manner that maximizes opportunities for low-carbon renewable energy production, economic stimulation, and environmental stewardship to provide long-term benefits for the nation.** This *Vision* is grounded in three foundational principles or "pillars"—optimization, growth, and sustainability—arrived at through extensive stakeholder input as being critical to ensuring the integrity of the research, modeling, and analysis conducted during the *Hydropower Vision* process (see Chapter 1). These are defined as follows:

- **Optimization:** Optimize the value and the power generation contribution of the existing hydropower fleet within the nation's energy mix to benefit national and regional economies, maintain critical national infrastructure, and improve energy security.
- **Growth:** Explore the feasibility of credible long-term deployment scenarios for responsible growth of hydropower capacity and energy production.
- **Sustainability:** Ensure that hydropower's contributions toward meeting the nation's energy needs are consistent with the objectives of environmental stewardship and water use management.

Through these foundational principles, both existing hydropower and future hydropower development were assessed, and a roadmap of potential actions was developed. Seven key insights of this *Hydropower Vision* collaborative effort characterize the important role that hydropower has and can continue to play in the U.S. power sector:

1. Hydropower has been a cornerstone of the U.S. electric grid, providing low-cost, low-carbon, renewable, and flexible energy services for more than a century.
2. Existing hydropower facilities have high value based on their ability to provide flexible generation and energy services, ancillary grid services, multi-purpose water management, and social and economic benefits, including avoidance of criteria air pollutants[3] and GHG emissions.

3. The Clean Air Act requires EPA to set National Ambient Air Quality Standards for six common air pollutants (criteria pollutants) based on the human health-based and/or environmentally-based criteria. *https://www.epa.gov/criteria-air-pollutants*

3. Hydropower has the potential to grow and contribute to additional electricity production in the future generation portfolio, including near term significant potential for economically and environmentally sustainable growth by optimizing existing infrastructure through facility upgrades and adding generation capabilities to non-powered dams (NPDs) and water conveyances, such as irrigation canals.
4. Long-term hydropower growth potential, particularly at undeveloped sites (new stream-reaches), will rely on the availability of innovative and economically competitive hydropower technologies that are not yet fully developed. The long-term potential will also depend on the extent to which new hydropower projects are able to be developed at lower costs and with improved environmental sustainability strategies.
5. The United States has significant resource potential for new pumped storage hydropower (PSH) development as a continued storage technology, enabling grid flexibility and greater integration of variable generation resources, such as wind and solar.
6. Technical design innovations, advanced project implementation strategies, optimized regulatory processes, and the application of sustainability principles will be important in determining hydropower's future.
7. Hydropower's economic and societal benefits are significant and include substantial cost savings in avoided mortality, morbidity, and economic damages from power sector emissions of criteria air pollutants and avoided global damages from GHG emissions.

The *Hydropower Vision* does not specifically evaluate or recommend new policy actions but instead analyzes the feasibility and certain benefits of varied hydropower deployment scenarios, all of which could inform policy decisions at the federal, state, tribal, and local levels.

# ES.2 State of the U.S. Hydropower Industry

**Hydropower (hydropower generation and pumped storage) has provided a stable and consistently low-cost energy source throughout decades of fluctuations and fundamental shifts in the electric sector, supporting development of the U.S. power grid and the nation's industrial growth in the 20th century and into the 21st century.** Hydropower is a scalable, highly reliable generation technology, and it offers significant operational flexibility to maintain grid reliability and integration of variable generation resources. Hydropower infrastructure is long-lived, and the resource is generally stable and predictable over long time periods.

**By the end of 2015, the U.S. hydropower generation fleet included 2,198 active power plants with a total capacity of 79.6 GW and 42 PSH plants totaling 21.6 GW, for a total installed hydropower capacity of 101 GW.**[4] The PSH capacity comprised the majority (97%) of the utility-scale electricity storage in the United States at the end of 2015. As of the end of 2015, hydropower was installed in 48 states. The geographic distribution of existing hydropower capacity in the United States is shown in Figure ES-1 and Figure ES-2, and cumulative deployment from 1890 to 2015 is shown in Figure ES-3. The majority of hydropower generation was installed between 1950 and 1990, and the majority of PSH was installed between 1960 and 1990 to complement operation of large, baseload coal and nuclear power plants and to cost-effectively balance electricity load and demand on the transmission grid.

**Hydropower provided 6.2% of net U.S. electricity generation and approximately half (48%) of all U.S. renewable power in 2015.** Hydropower has supplied a cumulative 10% of U.S. electricity generation over the past 65 years (1950–2015), and 85% of cumulative U.S. renewable power generation over the same time period.[5] As of 2013, hydropower supported

4. Uria-Martinez, R., P. O'Connor, M. Johnson. April 2015. "2014 Hydropower Market Report". Prepared by Oak Ridge National Laboratory for the U.S. Department of Energy. DOE/EE 1195. Accessed July 5, 2016. *http://energy.gov/eere/water/downloads/2014-hydropower-market-report*.
5. U.S. Energy Information Administration. October 27, 2015. Table 7.2b Electricity Net Generation: Electric Power Sector. Monthly Energy Review. Accessed July 5, 2016. *http://www.eia.gov/totalenergy/data/monthly/*.

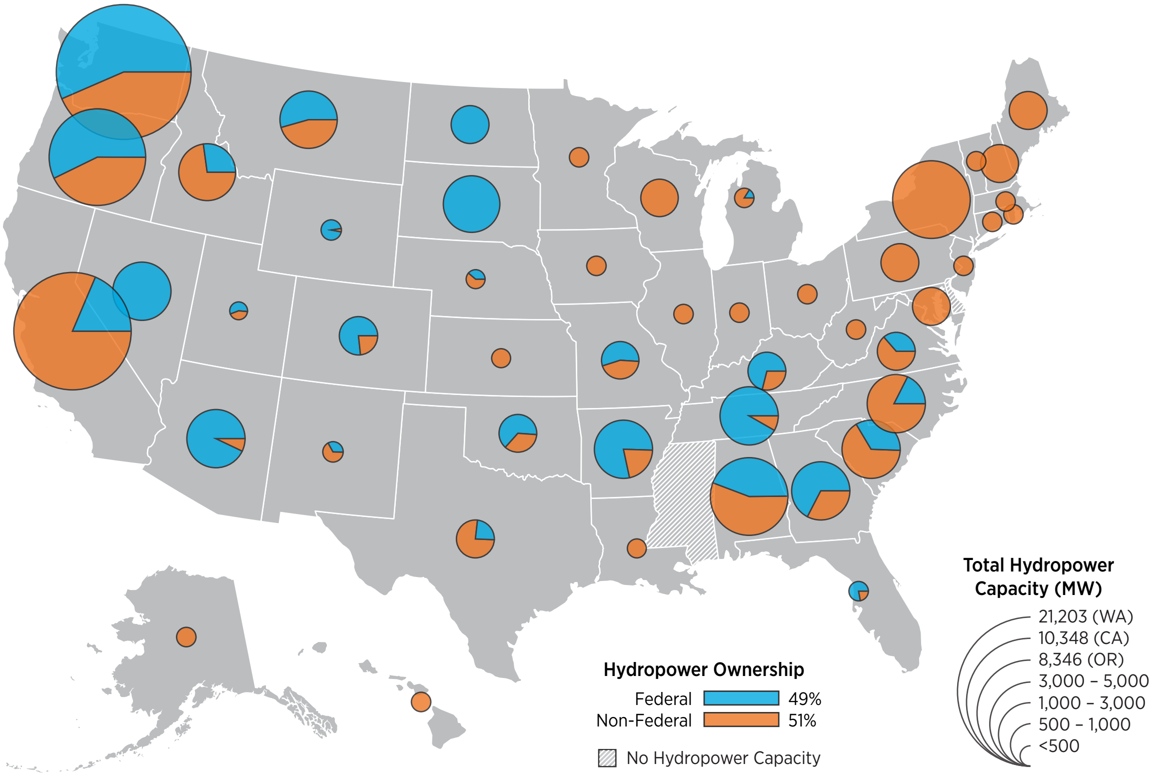



**Figure ES-1.** Existing hydropower generation capacity in the United States (79.6 GW)

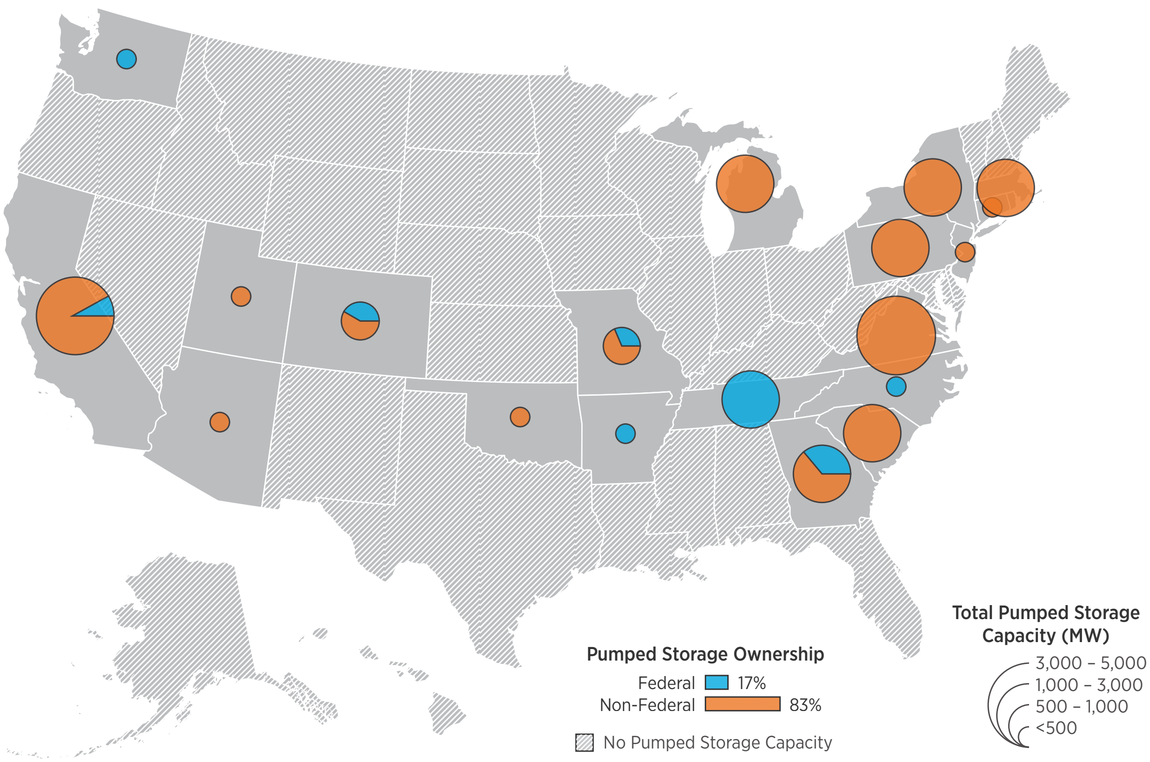



**Figure ES-2.** Existing pumped storage hydropower capacity in the United States (21.6 GW)

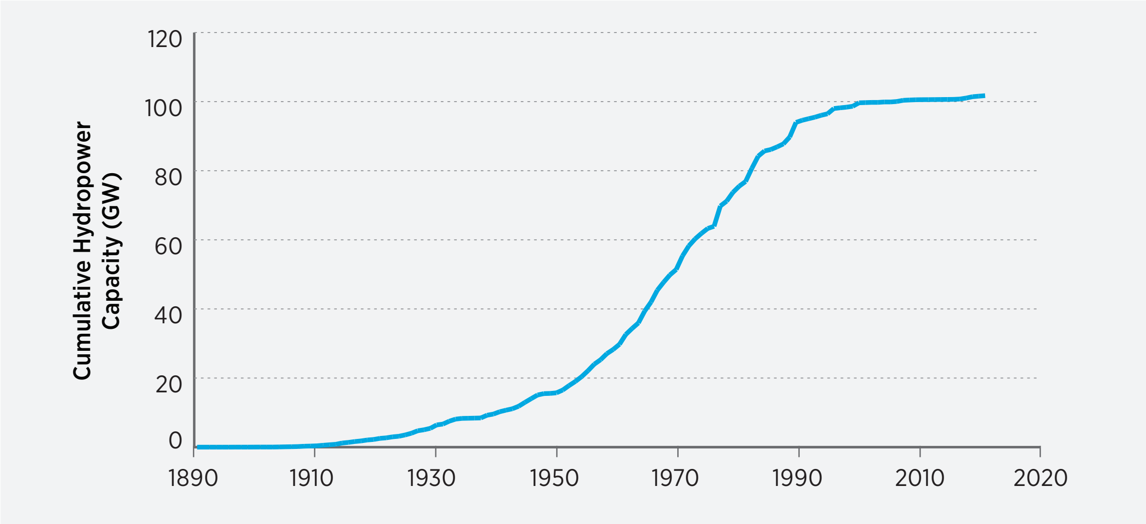



**Figure ES-3.** Cumulative U.S. hydropower capacity (GW), 1890–2015

approximately 143,000 jobs in the United States, including 118,000 total ongoing full-time equivalent jobs in operations and maintenance, and 25,000 temporary jobs in construction and upgrades.[6,7]

**Ownership of the existing hydropower fleet is diverse.** Federal agency ownership (including the U.S. Army Corps of Engineers, the U.S. Bureau of Reclamation, and the Tennessee Valley Authority) accounts for the majority (approximately 49%) of installed capacity; public ownership (including public utility districts, irrigation districts, states, and rural cooperatives) accounts for approximately 24% of installed capacity; and private ownership (including investor-owned utilities, independent power producers, and industrial companies) accounts for approximately 27% of installed capacity.

**Hydropower has provided a cumulative 10% of U.S. electricity generation over the past 65 years (1950–2015), and 85% of cumulative U.S. renewable power generation over the same time period.**

## ES.2.1 Public, Market, and Policy Trends

**The role and emerging future of hydropower is complex given that dams and reservoirs serve many functions, including flood management and control, irrigation, recreation, navigation, and drinking water supply.** The vast majority of the more than 87,000 existing dams in the United States[8] do not include hydropower generation plants. Those that do generate electricity (less than 2,200, or 3%) must meet both the ongoing power and non-power needs of multiple and varied interests and stakeholders within the context of complex regulatory frameworks.

**Reliable electricity delivery is increasingly important in the global flow of information and commerce, and the cost of power interruptions—whether accidental or intentional—makes power system stability and reliability ever more critical to national security.** The U.S. Department of Homeland Security lists the energy sector and the dams sector as two of the sixteen national critical infrastructures.[9] These infrastructures have assets, systems, and networks so vital

6. National Renewable Energy Laboratory, Conventional Hydropower Jobs and Economic Development Impacts (JEDI) model. Last updated November 5, 2015. Accessed July 5, 2016. *http://www.nrel.gov/analysis/jedi/*.

7. U.S. Department of Energy. Prepared by Navigant Consulting, Inc. DOE/EE-1400. Forthcoming (2016). “United States Hydropower Workforce Assessment and Future Scenarios”.

8. U.S. Army Corps of Engineers. 2013 National Inventory of Dams. May 26, 2015. Accessed July 5, 2016. *http://nid.usace.army.mil*.

9. “Critical Infrastructure Sectors.” Last published October 27, 2015. U.S. Department of Homeland Security. Accessed July 5, 2016. *https://www.dhs.gov/critical-infrastructure-sectors*.

to the nation that their incapacitation or destruction would have a debilitating effect on physical security, economic security, and public health and safety.

**Changes and trends in the electric sector call for a fresh look at the future role for hydropower.** Lower natural gas prices, as well as coal and nuclear power plant retirements, contribute to a changing generation mix and potential markets for new generation sources. An increasing need to integrate variable generation resources, such as solar and wind, will lead to greater demand for grid flexibility and balancing services. Hydropower generation and PSH provide these needed services due to their consistent availability and their capability for rapid response to changes in demand.

**Key market drivers of energy storage for grid and ancillary services—which PSH provides—include (1) substantial growth in variable generation; (2) governmental focus on initiatives to reduce carbon emissions; (3) the need for grid infrastructure modernization; and (4) the need to improve the resilience of the electrical grid to unforeseen interruptions.[10]**

**Public policy has long supported deployment of renewable energy at state and regional levels through policies such as renewable portfolio standards and regional GHG initiatives.** Increasing concern about the effects of carbon emissions on climate change led the U.S. Environmental Protection Agency in 2015 to issue carbon pollution standards through the Clean Power Plan, which instructs states to begin making meaningful progress toward reductions by 2022.[11] As policies develop, hydropower can play a role in carbon emissions reductions.

## ES.2.2 Opportunities and Challenges for Hydropower

**Hydropower's system benefits are large and have historically underpinned the nation's electric systems. Hydropower's growth is critically coupled with innovation that can enable hydropower resource opportunities to be economically competitive and environmentally sustainable in the context of other low-carbon energy options.** Keys to improved competitiveness are continued technical innovation to reduce capital and operating expenses, improved understanding and market valuation of system-wide grid reliability and stability services, and recognition and valuation of societal benefits from avoided power sector air pollution and GHG emissions.

Equally important to increasing hydropower's competitiveness are continued improvement in mitigating adverse effects, protection of fish and wildlife, and increased public awareness of progress made in this regard. Addressing these objectives will require continued technical innovation, measurable and implementable environmental sustainability metrics and practices, increased planning at the basin or watershed scale, and access to new science and assessment tools.

**Inherent market and regulatory challenges must be overcome to realize hydropower's potential to improve grid flexibility and facilitate integration of variable generation resources.** The full valuation, optimization, and compensation for hydropower generation and ancillary services in power markets is difficult, and not all benefits and services provided by hydropower facilities are readily quantifiable or financially compensated in today's market framework. In traditional and restructured markets, as well as in emerging environmental markets, many hydropower services and contributions are not explicitly monetized. In some cases, market rules undervalue operational flexibility, which is important to maintaining grid reliability and is a prime attribute of hydropower.

**In April 2016, the Federal Energy Regulatory Commission initiated Docket No. AD16-20-000 to examine whether barriers exist to the participation of electric storage resources—including PSH—in the capacity, energy, and ancillary service markets, potentially leading to unjust and unreasonable wholesale rates.** According to the Commission, this was motivated in part by trends of increasing exploration of the value electric storage resources may provide to the grid when acting as both generation and load and providing transmission services.[12]

10. Eller, A. and A. Dehamna. Energy Storage for the Grid and Ancillary Services. Navigant Consulting, Inc. May 2016 (paid report). Accessed July 5, 2016. *https://www.navigantresearch.com/research/energy-storage-for-the-grid-and-ancillary-services*.

11. U.S. Environmental Protection Agency. Clean Power Plan for Existing Power Plants. Accessed May 8, 2016. *https://www.epa.gov/cleanpowerplan/clean-power-plan-existing-power-plants.*

12. Federal Energy Regulatory Commission. Open Commission Meeting. Staff Presentation Item A-4. April 21, 2016. Accessed July 5, 2016. *http://www.ferc.gov/CalendarFiles/20160421110616-A-4-Presentation.pdf*.

**Uncertainty in licensing-related processes and outcomes may adversely affect development costs, timelines, and financing options.** Existing laws and regulations governing hydropower ensure that project development and operations are carried out responsibly and consistently. However, stakeholders have expressed concerns that regulatory process inefficiencies, overlaps, and interpretations can lead to delays and costs that result in long-term business risks to hydropower owners, operators, and developers.

**Future development of hydropower projects at previously undeveloped sites and waterways is likely to remain limited without innovative—even transformational—advances in technologies and project development methods to meet sustainability objectives.** Ongoing research and development activities, including non-traditional approaches, can lead to significant changes in the cost, configuration, and function of hydropower facilities that could transform development of new hydropower projects in the decades to come.

**Climate change creates uncertainty around water availability for hydropower generation, and this uncertainty can affect the long-term outlook of the hydropower industry.** Water availability—including more water in some areas and less in others—affects the energy production potential of hydropower resources, which in turn influences their economic attractiveness in the electric sector. A changing climate may also potentially impact water quality (e.g., temperature) and availability of water for thermal power plant cooling, while changing temperatures may impact electricity demand.

The degree to which these challenges can be effectively addressed will influence the levels of future hydropower growth and reinvestment in existing facilities and realization of the opportunities and benefits that the low costs, grid services, and long project operating life of hydropower can provide. See Chapter 2 for detailed discussion of the state of the industry and its trends, opportunities, and challenges.

# ES.3 Modeling Hydropower's Contributions and Future Potential

**For the *Hydropower Vision* report, computational electric sector models provided the foundation to carry out comprehensive analyses of the existing and future role of hydropower (hydropower generation and pumped storage) within the electric sector on a national scale.** These analytical modeling methods were used to evaluate a range of possible future outcomes for hydropower deployment based on potential technical innovation, economic factors, national priorities, stakeholder action or inaction, market forces, and requirements of environmental mitigation and environmentally sensitive areas. Because growth potential is tied to a set of complex and unpredictable variables, modeling results serve primarily as a basis to identify key factors and drivers that are likely to influence future pathways. Modeling results in the *Hydropower Vision* should not be interpreted as DOE predictions or targets.

**The primary tool used to assess potential growth trajectories and the basis to evaluate resulting cost and benefit impacts is the National Renewable Energy Laboratory's (NREL's) Regional Energy Deployment System (ReEDS) model.**[13] ReEDS is an electric sector capacity expansion model that simulates the cost of construction and operation of generation and transmission capacity to meet electricity demand and other power system requirements on a competitive basis over discrete study periods—2017, through 2030, and through 2050. Results from ReEDS include estimated electricity generation, geographic distribution of new electricity infrastructure additions, transmission requirements, and capacity additions of power generation technologies built and operated during the study period.

13. Short, W.; Sullivan, P.; Mai, T.; Mowers, M.; Uriarte, C.; Blair, N.; Heimiller, D.; Martinez, A. Regional Energy Deployment System (ReEDS). NREL/TP-6A20-46534. Golden, CO: National Renewable Energy Laboratory, December 2011; 94 pp. Accessed June 30, 2016: *http://www.nrel.gov/analysis/reeds/documentation.html*.

**The modeling analysis assumes policy as legislated and effective on December 31, 2015, including the U.S. Environmental Protection Agency's *Carbon Pollution Standards for Existing Power Plants* (Clean Power Plan).** This analysis cannot comprehensively represent all of the costs or benefits of hydropower. The analysis includes four metrics that DOE can objectively and transparently estimate using best available data, including GHG emissions avoidance. This analysis also does not attempt to assess the costs for past, present, or future environmental impacts and solutions, such as resource protections needed to mitigate potential effects on fish and wildlife.

Both the existing hydropower fleet and the potential for new development are included in the quantitative modeling. Although deployment of existing hydropower facilities occurred over more than a century, modeling results indicate that important growth opportunities remain. Hydropower resource opportunities for potential growth fall into four distinct categories:

1. **Existing power plants and dams** that can be upgraded and optimized for increased production and environmental performance;
2. **New power plants at existing non-powered dams and water conveyances such as canals and conduits** that are not powered but could be cost-effectively leveraged to support hydroelectric facilities;
3. **New and existing pumped storage hydropower** facilities and upgrades, including reservoirs and pumping/generating plants; and
4. **New stream-reach development,** including diversionary methods, new multi-purpose impoundments, or instream approaches.

Capacity additions from canals and conduits, resource potential in Alaska and Hawaii, and the potential for upgrades to existing PSH facilities are not currently within the ReEDS quantitative modeling framework, and therefore are not part of the modeled results. Instead, these resources are discussed qualitatively throughout the *Hydropower Vision* report.

## ES.3.1 Understanding Resource Estimates and Modeling Scenarios

***Hydropower Vision* uses the best available resource assessments to explore hydropower's market potential.** The process of converting existing estimates of total physical or technical resource potential[14] to a modeling result of realistically potential deployment requires making technical, economic, physical, and geographic assumptions and corrections. These assumptions and corrections reduce the size of the resource base to that which will be available to the model.

**The process flow for interpreting hydropower's future market potential from technical resource assessments is represented by Figure ES-4.** The initial resource base considered is denoted in the figure by the "Technical Resource Potential." This resource potential is then reduced to the resource potential available to a capacity expansion model by applying economic and other assumptions and corrections, resulting in the "Modeled Resource Potential." The potential for market deployment is calculated for future scenarios, denoted in the figure by "Modeling Results."

Parameters and assumptions for modeling future deployment scenarios include cost reduction through technology advancement, cost reduction though innovative financial mechanisms, consideration of social and environmental objectives, changes in fossil fuel costs over time, future market penetration of variable generation sources, potential effects of climate change, and others. See Chapter 3 for detailed discussion of resource assessments, the modeling methodology, and modeling results.

14. The technical potential of a specific renewable electricity generation technology estimates energy generation potential based on renewable resource availability and quality, technical system performance, topographic limitations, environmental, and land-use constraints only. The estimates do not consider (in most cases) economic or market constraints, and therefore do not represent a level of renewable generation that might actually be deployed. Source: A. Lopez, Roberts, B., Heimiller, D., Blair, N., and Porro, G. U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis. National Renewable Energy Laboratory. July 2012. NREL/TP-6A20-51946. Accessed June 27, 2016. *http://www.nrel.gov/docs/fy12osti/51946.pdf*.

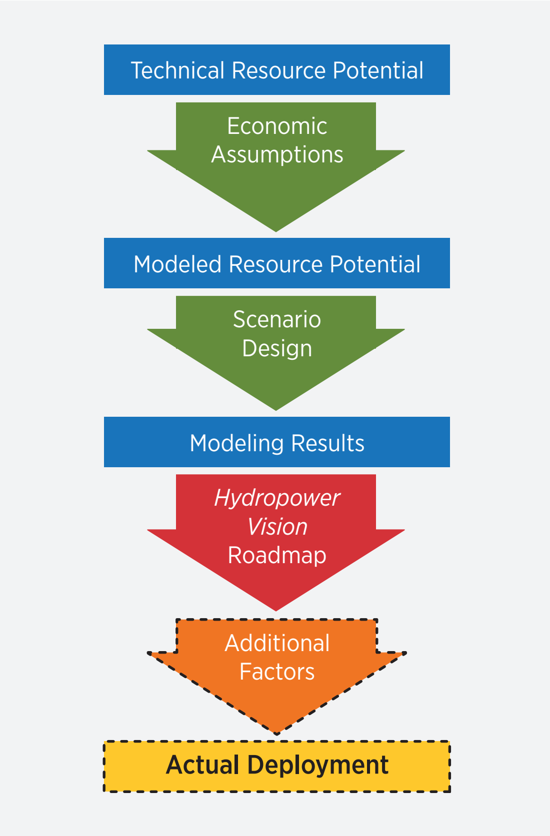



**Figure ES-4.** Process flow for interpreting hydropower's future market potential from technical resource assessments

**While modeling results identify potential deployment pathways and the influence of key parameters, they do not—and cannot—indicate what actual future deployment may be.** As indicated by Figure ES-4, actual deployment will be influenced by additional factors, including macroeconomic conditions, social and environmental considerations, policy, and others that are beyond the scope of the *Hydropower Vision* analysis. The *Hydropower Vision* roadmap (Chapter 4) provides a broad set of actions stakeholders may take to pursue opportunities for potential deployment identified in the modeling results.

## ES.3.2 Understanding the Future Potential for Hydropower

**More than 50 total hydropower deployment scenarios were evaluated by varying hydropower-specific parameters as well as broader non-hydropower specific parameters. The *Hydropower Vision* analysis found that the key drivers influencing deployment of new hydropower capacity were: (1) technology innovation to reduce cost; (2) improved market lending conditions that value the long asset life of hydropower facilities; and (3) the concurrent influence of environmental considerations.**

To consider the future potential for hydropower, the *Hydropower Vision* assesses the impacts of the key drivers through an *Advanced Technology* scenario, assuming significant hydropower cost reductions through innovation; a *Low Cost Finance scenario,* assuming cost savings based on lending terms with longer asset life; and a scenario combining *Advanced Technology* and *Low Cost Finance* scenario settings with a set of *Combined Environmental Considerations* to explore the concurrent influence of environmental considerations and services.[15] Additional scenarios included for reference purposes are a *Business-as-Usual* scenario that assumes continuation of existing, projected, and evolving trends, and a baseline scenario of no new unannounced hydropower to provide a reference baseline and enable social and economic impacts to be calculated. Table ES-1 summarizes assumptions that are constant across all scenarios, including *Business-as-Usual.* Table ES-2 summarizes the resource estimates and modeled resource potential used in the analysis, and model results for selected scenarios.

**The combined effect of the *Advanced Technology* and *Low Cost Finance* assumptions in lowering cost is greater than each effect individually.** For new hydropower generation capacity, *Advanced Technology* assumptions alone have little effect—an additional 0.8 GW by 2050 as compared to 5.2 GW under *Business-as-Usual;* while *Low Cost Finance* assumptions alone provide only a modest increase—an additional 1.8 GW

15. The *Combined Environmental Considerations* scenario avoids new stream-reach development (NSD) resource overlapping with seven environmental considerations and services (critical habitats, ocean connectivity, migratory fish habitat, species of concern, protected lands, national rivers inventory, and low disturbance rivers) to illustrate that accommodating the wide variety of existing values of uses of stream-reaches with NSD potential is essential for realizing sustainable hydropower potential. Regulatory permitting processes are parameters that cannot be varied in the model.

**Table ES-1.** Constants across Modeled Scenarios

| Input Type | Input Description |
|---|---|
| Electricity demand | AEO 2015 Reference Case (average annual electricity demand growth rate of 0.7%) |
| Fossil technology and nuclear power | AEO 2015 Reference Case |
| Non-hydro/wind/solar photovoltaics renewable power costs | NREL Annual Technology Baseline 2015 Mid-Case Projections |
| Policy | As legislated and effective on December 31, 2015.[a] |
| Transmission expansion | Pre-2020 expansion limited to planned lines; post-2020, economic expansion, based on transmission line costs from Eastern Interconnection Planning Collaborative |

Note: "AEO" refers to the U.S. Electricity Information Administration's Annual Energy Outlook.

a. Though the Supreme Court issued a stay of the Clean Power Plan (CPP) in February 2016, the CPP is treated as law in all scenarios. The CPP is modeled using mass-based goals for all states with national trading of allowances available. Although states can ultimately choose rate- or mass-based compliance and will not necessarily trade with all other states, a nationally traded mass-based compliance mechanism is viewed as a reasonable reference case for the purpose of exploring hydropower deployment under a range of electricity system scenarios.

by 2050 as compared to *Business-as-Usual* deployment. However, by combining the two and taking into account sustainability principles through the *Combined Environmental Considerations* assumptions, an additional 7.6 GW is deployed as compared to *Business-as-Usual,* for a total of 12.8 GW of new generation capacity by 2050 (Figure ES-5 and Table ES-2). Nearly three-quarters (73%) of this capacity (9.4 GW) is deployed by 2030 (Table ES-3).

The majority of the 12.8 GW of new capacity through 2050 is from upgrades to existing facilities—5.2 GW is added under *Business-as-Usual,* and an additional 1.1 GW is added under the *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* scenario for a total of 6.3 GW from upgrades to existing facilities (Figure ES-6). To this, 40 MW is added from the powering of NPDs under *Business-as-Usual;* and 4.8 GW is added from the powering of NPDs and 1.7 GW from new stream-reach development (NSD), both under the *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* scenario.

For new PSH capacity, *Advanced Technology* assumptions alone have a modest effect (2.6 GW by 2050) as compared to *Business-as-Usual* deployment (0.5 GW in 2050), while *Low Cost Finance* assumptions alone provide a significant increase in deployment,

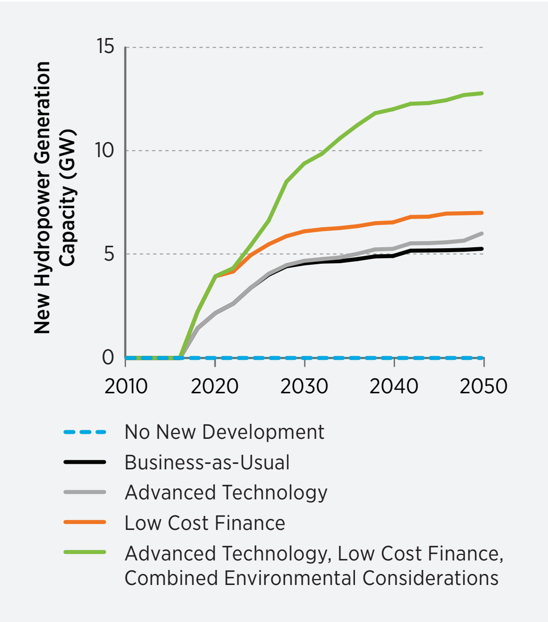



**Figure ES-5.** ReEDS modeled deployment of new hydropower generation capacity, selected scenarios, 2017–2050 (GW)

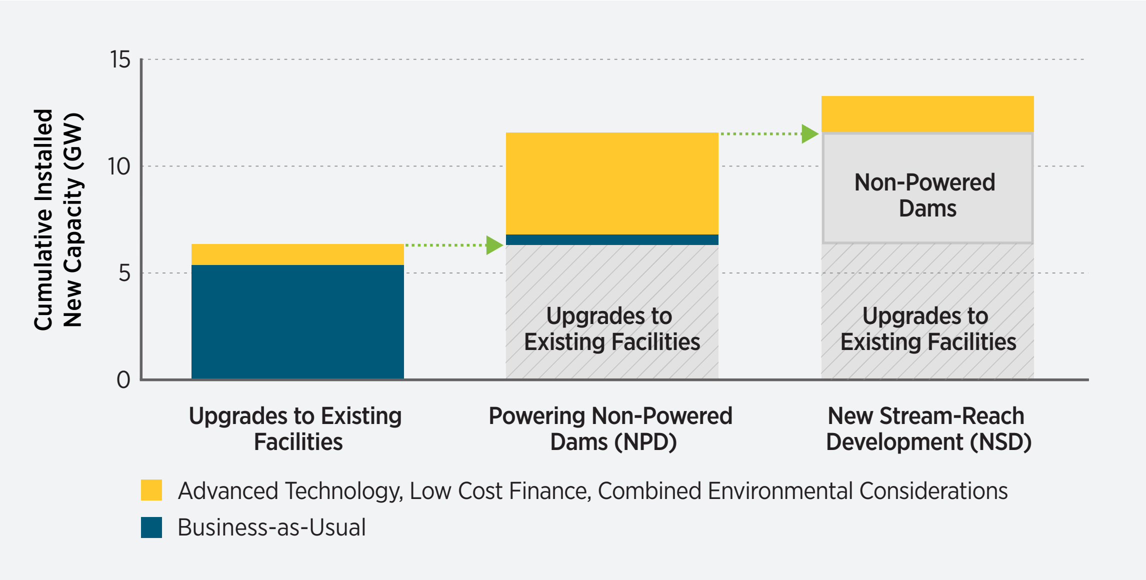



**Figure ES-6.** ReEDS modeled cumulative 2050 deployment of new hydropower generation capacity by resource category (GW)

with 22.6 GW by 2050 (see Figure ES-7). Under the scenario combining *Advanced Technology, Low Cost Finance, Combined Environmental Considerations,* 35.5 GW of new PSH capacity deployment occurs by 2050 (see Table ES-1), with approximately half of this (16.2 GW, or 53%) occurring by 2030 (see Table ES-2).

Deployment of new advanced PSH technology with improved capabilities, such as closed-loop adjustable-speed, can facilitate integration of variable generation—including wind and solar—due to its ability to provide needed operating reserves, grid flexibility, and system inertia. With increased PSH deployment under *Advanced Technology* and *Low Cost Finance* assumptions, PSH provides more operating reserves (52%) than any other technology by 2050. As discussed in Text Box ES-1, the *Hydropower Vision* analysis indicates there is a positive correlation between PSH and variable generation resource deployment.

Notable observations from the analysis of deployment beyond *Business-as-Usual* include:

- U.S. hydropower could grow from 101 GW of combined generating and storage capacity in 2015 to nearly 150 GW by 2050;
- In the near term (before 2030), hydropower generation growth is likely to be driven primarily by optimizing and upgrading the existing fleet, and powering non-powered dams;

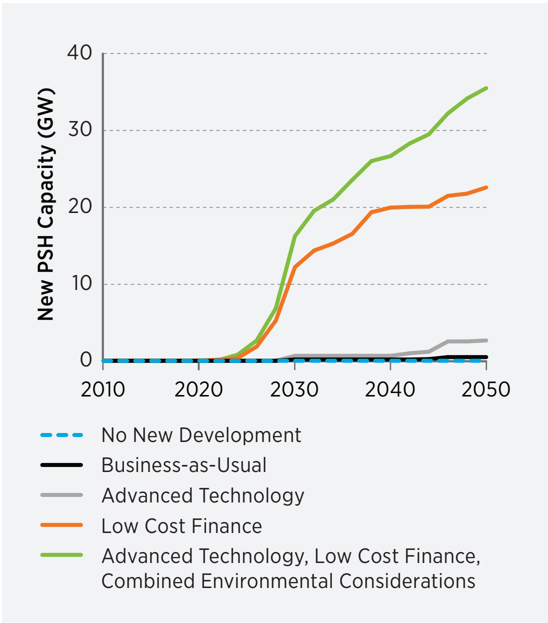



**Figure ES-7.** ReEDS modeled deployment of new pumped storage hydropower capacity, selected scenarios, 2017–2050 (GW)

**Table ES-2.** Resource Estimates, Modeled Resource Potential, and Modeling Results for Cumulative Hydropower Capacity Additions in the United States under Selected Scenarios, 2050

| Resource Category | Technical Resource Potential (GW)[a] | Modeled Resource Potential (GW)[b] | Modeling Results by Scenario, 2050 | | | |
|---|---|---|---|---|---|---|
| | | | *Business-as-Usual Reference* (GW) | *Advanced Technology Only* (GW) | *Low Cost Finance Only* (GW) | *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* (GW) |
| Upgrades and Optimization of Existing Hydropower Plants | 8–10% increase in generation | 6.9 | 5.2 | 5.2 | 6.3 | 6.3 |
| Powering of Non-Powered Dams[b] | 12 | 5 | 0 | 0.8 | 0.7 | 4.8 |
| Powering Existing Canals and Conduits[c] | 2 | n/a | | | | |
| New Stream-Reach Development[d] | 65.5 | 30.7 | 0 | 0 | 0 | 1.7 |
| New Pumped Storage Hydropower | >1,000 | 109 | 0.5 | 2.6 | 22.6 | 35.5 |

Note: Potential in Alaska and Hawaii is not included due to lack of contemporary high-resolution resource assessments.

a. Existing technical potential estimates for NPD were modified to include the removal of some existing dams slated for removal, and the addition of some projects omitted from the 2012 resource assessment.

b. The modeled resource potential is the portion of the technical resource potential made available to the model, e.g., economic assumptions and corrections have been applied to reduce the technical resource potential to the modeled resource potential.

c. Canals and conduits are discussed qualitatively in the report as there have been no nationwide resource assessments for them.

d. Existing technical potential estimates for NSD were modified for reaches in a handful of Western basins that were discovered to have relied on an earlier version of the site sizing methodology.

**Table ES-3.** Summary of Modeling Results for the *Business-as-Usual* and *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* Scenarios in 2030 and 2050

| Resource Category | *Business-as-Usual* Scenario (GW) | | *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* Scenario (GW) | |
|---|---|---|---|---|
| | 2030 | 2050 | 2030 | 2050 |
| **Total New Hydropower Generation Capacity** | 4.5 | 5.2 | 9.4 | 12.8 |
| Upgrades and Optimization of Existing Hydropower Plants | 4.5 | 5.2 | 5.6 | 6.3 |
| Powering of Non-Powered Dams | 0.04 | 0.04 | 3.6 | 4.8 |
| New Stream-Reach Development | 0 | 0 | 0.2 | 1.7 |
| **New Pumped Storage Hydropower Capacity** | 0.2 | 0.5 | 16.2 | 35.5 |
| ***Total New Hydropower Capacity*** | 4.7 | 5.7 | 25.6 | 48.3 |

- In the mid-to-long term (2030–2050), additional growth may come through sustainable deployment of NPD and NSD; and
- PSH growth can increase substantially in both the 2030 and 2050 periods, assisting variable generation growth by providing flexibility and other important grid services (Text Box ES-1).

The analysis provides a quantitative basis for describing the characteristics of potential hydropower deployment in terms of general geographic location, type of resource deployed, resulting electric sector composition, and system cost.

Text Box ES-1.

## Pumped Storage Hydropower Complements Variable Generation

**The United States has significant resource potential for new PSH development. New advanced PSH technology with improved capabilities such as adjustable speed, closed-loop, and modular designs can further facilitate integration of variable generation, such as wind and solar, due to its ability to provide grid flexibility, reserve capacity, and system inertia.**[a] The *Hydropower Vision* analysis (Chapter 3) indicates there is a correlation between PSH and variable generation deployment in the 2050 timeframe (Figure ES-8). The figure indicates that, under the modeling scenario combining *Advanced Technology* and *Low Cost Finance* assumptions, deployment of 35.5 GW of new PSH by 2050 corresponds with roughly 45% of national demand met by variable generation. However, the exact relationship between PSH and variable generation resources is highly dependent on the characteristics of the generation and transmission assets within balancing areas, and the data shown here do not necessarily imply a causal relationship. Modeling does not evaluate or designate specific PSH locations within a balancing area. PSH development will require location-specific compliance with applicable regulations, including environmental considerations.

**PSH is complementary to variable generation, as it can reduce curtailment of excess generation by providing load and energy storage,** thus enabling greater integration of variable generation resources into the system. PSH is a proven low-risk technology with a track record of high efficiency in providing load, energy storage, and grid services. Additionally, PSH is more flexible, has longer facility lifetimes, and has lower operating costs than other technologies that can provide these services in facilitating the integration of variable generation resources onto the grid.

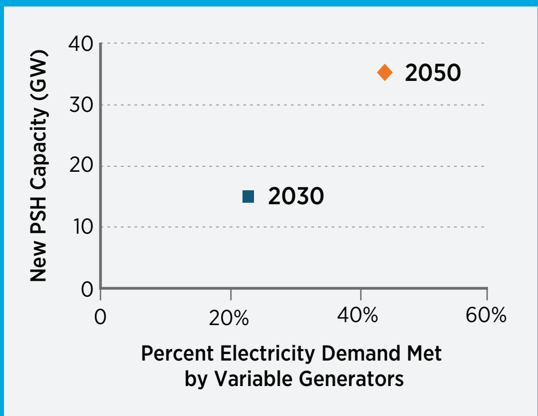



**Figure ES-8.** Relationship between new pumped storage hydropower growth and generation from variable generators under *Advanced Technology* and *Low Cost Finance* assumptions

Because decision makers need better information on the role and value of grid storage, key recommendations for PSH in the *Hydropower Vision* roadmap include the development of tools that would help evaluate the feasibility of conversion from fixed-speed to adjustable-speed technologies, and investigation of market mechanisms that would accurately compensate PSH for the full range of services provided to the power grid.

a. U.S. Department of Energy. February 2015. "Pumped Storage and Potential Hydropower from Conduits. Report to Congress." Accessed July 6, 2016. *http://energy.gov/sites/prod/files/2015/06/f22/pumped-storage-potential-hydropower-from-conduits-final.pdf*

### ES.3.3 Exploring New Hydropower Potential while Addressing Environmental Considerations

**The largest remaining potential for additional hydropower generation capacity is through consideration of further development of new projects on undeveloped stream-reaches.** Significant federal and private investment in research and development into new and transformative hydropower technologies and project designs capable of minimizing adverse environmental and social impacts will be necessary for this resource to be considered (Text Box ES-2).

### ES.3.4 Technical Innovation Can Enable New Stream-Reach Development Projects

**The results of the forward-looking analysis presented in *Hydropower Vision* imply that future development of projects at previously undeveloped sites and waterways (NSD) is likely to remain limited without innovative—even transformational— advances in technologies and project development methods to meet sustainability objectives.** While it is difficult to predict how these advances will take shape in the coming decades, trends in innovation do offer indications of how non-traditional approaches could transform development of hydropower projects. Several examples of nascent design methodologies and technical advances and are provided in Text Box ES-3.

Text Box ES-2.

#### Expanding New Stream-Reach Development Hydropower: A National Sustainability Challenge

**Realizing sustainable and responsible hydropower development means that protecting the wide variety of existing values of stream-reaches with NSD potential is essential.** To examine the influence of environmental and ecological attributes on NSD development and provide better context for the future of the hydropower industry, the *Hydropower Vision* modeling analysis employs a series of sensitivity scenarios exploring how potential NSD deployment intersects with other existing priority uses of the nation's water resources, such as protecting habitat for key aquatic and terrestrial species, and adding drinking water supplies. Under the modeled *Hydropower Vision* scenarios and reflecting on the *Combined Environmental Consideration* scenario, the study finds that 1.7 GW of NSD are realizable in locations where there is no overlap with areas designated to have particular environmental sensitivities by 2050.

**While as of the end of 2015, NSD is the most costly and environmentally challenging class of hydropower to develop, the hydropower community can pursue this resource by developing technology solutions that balance efficiency, economics, and environmental sustainability.** This NSD resource potential provides an opportunity for the nation to look beyond the modeled 1.7 GW deployment scenario. Such potential could be harnessed in a variety of ways, including diversionary methods, new multi-purpose impoundments, or instream approaches. Independent of the methodology considered, new technology options are needed to responsibly and effectively harness opportunities for NSD.

**DOE recognizes that any given growth trajectory for NSD is subject to economic and environmental considerations.** Assessments of NSD potential at the national scale account for factors that preclude development, such as designation as a National Park, Wild and Scenic River, or Wilderness Area, but even sites that appear promising when evaluated at the national scale require comprehensive feasibility assessments at watershed or basin scales. Detailed site assessments consider, for example, the potential presence of threatened and endangered species, cultural sites, and other sensitive or protected resources. Furthermore, consideration of NSD potential could be complemented by consideration of removing non-hydro, obsolete dams and barriers, where the net result could be increased energy yield and more rivers restored to natural conditions.

Text Box ES-3.

## Future Hydropower Technologies

### *Advances in Project Evaluation and Design*

Environmentally sustainable hydropower projects should be sited, built, and operated to balance among ecological considerations—such as species diversity, water quality, recreation, and physical processes within the ecosystem. Innovative approaches that achieve multiple objectives require integrated planning that accounts for multiple factors, including watershed, infrastructure, and socioeconomics. Figure ES-9 illustrates an integrated approach under which natural stream functionality can be taken into account in establishing design objectives, design constraints, and functional requirements during project planning and design. If environmental objectives are integrated fully into the design paradigm for components and facilities from the outset, there will be opportunities for advanced modeling, manufacturing, installation, operation, and maintenance innovations to reduce costs and improve generation and environmental performance simultaneously.

Decision making in project evaluation and design can be enhanced through identification of environmental metrics to model, evaluate, and refine the performance of hydropower systems for specific sites and watersheds. A DOE initiative, Environmental Metrics for New Hydropower, is identifying a suite of scientifically rigorous environmental metrics for use by designers, decision makers, policy makers, researchers and other stakeholders in evaluating hydropower projects. DOE has also initiated a Basin-Scale Opportunity Assessment to develop multidisciplinary approaches and tools for basin-scale water resource planning processes, applying Geographic Information Systems to assimilate and evaluate data in a multi-scale, hydrologic context.

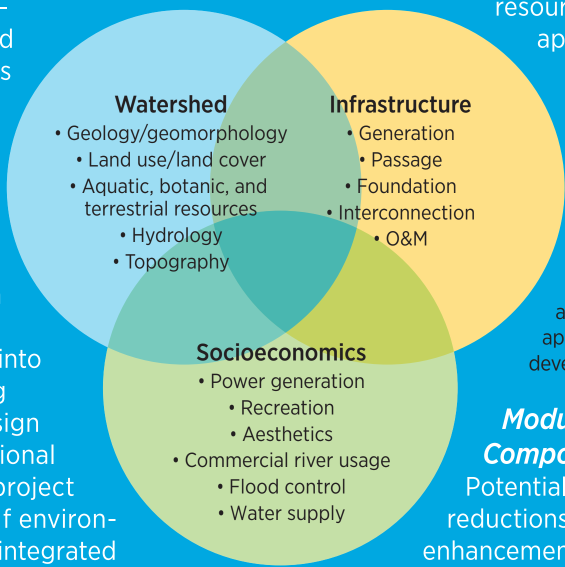



**Figure ES-9.** Primary linkage relations and indices for an integrated approach to hydropower development

### *Modular and Integrated Components*

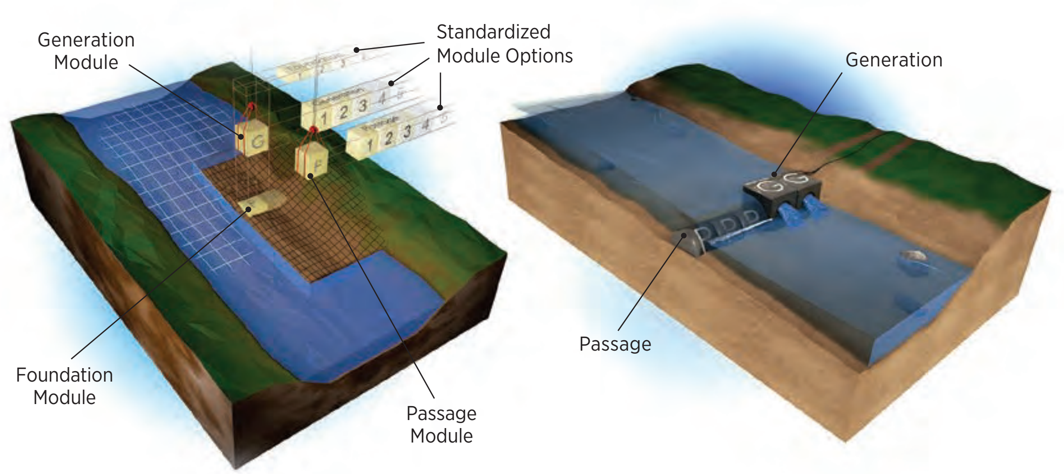
Potential hydropower cost reductions and performance enhancements can be realized through common equipment configurations. Several simplification strategies are emerging, such as integrated turbine/generator units, fabrication using alternative materials and additive manufacturing, and elimination of traditional penstocks and powerhouses.

Figure ES-10 illustrates an example standardized approach under which a suite of modular components for foundation, generation, and stream passage may be considered and fit together to meet site-specific parameters as well as environmental and power generation objectives.

a. Kao, S. C.; McManamay, R. M.; Stewart, K. M.; Samu, N. M.; Hadjerioua, B.; DeNeale, S. T.; Yeasmin, D.; Pasha, M. F. K.; Oubeidillah, A.; Smith, B. T. 2014. New Stream-Reach Development: A Comprehensive Assessment of Hydropower Energy Potential in the United States. GPO DOE/EE-1063. Washington, DC. *http://nhaap.ornl.gov/sites/default/files/ORNL_NSD_FY14_Final_Report.pdf*

b. The assessment methodology considers only the physical characteristics of each stream and landscape—such as hydraulic head and flow—and does not consider feasibility issues arising from environmental impacts, cost, or benefits. Areas protected by federal legislation limiting the development of new hydropower (national parks, wild and scenic rivers, and wilderness areas) are excluded. Only stream-reaches with 35 cubic feet of water per second or greater annual mean flow were considered.

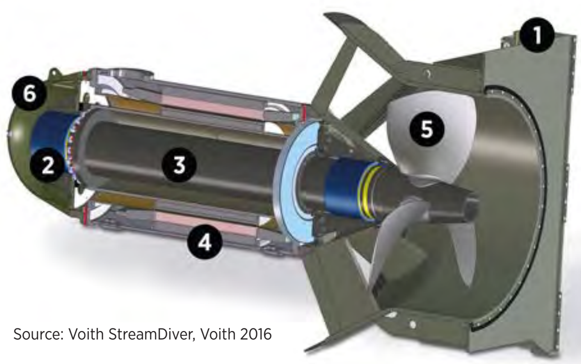
*Text Box ES-3 (continued)*




Source: DOE/Oak Ridge National Laboratory

**Figure ES-10.** Conceptual illustration of modular approach to new in-stream hydropower facility

Potential sites for NSD are predominantly low head with variable flow rates. For these sites, estimated costs would be too high if traditional generating equipment and civil configurations were employed. Several new turbine/generator configurations illustrate how compact integrated designs can simplify facility design, limit the need for civil works, and lower lifetime maintenance requirements. Figure ES-11 offers two designs in which turbines are integrated in one housing with a permanent magnet generator, simplifying both the mechanical and electrical elements of the systems while improving overall efficiency and reliability.




Source: Voith StreamDiver, Voith 2016

1. Turbine housing with guide vanes
2. Radial and axial bearing coating on shaft ends
3. Shaft
4. Generator/turbine
5. Runner
6. Bulb nose

Source: Amjet Turbine, Amjet 2016

**Figure ES-11.** Examples of compact, integrated generator/turbine designs

# ES.4 Results: Overall Positive Benefit to the Nation

**The existing hydropower (hydropower generation and pumped storage) fleet, and new deployment as modeled in the *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* scenario provide significant economic and social benefits: $209 billion savings from avoided global damages from GHG emissions; 6,700–16,200 premature deaths avoided with $58 billion savings in avoided mortality, morbidity, and economic damages from cumulative reduction in emissions of $SO_2$, $NO_X$, and $PM_{2.5}$; and 30 trillion gallons of avoided water withdrawals between 2017 and 2050. Additionally, more than 195,000 jobs are supported in 2050 (Figure ES-12).**

### Benefits—Existing and New Capacity, 2017–2050[a,b,c]

| | Economic Investment | Greenhouse Gases | Air Pollution | Water | Jobs |
|---|---|---|---|---|---|
| **Existing Fleet and New Capacity Additions Combined (149.5 GW)** | $148 billion in cumulative economic investment[d]<br><br>$110 billion for hydropower generation and $38 billion for PSH | Cumulative GHG emissions reduced by 5,600,000,000 metric tons $CO_2$-equivalent, saving $209 billion in avoided global damages | $58 billion savings in avoided mortality, morbidity, and economic damages from cumulative reduction in emissions of $SO_2$, $NO_X$, and $PM_{2.5}$<br><br>6,700–16,200 premature deaths avoided | Cumulative 30 trillion gallons of water withdrawals avoided for the electric power sector | Over 195,000 hydropower-related gross jobs spread across the nation in 2050 |

**Figure ES-12.** Selected benefits and impacts from the existing hydropower fleet and from new deployment, 2017–2050

a. Cumulative benefits are reported on a Net Present Value basis ($2015) for the period of 2017 through 2050.

b. Estimates reported reflect central values within a range of estimates as compared to the *baseline scenario* with no new hydropower.

c. Existing fleet includes new projects and plant retirements announced as of the end of 2015; new development reflects the modeled scenario titled *Advanced Technology, Low Cost Finance, and Combined Environmental Considerations.*

d. Capital investment and annual operating expenses, 2017–2050.

### Benefits—Existing Capacity, 2017–2050[a,b,c]

| | Economic Investment | Greenhouse Gases | Air Pollution | Water | Jobs |
|---|---|---|---|---|---|
| **Existing Fleet (101.2 GW)** | $77 billion in cumulative economic investment[d] | Cumulative GHG emissions reduced by 4,900,000,000 metric tons $CO_2$-equivalent, $184.5 billion savings | $58 Billion savings in avoided mortality, morbidity, and economic damages from cumulative reduction in emissions of $SO_2$, $NO_X$, and $PM_{2.5}$ | Cumulative 30 trillion gallons of water withdrawals avoided for the electric power sector | 120,500 hydropower-related gross jobs spread across the nation in 2050 |

**Figure ES-13.** Selected cumulative benefits and impacts from the existing hydropower fleet, 2017–2050

a. Cumulative benefits are reported on a Net Present Value basis ($2015) for the period of 2017 through 2050.

b. Estimates reported central values within a range of estimates as compared to the *baseline scenario* with no new hydropower.

c. Existing fleet includes new projects and plant retirements announced as of the end of 2015.

d. Capital investment and annual operating expenses, 2017–2050.

To estimate selected impacts, costs, and benefits for both the existing hydropower fleet and for new hydropower capacity deployment, the *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* scenario was compared to a baseline scenario under which no new unannounced (as of 2016) hydropower is built.

## ES.4.1 Impacts: Existing Fleet

The *Hydropower Vision* analysis found that cumulative GHG and air pollution impacts of the existing hydropower fleet between 2017 and 2050 total $185 billion in savings from avoided global damages from power sector GHG emissions and $58 billion in savings from avoided mortality, morbidity, and economic damages from cumulative reduction in emissions of $SO_2$, $NO_x$, and $PM_{2.5}$ (see Figure ES-13), as compared to a baseline of no new unannounced hydropower.

## ES.4.2 Impacts: New Capacity Additions

The cumulative impacts from avoided power sector GHG emissions from new hydropower capacity additions between 2017 and 2050 total nearly $25 billion in savings from avoided global damages (Figure ES-14 and Table ES-4) as compared to *Business-as-Usual.*

**Benefits—New Capacity, 2017–2050**[a,b,c]

| | Economic Investment | Greenhouse Gases | Air Pollution | Water | Jobs |
|---|---|---|---|---|---|
| **New Capacity Additions (48.3 GW)** | $71 billion in cumulative economic investment[d] | Cumulative GHG emissions reduced by 700,000,000 metric tons $CO_2$-equivalent, $24.5 Billion savings | n/a[e] | n/a[f] | 76,000 hydropower-related gross jobs spread across the nation in 2050 |

**Figure ES-14.** Selected benefits and impacts from new hydropower capacity additions under the *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* scenario, 2017–2050

a. Cumulative benefits are reported on a Net Present Value basis ($2015) for the period of 2017 through 2050.

b. Estimates reported reflect central values within a range of estimates as compared to the *baseline scenario* with no new hydropower.

c. Existing fleet includes new projects and plant retirements announced as of the end of 2015; new development reflects the modeled scenario titled *Advanced Technology, Low Cost Finance, and Combined Environmental Considerations*.

d. Capital investment and annual operating expenses, 2017-2050.

e. In the model, once the Clean Power Plan carbon cap is realized, the addition of new hydropower can displace marginal natural gas generation, thereby allowing for additional coal generation—and associated criteria pollutant emissions which reduced the calculated value of avoided air pollution emissions for new hydropower deployment by $6.2 billion over the 2017-2050 time period. However, this result reflects the model's use of AEO 2015 Reference Case natural gas prices, which are higher than those in the more recent AEO 2016 Reference Case. AEO 2016 data were unavailable for inclusion in the *Hydropower Vision* analysis, but lower natural gas prices could allow new hydropower to displace more coal relative to natural gas. Due to the sensitivity of this result to recently updated natural gas price projections, the $6.2 billion reduction in value is not reflected in the total value of avoided $SO_2$, $NO_x$, and $PM_{2.5}$ in the *Advanced Technology, Low Cost Finance, and Combined Environmental Considerations* scenario.

f. Cumulative 2017-2050 water use impacts from new hydropower capacity in the *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* scenario include a 0.1% increase in water withdrawals (0.8 trillion gallons). Given the magnitude of these impacts relative to those from the existing fleet and model precision limitations generally, these results are not reflected in the avoided water use impacts reported here.

**Table ES-4.** Cumulative Impacts[a] of Hydropower under the *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* Scenario, 2017–2050

| Resource Category | Capacity, 2050 (GW) | Avoided GHG Emissions ($B) | Avoided Emissions of $SO_2$, $NO_x$, and $PM_{2.5}$ ($B)[b] | Avoided Water Use (trillion gallons)[c] | Annual Jobs Supported, 2050 |
|---|---|---|---|---|---|
| Existing Hydropower | 101.2 | 184.6 | 57.8 | 30.1 withdrawn, 2.2 consumed | 120,500 |
| New Hydropower | 48.3 | 24.5 | n/a[d] | n/a[e] | 76,000 |
| *Total* | 149.5 | 209 | 57.8 | 30.1 withdrawn, 2.2 consumed | 196,500 |

a. As compared to a baseline scenario, under which no new unannounced (as of 2016) hydropower is built.

b. Savings in avoided mortality, morbidity, and economic damages.

c. Water withdrawal is water that is removed from the ground or diverted from a water source for use, but then returned to that source, Water consumption is water that is removed from the immediate water environment altogether, e.g., through evaporation or use for production and crops.

d. The Clean Power Plan (CPP)—which is estimated to provide substantial air quality benefits[f]—limits total carbon emissions but does not directly limit $SO_2$, $NO_x$, and $PM_{2.5}$ emissions. In the model, once the CPP carbon cap is realized, the addition of new hydropower can displace marginal natural gas generation, thereby allowing for additional coal generation—and associated criteria pollutant emissions which reduced the calculated value of avoided air pollution emissions for new hydropower deployment by $6.2 billion and avoided water withdrawals by 0.8 trillion gallons over the 2017–2050 time period. However, this result reflects the model's use of AEO 2015 Reference Case natural gas prices, which are higher than those in the more recent AEO 2016 Reference Case. AEO 2016 data were unavailable for inclusion in the *Hydropower Vision* analysis, but lower natural gas prices could allow new hydropower to displace more coal relative to natural gas. Due to the sensitivity of this result to recently updated natural gas price projections, the $6.2 billion reduction in value is not reflected in the total value of avoided $SO_2$, $NO_x$, and $PM_{2.5}$ and the 0.8 trillion gallon reduction is not reflected in the avoided water withdrawals total in the Advanced Technology, Low-Cost Finance, and Combined Environmental Considerations scenario.

e. Cumulative 2017-2050 water use impacts from new hydropower capacity in the Advanced Technology, Low-Cost Finance, Combined Environmental Considerations scenario include a 0.1% increase in water withdrawals (0.8 trillion gallons) and a 0.0% change in water consumption (0.00 trillion gallons). Given the magnitude of these impacts relative to those from the existing fleet and model precision limitations generally, these results are also not reflected in the avoided water use impacts reported here; they are however, summarized in the main body of Chapter 3.

f. EPA (Environmental Protection Agency). 2015. Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units. Washington, D.C.: Environmental Protection Agency. Accessed July 6, 2016. *https://www.federalregister.gov/articles/2014/06/18/2014-13726/carbon-pollution-emission-guidelines-for-existing-stationary-sources-electric-utility-generating*.

## ES.4.3 Impacts: Combined Existing Fleet and New Capacity Deployment

The overall impacts to human health through reduction of air pollution from the combined capacity of existing and new hydropower were calculated through 2050 (Chapter 3) for avoided fossil-fueled power plant emissions to comprise 330,000 metric tonnes of $PM_{2.5}$, 2,760,000 metric tonnes of $NO_x$, and 1,640,000 metric tonnes of $SO_2$. These reductions could result in avoidance of 6,700–16,200 premature deaths. Cumulative capital and operating expenditures from 2017 to 2050 are approximately $110 billion for hydropower generation and $38 billion for PSH.

**Key modeling takeaways:**

1. Across the breadth of scenarios, new hydropower capacity could add several billion dollars in societal value in the form of avoided GHG and air pollution emissions, avoided water consumption, and avoided water withdrawals.
2. Investments in the hydropower industry are expected to be on the order of $4.2 billion per year under *Business as Usual*, and $9.9 billion per year under the *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* scenario.
3. The existing fleet will continue to contribute a substantial majority of the societal benefits of hydropower as a whole.

# ES.5 The Way Forward: The *Hydropower Vision* Roadmap

**The *Hydropower Vision* roadmap was developed through extensive collaboration, contributions, and rigorous peer review from industry, the electric power sector, non-governmental organizations, academia, national laboratories, and representatives of government agencies.** The roadmap (Chapter 4) outlines, in a non-prescriptive manner, potential actions for consideration by all stakeholder sectors to address many of the challenges that have affected hydropower (hydropower generation and pumped storage) in recent decades. These roadmap actions are intended to leverage the existing hydropower fleet and potential for sustainable hydropower growth to increase and support the nation's renewable energy portfolio, economic development, environmental stewardship, and effective use of resources through specific technical, environmental, economic, and institutional stakeholder actions. It is beyond the scope and purview of the *Hydropower Vision* to suggest policy preferences or recommendations, and no attempt is made to do so.

**The roadmap actions are based on the three foundational "pillars" of the *Hydropower Vision*—hydropower optimization, growth, and sustainability.** The intended results of the roadmap actions, as aligned to these foundational pillars, are:

- **Optimization:** Investment in technology advancement, modernization, and environmental performance to ensure that the existing wide range of high-value, multi-use benefits of the hydropower fleet do not diminish.
- **Growth:** Development of the next generation of hydropower facilities, and a trained workforce to support them, that leverage untapped infrastructure, technology advancement, plant modernization, improved environmental performance, and cost reduction pathways.
- **Sustainability:** Ensure that environmental objectives are incorporated throughout the full hydropower facility life cycle.

Within the five topical areas listed, the roadmap identifies 21 sub-categories and 64 actions. The *Hydropower Vision* roadmap strategic approach is summarized in Table ES-5 and high-level *Hydropower Vision* roadmap actions are summarized in Table ES-6. The defined roadmap action areas are:

1. **Technology Advancement:** Innovative technology and system design concepts will be essential to attaining the necessary outcomes of cost reduction, improved performance, and environmental stewardship. These include advances such as standardized powertrain components, biologically-based equipment design and evaluation, additive manufacturing, modular civil structure design, and alternative closed-loop PSH systems. Technical progress will require demonstration of environmental mitigation technologies for facilities of all sizes and performance testing and validation of hydropower innovations. New technologies will need to accommodate demands for greater operational flexibility with growing integration of variable generation resources into the electric grid.
2. **Sustainable Development and Operation:** An integrated approach to hydropower project development that incorporates environmental objectives, metrics, and methodologies is required to balance environmental, social, and economic factors in a future in which climate change may influence water resources and ecosystem health. Extensive stakeholder collaboration will be necessary to address interactions of individual hydropower projects with other hydropower projects and water uses within and among basins or watersheds to achieve optimum delivery of power and non-power benefits. Reservoir operations and other basin/watershed factors or competing uses and demands should be evaluated during planning processes to ensure that new development is compatible with and supports multiple objectives under changing energy demands and hydrologic conditions over time.
3. **Enhanced Revenue and Market Structures:** Improved market structures and compensation mechanisms could more appropriately incentivize new and existing hydropower for the numerous services and benefits it provides, including energy production, capacity, ancillary grid support

services, operational flexibility, energy storage, and other essential grid reliability services. Important actions in this area include determining how much flexibility is provided by hydropower in existing grid operations, exploring opportunities to enhance market valuation of that flexibility, and examining how and on what time scale settlement of prices in energy markets could facilitate better utilization of hydropower flexibility to support integration of variable renewable generation resources.

4. **Regulatory Process Optimization:** While the approval and compliance processes administered by various authorities provide a consistent framework to assess potential impact and develop and implement mitigation measures to minimize and avoid those impacts, they also result in uncertainty in field study and administrative costs, and implementation schedules that can render it challenging to undertake, finance, and complete projects. Regulatory process enhancements that reduce implementation timeframes may be possible through process efficiency improvements and by providing stakeholders with an increased knowledge base, easier access to information, and increased capabilities for collaboration. Achieving outcomes more quickly and predictably may reduce the risks and costs to the developer without a reduction in environmental protection. Actions in this topical area include, but are not limited to, assessment of science and technology innovations affecting environmental impact or mitigation.
5. **Enhanced Collaboration, Education, and Outreach:** The awareness of hydropower's benefits as well as its impacts can be increased through development and dissemination of objective and verified information. Hydropower facility owners and developers could benefit from an ongoing national-scale effort to identify and regularly update benchmarks and best practices for maintaining, operating, and constructing hydropower facilities, as well as by performing retrospective operational performance studies. In order to maintain and grow the industry, the nation could sustain and expand its highly qualified and well-trained workforce by developing hydropower-specific curricula for vocational and university programs to motivate, prepare, and provide training opportunities for new professionals to enter the hydropower field.

**Key findings from the roadmap include:**

1. The hydropower industry and research community will need to take an innovative approach to designing a suite of technologies and civil structures that can successfully balance multiple objectives, including cost-effective energy production, penetration of variable renewable generation resources, water management, and environmental protection.
2. Collaboration is critical across all roadmap action areas, whether it's within the industry to develop the next generation of technologies; amongst stakeholders to better improve the regulatory process; or between industry and academia to prepare the incoming workforce.
3. Improving the environmental performance of hydropower technologies can help achieve environmental objectives. Developing a comprehensive set of science-based environmental performance metrics and assessment tools will further the design and sustainable operation of hydropower projects.
4. Undertaking actions such as establishing better mechanisms for collaboration and disseminating successful practices can improve regulatory process implementation.
5. Outreach actions cut across all roadmap areas. Articulating and disseminating objective information regarding hydropower's role as an established and cost-effective renewable energy source, its importance to grid stability and reliability, and its ability to support variable generation can help increase hydropower's acceptance and lead to: (a) increased investor confidence; (b) improved understanding among stakeholders of environmental, social, and regulatory objectives; (c) improved compensation for grid services; and (d) enhanced eligibility in renewable and clean energy markets.

While the roadmap includes collective steps that can be taken by many parties working in concert, it cannot and does not represent federal agency obligations or commitments.

**Table ES-5.** *Hydropower Vision* Roadmap Strategic Approach

| **Core Challenge** | **Facilitate and leverage the existing hydropower fleet and sustainable hydropower growth to increase and support the nation's renewable energy portfolio, economic development, environmental stewardship, and effective use of resources.** | | |
|---|---|---|---|
| **Key Objectives** | **Optimization**<br>Advance the nation's hydropower fleet by maintaining its long-standing economic value, energy contribution, and critical water management infrastructure, while modernizing and optimizing its facilities, operations, and environmental performance. | **Growth**<br>Expand hydropower through innovative technologies, utilization of existing infrastructure, enhanced value recognition in electricity and environmental markets, and improved efficiency in regulatory processes. | **Sustainability**<br>Maintain the overall value of hydropower to the nation through balancing economic, social, and energy-related factors with the co-objective of responsible environmental stewardship. |
| **Intended Results** | Investment in technology advancement, modernization, and environmental performance to ensure that the existing wide range of high-value, multi-use benefits of the hydropower fleet do not diminish. | Development of the next generation of hydropower facilities—and a trained workforce to support them—that leverage untapped infrastructure, technology advancement, plant modernization, improved environmental performance, and cost reduction pathways. | Capture and increase of the enduring economic and social value of hydropower through reduction of environmental impacts and continuous improvement of power systems and other project resources to ensure that sustainability objectives are incorporated throughout the full hydropower facility life cycle. |
| **Linkage to *Hydropower Vision*** | The modeling within the *Hydropower Vision* presents potential hydropower development scenarios based on varying assumptions about key factors influencing growth over a 35-year period and beyond. Activities undertaken within the five Action Areas listed below are designed to incorporate the Core Challenge, Key Objectives, and Intended Results, and can significantly affect which of those development scenarios will ultimately be realized. | | |
| **Roadmap Action Areas** | 4.1 Technology Advancement<br>4.2 Sustainable Development and Operation<br>4.3 Enhanced Revenue and Market Structures<br>4.4 Optimizing Regulatory Process Optimization<br>4.5 Enhanced Collaboration, Education, and Outreach<br>*Roadmap Action Areas are numbered "4.x" in order to correspond with Chapter 4 of the Hydropower Vision report.* | | |
| **Sectors of Potential Growth** | • Upgrades to existing hydropower facilities (Upgrades)<br>• Powering of existing non-powered dams (NPD)<br>• Installations in existing water conveyance infrastructure (Conduits)<br>• Pumped storage hydropower (PSH)<br>• New stream-reach development (NSD)<br>*Each action in the roadmap indicates the specific growth sector(s) to which it applies.* | | |

**Table ES-6.** High-Level *Hydropower Vision* Roadmap Actions
*(Roadmap Action Areas are numbered "4.x" in order to correspond with Chapter 4 of the Hydropower Vision report.)*

| |
|---|
| **4.1 Technology Advancement** |
| **Action 4.1.1—Develop Next-Generation Hydropower Technologies**<br>The next generation of hydropower and PSH technologies must be able to realize high efficiencies and enhanced performance, while minimizing environmental footprint and lowering capital costs. |
| **Action 4.1.2—Enhance Environmental Performance of New and Existing Hydropower Technologies**<br>Environmental performance (e.g., fish survival rates, water quality) of hydropower and PSH technologies is a significant concern of all parties and should thus be evaluated and, when necessary, modified to ensure continual improvement. |
| **Action 4.1.3—Validate Performance and Reliability of New Hydropower and PSH Technologies**<br>Validating performance of new hydropower and PSH technologies can increase investor confidence, thereby facilitating greater deployment of new capacity. |
| **Action 4.1.4—Ensure Hydropower Technology Can Support Increased Use of Variable Renewable Generation Resources**<br>Technology innovation can minimize increased wear and tear on hydropower and PSH machinery that results from increased penetrations of variable renewable generation resources, such as wind and solar, in power systems. |
| **4.2 Sustainable Development and Operation** |
| **Action 4.2.1—Increase Hydropower's Resilience to Climate Change**<br>Providing frameworks for assessing climate change impacts can improve the ability of hydropower projects to operate under resultant increases in variability (e.g., temporal and spatial changes in water availability or water use). |
| **Action 4.2.2—Improve Coordination among Hydropower Stakeholders**<br>Improved coordination and collaboration among hydropower stakeholders can facilitate better realization of multiple objectives (e.g., social, environmental, electricity generation) through hydropower development planning. |
| **Action 4.2.3—Improve Integration of Water Use within Basins and Watersheds**<br>The development of innovative tools and approaches can increase opportunities for better integration of multiple water uses and objectives. |
| **Action 4.2.4—Evaluate Environmental Sustainability of New Hydropower Facilities**<br>Developing quantifiable environmental sustainability metrics and applying them to the development and operation of new hydropower facilities can lead to greater consistency in permitting processes and qualification for national, state, and local renewable energy goals. |
| **4.3 Enhanced Revenue and Market Structures** |
| **Action 4.3.1—Improve Valuation and Compensation of Hydropower in Electricity Markets**<br>Enhancing existing market approaches and developing new approaches can help facilitate full recognition and compensation of the suite of grid services, operational flexibility, and system-wide benefits offered by new and existing hydropower. |
| **Action 4.3.2—Improve Valuation and Compensation of PSH in Electricity Markets**<br>Enhanced market rules related to scheduling and operation of PSH in electricity markets can facilitate use of the full value of this energy storage technology. |

*Continued next page*

*Table ES-6. continued*

| |
|---|
| **Action 4.3.3—Remove Barriers to the Financing of Hydropower Projects**<br>The economics of developing new hydropower projects can be improved by facilitating access to low-cost capital and investors with long-term perspective. |
| **Action 4.3.4—Improve Understanding of and Eligibility/Participation in Renewable and Clean Energy Markets.**<br>Creating a set of tools to better understand policy rules and market eligibility can help reduce confusion and point developers towards the highest value markets for which their hydropower projects are eligible. |
| **4.4 Regulatory Process Optimization** |
| **Action 4.4.1—Provide Insights into Achieving Improved Regulatory Outcomes**<br>Identifying and disseminating best practices can help lead to successful energy, environment-related, and socioeconomic outcomes of the hydropower regulatory process. |
| **Action 4.4.2—Accelerate Stakeholder Access to New Science and Innovation for Achieving Regulatory Objectives**<br>Improving the ability of stakeholders to use new science and innovation can enhance environmental outcomes; increase the value of hydropower facilities; and reduce costs of permitting, licensing, and compliance. |
| **Action 4.4.3—Analyze Policy Impact Scenarios**<br>Improving the ability to assess potential impacts of policy options on markets, power systems, ecosystems, and populations—all on local, regional, and national scales—can inform decision makers. |
| **Action 4.4.4—Enhance Stakeholder Engagement and Understanding within the Regulatory Domain**<br>Activities under this action will ensure all stakeholders have access to the knowledge and experience necessary to participate effectively in planning, decision making, and regulatory processes. |
| **4.5 Enhanced Collaboration, Education, and Outreach** |
| **Action 4.5.1—Increase Acceptance of Hydropower as a Renewable Energy Source**<br>Demonstrating and communicating that hydropower is a core renewable energy source can both increase public understanding and encourage inclusion of hydropower in clean energy planning and markets, as appropriate. |
| **Action 4.5.2—Compile, Disseminate, and Implement Best Practices and Benchmarking in Operations and Research and Development**<br>Compiling and disseminating methods and best practices from leading performers in all segments of the hydropower industry can drive improvements in hydropower performance. |
| **Action 4.5.3—Develop and Promote Professional and Trade-Level Training and Education Programs**<br>Evaluating and developing comprehensive training and education programs, with engagement from high school to university and trade school levels, can help encourage and anticipate the technical and advanced-degree workforce required to meet the industry's long-term needs. |
| **Action 4.5.4—Leverage Existing Research and Analysis of the Federal Fleet in Investment Decisions**<br>Extensive research data about the federal hydropower fleet exist and should be made available in compiled form to be used by policymakers and agency staff in making federal investment decisions. |
| **Action 4.5.5—Maintain the Roadmap in Order to Achieve the Objectives of the *Hydropower Vision***<br>The *Hydropower Vision* roadmap should be regularly updated by tracking hydropower technology advancement and deployment progress, and prioritizing research and development activities. |

# ES.6 Conclusions

**One of the greatest challenges for the United States in the 21st century is producing and making available clean, affordable, and secure energy. Hydropower (hydropower generation and pumped storage) has been and can continue to be a substantial part of addressing that challenge.** Although the hydropower industry has adopted improved technology and exhibited significant growth over the past century, the path that led to its historical growth rates is different today, and continued evolution of that path—including transformative innovation—is needed.

**The *Hydropower Vision* report highlights the national opportunity to capture additional domestic low-carbon renewable energy with responsible development of advanced hydropower technologies across all U.S. market sectors and regions.** Where objectively possible, the analysis quantifies the associated costs and benefits of this deployment and provides a roadmap for the collaboration needed for successful implementation.

## ES.6.1 The Opportunity

**The *Hydropower Vision* analysis modeled a future scenario combining *Advanced Technology*, *Low Cost Finance,* and *Combined Environmental Considerations*, finding that U.S. hydropower could grow from 101 GW of combined generating and storage capacity in 2015 to nearly 150 GW by 2050, realizing over 50% of this growth by 2030. Growth under this modeled scenario would result from a combination of 13 GW of new hydropower generation capacity (upgrades to existing plants, adding power at existing dams and canals, and limited development of new stream-reaches), and 36 GW of new pumped storage capacity.** Additional NSD above this scenario could conceivably become economically viable in the future if significant and transformative innovation were achieved that could address a range of environmental considerations. Increasing hydropower can simultaneously deliver an array of benefits to the nation that address issues of national concern, including climate change, air quality, public health, economic development, energy diversity, and water security. For example, the 5.6 gigatonnes of carbon dioxide equivalent[16] avoided over the period 2017–2050 delivers $209 billion in savings for avoided global damages. Based on the cost quantifications of the *Hydropower Vision,* the value of these types of long-term social benefits can be provided by hydropower and exceed the initial industry investment. Additionally, new PSH technology can further facilitate integration of variable generation resources such as wind and solar into the national power grid due to its ability to provide grid flexibility, reserve capacity, and system inertia.

## ES.6.2 The Risks of Inaction

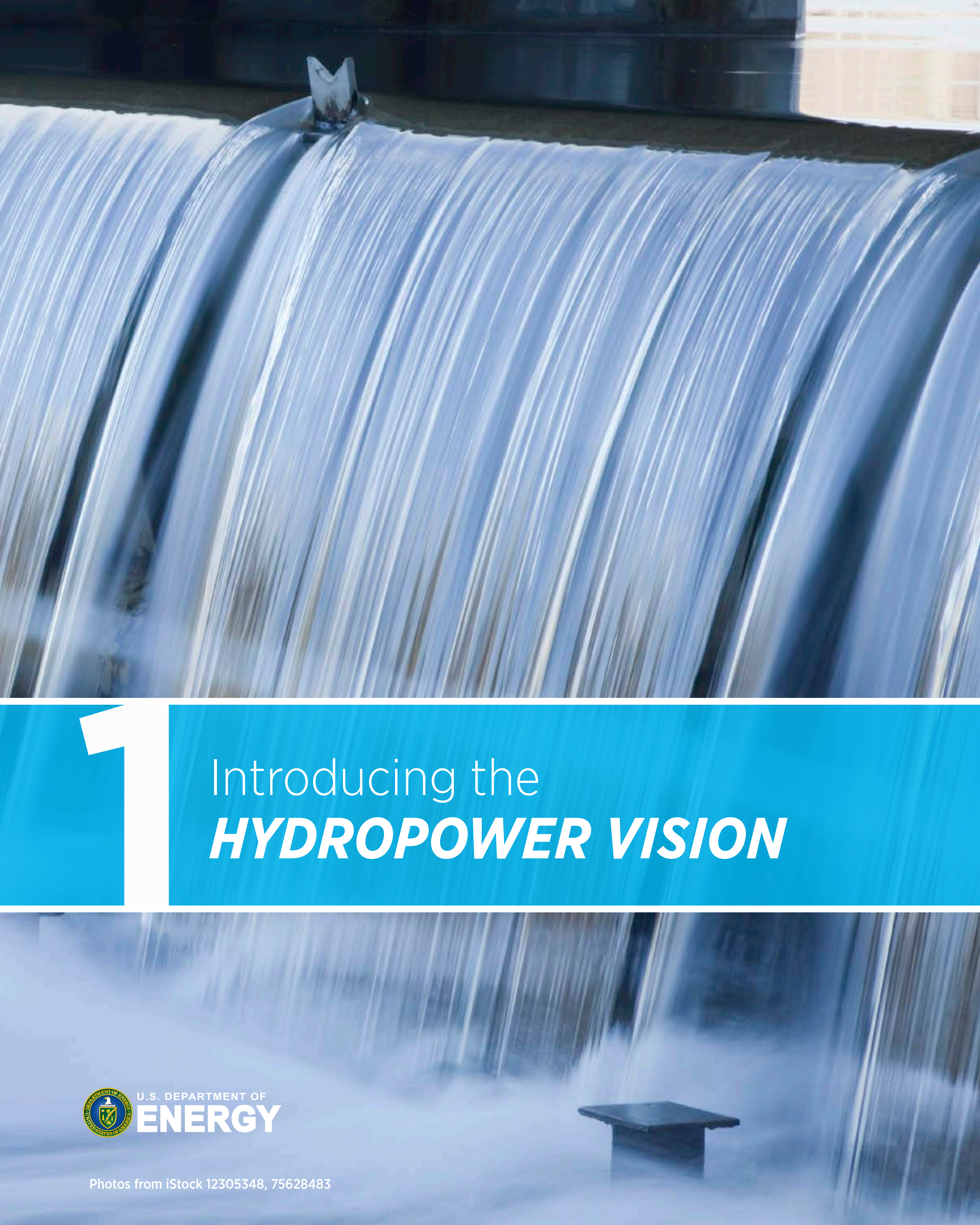
**While the industry is mature, many actions and efforts remain critical to further advancement of domestic hydropower as a key energy source of the future. This includes continued technology development to increase efficiency, advance sustainability, and drive down costs, as well as the availability of market mechanisms that take into account the value of grid reliability services, air quality and reduced emissions, and long asset lifetimes.** The lack of well-informed, coordinated actions to meet these challenges reduces the likelihood that potential benefits to the nation will be realized. Failure to address business risks associated with hydropower development costs and development timelines—including uncertainties related to negotiation of interconnect

16. Carbon dioxide equivalent is a measure used to compare the emissions from various greenhouse gases based upon their global warming potential. "Glossary of Statistical Terms, Carbon Dioxide Equivalent." Last updated April 4, 2013. Organization for Economic Co-operation and Development. Accessed July 7, 2016. *https://stats.oecd.org/glossary/detail.asp?ID=285.*

fees and power sales contracts, regulatory process inefficiencies, environmental compliance, financing terms, and revenue sources— could mean that opportunities for new deployment will not be realized. Engagement with the public, regulators, and other stakeholders is needed to address environmental considerations effectively. Continued research and analysis on energy policy and hydropower costs, benefits, and effects is important to provide accurate information to policymakers and for public discourse. Finally, regularly revisiting the *Hydropower Vision* roadmap and updating priorities across stakeholder groups and disciplines is essential to ensuring coordinated pathways toward a robust and sustainable hydropower future.

## ES.6.3 The Way Forward

**The *Hydropower Vision* roadmap identifies a high-level portfolio of new and continued actions and collaborations across many fronts to help the nation realize the long-term benefits of hydropower, while protecting the nation's energy, environmental, and economic interests.** Stakeholders and other interested parties must take the next steps in refining, expanding, operationalizing, and implementing a credible hydropower future. These steps could be developed in formal working groups or informal collaborations and will be critical in overcoming the challenges, capitalizing on the opportunities, and realizing the national benefits detailed in the *Hydropower Vision* report.



# 1 Introducing the *HYDROPOWER VISION*

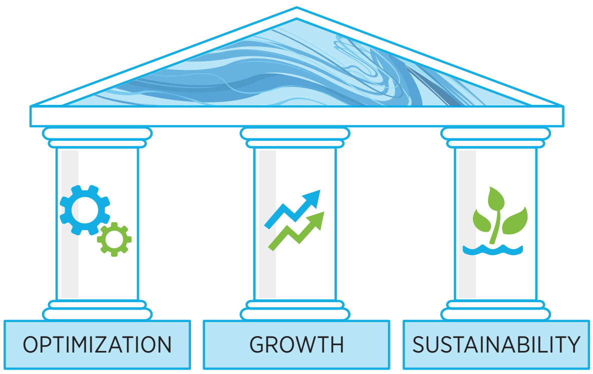
U.S. DEPARTMENT OF ENERGY

Photos from iStock 12305348, 75628483



# Overview

Hydropower has provided clean, affordable, reliable, and renewable electricity in the United States and supported development of the U.S. power grid and the nation's industrial growth for more than a century. In addition to providing a stable and consistently low-cost energy source throughout decades of fluctuations and fundamental shifts in the electric sector, hydropower is a scalable, reliable generation technology that offers operational flexibility to maintain grid reliability and support integration of variable generation resources.




**The *Hydropower Vision* report is grounded on three equally important foundational pillars arrived at through extensive stakeholder input.**

A range of cost-effective, low-carbon generation options—including hydropower—are required to reduce and avoid the power-sector emissions that contribute to climate change and human health impacts. As such, the U.S. Department of Energy's (DOE's) Wind and Water Power Technologies Office has led a broad-based collaborative effort to develop a first-of-its-kind comprehensive analysis identifying a set of potential pathways for the environmentally sustainable expansion of hydropower in the United States.

## *Developing a Hydropower Vision*

Developed through DOE's collaboration with more than 300 experts from over 150 hydropower industry companies, environmental organizations, state and federal governmental agencies, academic institutions, electric power system operators, research institutions, and other stakeholder groups, the *Hydropower Vision* report documents a set of pathways to responsibly manage, optimize, and develop the hydropower sector in a manner that maximizes opportunities for low-cost, low-carbon renewable energy production, economic stimulation, and environmental stewardship to provide long-term benefits for the nation.

The *Hydropower Vision* is grounded in three foundational principles, or "pillars"—optimization, growth, and sustainability—arrived at through extensive stakeholder input and identified as critical to ensuring the integrity of the research, modeling, and analysis conducted during the *Hydropower Vision* collaborative process. These pillars are defined as follows:

- **Optimization**: Optimize the value and the power generation contribution of the existing hydropower fleet within the nation's energy mix to benefit national and regional economies; maintain critical national infrastructure; and improve energy security.
- **Growth**: Explore the feasibility of credible long-term deployment scenarios for responsible growth of hydropower capacity and energy production.
- **Sustainability**: Ensure that hydropower's contributions toward meeting the nation's energy needs are consistent with the equally important objectives of environmental stewardship and responsible water use management.

Several key insights of the *Hydropower Vision* collaborative effort that characterize the role hydropower has and can play in the U.S. power sector are discussed throughout Chapter 1.

## *Understanding the Role of U.S. Hydropower*

Hydropower is a cornerstone of the U.S. electric grid, providing low-cost, low-carbon, renewable, and flexible energy services. As of 2015 year-end, the U.S. had a total installed hydropower capacity of 101 gigawatts (GW), consisting of 79.6 GW of hydropower generation plants and 21.6 GW of pumped storage hydropower (PSH). As of the beginning of 2014, hydropower supported approximately 143,000 jobs in the United States, with 2013 hydropower-related expenditures supporting $17.1 billion in capital investment and $5.9 billion in wages paid to workers.

Existing hydropower facilities have high value based on their ability to provide flexible generation and energy services; ancillary grid services; multi-purpose water management; and social and economic benefits, including avoidance of criteria air pollutants[1] and greenhouse gas (GHG) emissions. Hydropower is the largest U.S. renewable power source, providing approximately half (48%) of all U.S. renewable power in 2015.

## *Key Factors and Trends Motivating the Hydropower Vision*

Trends specific to the U.S. electric sector, as well as broader national and global factors, motivated the development of the *Hydropower Vision.* A range of cost-effective, low-carbon generation options—including hydropower—are needed to reduce the power-sector emissions that contribute to climate change. A secure and stable domestic energy sector, including critical energy and water management infrastructure, is needed to support national energy and climate security.

Because hydropower is a stable renewable resource with long-lived infrastructure, it can provide a hedge against the future volatility of electricity prices in a changing market. While increases in U.S. natural gas resources and declines in natural gas cost from 2009 through 2015 have contributed to an increased share of natural-gas-fired electric generation capacity in the U.S. electric generation mix, several existing coal and nuclear plants have retired or announced pending retirement due to market competition, safety, or other reasons. This has allowed new markets for generation, including renewable generation, to open up. Hydropower is complementary to increased integration of variable generation resources, such as wind and solar, into the power system, since hydropower can reduce curtailment of excess generation by providing load management and energy storage.

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1. The Clean Air Act requires the U.S. Environmental Protection Agency to set National Ambient Air Quality Standards for six common air pollutants (criteria pollutants) based on the human health-based and/or environmentally-based criteria. See *https://www.epa.gov/criteria-air-pollutants* .

## Opportunities and Challenges for Hydropower

While hydropower's system-wide benefits are large and have historically underpinned the nation's electric systems, hydropower's future growth is coupled with the ability of innovation to enable hydropower resource opportunities to be economically competitive and environmentally sustainable. Keys to improved competitiveness are continued technical innovation to reduce capital and operating expenses; improved understanding and market valuation of system-wide grid reliability and stability services; and recognition and valuation of societal benefits from avoided power-sector air pollution and GHG emissions. Equally important to increasing hydropower's competitiveness is continued improvement in mitigating adverse effects, such as impacts on fish and wildlife, and increased public awareness of progress made in this regard.

Future hydropower development will require close coordination among developers, regulators, and affected stakeholders to reduce potential conflicts and meet multiple objectives pertaining to the use of water resources. There is increasing interest in these types of planning processes being carried out at the scale of entire river basins to better address potential system effects and the diverse set of interests that may be affected by a given project.

## Modeling Hydropower's Contributions and Future Potential

Hydropower has the potential to grow and contribute to additional electricity production in the future generation portfolio. In the near term, there is significant potential for economically and environmentally sustainable growth by optimizing existing infrastructure through facility upgrades, and adding generation capabilities to non-powered dams (NPD) and water conveyances such as irrigation canals. In the longer term, capacity may be added through new stream-reach development (NSD). Additionally, the United States has resource potential for new pumped storage hydropower (PSH) development as a storage technology, which can enable grid flexibility and greater integration of variable generation resources.

*Hydropower Vision* uses the best available resource assessments to explore hydropower's market potential. Chapter 1 explains the process for interpreting hydropower's future market potential from technical resource assessments, using computational economic and dispatch models. These models provided the foundation to carry out comprehensive analyses of the existing and future role of hydropower within the electric sector on a national scale, and were used to evaluate a range of possible future outcomes for hydropower deployment. Actual deployment will be influenced by additional factors, including macroeconomic conditions, social and environmental considerations, policy, and others that are beyond the scope of the *Hydropower Vision* analysis.

## Future Hydropower Technologies

Long-term hydropower growth potential, particularly at undeveloped sites (new stream-reaches), will be influenced by the extent to which new hydropower technologies and projects are able to be developed at lowered costs and with improved environmental performance. Chapter 1 describes innovations and non-traditional approaches in project development and applications of advanced technologies that could transform development of new hydropower projects in the decades to come. Integrated planning methods may allow advanced modeling, manufacturing, installation, operation, and maintenance innovations to reduce costs and improve generation and environmental performance simultaneously. Advanced technology approaches include cost-conscious design and manufacturing processes, modular systems, compact turbine/generator designs, and innovative passage technologies.

## The Hydropower Vision Roadmap

Technical design innovation, implementation of advanced project strategies, optimization of regulatory processes, and application of the principles of sustainability will all be important to determining hydropower's future. The *Hydropower Vision* roadmap (Chapter 4) outlines a non-prescriptive set of actions for consideration by all stakeholder sectors to address many of the challenges that have affected hydropower projects. Addressing these challenges can facilitate the optimization, growth, and sustainability of the nation's hydropower sector. Chapter 1 details several key insights from the roadmap.

### *Opportunity, Risk of Inaction, and the Way Forward*

The *Hydropower Vision* analysis (Chapter 3) found that hydropower's economic and societal benefits are significant and include cost savings in avoided mortality, morbidity, and economic damages from power-sector emissions of criteria air pollutants and avoided global damages from GHG emissions. Hydropower has been, and can continue to be, a substantial part of addressing the challenge of producing and making available clean, affordable, and secure energy for the nation.

The analysis modeled a credible future scenario combining assumptions on advanced technology, low-cost finance, and a combination of environmental considerations. The results indicate that U.S. hydropower could grow from 101 GW of combined generating and storage capacity in 2015 to nearly 150 GW by 2050, with more than 50% of this growth realized by 2030. However, while the industry is mature, many future actions and efforts remain critical to further advancement of domestic hydropower as a key energy source of the future. As previously noted, the *Hydropower Vision* roadmap identifies a high-level portfolio of new and continued actions and collaborations across many fronts to help the United States realize the long-term benefits of hydropower while protecting the nation's energy, environmental, and economic interests.

# 1.0 Introduction

Hydropower has provided clean, affordable, reliable, and renewable electricity in the United States for more than a century. As of 2016, hydropower accounted for more than 6% of net U.S. power-sector electricity generation, nearly 9% of U.S. electric generating capacity, and 97% of U.S. utility-scale electrical storage capacity [1, 2, 3]. Because a range of cost-effective, low-carbon generation options—including hydropower—are required to reduce and avoid the power-sector emissions that contribute to climate change and human health impacts, the U.S. Department of Energy's (DOE's) Wind and Water Power Technologies Office has led a first-of-its-kind comprehensive analysis to identify a set of potential pathways for the environmentally sustainable expansion of hydropower in the United States.

Hydropower has supported development of the U.S. power grid and the nation's industrial growth through the 20th century and into the 21st century. In addition to providing a stable and consistently low-cost energy source throughout decades of fluctuations and fundamental shifts in the electric sector, hydropower is a scalable, reliable generation technology that offers operational flexibility to maintain grid reliability and support integration of variable generation resources. Hydropower infrastructure is long-lived, and the resource is generally stable and predictable over long time periods.

Formulated through a broad-based collaborative effort, the *Hydropower Vision* initiative was undertaken to realize four primary objectives:

- Document the history and existing state of hydropower—consisting of both hydropower generation and pumped storage hydropower (PSH)—in the United States, including key technical advancements, societal benefits, and areas that must be addressed to facilitate future opportunities for sustainable hydropower development and operations;[2]
- Identify potential pathways for hydropower to expand its contribution to the electricity and water management needs of the nation from 2017 through 2030 and 2050, including supporting the growth of other renewable energy technologies, reducing carbon emissions, improving air quality, reducing water used for thermal cooling in the power sector, and fostering economic development and job growth;
- Examine critical environmental and social factors to assess how existing hydropower operations and potential new projects can be operated and delivered to minimize adverse effects and realize highest overall benefit; and
- Develop a roadmap identifying sets of stakeholder actions that could support continued responsible planning, operations, and expansion of new and existing hydropower facilities.

2. Hydropower, as assessed in this report, includes new or conventional technologies that use diverted or impounded water to create hydraulic head to power turbines, and pumped storage hydropower facilities in which stored water is released to generate electricity and then pumped to replenish a reservoir. Throughout this report, the term "hydropower" generally encompasses all categories of hydropower. If a distinction needs to be made, the term "hydropower generation" distinguishes other types of projects from "pumped storage hydropower," or PSH.

# 1.1 Developing a *Hydropower Vision*

The *Hydropower Vision* report was developed with extensive stakeholder engagement, including input from multiple federal agencies involved in water resource issues. The *Hydropower Vision* establishes principles of optimization, growth, and sustainability for the nation's hydropower sector, and provides insights highlighting hydropower's importance to the nation.

**The *Hydropower Vision* was developed with extensive stakeholder engagement.**

The *Hydropower Vision* report resulted from DOE's collaboration with more than 300 experts from over 150 hydropower industry companies, environmental organizations, state and federal governmental agencies, academic institutions, electric power system operators, research institutions, and other stakeholder groups. Collectively, these participants were instrumental in documenting the state of the industry and identifying future opportunities for growth, as well as pinpointing challenges that need to be addressed to assure hydropower continues to evolve and contribute value to the nation for decades to come.

Individual expert opinion was provided at regular intervals throughout the project by a Senior Peer Review Group comprising 17 senior executives who are intimately aware of hydropower deployment and market issues. The group included broad representation of the hydropower industry, electric power sector, non-governmental organizations, developers, and federal agencies. The Senior Peer Review Group individually provided their review of the report and did not function as a consensus-building body. All decisions regarding final report content were made by DOE. The Senior Peer Review Group and DOE adhered to the requirements of the Information Quality Act, including DOE's associated guidelines and the Office of Management and Budget's peer review bulletin.[3,4]

Ten topical task forces conducted analyses, provided information, and generated draft text for consideration in this report. The task force topics were: technology; project development; sustainability, environmental, and regulatory considerations; grid integration and transmission; operations, maintenance, and performance optimization; markets; pumped storage; economic development; modeling and analysis; and communications.

Representatives from four DOE national laboratories—Argonne National Laboratory, the National Renewable Energy Laboratory, Oak Ridge National Laboratory, and Pacific Northwest National Laboratory—provided the leadership and technical expertise for each of the task forces. Other task force members included representatives from the hydropower industry (domestic and international), academia, the electric power sector, non-governmental organizations, and governmental organizations with regulatory, ownership, and other interests. In addition to the task forces and Senior Peer Review Group, external peer reviewers who were not otherwise involved in the preparation of the report reviewed the draft report content for accuracy and objectivity.

**The *Hydropower Vision* engaged multiple federal agencies.**

Cooperation with other federal agencies has been a consistent part of the DOE's hydropower research, development, deployment, and demonstration efforts, as has scientific leadership and technical expertise provided by DOE's national laboratories. Given the role of federal agencies in hydropower ownership and regulation, this interagency cooperation was critical during fact-finding and analysis carried out for the *Hydropower Vision.*

A 2010 multiagency memorandum of understanding (MOU) established a framework for federal collaboration specifically targeting sustainable hydropower. The MOU was signed by the DOE, the Department of the Interior, and the U.S. Army Corps of Engineers (Corps) in 2010 and extended in 2015. It established a Federal Inland Hydropower Working Group, with 15 federal

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3. The Department of Energy's Information Quality Guidelines are developed in accordance with Section 515, Treasury and General Government Appropriations Act (Information Quality Act) Public Law 106-554. See *http://energy.gov/cio/department-energy-information-quality-guidelines*.

4. The Office of Management and Budget's "Final Information Quality Bulletin" provides guidelines for properly managing peer review at federal agencies in compliance with section 515(a) of the Information Quality Act (Pub. L. No. 106-554). The *Hydropower Vision* assessment followed these guidelines.

entities as members.[5] Thirteen overarching goals are established by the MOU, with specific collaborative activities delineated for each. DOE reports created under the MOU umbrella provided citable data that are incorporated into the *Hydropower Vision.*

**The *Hydropower Vision* establishes principles of optimization, growth, and sustainability.**
For purposes of the *Hydropower Vision*, sustainable hydropower projects are those that are sited, designed, constructed, and operated to balance social, environmental, and economic objectives at multiple geographic scales (i.e., national, regional, basin, site). While hydropower development has in some cases had adverse effects on river systems and the species that depend upon them, hydropower offers many benefits continues to make advances in environmental performance. Accordingly, *Hydropower Vision* sets increasing expectations for hydropower development under which gains are maintained and the trend of improvement continues. Sustainable hydropower fits into the water-energy system by ensuring that the ability to meet energy needs is balanced with the functions and co-objectives of other water management missions in the present, as well as into the years ahead. In some cases, dam removal and site restoration may be part of meeting the sustainability objective.

*Hydropower Vision* is grounded in three foundational principles or "pillars"—optimization, growth, and sustainability—arrived at through extensive stakeholder input and identified as critical to ensuring the integrity of the research, modeling, and analysis conducted during the *Hydropower Vision* collaborative process. These pillars are defined as follows:

- **Optimization:** Optimize the value and the power generation contribution of the existing hydropower fleet within the nation's energy mix to benefit national and regional economies; maintain critical national infrastructure; and improve energy security.
- **Growth**: Explore the feasibility of credible long-term deployment scenarios for responsible growth of hydropower capacity and energy production.
- **Sustainability**: Ensure that hydropower's contributions toward meeting the nation's energy needs are consistent with the equally important objectives of environmental stewardship and responsible water use management.

**Insights from the *Hydropower Vision* highlight hydropower's importance.**
Several key insights of this *Hydropower Vision* collaborative effort characterize the role that hydropower has and can play in the U.S. power sector:

1. Hydropower has been a cornerstone of the U.S. electric grid, providing low-cost, low-carbon, renewable, and flexible energy services for more than a century.
2. Existing hydropower facilities have high value based on their ability to provide flexible generation and energy services; ancillary grid services; multi-purpose water management; and social and economic benefits, including avoidance of criteria air pollutants[6] and greenhouse gas (GHG) emissions.
3. Hydropower has the potential to grow and contribute to additional electricity production in the future generation portfolio. In the near term, there is significant potential for economically and environmentally sustainable growth by optimizing existing infrastructure through facility upgrades, and adding generation capabilities to non-powered dams (NPDs) and water conveyances such as irrigation canals.
4. Long-term hydropower growth potential, particularly at undeveloped sites (new stream-reaches, or NSDs), will be influenced by the extent to which new hydropower technologies and projects are developed at lowered costs and with improved environmental performance.
5. The United States has resource potential for new pumped storage hydropower (PSH) development as a storage technology, which can enable grid flexibility and greater integration of variable generation resources, such as wind and solar.

5. The members of Federal Inland Hydropower Working Group are the Corps, Bonneville Power Administration, the Bureau of Indian Affairs, the U.S. Bureau of Reclamation, DOE, the U.S. Environmental Protection Agency, the Federal Energy Regulatory Commission, the U.S. Fish and Wildlife Service, the U.S. Forest Service, the National Oceanic and Atmospheric Administration, the National Park Service, Southeastern Power Administration, Southwestern Power Administration, the U.S. Geological Survey, and the Western Area Power Administration. For more information see: *http://en.openei.org/wiki/Federal_Memorandum_of_Understanding_for_Hydropower/Federal_Inland_Hydropower_Working_Group*.

6. The Clean Air Act requires EPA to set National Ambient Air Quality Standards for six common air pollutants (criteria pollutants) based on the human health-based and/or environmentally-based criteria. *https://www.epa.gov/criteria-air-pollutants*

6. Technical design innovation, implementation of advanced project strategies, optimization of regulatory processes, and application of the principles of sustainability will all be important to determining hydropower's future.
7. Hydropower's economic and societal benefits are significant and include cost savings in avoided mortality, morbidity, and economic damages from power-sector emissions of criteria air pollutants and avoided global damages from GHG emissions.

The *Hydropower Vision* does not define numeric goals or targets for hydropower development, and it does not specifically evaluate nor recommend new policy actions. The *Hydropower Vision* instead analyzes the feasibility and potential benefits of varied hydropower deployment scenarios, all of which could inform policy decisions at the federal, state, tribal, and local levels.

## 1.2 Understanding the Role of U.S. Hydropower

By the end of 2015, the U.S. hydropower[7] generation fleet included 2,198 active power plants with a total capacity of 79.6 gigawatts (GW) and 42 PSH plants totaling 21.6 GW, for a total installed hydropower capacity of 101 GW [3]. Hydropower is currently the largest U.S. renewable power source, providing nearly half (48%) of all U.S. renewable power in 2015. Forty-eight states have hydropower facilities, and ten of these states generated more than 10% of their electricity from hydropower in 2015 [4].

**Hydropower has been the cornerstone of low-cost, low-carbon, renewable, and flexible contributions to the U.S. electric grid.**

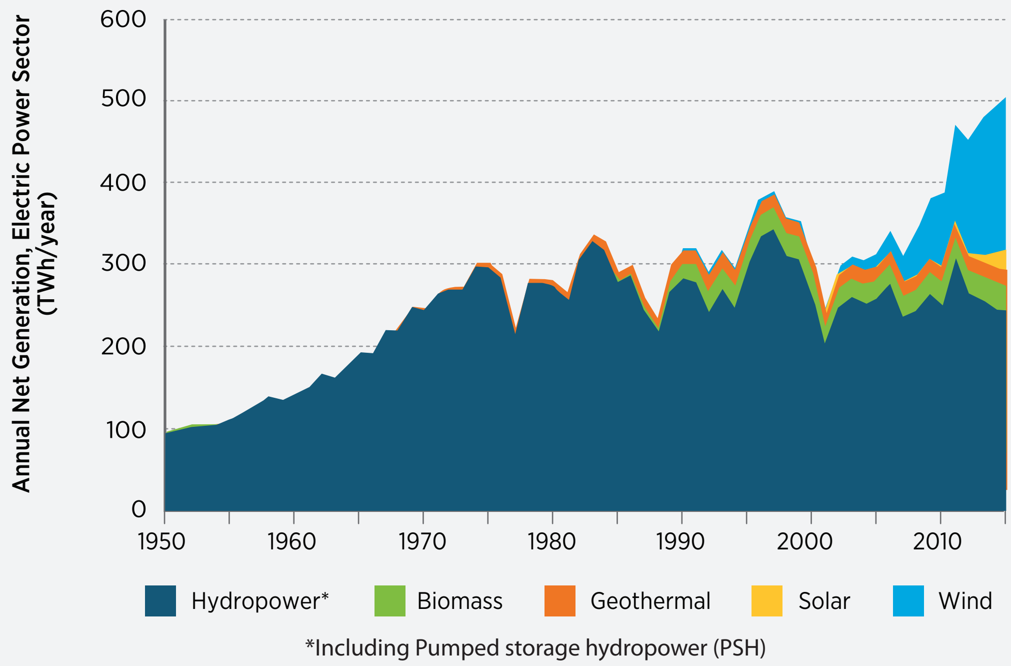
Hydropower has played an important role in U.S. industrial development. Hydropower supported rapid expansion of the nation's production of aluminum for aircraft during World War II, and helped support developing post-war industries, including automobile and durable goods manufacturing [5]. Hydropower has also played an major role in U.S. clean power generation, providing on average 10% of U.S. electricity generation over the 65 years leading up to 2015 (1950–2015), and 85% of cumulative U.S. renewable power generation over the same time period (Figure 1-1) [1].

**Hydropower provided a cumulative 10% of U.S. electricity generation and more than 85% of cumulative U.S. renewable power generation between 1950 and 2015.**

**Hydropower supports jobs and provides economic value.**
As of the beginning of 2014, hydropower supported approximately 143,000 jobs in the United States, comprising 118,000 total ongoing full-time equivalent jobs in operations and maintenance and 25,000 temporary jobs in construction and upgrades [6]. DOE estimates that the full-time jobs include 23,000 direct jobs at operating sites, with jobs such as plant operators, mechanical maintenance workers, and hydropower engineers; 54,000 direct jobs in the supply chain; and 41,000 induced jobs from the resulting economic activity [6]. In 2013, expenditures related to hydropower supported roughly $17.1 billion in economic output (capital investment) and $5.9 billion in earnings (wages paid to workers) [6].

**Hydropower provides flexibility and essential grid services.**
Hydropower provides many ancillary and essential reliability services that ensure national grid stability and flexibility. Grid services, including regulation and frequency response, load-following and flexibility

7. This report does not address marine (wave, current, and tidal) and river hydrokinetic technologies, as marine and hydrokinetic technologies are defined by Congress as separate and distinct from hydropower [58].




Source: Energy Information Administration 2016 [1]

**Figure 1-1.** Annual U.S. renewable electricity net generation (terawatt-hours per year), electric power sector, 1950–2015

reserve, energy imbalance service, spinning reserve, supplemental (non-spinning) reserve, reactive power and voltage support, and black start (restoration) service, are discussed in Chapter 2 (see Text Box 2-2a). These services contribute to maintenance of power system balance on time scales ranging from sub-seconds to hours.

**Existing hydropower facilities have high value due to flexibility, grid support services, and social and economic benefits, including avoidance of GHGs and criteria air pollutants.**

Certain grid services, known as essential reliability services, are considered critical to maintaining the operations and stability of the national grid. These services are identified by the North American Electric Reliability Corporation as frequency response, ramping, and voltage support, and are discussed in Chapter 2 (see Text Box 2-2b). Hydropower facilities, with storage and fast ramping ability, can react quickly to system disturbances and contribute to greater flexibility and reliability of power system operation [7].

Pumped storage hydropower—where water is pumped to an upper reservoir when demand and market price is low, and then released back through turbines to generate electricity as needed—also has the capability to absorb large amounts of generation, providing grid operators with an important tool to avoid operational and reliability problems associated with over-generation conditions. Hydropower also provides short- and long-term energy storage in the form of the energy potential of impounded water.

Hydropower's ability to rapidly absorb load or supply power to serve load as needed is critical for grid stability and voltage support. The ancillary and essential reliability services provided by hydropower are particularly important in compensating for unexpected voltage sags from thermal or nuclear plants going offline, transmission line outages, and providing system restoration. These services also provide quick response in regions with high penetrations of variable generation sources, such as wind and solar.

**Hydropower supports integration of variable generation resources.**
Hydropower's ability to provide grid ancillary services and essential reliability services makes the technology suited to cost-effectively support increased integration of variable generation resources into the power grid and balance the variable generation of changes over time due to factors outside the direct control of the operator, e.g., wind or solar resource. PSH in particular is complementary to integration of variable generation resources, as PSH can reduce curtailment of excess generation by providing load management and energy storage. *Hydropower Vision* analysis presented in Chapter 3 indicates there is a positive correlation between PSH and variable generation deployment.

**Hydropower produces low carbon and criteria pollutant air emissions.**
Because its fuel (water) is renewable, the hydropower electricity generation process has very low life cycle GHG and criteria air pollutant emissions [8]. The potential for biogenic GHG emissions (mainly methane) from bodies of impounded water, independent of whether such an impoundment is equipped with hydropower, is a complex issue and subject to ongoing research [9]. Given the state of scientific understanding and discourse, including persistent uncertainties, the *Hydropower Vision* does not attempt to address hydropower-related biogenic GHG emissions. Instead, Chapter 3 provides an introduction to the subject and a review of the literature. It is unlikely that powering existing NPDs would result in methane production higher than that caused by natural conditions in rivers and lakes.

**Hydropower is integrated with multiple water uses.**
The existing role and emerging future of hydropower is complex. Dams and reservoirs serve many functions, including flood management and control, irrigation, recreation, navigation, and drinking water supply. The vast majority of the more than 87,000 existing dams in the United States do not include hydropower generation plants. Those that do generate electricity (less than 2,200) must meet both the ongoing power and non-power needs of multiple and varied interests and stakeholders within the context of complex and sometimes redundant regulatory frameworks. In terms of number of sites, the top three uses of federally owned hydropower reservoirs—approximately 50% of installed capacity—are recreation, flood control, and irrigation [10].

The complex interplay among hydropower facilities, the geographic areas in which they are located, the ecosystems and aquatic life that are affected, relevant power-producing operations, and the roles that water impoundments of varying scales all play in water management highlights the need for a coordinated and balanced approach to prioritization, planning, and facility design and management among a multitude of stakeholders.

**Hydropower has direct interaction with the riverine environment.**
Because hydropower interacts directly with water and the related riverine environment, hydropower generation facilities can directly influence riverine ecosystem health above and below a facility. Potential environmental impacts include: timing of release and amount of stream flows; water quality effects, including water temperature, turbidity, and oxygen content; fragmentation of riverine habitat; alteration of fish migration patterns; alteration or destruction of fish habitat; fish injury or mortality from turbine passage; possible damage to or inundation of archaeological, cultural, or historic sites; changes in visual quality; and increase in the potential for stream-bank erosion. Mitigation of these potential adverse environmental or fish and wildlife impacts is required (see Chapter 2).

Public and private funding has been allocated to improve conditions for fish affected by hydropower projects, primarily diadromous migratory species.[8] For example, the National Oceanic and Atmospheric Administration (NOAA) partners with conservation organizations, energy companies, states, tribes and citizens to evaluate barriers to improve fish passage. NOAA opens fish passage and conducts dam removals by providing grant funding, providing technical assistance to partners, and participating in the hydropower project relicensing process. Since 1996, NOAA and its partners have invested more than half a billion dollars to restore access for migratory fish to approximately 16,000 miles of rivers and streams.

8. There are two categories of diadromous fishes (species that spend part of their lives in fresh water and part in salt water). An anadromous species, born in fresh water, spends most of its life in the sea and, when mature, returns to fresh water to spawn. This freshwater/saltwater cycle is essential to survival for these fishes. Salmon, smelt, shad, striped bass, and sturgeon are common examples. Catadromous species, such as the American eel, hatch or are born in marine habitats, migrate to freshwater areas where they spend the majority of their lives, and then return to the sea to spawn.

Researchers have developed innovative upstream and downstream passage facilities, innovations in combining temperature control structures with passage facilities, and design tools that allow manufacturers to build turbines that reduce fish injury and mortality associated with turbine passage. DOE- and industry-funded projects for features such as advanced turbines and biologically based design and evaluation tools help enable improvements in turbine environmental performance. Additional work has focused on mitigation of environmental impacts that affect aquatic organisms, such as degraded water quality associated with hydropower facilities and elevated levels of total dissolved gases at Columbia River projects.

**Hydropower infrastructure has a long lifetime.** Hydropower facilities have a long capital lifetime as compared to other generating technologies, with an average operational lifespan on the order of 100 years [11]. In the United States, more than 1,500 facilities installed prior to World War II are still operational, with 10.2 GW of combined capacity [12]. Although the lifetime of the impoundment is generally greater than that of the power plant, the turbines, buildings, water retaining structures, and other components of the facility are regularly serviced and often replaced or rehabilitated during these long operating periods. Therefore, it is expected that much of the existing hydropower infrastructure will continue to function for many more decades if properly maintained, operated, and upgraded.

## 1.3 Key Factors and Trends Motivating the *Hydropower Vision*

Changes and trends specific to the U.S. electric sector, as well as broader national and global factors, have motivated the development of the *Hydropower Vision* to evaluate the potential for optimization, growth, and sustainability of U.S. hydropower. As discussed in this section, requirements for electric generation capacity and the choices of fuel mix are influenced by many factors, including national priorities, social and environmental concerns, policy and regulation, energy markets, and advances in technology and operations.

**Hydropower can reduce carbon emissions.** A range of cost-effective low-carbon generation options, including hydropower, are needed to reduce the power-sector emissions that contribute to climate change. President Barack Obama's 2013 Climate Action Plan calls for the deployment of clean energy[9] to support reduced carbon pollution from power plants; American leadership in renewable energy; and long-term investment in clean energy innovation [13]. The National Security Strategy, issued by the U.S. Department of Defense in February 2015, specifies that climate change is an urgent and growing threat to national security. The DOD report states that climate change impacts are already occurring, and that their scope, scale, and intensity are projected to increase over time [14].

State and local governments have enacted policies to encourage GHG emission reductions for many years. Examples include the California Global Warming Solutions Act of 2006 [15], and the Regional Greenhouse Gas Initiative—a cooperative GHG cap-and-trade agreement that became effective on January 1, 2009 in the northeastern United States and eastern Canada. Increasing concern about the effects of carbon emissions on climate change led the U.S. Environmental Protection Agency to issue the Clean Power Plan in August 2015 to adopt carbon pollution standards for existing power plants, and instruct states to begin making meaningful progress toward reductions by 2022 [16]. The Clean Power Plan establishes unique emission rate goals and mass equivalents for each state, and is projected to reduce power-sector carbon emissions 32% from 2005 levels by 2030 [17]. Hydropower can play a role in carbon emission avoidance and reduction into the future.

9. The President's Climate Action Plan defines clean energy as renewable energy (wind, solar, geothermal, hydropower, biomass, and advanced biofuels), natural gas, nuclear power, and "clean coal."

**Hydropower supports a broader definition of national security.**

Power system stability and reliability, such as that provided by hydropower, is critical to national security. In releasing the first installment of the national Quadrennial Energy Review,[10] the U.S. Administration stated [18]:

> ***"The focus of U.S. energy-policy discussions has shifted from worries about rising oil and natural gas imports to debates about how much and what kinds of U.S. energy should be exported, concerns about safety and resilience, integrating renewable sources of energy, and the overriding question of what changes in patterns of U.S. energy supply and demand will be needed—and how they can be achieved—for the United States to do its part in meeting the global climate-change challenge."***
>
> **White House Office of the Press Secretary, April 21, 2015.**

According to the Quadrennial Energy Review, while the concept of "oil security" has come to serve as a proxy for "energy security," energy security needs to be more broadly defined to cover not only oil but all other sources of supply. Energy security should also be based not only on the ability to withstand shocks in price and availability, but also to be able to recover quickly from any volatility. In the electric sector, this means the ability to operate a reliable and secure grid as well as the flexibility to avoid and recover quickly from any widespread outages. Hydropower is one of the few electricity sources that can provide these critical flexibility functions, including black-start capability[11] and the ability to ramp up power production quickly.

The International Energy Agency (IEA) is a 29-member autonomous organization made up of countries and founded in 1974. The organization was initially designed to help countries coordinate a collective response to major disruptions in the supply of oil. IEA defines energy security in a broad manner, similar to the Quadrennial Energy Review:

> ***"IEA defines energy security as the uninterrupted availability of energy sources at an affordable price. Energy security has many aspects: long-term energy security mainly deals with timely investments to supply energy in line with economic developments and environmental needs. On the other hand, short-term energy security focuses on the ability of the energy system to react promptly to sudden changes in the supply-demand balance"*** *[60].*

As defined by the IEA, lack of energy security is linked to the negative economic and social impacts of either physical unavailability of energy, or prices that are not competitive or are overly volatile. Hydropower and most renewable energy sources have relatively stable operational costs over time, since they are not subject to market-driven fuel price fluctuations. Concerns about physical unavailability of supply are more prevalent in energy markets where transmission systems must be kept in constant balance, such as electricity and, to some extent, natural gas. Hydropower, through large impoundments and PSH, can provide long-term electricity storage services. The long-term aspect of energy security was also included in the IEA's founding objectives, which called for promoting alternative energy sources in order to reduce oil import dependency [19].

**Hydropower is part of the nation's critical infrastructure.**

Reliable electricity delivery is increasingly important in the global flow of information and commerce, and the cost of power interruptions—whether accidental or intentional—makes power system stability and reliability ever more critical to national security. The energy and dams sectors are two of the 16 critical infrastructure sectors listed by the U.S. Department of Homeland Security under Presidential Policy Directive 21 [20]. The directive defines critical infrastructure as assets, systems, and networks—physical or virtual—that are considered so vital to the United States that their incapacitation or destruction would have a debilitating effect on security, national economic security, national public health or safety, or any combination thereof [21]. The Department of Homeland

10. In response to a 2010 recommendation by the President's Council of Advisors on Science and Technology , the Administration initiated a quadrennial cycle of energy reviews to provide a multiyear roadmap for U.S. energy policy. More information on the Quadrennial Energy Review is available at: *http://energy.gov/epsa/downloads/quadrennial-energy-review-full-report*.

11. A black start is the process of restoring a power station to operation without relying on the external electric power transmission network. It is not economical to provide a large standby generation capacity at each station, so black-start power must be provided over designated power lines from another station. Hydroelectric power plants are often designated as the black-start sources to restore network interconnections.

Security provides strategic guidance and coordinates the overall federal effort to promote the security and resilience of the nation's critical infrastructure, including hydropower.

**Public policy influences renewable energy deployment.**
Public policy has supported deployment of renewable energy at state and regional levels through policies such as renewable portfolio standards (RPS) and other initiatives. Hydropower is characterized as renewable and "clean" because its energy source is not depleted during use and carbon-based fuels are not burned as part of energy production. Some state RPS and federal policies, however, exclude hydropower from consideration or give hydropower reduced credit compared to other renewable sources of generation. In addition to state and regional initiatives, the federal government has supported development of clean, renewable energy through a variety of mechanisms, including federal funding for research, development, demonstration, and deployment.

As of April 2016, mandatory RPS policies exist in 29 states [22], the District of Columbia, and Puerto Rico and voluntary renewable targets in eight states. Hydropower is an eligible technology in most of the states' RPS policies, but there are generally restrictions on which hydropower projects can be included. Of the 30 states (including the District of Columbia) in which hydropower is eligible for the RPS, 23 allow new hydropower development and five others explicitly prohibit new dams [23]. Two of the states prohibiting new dams allow new run-of-river facilities to qualify for the RPS. Because of concern over the ecological impacts of large dams, large hydropower—most frequently defined as greater than 30 megawatts (MW)—is limited in inclusion in state RPS policies. In contrast, 25 states allow small hydro, generally defined between 3 and 60 MW (depending on the state).

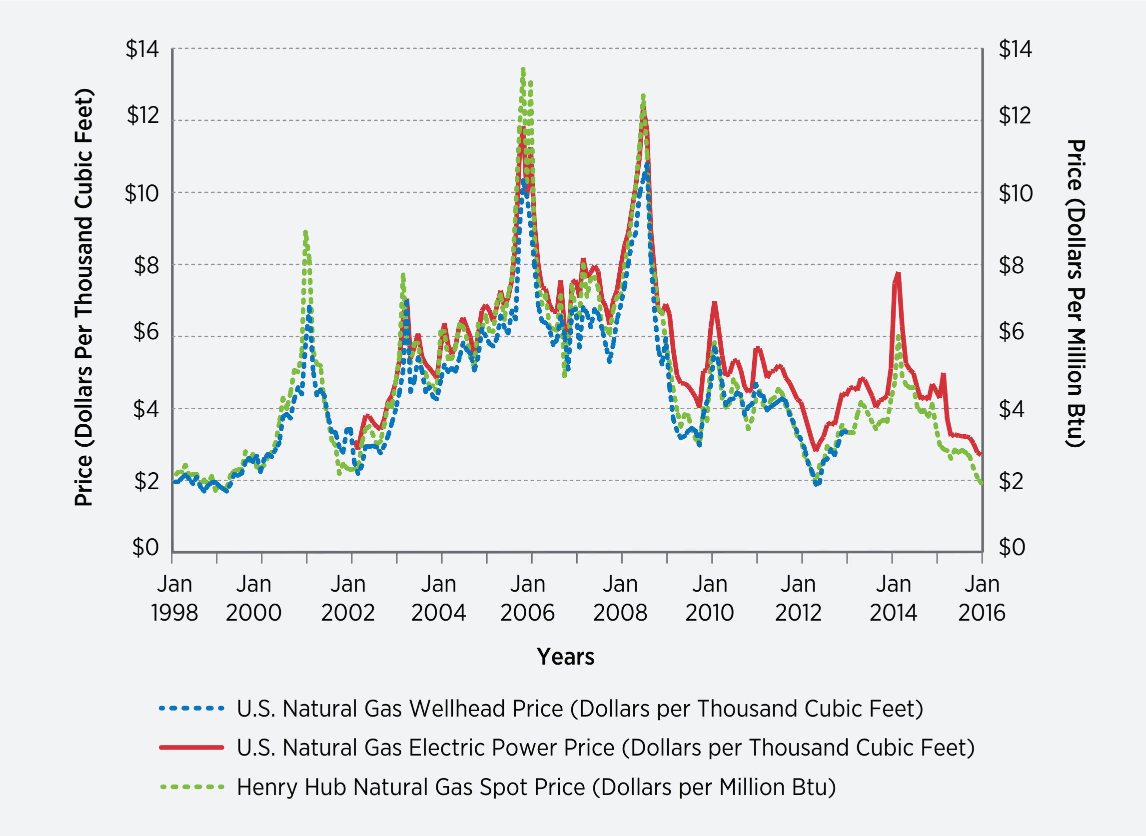
As other renewables become more mature (e.g., wind power approached 5% of total electricity generation in 2015), state programs may reassess the value of distinguishing hydropower from "non-hydro" renewables. Whether or not hydropower (either new or existing) should be included or excluded from renewable energy incentive programs or market compensation mechanisms is ultimately dependent upon the goals of specific policies and their related implementation approaches.

**Hydropower provides a hedge against electric price volatility.**
As a stable renewable resource with long infrastructure life, hydropower provides a direct hedge against the volatility of electricity prices. Hydropower additionally provides an indirect hedge against price volatility, through grid support for increased integration of variable generation resources such as wind and solar—which, as fuel-free power sources, also have stable long-term pricing.

While hydraulic fracturing for oil and natural gas extraction has been used for more than a century, technological improvements in the early 2000s allowed the technology to be successfully applied to U.S. oil shales bearing natural gas deposits and other unconventional natural gas resources. Between 2005 and 2010, the shale gas industry in the United States grew 45% per year. As a proportion of the country's overall gas production, shale gas increased from 4% in 2005 to 24% in 2012 [24]. As illustrated in Figure 1-2, this increase in supply coincided with a measurable decrease in U.S. natural gas prices from 2009 through 2015. Prices for natural gas used to generate electricity (solid red line in Figure 1-2) can affect the value of electricity sales in power markets.

**Coal and nuclear retirements create markets for new generation.**
According to the Energy Information Administration (EIA) and other market analysts, the role of coal and nuclear technologies in the U.S. generation mix has been changing since 2009. Low natural gas prices and slower growth of electricity demand have both altered the competitiveness of these technologies relative to other fuels [27]. Coal-fired plants also must comply with requirements of the Mercury and Air Toxics Standards and other environmental regulations, and some nuclear plants are experiencing increasing operations and maintenance costs or capital addition costs. As existing coal and nuclear plants retire—whether due to market competition, safety, or other reasons—new markets for generation, including hydropower, open up.

To estimate future national energy needs, EIA publishes an Annual Energy Outlook (AEO) presenting long-term (25-year) annual projections of U.S. energy supply, demand, and prices. A *Reference Case* is established by EIA to provide a business-as-usual trend estimate, given known technology, technological and demographic trends, as well as federal, state, and local laws and regulations in effect at the time.




Source: EIA Natural Gas Monthly [25]

**Figure 1-2.** Trends in U.S. natural gas prices, 1998–2015

Under EIA's AEO 2015 *Reference Case* [27], 40.1 GW of coal-fired capacity would be retired from 2013–2040, with more than 90% (37.4 GW) of this capacity being retired by 2020. Under EIA's AEO 2014 *Accelerated Coal Retirements Case*, 110 GW of capacity out of the total installed 310 GW of coal-fired generating capacity available at the end of 2012 would be retired by 2040 [26]. By contrast, natural gas combined cycle capacity would increase by 93 GW from 2013–2040 under the AEO 2015 *Reference Case.*

From 2010 through June 2016, fourteen U.S. nuclear reactors totaling 11.9 gigawatts of electric capacity were or had closures accounted by their owners [28]. According to the Natural Resources Defense Council, three of the reactors closed for primarily mechanical or safety reasons, whereas 11 reactors closed or will close primarily because of an inability to compete in existing market conditions [28]. Under EIA's AEO 2015 *Reference Case,* nuclear capacity would experience net growth of 5.9 GW (6%) from 2013–2040. Under the AEO 2014 *Accelerated Nuclear Retirements Case,*[12] 42 GW of nuclear capacity would be retired through 2040.[13]

The loss of generating capacity due to ongoing retirement of coal-fired plants is largely being replaced by the addition of gas-fired and variable generation resources [29]. Increases in natural gas resources and declines in gas cost from 2009 through 2015 have

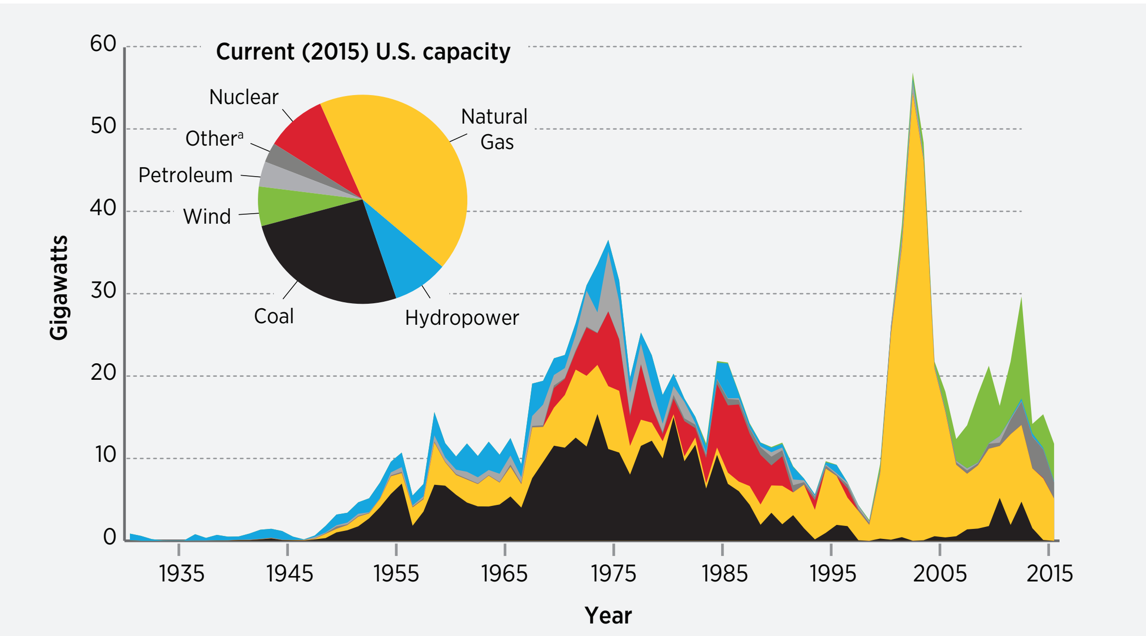
12. Because EIA now publishes shorter and longer editions of the AEO in alternating years, AEO 2015 does not include all of the alternative cases presented in AEO 2014.

13. In a 2015 National Renewable Energy Laboratory report using different retirement assumptions than EIA, and under a modeled "central scenario," roughly half of the existing (as of 2012) coal capacity and nearly all of the existing oil and gas steam turbines and existing nuclear units are retired by 2050 [32].

contributed to an increased share of natural-gas fired electric generation capacity added to the U.S. electric generation mix (Figure 1-3), with natural gas generation roughly doubling between 2000 (518 terawatt-hours [TWh]) and 2014 (1,029 TWh) [1]. As can also be seen in Figure 1-3, wind power capacity additions have increased since about 2010, due to technological advances, lower cost, favorable markets, and ease in siting and permitting. These developments in the national energy mix imply a growing opportunity for hydropower, not only for generation but for maintaining grid system efficiency and stability.

**Hydropower can support an increasing need to integrate variable generation.**
Deployment of variable generation resources is increasing over time, making balancing of the U.S. electric power system all the more critical. In the future, electric vehicles, distributed generation, smart grid functions, and other changes could further affect grid operations. While the electric power system has provided reliable electricity for more than a century, much of the existing electric grid was designed and built decades ago using system design models and concepts that may require restructuring to meet the needs of a low-carbon economy (as discussed previously).

Hydropower can be an integral part of this future energy mix because of its ability to provide ancillary and essential reliability grid services. As the electric power system evolves, power system flexibility will be needed at time scales that range from sub-second for inertial/frequency response, to minutes or hours, during which there will be an increase in the need for regulating and ramping capability. Transmission system operators require tools and resources to realize this increased level of flexibility, which will also require new strategies for managing grid operations. Some of the new tools and methods include expanding balancing areas,[14] increasing the ramping capability of the generation fleet, using dispatchable demand resources, adding power flow controllers, and increasing energy storage to maintain reliability [33]. Corresponding to these new tools and

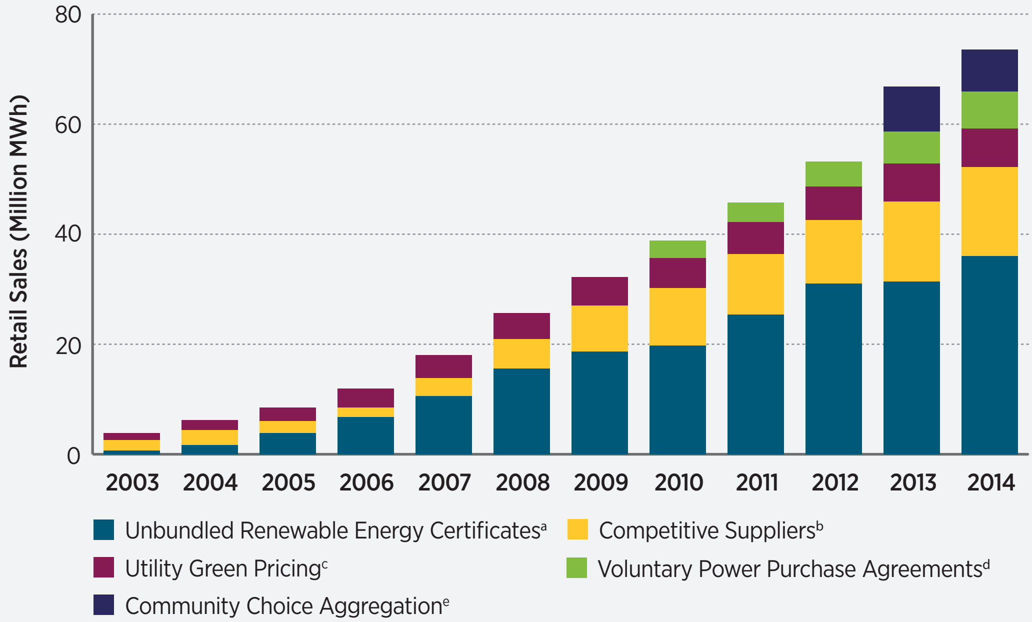



Source: EIA [30], Federal Energy Regulatory Commission Energy Infrastructure Updates 2011-2015 [31]

a. Other includes biomass, geothermal steam, solar, waste heat, tires, and miscellaneous technology such as batteries, fuel cells, energy storage, and fly wheel.

**Figure 1-3.** Cumulative U.S. electric generating capacity by fuel type, 1930–2015 (EIA, FERC)

14. Large transmission grids can be broken into smaller transmission "balancing authority areas," where reliability requirements can be met while balancing load with generation and interchanges of neighboring regions.




Notes: The unbundled renewable energy certificate market allows consumers to purchase RECs separate from power. Competitive supply allows customers to purchase renewable electricity directly from alternate suppliers. Utility green pricing bundles renewable energy certificates with electricity sales. Voluntary power purchase agreements allow negotiated long-term purchases of renewable energy. Community choice aggregation allows communities aggregate their load and purchase electricity from an alternate electricity supplier, while still receiving transmission and distribution service from their existing utility.

Sources: Bird and Swezey [35], Heeter and Nicholas [36], and Heeter et al [37]

**Figure 1-4.** Estimated voluntary U.S. sales of renewable energy, 2003–2014

approaches is the need for financial incentives to support their development and deployment, in order to meet required levels of system flexibility.

**Market drivers for utility-scale grid storage are increasing.**

Key market drivers of energy storage for grid support services, such as PSH, include: (1) growth in renewable energy deployment; (2) governmental focus on initiatives to reduce carbon emissions; (3) the need for modernization of grid infrastructure; and (4) the need to improve the resilience of the electrical grid to unforeseen interruptions [34]. PSH is a low-risk technology with a proven track record and high efficiency in providing load management, energy storage, and grid services. Additionally, PSH is more flexible and has longer facility lifetimes and lower cost compared to other technologies that can provide these services in facilitating the integration of variable generation resources into the grid. A detailed discussion of PSH is found in Chapter 2, Section 2.7 of the *Hydropower Vision* report.

**There is increased public and private interest in renewable energy.**

As shown by increases in voluntary purchases of renewable energy, public and private interest in and understanding of the role and value of renewable energy continues to increase. In 2014, voluntary retail sales of renewable energy totaled 74 TWh, representing 2.0% of total U.S. electricity sales and four times the voluntary green power sales of 18 TWh in 2007 (Figure 1-4) [35, 36, 37]. One of many examples of private sector investment in renewable energy is the U.S. Environmental Protection Agency's Green Power Partnership. Nearly 25 TWh in combined green power usage was reported in 2015 for the Top 100 Green Power Partners, enough to power nearly 2.3 million homes. This includes 14 TWh used by the 76 Fortune 500 Green Power Partners [38].

**Private and public owners are investing in hydropower generation.**
Hydropower growth occurs in three different ways: unit additions and upgrades at existing facilities; adding hydropower generating equipment to existing NPDs and conduit projects; and NSD. Installed hydropower capacity in the United States experienced a net increase of 1.48 GW from 2005 to 2013, with capacity additions to existing projects accounting for 86% of the increase. Capital investment toward modernizing and upgrading the existing fleet continues, with private and public owners investing more than $6 billion in refurbishments, replacements, and upgrades to hydropower plants from 2005-2014 [3].

**Technology innovation enables low-cost, sustainable hydropower development.**
Development of hydropower technologies and operations with reduced adverse impacts is vital if hydropower is to be deployed in an environmentally sustainable manner and at lower cost. Some of the innovations emerging for low-head hydropower include concepts such as mechanically unregulated turbines that vary speed with head or flow, and permanent magnet-type generators that produce an output voltage that varies with head and flow. Other technologies are being developed for very low-head turbines, such as a direct-drive variable speed permanent magnet-type generator that can be placed directly in a flow channel with approximately 4–8 feet of head. This concept can reduce civil works required for intake structures or water conveyance, and the associated cost of those works. Innovative technologies are being developed for safe and effective fish passage at dams, including high head dams and dams with a large range of reservoir levels [39]. Such innovations and improvements are being integrated into both the existing fleet and new projects, and this trend of improved environmental performance is expected to continue. Future hydropower technologies are discussed further in Section 1.7.

# 1.4 Opportunities and Challenges for Hydropower

The *Hydropower Vision* identifies opportunities and challenges for hydropower through its documentation, modeling and analysis, and stakeholder roadmap. Hydropower's system-wide benefits are large and have historically underpinned the nation's electric systems. Hydropower's growth is critically coupled with the ability of innovation to enable hydropower resource opportunities to be economically competitive and environmentally sustainable.

Keys to improved competitiveness include continued technical innovation to reduce capital and operating expenses, improved understanding and market valuation of system-wide grid reliability and stability services, and recognition and valuation of societal benefits from avoided power-sector air pollution and GHG emissions. Equally important to increasing hydropower's competitiveness is continued improvement in mitigating adverse effects, such as impacts on fish and wildlife, and increased public awareness of progress made in this regard. Addressing these objectives is likely to require continued technical innovation, actionable and measurable environmental sustainability metrics and practices, planning at the basin or watershed scale, and access to new science and assessment tools.

The degree to which such challenges can be effectively addressed will influence the levels of future hydropower growth and reinvestment in existing facilities. In turn, it will affect realization of the opportunities and benefits provided by low-cost hydropower generation, grid support, and long project operating life. Chapter 2 provides detailed discussion of the state of the hydropower industry and its trends, opportunities, and challenges.

**Hydropower services could benefit from improved valuation.**
Inherent market and regulatory challenges must be overcome to realize hydropower's potential to improve grid flexibility and facilitate integration of variable generation resources. The full accounting, optimization, and compensation for hydropower

generation, grid ancillary services and essential grid reliability services in power markets is difficult, and not all benefits and services provided by hydropower facilities are readily quantifiable or financially compensated in today's market framework. In both traditional and restructured market environments, many hydropower services and contributions are not explicitly monetized, and, in some cases, market rules undervalue operational flexibility.

With regard to PSH, in April 2016, the Federal Energy Regulatory Commission (FERC) initiated a proceeding (Docket No. AD16-20-000)—to examine whether barriers exist to the participation of electric storage resources in the capacity, energy, and ancillary service markets potentially leading to unjust and unreasonable wholesale rates [40]. This action was motivated in part by trends of increasing exploration of the value electric storage resources may offer the grid when providing transmission services and acting as both generation and load.

**Hydropower must account for potential impacts of climate change.**

Climate change creates uncertainty around water availability for hydropower generation, and this uncertainty can affect the long-term outlook of the hydropower industry. Water availability—including more water in some areas and less in others—affects the energy production potential of hydropower resources, which, in turn, influences their economic attractiveness in the electric sector. A changing climate may also impact the availability of water for thermal power plant cooling; electricity demand; and aquatic systems, such as warmer streams influencing the health of fish and other species.

**Hydropower development can benefit from improved planning and reduced regulatory uncertainty.**

Uncertainty in licensing processes and outcomes can adversely affect development costs, timelines, and financing options. Existing regulatory statutes and related regulatory processes governing hydropower ensure that project development and operations are carried out responsibly and consistently. However, there is concern that regulatory process inefficiencies, overlaps, and interpretations can result in delays and costs that cause long-term business risks to hydropower owners, operators, and developers.

Modernizing future regulations and enhancing communication and coordination among commercial entities and federal, state, and local regulatory bodies could help ensure mutually beneficial improvements in process efficiency and potentially reduce individual project development costs and timeframes, while maintaining or improving environmental protection. In addition, given the interrelated nature of watersheds and related ecosystems within a given drainage basin, applying comprehensive basin-wide planning methodologies may provide an opportunity to preserve or rehabilitate the health of river systems, while promoting efficient use of water resources for power production and other purposes.

**Opportunities exist for collaboration among federal agencies.**

There are opportunities for coordination and collaboration among federal agencies to meet mutual objectives with regard to sustainable hydropower development and operations, as well as broader water resource use, planning, and protection needs. Increased efficiencies in regulatory compliance and water resource planning processes that lead to lowered costs, reduced uncertainties, and better coordination among affected stakeholders can facilitate refinement and broad adaptation of future advanced technologies for sustainable development.

Federal agencies have worked together on several initiatives to help continually improve regulatory and water resource planning processes. These actions serve as examples of how collaboration and coordination may help further cost-effective, sustainable hydropower development in the future. Examples of this are discussed here and include:

- An agreement between the Corps and FERC to synchronize NPD approvals;
- DOE's Basin Scale Opportunity Assessment Initiative; and
- Release of DOE's Regulatory and Permitting Information Desktop, or RAPID, Toolkit.

While there is abundant potential to add power at NPDs, particularly those controlled by the Corps, development of such sites can be delayed by overlapping Corps and FERC licensing and permitting processes. Through an existing MOU and facilitated by DOE, the Corps and FERC agreed within a collaborative framework to enable permitting reviews to occur in a more coordinated manner [41]. As the result of this agreement and input from affected stakeholders, a coordinated set of processes has been identified to reduce cost, timeframes, uncertainties, and risks for developers. These process improvements include simultaneous FERC and Corps environmental reviews; single rather than redundant National Environmental Policy Act documentation; and one Water Quality Certification application rather than two.

Future hydropower development will require close coordination among developers, regulators, and affected stakeholders to reduce potential conflicts and meet multiple objectives pertaining to the use of water resources. There is increasing interest in these types of planning processes being carried out at the scale of entire river basins to better address potential system effects and the diverse set of interests that may be affected by a given project. As part of the MOU between the DOE, Corps, and the U.S. Bureau of Reclamation (Reclamation) [42], the DOE initiated the Basin Scale Opportunity Assessment Initiative to develop multidisciplinary approaches and tools aimed at facilitating basin-scale water resource planning processes [43]. The project has implemented various tools and techniques in four river basins throughout the United States (Bighorn, Connecticut, Deschutes, and Roanoke). The primary focus is on applying Geographic Information Systems to rapidly assimilate and evaluate planning data in a multi-scale, hydrologic context. These methods are being integrated into interactive, web-based tools to demonstrate possible means of deployment to the hydropower community.

Navigating the complex system of federal and state regulations to secure project approvals can be creates hurdles for renewable energy developers. Uncertainty regarding the duration and outcome of the permitting process can be a deterrent for investment in clean energy and can delay construction of renewable energy and related transmission projects. DOE's Hydropower Regulatory and Permitting Information Desktop Toolkit was developed to make permitting information rapidly accessible from one location, by providing links to permit applications, processes, manuals, and related information for both state and federal levels (Text Box 1-1).

**Existing hydropower facility economic performance should be maintained.**
Existing hydropower facilities, the backbone of any future hydropower expansion, require maintenance to avoid potential degradation of capacity or generation. Maintaining this capacity is important because a large proportion of future electricity generation and other hydropower benefits will derive from the existing fleet.

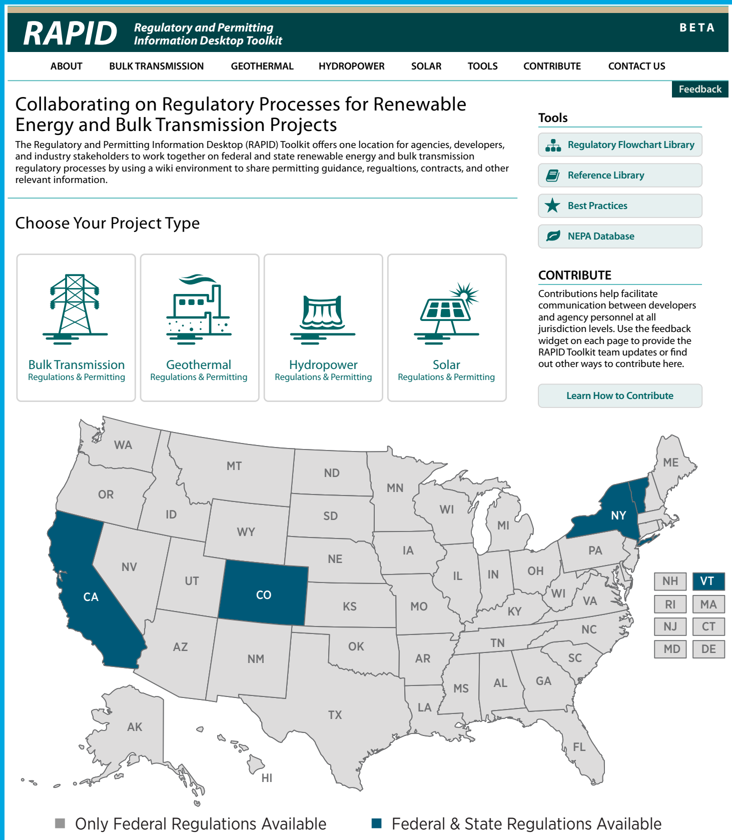
Some hydropower stakeholders have raised concerns that generation at Corps facilities—which account for approximately 24% of total U.S. hydropower generation—may be declining due to aging infrastructure, and many of its hydropower assets have fallen below the generally accepted hydropower industry goal of 95% unit availability [44]. While the exact effects of aging infrastructure on Corps facilities have not been documented on a nationwide basis and, as such, remain uncertain [44], the Corps reports that forced outages (generating units unavailable to produce power due to unanticipated breakdown) increased from 4% to 5.5% during the 2008–2014 period [45]. Efforts are underway in the Federal Columbia River Power System to systematically replace turbine units at main stem Corps facilities.

Net generation from Reclamation facilities has remained relatively constant from 2004 to 2014, and Reclamation has stated that its project performance is generally favorable compared with most industry benchmarks [44]. The Tennessee Valley Authority hydropower modernization program began in 1992 to address the reliability issues of an aging fleet and increase the Authority's hydroelectric capacity and efficiency over the long term. The program increased hydropower capacity by 560 MW (9.48% increase) and realized an average efficiency gain of 4.8% from 1992–2010 [46]. Similar opportunities for optimization exist in the non-federal fleet.

Text Box 1-1.

## Hydropower Regulatory and Permitting Information Desktop Toolkit

The DOE's Hydropower Regulatory and Permitting Information Desktop (RAPID) Toolkit development effort, which began in 2014, documents and presents easily navigable information on federal and state permitting processes and regulatory approvals required for the development of hydropower projects. In addition, the RAPID Toolkit allows users to document best practices for complying with the range of regulatory processes. RAPID facilitates collaboration among federal and state regulatory agencies, as well as other industry stakeholders, in reviewing and coordinating the permitting process for both small and large conventional hydropower, run-of-river hydropower, in-conduit, and pumped storage projects. The RAPID Toolkit seeks to help both developers and regulatory agencies by increasing clarity of and efficiency in the regulatory process.




**RAPID screen shot with example data map**

Source: RAPID website, *http://en.openei.org/wiki/RAPID/Hydropower*

**Federally owned facilities face unique challenges.** Multipurpose federally owned and operated dams—roughly half of existing national hydropower capacity—have limited operational flexibility and face financing constraints that other public and privately owned facilities do not. As with expansions and upgrades, new federal developments are dependent upon Congressional actions. Federal facilities face limited operational flexibility (i.e., due to limits derived from Congressional authorization and negotiated operating guidelines to balance multiple uses of water resources and dam/reservoir infrastructure); and demand for water by competing uses (e.g., municipal water supply, navigation, and recreation) [44].

# 1.5 Modeling Hydropower's Contributions and Future Potential

For the *Hydropower Vision,* computational economic and dispatch models provided the foundation for comprehensive analyses of the existing and future role of hydropower within the electric sector on a national scale. These analytical modeling methods were used to evaluate a range of possible future outcomes for hydropower deployment based on potential technical innovation, economic factors, national priorities, stakeholder action or inaction, market forces, and requirements for environmental mitigation and environmental sensitivity. Because growth potential is tied to a set of complex and unpredictable variables, the modeling results presented in Chapter 3 serve primarily as a basis to identify key factors and drivers that are likely to influence future pathways. Modeling results presented in *Hydropower Vision* should not be interpreted as DOE predictions or targets.

The primary tool used to assess potential growth trajectories and the basis to evaluate resulting cost and benefit impacts is the National Renewable Energy Laboratory's Regional Energy Deployment System (ReEDS) model [47]. ReEDS is an electric sector capacity expansion model that simulates the cost of construction and operation of generation and transmission capacity to meet electricity demand and other power system requirements on a competitive basis over discrete study periods—in 2017, through 2030, and through 2050. Results from ReEDS include estimated electricity generation, geographic distribution of new electricity infrastructure additions, transmission requirements, and capacity additions of power generation technologies built and operated during the study period.

The modeling analysis assumes policy as effective on December 31, 2015, including the U.S. Environmental Protection Agency's *Carbon Pollution Standards for Existing Power Plants* (Clean Power Plan [16]).[15]

This analysis cannot comprehensively represent all of the costs or benefits of hydropower—it only represents factors that DOE can objectively quantify. This analysis also does not attempt to assess the costs for past, present, or future environmental impacts and solutions, such as resource protections needed to mitigate potential effects on fish and wildlife.

Both the existing hydropower fleet and the potential for new development are included in the quantitative modeling. Although deployment of existing hydropower facilities occurred over more than a century, modeling results indicate that important growth opportunities remain. Hydropower resource opportunities for potential growth fall into four distinct categories:

1. **Existing power plants and dams** that must be maintained and can be upgraded and optimized for increased production and environmental performance;
2. **New power plants at existing NPDs and water conveyances such as canals and conduits** that are not powered, but could be cost-effectively leveraged to support hydroelectric facilities;
3. **New and existing PSH** facilities and upgrades, including reservoirs and pumping/generating plants; and
4. **NSD,** including diversionary methods, new multi-purpose impoundments, or instream approaches.

Capacity additions from canals and conduits, resource potential in Alaska and Hawaii, and the potential for upgrades to existing PSH facilities are not available within the ReEDS quantitative modeling framework, and are therefore not part of the modeled results. Instead, these resources are discussed qualitatively throughout the *Hydropower Vision* report.

15. The U.S. Supreme Court stayed implementation of the Clean Power Plan on February 9, 2016. For the purposes of this report, DOE is assuming full implementation of the Clean Power Plan as described in the October 23, 2015, Federal Register notice at 80 Fed. Reg. 64661.

### 1.5.1 Resource Estimates and Modeling Scenarios

The *Hydropower Vision* uses the best available resource assessments to explore hydropower's market potential. The process of converting existing estimates of total physical or technical resource potential[16] to a modeling result of realistically potential deployment requires making technical, economic, physical, and geographic assumptions and corrections. These assumptions and corrections reduce the size of the resource base from total technical potential to that resource which will be available to the model.

The process flow for interpreting hydropower's future market potential from technical resource assessments is represented by Figure 1-5. The initial resource base considered is denoted in the figure by the "Technical Resource Potential." This resource potential is then reduced to the resource potential available to a capacity expansion model by applying economic and other assumptions and corrections, resulting in the "Modeled Resource Potential." The potential for market deployment is then calculated for future scenarios, denoted in the figure by "Modeling Results."

Parameters and assumptions for modeling of future deployment scenarios include cost reduction through technology advancement, cost reduction though innovative financial mechanisms, consideration of social and environmental objectives, changes in fossil fuel costs over time, future market penetration of variable generation resources, potential effects of climate change, and others. See Chapter 3 for detailed discussion of resource assessments, the *Hydropower Vision* modeling methodology, and modeling results.

While modeling results provided in Chapter 3 identify potential deployment pathways and the influence of key parameters, they do not—and cannot—indicate what actual future deployment may be. As indicated by Figure 1-5, actual deployment will be influenced by additional factors, including macroeconomic conditions, social and environmental considerations, policy, and others that are beyond the scope of the *Hydropower Vision* analysis. The *Hydropower Vision* roadmap (Chapter 4) provides a broad set of actions stakeholders may take to pursue opportunities for potential deployment identified in the modeling results.

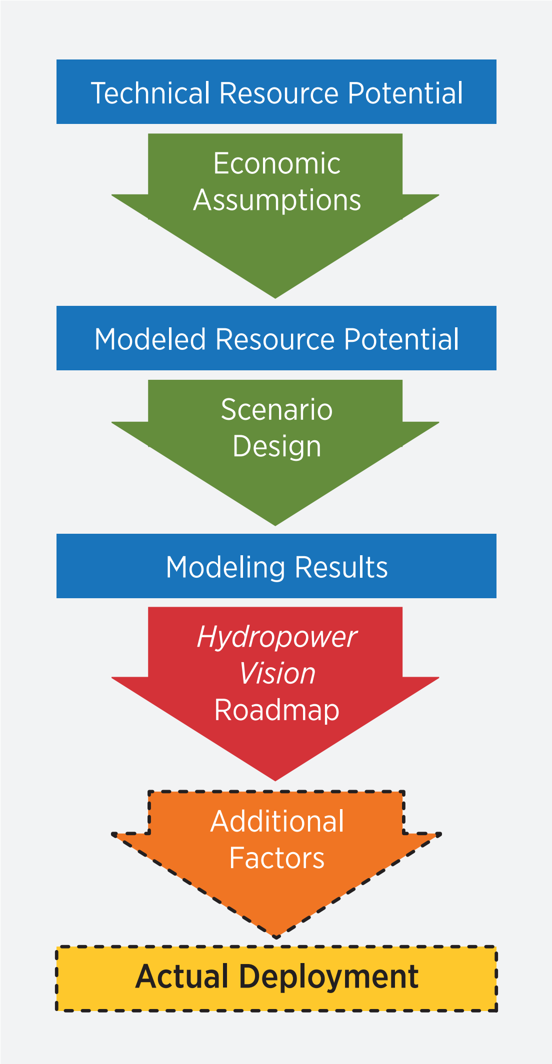



**Figure 1-5.** Process flow for interpreting hydropower's future market potential from technical resource assessments

16. The technical potential of a specific renewable electricity generation technology estimates energy generation potential based on renewable resource availability and quality, technical system performance, topographic limitations, and environmental and land-use constraints only. The estimates do not consider (in most cases) economic or market constraints, and therefore do not represent a level of renewable generation that might actually be deployed [48].

## 1.5.2 Characterizing the Potential for Hydropower Growth

Although future economic and societal needs and priorities can be anticipated, they are not fully predictable. Ongoing and sometimes rapid developments in information, manufacturing, and grid management technologies illustrate that—within the time frame of the *Hydropower Vision*—important and unanticipated changes in the needs for and uses of the key attributes of hydropower may lead to new and potentially sizable market opportunities. Through pursuit of actions laid out in the *Hydropower Vision* roadmap, the hydropower industry can build on its inherent operational flexibility and position itself to adapt to alternative market structures in the future. Regular and increasingly refined analysis of potential growth scenarios will help inform industry responsiveness.

*Hydropower Vision* takes into account several considerations regarding the potential and value of hydropower growth:

- As with existing hydropower infrastructure, better understanding of the market value for ancillary services provided by new hydropower facilities and those historically uncompensated or undercompensated from existing hydropower facilities can better inform market investment and policy decisions.
- PSH plants reduce overall system generation costs by helping to balance the complex operation of the electrical grid and provide a number of valuable grid services, such as operating reserves and voltage support, which are ancillary to power production. While there is significant resource potential for new PSH development in the United States, accessing this resource will require coordinated effort to address existing cost, market, environmental, and regulatory challenges.
- A variety of small hydropower projects may be able to be placed throughout the grid, particularly on distribution systems (distributed generation). For example, development of new technologies that enable cost-effective integration of small-scale, modular power generation into existing water infrastructure (such as conduits and pipelines) and conveyances may open up new markets using existing local distribution grids.
- Because hydropower depends on water availability, regional water management adaptations in response to climatic fluctuation may impact the potential for long-term growth in hydropower generation.
- Canadian and U.S. hydropower both serve the North American transmission grid. Therefore, long-term planning for and investment in operation of U.S. hydropower may need to consider potential regional and national grid and power market impacts of any increasing Canadian capacity.

The *Hydropower Vision* analysis of potential for growth takes into account several resource assessments examining opportunities for increased U.S. hydropower generation (Text Box 1-2) and untapped hydropower potential. Existing hydropower facilities may increase generation and environmental performance through technology upgrades and deployment of additional generating units. Suitable NPDs, as well as existing conduits and canals, may be retrofitted for power production. Suitable undeveloped stream-reaches have power production potential; developing this resource will involve working with resource agencies and river stakeholders on protection, mitigation, and enhancement measures to alleviate any adverse project effects. Such collaboration can provide an opportunity to identify win-win scenarios and meet multiple objectives for the use of rivers, e.g., basin-scale planning approaches and innovative hydropower technology and civil works with lower costs and reduced environmental footprints. Existing PSH facilities may be retrofitted with more efficient variable-speed turbines and higher capacity generating equipment, and new PSH facilities may be developed at suitable sites.

Text Box 1-2.

## Hydropower Resource Potential in the United States

**Upgrades and Optimization of Existing Hydropower Plants:** Improvements to existing hydropower facilities can make them more efficient and flexible, reduce adverse impacts to fish, and aerate to improve water quality. A 2014 analysis of a sample of existing facilities found an annual generation-weighted upgrade potential of 7.1% [49]. Extrapolating this to the existing base of hydropower generating capacity in the United States yields a fleet-wide upgrade estimate of at least 5 GW (approximately 13 TWh per year) of additional capacity that may be obtained through restoring and upgrading existing hydropower facilities [50]. In some cases, even greater gains are possible—seven hydropower modernization projects funded through the American Recovery and Reinvestment Act of 2009 resulted in generation increases averaging 35% at existing project facilities [49].

**Powering of Non-Powered Dams:** Existing NPDs can be retrofitted for hydropower generation without the costs and impacts of additional dam construction and operation, and with reduced environmental impact (e.g., no new impoundment). A 2012 study found that the nation has more than 50,000 suitable NPDs with the technical potential to add about 12 GW (31 TWh/year) of hydropower capacity [51]. The 100 largest capacity facilities—primarily locks and dams on the Ohio, Mississippi, Alabama, and Arkansas Rivers, operated by the Corps—could provide 8 GW of power combined.

**Powering of Existing Canals and Conduits:** Although water conveyance infrastructures such as irrigation canals or pressurized pipelines that deliver water to municipalities, industry, or agricultural water users are not usually designed for energy purposes, renewable energy can be captured from them without the need to construct new dams or diversions. While the potential is not well quantified, it is estimated that perhaps 1–2GW of generating potential in this form exists nationwide. Legislation has reduced some of the regulatory barriers that may have hindered full development of this energy resource [52].

**Low-Impact New Stream-Reach Development:** A 2014 national study found that a portion of the more than 3,000,000 million stream-reaches in the United States may offer new hydropower development opportunities [53]. The study concluded that the technical resource potential is over 65 GW (347 TWh/year) after exclusion of federally protected lands—i.e., designated National Parks, national Wild and Scenic Rivers, and Wilderness areas. Each stream-reach was assigned key social, economic, and environmental attributes. A given portion of these undeveloped stream-reaches may be economically feasible to develop for hydropower only after taking into account other uses and environmental considerations. More than 60% of the undeveloped stream resource potential would operate at less than 25 feet of head.

**New Pumped Storage Hydropower:** Facing a future with growing levels of variable generation, many developers and utilities are investigating the construction of new PSH to provide additional grid flexibility. These projects are typically large (500–2,000 MW), utility-scale facilities. Some would be "closed-loop" designs not connected to natural water bodies, thereby avoiding many of the environmental considerations associated with hydropower development. Additionally, DOE is investigating the feasibility of developing small (1–200 MW), modular PSH technologies that could reduce the permitting, financing, and environmental "footprint" challenges faced by larger, traditional PSH systems [54].

See Chapter 3, Table O3-3, for discussion of how these technical resource potential estimates are used to inform the modeled resource potential of the *Hydropower Vision* analysis.

# 1.6 Future Hydropower Technologies

The results of the forward-looking analysis presented in *Hydropower Vision* imply that future development of projects at previously undeveloped sites and waterways is likely to remain limited without innovative—even transformational—advances in technologies and project development methods to meet sustainability objectives. While facility upgrades and expansions as well as NPD projects will also benefit from these innovations, development of NSD projects are the most dependent on them. It is difficult to predict how these advances will take shape in the coming decades, but innovation trends offer indications of how non-traditional approaches could transform development of hydropower projects.

The innovations in project development and applications of advanced technologies described in this section are examples of non-traditional approaches that could transform development of new hydropower projects. Information characterizing the predominant existing technologies and design trends are in Chapter 2.

## 1.6.1 Advances in Sustainable Project Evaluation and Design

Innovative approaches that achieve multiple objectives require integrated planning methods. Figure 1-6 illustrates an integrated approach under which natural stream functionality is taken into account in establishing primary design objectives, design constraints, and functional requirements during the project planning and design process. If environmental objectives are integrated fully into the design paradigm for system components and facilities from the outset, there will be opportunities for advanced modeling, manufacturing, installation, operation, and maintenance innovations to reduce costs and improve generation and environmental performance simultaneously.

Environmentally sustainable hydropower projects should be sited, built, and operated to strike a balance between ecological considerations—such as species diversity, water quality, recreation, and physical processes within the ecosystem—and the needs of hydropower developers and operators to generate and sell power. Jager et al. [55] state, "making spatial decisions about hydropower development at the extent of large river basins and the resolution of smaller watersheds as planning units will produce solutions with higher ecological value that accommodate sustainable hydropower development." The process of making decisions that result in higher value solutions can be enhanced through identification of specific environmental metrics and based on scientific data to model, evaluate, and refine the performance of proposed hydropower system designs within the context of a specific site and watershed.

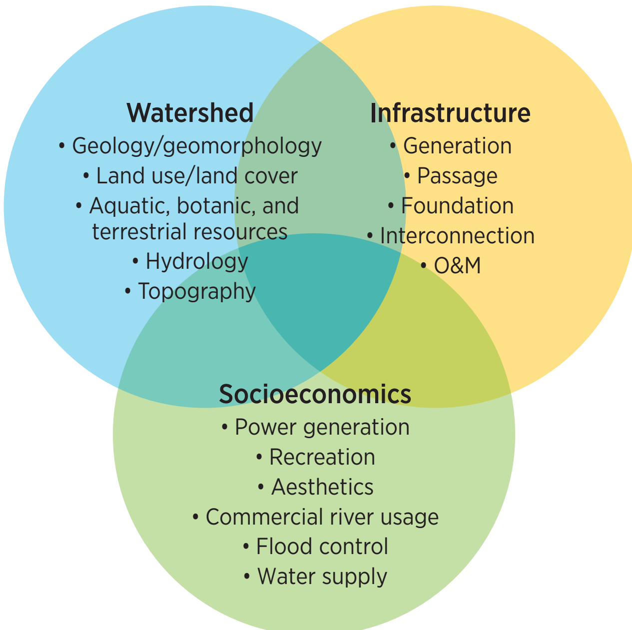



**Figure 1-6.** Primary linkage relations and indices for an integrated approach to hydropower development

The DOE project, *Environmental Metrics for Hydropower,*[17] is intended to help enhance the scientific basis for assessing environmental effects of next-generation hydropower developments in new stream-reaches. The outcome of this initiative will be a suite of scientifically rigorous metrics and related data from which hydropower developers, policy makers, and other stakeholders can select to evaluate design and performance of new, low-impact hydropower. Specific metrics may pertain, for instance, to geomorphology or to the function of streams in supporting successful reproduction of species.

The objective of DOE's *Biologically-Based Design and Evaluation Initiative for Hydropower* effort is to further biologically-based design, evaluation, and operation of hydropower turbines to limit the impacts on fish when they pass through turbines [56]. Applied research will be used to develop (1) tools that predict biological performance and (2) tools to evaluate empirical field measurements, and (3) methods to interpret population-level effects of given designs on fish injury and mortality.

The examples of new technologies presented in this section illustrate that there is ongoing research and development activity that can lead to measurable changes in the cost, configuration, and function of hydropower facilities in the decades to come. The *Hydropower Vision,* however, does not attempt to predict which technologies and design approaches will be implemented in the marketplace. Innovative approaches that have not yet been developed are likely to also impact how future projects are configured and operated.

### 1.6.2 Cost-Conscious Design and Manufacturing Processes

Potential hydropower cost reductions can be realized through standardization, consistency of implementation, and data-driven process improvements in project design, equipment procurement and fabrication, installation, and lifecycle management.

Improved design approaches and commonality of equipment configurations can reduce typical maintenance requirements, increase predictability in operations planning, and reduce the need for site-specific environmental assessment or customized technical solutions. Simplification strategies are emerging to reduce life cycle costs, including integrated turbine/generator units, and eliminating the traditional penstock and powerhouse.

New materials and additive manufacturing, or the three-dimensional printing of components in layers, enables fabrication of components with fewer bolted connections, decreased manufacturing labor costs, and higher factory throughput. These features have already led to cost reductions of mass-produced components in other industrial sectors, e.g., pumps and pump impellers. Applied research has shown a systematic assembly of composite hydropower turbines could lead to reduced labor costs and substantial weight reductions [57]. A DOE project is assessing alternative materials to build stronger, lighter, less expensive components, by combining dissimilar materials to adhere metallic microparticles to turbine blades in order to address cavitation problems.

### 1.6.3 Modular Systems

The DOE Standard Modular Hydropower project (Text Box 1-3) is intended to catalyze development of a suite of standardized components that preserve the functionality of natural streams in conjunction with electricity production. The project will also explore systemic analyses of undeveloped stream sites to establish broad classes for which standardized component modules would be most successful in preserving natural functions.

17. The *Environmental Metrics for Hydropower* initiative is a multiyear project started in FY 2016 at Oak Ridge National Laboratory. See *http://hydropower.ornl.gov for more information*.

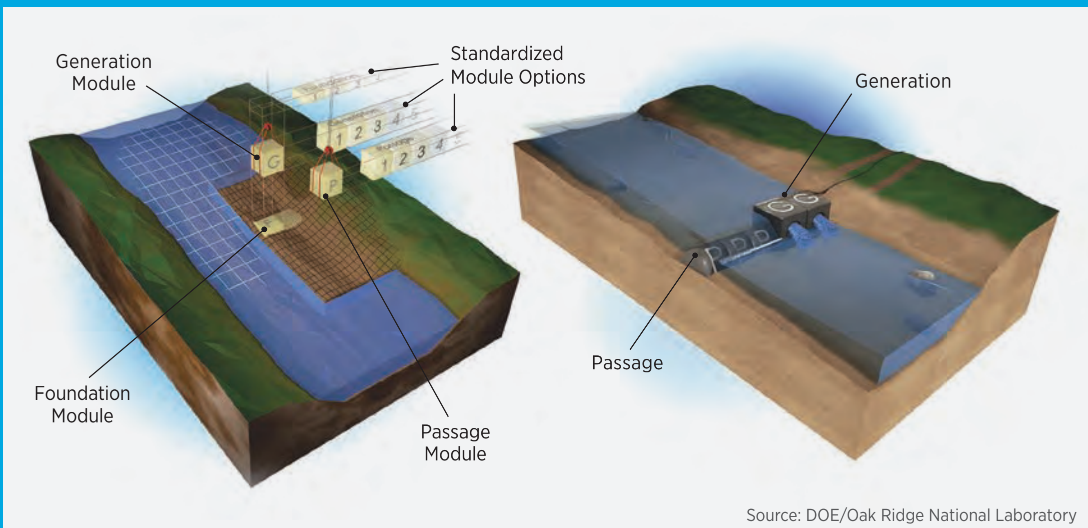
Text Box 1-3.

## Standard Modular Hydropower Approach

DOE is laying the groundwork for enhanced understanding of how low-impact and low-cost hydropower generation can be compatible with and even enhance the existing uses and functions of natural streams. The Standard Modular Hydropower project considers future hydropower facilities as integrated combinations of standard and validated modules, each with a primary objective, multiple functional requirements, and multiple design constraints. Research will focus on modules specific to power generation, fish and vessel passage, and stream connectivity, water quality improvement, streambed interface, installation, and grid interconnection. Initial categories of design constraints and specifications include aesthetics, public health and safety, environmental disturbance, operability, reliability and maintainability, security, module interoperability, and manufacturability.

Modules will be defined and validated by their adherence to these types of specifications, developed through research and development phases and drawing collaboratively on the expertise of industry, academia, national laboratories, non-governmental organizations, and agencies. The specification phases will be followed by cost modeling, supply chain, and manufacturing optimization, and technology transfer activities to enable physical modules to be demonstrated and deployed.

The conceptual rendering of Standard Modular Hydropower illustrates how different modules for foundation, generation, and stream passage may be considered and fit together to meet site-specific parameters, as well as environmental and power generation objectives.




Conceptual illustration of modular approach to new in-stream hydropower facility

## 1.6.4 Compact Turbine/ Generator Designs

Potential sites for NSD are predominantly low head, with variable flow rates. Several new turbine/generator configurations illustrate how compact and modular designs can simplify facility design, limit the need for civil works, and reduce lifetime maintenance requirements at sites with these characteristics.

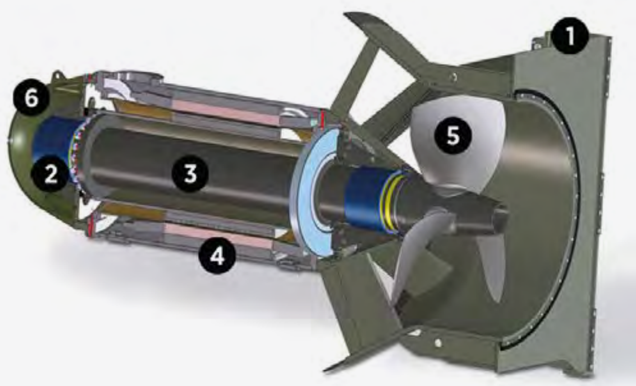
Two compact turbines with bulb-enclosed permanent magnet generators are shown in Figure 1-7. Permanent magnet generators eliminate the need for external excitation, allowing simplification of the mechanical design and improved system efficiency and reliability.

The Archimedes screw, historically used as a water pump, has emerged as another potential solution for high-flow, low-head sites. Water that enters the top of the screw is slowly pulled down by gravity, rotating the blades (Figure 1-8). This type of turbine is generally considered fish-friendly due to slow operating speeds and large blade spacing.

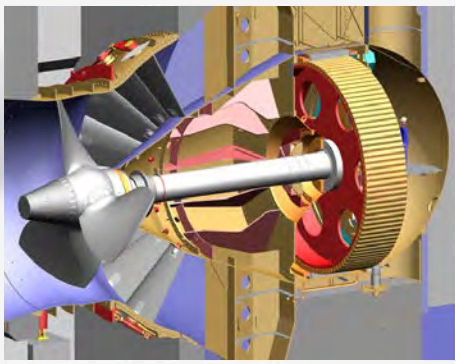
Figure 1-9 illustrates another example of an innovative compact turbine/generator combination. In this case, the permanent magnets are mounted directly to the blades of the turbine in a lightweight composite turbine housing that reduces overall weight. Variable-speed technology eliminates the need for mechanical controls.

Most innovative compact turbine generator units can be installed in existing infrastructure—including NPDs, irrigation canals, and other types of water conveyances—often in a standardized modular fashion. Figure 1-10 shows multiple units installed on an existing dam.

A key factor at low-head sites is the volume of concrete necessary for a powerhouse. Low-head turbines have larger diameters to accommodate higher discharges, which increases the structural stability requirements. Compact turbine technologies that incorporate the generator and turbine runner into a single rotating unit, however, may eliminate the need for a conventional powerhouse (Figure 1-11).




1. Turbine housing with guide vanes
2. Radial and axial bearing coating on shaft ends
3. Shaft
4. Generator/turbine
5. Runner
6. Bulb nose



Sources: Voith, Andritz

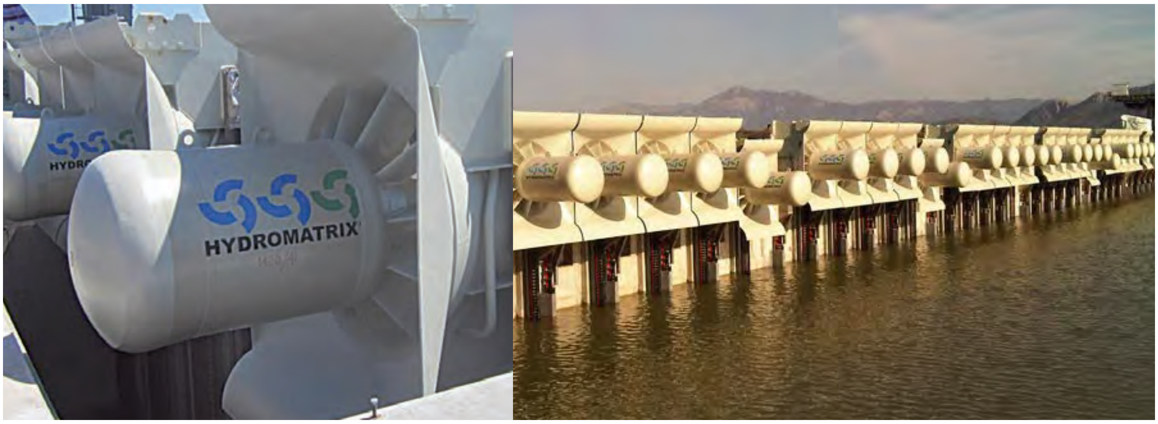
**Figure 1-7.** Examples of compact turbine and permanent magnet generator designs: Voith StreamDiver turbine module encased in a bulb (left); Andritz bulb-type turbine (right)

Source: The New England Hydropower Company

**Figure 1-8.** Archimedes screw for hydropower generation

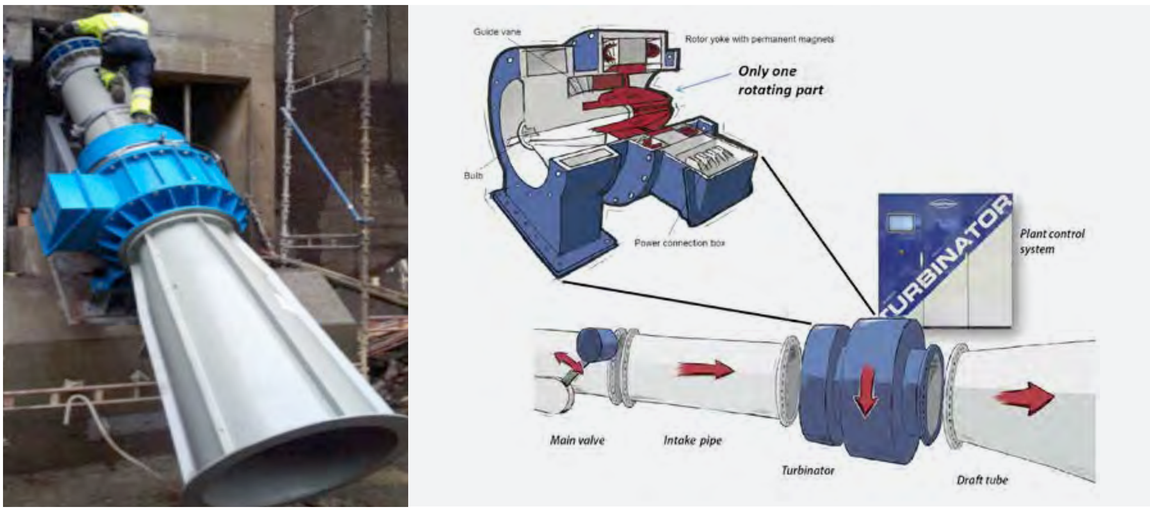
Source: Amjet

**Figure 1-9.** Composite housing with combined turbine/generator assembly




Source: Andritz Hydro

**Figure 1-10.** Modular application of standard turbine runners to an existing dam




Source: Opsahl 2013

**Figure 1-11.** Inclined (left) and horizontal (right) integrated turbine-generator technology installed without a powerhouse

## 1.6.5 Passage Technologies

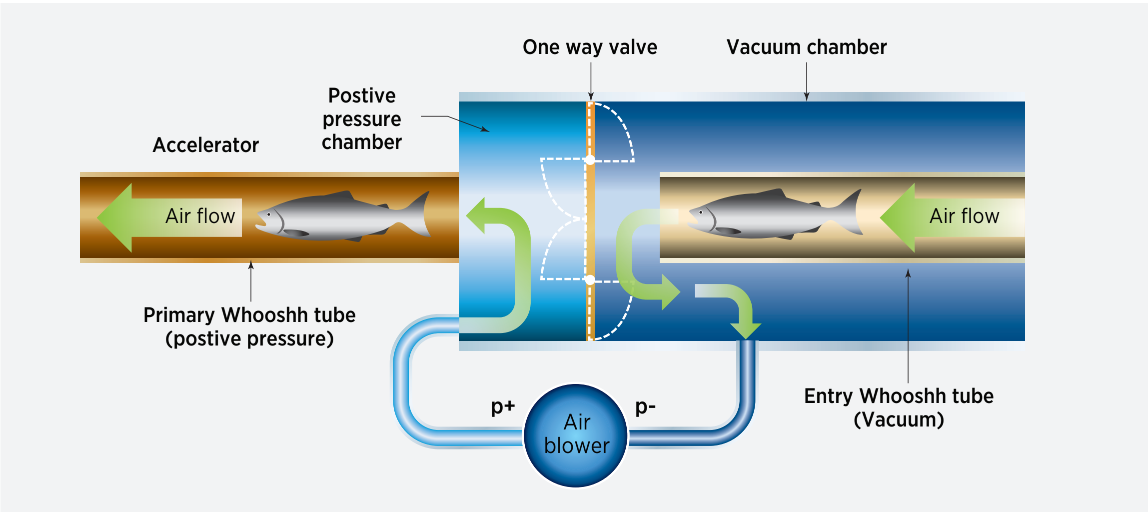
The use of a dam, weir, or diversion structure is common for most hydropower projects. These structures allow water flow while creating hydraulic head to drive the turbine. However, they also typically create disruptions in the complex interplay between water, organisms, sediment, nutrient cycles, and other elements of an aquatic ecosystem. During the project design phase, technical solutions must consider passage requirements for (at the least) water, fish, sediment, and recreation.

The need for inexpensive, effective, and standardized passage facilities has led to the investigation and demonstration of innovative approaches. An emerging trend in downstream passage is the use of nature-like fish channels, which incorporate natural riverine features into complex bathymetries with space for internal habitat development. Figure 1-12 illustrates a natural fish passage facility designed in collaboration with the Massachusetts Division of Marine Fisheries, the National Marine Fisheries Service, and the U.S. Fish and Wildlife Service to restore river herring and American eel populations; and a novel design combining fish and recreational vessel passage around a dam in Wichita, KS.

A novel approach to moving migrating fish upstream past hydropower facilities is the Whooshh Fish Transport System. This transport system uses a flexible tube and pressure (Figure 1-13) to guide fish over and around structures. The system has the potential to facilitate fish passage more quickly and safely, and at lower cost, with passage results at least comparable to traditional trap and haul fish transport methods [59].

Sources: MKEC Engineering; Alicia Pimental

**Figure 1-12.** Combined fish and recreational boating passage, Wichita, KS (left); "nature-like" Acushnet Fishway, New Bedford, MA (right)




Source: Whooshh Innovations, LLC

**Figure 1-13.** Whooshh Fish Transport System

# 1.7 The *Hydropower Vision* Roadmap

The *Hydropower Vision* roadmap for national action was developed through extensive collaboration, contributions, and rigorous peer review from industry, the electric power sector, non-governmental organizations, academia, national laboratories, and representatives of government agencies. The roadmap (Chapter 4) outlines, in a non-prescriptive manner, five topical areas, 21 topical sub-categories, and 64 actions for consideration by all stakeholder sectors to address many of the challenges that have affected hydropower. These roadmap actions are intended to leverage the existing hydropower fleet and potential for sustainable hydropower growth to increase and support the nation's renewable energy portfolio, economic development, environmental stewardship, and effective use of resources through specific technical, environmental, economic, and institutional stakeholder actions. It is beyond the scope and purview of the *Hydropower Vision* to suggest policy preferences or recommendations, and no attempt is made to do so.

Key insights from the roadmap include:

- The hydropower industry and research community will need to take an innovative approach to designing a suite of technologies and civil structures that can successfully balance multiple objectives, including cost-effective energy production, penetration of variable generation from renewable energy resources, water management, and environmental protection.
- Collaboration is critical across all roadmap action areas, including within the industry to develop the next generation of technologies; among stakeholders to improve regulatory efficiency; or between industry and academia to prepare the incoming workforce.
- Improving the environmental performance of hydropower technologies can help achieve sustainability objectives, and developing a comprehensive set of science-based environmental performance metrics will further the design and sustainable operation of hydropower projects.
- Undertaking actions such as establishing better mechanisms for collaboration and disseminating successful practices can improve regulatory process implementation.
- Outreach actions cut across all roadmap areas.

Articulating and disseminating objective information regarding hydropower's role as an established and cost-effective renewable energy source, its importance to grid stability and reliability, and its ability to support variable generation can help increase hydropower's acceptance and lead to: (a) increased investor confidence, (b) improved understanding among stakeholders of environmental, social, and regulatory objectives, (c) improved compensation for grid services, and (d) enhanced eligibility in renewable and clean energy markets.

While the roadmap includes collective steps that can be taken by many parties working in concert, it cannot and does not represent federal agency obligations or commitments.

## 1.7.1 Opportunity, Risk of Inaction, and the Way Forward

One of the greatest challenges for the United States in the 21st century is producing and making available clean, affordable, and secure energy. Hydropower has been, and can continue to be a substantial part of addressing that challenge. Although the hydropower industry has adopted improved technology and exhibited significant growth over the past century, the path that led to its historical growth rates is different under modern conditions, and continued evolution of that path—including transformative innovation—is needed.

The *Hydropower Vision* report highlights the national opportunity to capture additional domestic low-carbon energy with responsible development of advanced hydropower technologies across all U.S. market sectors and regions. Where objectively possible, the analysis quantifies the associated costs and benefits of this deployment and provides a roadmap for the collaboration needed for successful implementation.

## 1.7.2 The Opportunity

The *Hydropower Vision* analysis (Chapter 3) modeled a credible future scenario combining *Advanced Technology, Low Cost Finance* and *Combined Environmental Considerations.* Findings indicate that U.S. hydropower could grow from 101 GW of combined generating and storage capacity in 2015 to nearly 150 GW by 2050, realizing over 50% of this growth by 2030. NSD beyond this scenario could conceivably become economically viable in the future if significant and transformative innovation is achieved that can address a range of environmental considerations. Increasing hydropower can simultaneously deliver an array of benefits to the nation that address issues of national concern, including climate change, air quality, public health, economic development, energy diversity, and water security. Additionally, new PSH technology can further facilitate integration of variable generation resources—such as wind and solar—into the national power grid due to its ability to provide grid flexibility, reserve capacity, and system inertia.

## 1.7.3 The Risks of Inaction

While the industry is mature, many future actions and efforts remain critical to further advancement of domestic hydropower as a key energy source of the future. This includes continued technology development to increase efficiency, further sustainability, and drive down costs; as well as the availability of market mechanisms that take into account the value of grid reliability services, air quality and reduced emissions, and long asset lifetimes. A lack of well-informed, coordinated actions to meet these challenges reduces the likelihood that potential benefits to the nation will be realized. Failure to address business risks associated with hydropower development costs and development timelines—including uncertainties related to negotiation of interconnect fees and power sales contracts, regulatory process inefficiencies, environmental compliance, financing terms, and revenue sources— could mean that opportunities for new deployment will not be realized.

Engagement with the public, regulators, and other stakeholders is needed to enable environmental considerations to be effectively addressed. Continued research and analysis on energy policy and hydropower costs, benefits, and effects is important to provide accurate information to policy makers and for the public discourse. Finally, a commitment to regularly revisit the *Hydropower Vision* roadmap and update priorities across stakeholder groups and disciplines is essential to ensuring coordinated pathways toward a robust and sustainable hydropower future.

## 1.7.4 The Way Forward

The *Hydropower Vision* roadmap identifies a high-level portfolio of new and continued actions and collaborations across many fronts to help the United States realize the long-term benefits of hydropower, while protecting the nation's energy, environmental, and economic interests. Stakeholders and other interested parties must take the next steps in refining, expanding, operationalizing, and implementing a credible hydropower future. These steps could be developed in formal working groups or informal collaborations, and will be critical in overcoming the challenges, capitalizing on the opportunities, and realizing the national benefits detailed within the *Hydropower Vision.*

# Chapter 1 References

[1] U.S. Energy Information Administration. Monthly Energy Review. U.S. Department of Energy. Accessed July 1, 2016. *http://www.eia.gov/totalenergy/data/monthly/*.

[2] Federal Energy Regulatory Commission, Energy Infrastructure Updates (2011-2015). Accessed July 1, 2016. *http://www.ferc.gov/legal/staff-reports.asp/*.

[3] Uria-Martinez, R., P. O'Connor, M. Johnson. 2015. "2014 Hydropower Market Report". Prepared by Oak Ridge National Laboratory for the U.S. Department of Energy. DOE/EE 1195. April 2015. *http://energy.gov/eere/water/downloads/2014-hydropower-market-report.*

[4] U.S. Energy Information Administration. Electricity Data Browser. Accessed July 12, 2016. *http://www.eia.gov/electricity/data/browser/*.

[5] "The History of Hydropower Development in the United States." c2015. U.S. Bureau of Reclamation. *http://www.usbr.gov/power/edu/history.html*.

[6] U.S. Department of Energy. Prepared by Navigant Consulting, Inc., and the National Renewable Energy Laboratory. DOE/EE-1400. Forthcoming (2016). "United States Hydropower Workforce Assessment and Future Scenarios".

[7] Koritarov, V.; T. Veselka; J. Gasper; B. Bethke; A. Botterud; J. Wang; M. Mahalik; Z. Zhou; C. Milostan; J. Feltes; Y. Kazachkov; T. Guo; G. Liu; B. Trouille; P. Donalek; K. King; E. Ela; B. Kirby; I. Krad; and V. Gevorgian. 2014. Modeling and Analysis of Value of Advanced Pumped Storage Hydropower in the United States. Technical Report, ANL/DIS-14/7. Argonne National Laboratory, Argonne, IL, June 2014. Accessed July 12, 2016: *http://www.ipd.anl.gov/anlpubs/2014/07/105786.pdf*

[8] Kumar, A.; T. Schei; A. Ahenkorah; R. Caceres Rodriguez; J.-M.; Devernay; M. Freitas; D. Hall; Å. Killingtveit; and Z. Liu. 2011. "Hydropower." In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation; Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA. Accessed July 12, 2016. *http://www.ipcc.ch/report/srren/*.

[9] United Nations Educational, Scientific and Cultural Organization and the International Hydropower Association (UNESCO). Research project on the greenhouse gas status of freshwater reservoirs. 2015 World Hydropower Congress, Beijing, China. May 20, 2015.

[10] Bonnet, M.; A. Witt; K. Stewart; B. Hadjerioua; and M. Mobley. The Economic Benefits of Multipurpose Reservoirs in the United States-Federal Hydropower Fleet. September 2015. ORNL/TM-2015/550. Accessed July 12, 2016. *http://info.ornl.gov/sites/publications/files/Pub59281.pdf*.

[11] Cada, G.F.; T.J. Carlson; D.D. Dauble; R.T. Hunt; M.J. Sale; and G.L. Sommers. "Hydropower: Setting a Course for Our Energy Future." Wind and Hydropower Technologies Program (Brochure). National Renewable Energy Laboratory for the U. S. Department of Energy. DOE/GO-102004-1981; NREL/BR-500-34916. July 2004. Accessed July 12, 2016. *http://www.nrel.gov/docs/fy04osti/34916.pdf*.

[12] U.S. Energy Information Administration. Form 860_US Capacity by Generator Unit_Y1891-Y2014. U.S. Department of Energy. October 21, 2015 Accessed July 12, 2016. *http://www.eia.gov/electricity/data/eia860/index.html.*

[13] Executive Office of the President, "The President's Climate Action Plan." June 2013. Accessed July 12, 2016. *https://www.whitehouse.gov/sites/default/files/image/president27sclimateactionplan.pdf.*

[14] U.S. Department of Defense. Report on National Security Implications of Climate-Related Risks and a Changing Climate. July 2015. Accessed July 12, 2016. *http://archive.defense.gov/pubs/150724-congressional-report-on-national-implications-of-climate-change.pdf.*

[15] California Air Resources Board. Assembly Bill 32 Overview. Accessed July 12, 2016. *http://www.arb.ca.gov/cc/ab32/ab32.htm.*

[16] U.S. Environmental Protection Agency. Clean Power Plan for Existing Power Plants. Accessed July 12, 2016: *https://www.epa.gov/cleanpowerplan/clean-power-plan-existing-power-plants.*

[17] U.S. Environmental Protection Agency. Regulatory Impact Analysis for the Clean Power Plan Final Rule. Docket ID EPA-452-R-15-003. 2015. Research Triangle Park, NC: U.S. Environmental Protection Agency. Accessed July 12, 2016: *http://nepis.epa.gov/Simple.html*.

[18] The White House. Fact Sheet: Administration Announces New Agenda to Modernize Energy Infrastructure, Releases Quadrennial Energy Review. Office of the Press Secretary. April 2015. Accessed July 12, 2016. *https://www.whitehouse.gov/the-press-office/2015/04/21/fact-sheet-administration-announces-new-agenda-modernize-energy-infrastr*.

[19] "What is energy security?" ©2016. International Energy Agency. Accessed July 12, 2016. *http://www.iea.org/topics/energysecurity/subtopics/whatisenergysecurity/*

[20] The White House. Office of the Press Secretary. Presidential Policy Directive—Critical Infrastructure Security and Resilience (PPD-21). February 2013. Accessed July 12, 2016: *https://www.whitehouse.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil.*

[21] "Critical Infrastructure Sectors," October 27, 2015. U.S. Department of Homeland Security. Accessed July 12, 2016. *http://www.dhs.gov/critical-infrastructure-sectors.*

[22] Barbose, G. U.S. Renewables Portfolio Standards 2016 Annual Status Report. Lawrence Berkeley National Laboratory. LBNL-1005057. April 2016. Accessed July 12, 2016. *https://emp.lbl.gov/projects/renewables-portfolio.*

[23] Stori, V. Environmental Rules for Hydropower in State Renewable Portfolio Standards. Clean Energy States Alliance. April 2013. Accessed July 12, 2016. *http://www.cesa.org/resource-library/resource/environmental-rules-for-hydropower-in-state-renewable-portfolio-standards*.

[24] *The Economist.* "Natural gas: Shale of the century." June 2, 2012. Accessed July 12, 2015. *http://www.economist.com/node/21556242.*

[25] U.S. Energy Information Administration. Selected national average natural gas prices, 2010-2015. Natural Gas Monthly. Accessed July 12, 2016. *http://www.eia.gov/naturalgas/monthly/.*

[26] U.S. Energy Information Administration. Issues in Focus - Implications of accelerated power plant retirements. Annual Energy Outlook 2014. DOE/EIA-0383(2014). April 2014. Accessed July 12, 2016. *http://www.eia.gov/forecasts/archive/aeo14/section_issues.cfm#power_plant.*

[27] U.S. Energy Information Administration. April 2015. Annual Energy Outlook 2015. Accessed July 12, 2016: *http://www.eia.gov/forecasts/aeo/.*

[28] "Diablo Canyon Nuclear Closure Plan: An Important Model." June 22, 2016. McKinzie, M. Natural Resources Defense Council. Accessed July 12, 2016: *https://www.nrdc.org/experts/matthew-mckinzie/diablo-canyon-nuclear-closure-plan-important-model.*

[29] Nuclear Energy Regulatory Commission. 2015 Summer Reliability Report. May 2015. Accessed July 12, 2016. *http://www.nerc.com/pa/RAPA/ra/Pages/default.aspx*.

[30] U.S. Energy Information Administration, Form EIA-860 Annual Electric Generator Report, and Form EIA-860M. Hydropower has a long history in the United States. July 2011. Accessed July 12, 2016. *http://www.eia.gov/todayinenergy/detail.cfm?id=2130*.

[31] Federal Energy Regulatory Commission, Energy Infrastructure Updates (2011-2015). Accessed July 12, 2016. *http://www.ferc.gov/legal/staff-reports.asp.* For December 2015, *http://www.ferc.gov/legal/staff-reports/2015/dec-infrastructure.pdf.*

[32] Sullivan, P., W. Cole, N. Blair, E. Lantz, V. Krishnan, T. Mai, D. Mulcahy, and G. Porro. 2015 Standard Scenarios Annual Report: U.S. Electric Sector Scenario Exploration. NREL/TP-6A20-64072. Golden, CO: National Renewable Energy Laboratory, 2015. Accessed July 12, 2016. *http://primo-pmtna01.hosted.exlibrisgroup.com/Pubs:PUBS:NREL_HORIZON99724*.

[33] U.S. Department of Energy. Quadrennial Technology Review - An Assessment of Energy Technologies and Research Opportunities. September 2015. Accessed July 12, 2016. *http://energy.gov/qtr.*

[34] Eller, A., and A. Dehamna. Energy Storage for the Grid and Ancillary Services. Navigant Consulting, Inc. May 2016. Accessed July 12, 2016. *https://www.navigantresearch.com/research/energy-storage-for-the-grid-and-ancillary-services* .

[35] Bird, L. and B. Swezey. Green Power Marketing in the United States: A Status Report (Ninth Edition). National Renewable Energy Laboratory. NREL/TP-640-40904. November 2006. Accessed July 12, 2016. *http://apps3.eere.energy.gov/greenpower/resources/pub_alpha.shtml?alpha_char=B.*

[36] Heeter, J. and T. Nicholas. October 2013. Status and Trends in the U.S. Voluntary Green Power Market (2012 Data). National Renewable Energy Laboratory. NREL/TP-6A20-60210. Accessed July 12, 2016. *http://primo-pmtna01.hosted.exlibrisgroup.com/Pubs:PUBS:NREL_HORIZON81700*.

[37] Heeter, J.; K. Belyeu; and K. Kuskova-Burns. Status and Trends in the U.S. Voluntary Green Power Market. National Renewable Energy Laboratory. NREL/TP-6A20-63052. November 2014. Accessed July 12, 2016. *http://primo-pmtna01.hosted.exlibrisgroup.com/Pubs:PUBS:NREL_HORIZON98848.*

[38] U.S. Environmental Protection Agency. National Top 100. EPA Green Power Partnership. October 2015. Accessed July 12, 2016. *http://www3.epa.gov/greenpower/toplists/top100.htm.*

[39] "Making Way for Fish Migration: Celebrating World Fish Migration Day (May 21, 2016)." May 16, 2016. National Oceanic and Atmospheric Administration Fisheries. Accessed July 13, 2016. *http://www.fisheries.noaa.gov/stories/2016/05/05-world-fish-migration-day-2016.html.*

[40] Federal Energy Regulatory Commission. Open Commission Meeting. Staff Presentation Item A-4. April 21, 2016. Accessed July 12, 2016. *http://www.ferc.gov/CalendarFiles/20160421110616-A-4-Presentation.pdf.*

[41] U.S. Army Corps and FERC, 2011. MOU on Non-Federal Hydropower Projects - Memorandum of Understanding between United States Army Corps of Engineers and the Federal Energy Regulatory Commission on Non-federal Hydropower Projects. Accessed July 12, 2016. *http://www.ferc.gov/legal/mou.asp*.

[42] U.S. Department of Energy, U.S. Department of the Interior, U.S. Army Corps of Engineers, 2010. Hydropower Memorandum of Understanding for Hydropower. Accessed July 12, 2016. *http://energy.gov/eere/water/downloads/hydropower-memorandum-understanding.*

[43] Basin Scale Opportunity Assessment. Pacific Northwest National Laboratory. Accessed July 13, 2016. *http://basin.pnnl.gov/.*

[44] Bracmort, K.; A. Vann; and C.V. Stern. Hydropower: Federal and Nonfederal Investment. Congressional Research Service. CRS Report R42579. July 12, 2015. Accessed July 12, 2016. *https://www.fas.org/sgp/crs/misc/R42579.pdf.*

[45] Personal communication with E. Hansen, Office of the Assistant Secretary of the Army (Civil Works), June 29, 2016. Data cited based on Corps annual performance reports.

[46] Tennessee Valley Authority. Strategic Sustainability Performance Plan. Accessed July 12, 2014. *https://www.tva.gov/About-TVA/Guidelines-and-Reports/Sustainability-Plans-and-Performance*.

[47] Short, W., P. Sullivan, T. Mai, M. Mowers, C. Uriarte, N. Blair, D. Heimiller, A. Martinez, Regional Energy Deployment System (ReEDS). NREL/TP-6A20-46534. Golden, CO: National Renewable Energy Laboratory, December 2011; 94 pp. Accessed July 12, 2016. *http://www.nrel.gov/analysis/reeds/documentation.html*.

[48] Lopez, A., B. Roberts; D. Heimiller; N. Blair; and G. Porro. U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis. National Renewable Energy Laboratory. July 2012. NREL/TP-6A20-51946. Accessed July 12, 2016. *http://www.nrel.gov/docs/fy12osti/51946.pdf.*

[49] U.S. Department of Energy. 2014 Water Power Program Peer Review Compiled Presentations—Hydropower Technologies. Accessed July 12, 2016. *http://energy.gov/eere/water/downloads/2014-water-power-program-peer-review-compiled-presentations-hydropower.*

[50] Smith, B. T.; Zhang, Q. 2015. Final report for aggregated baseline assessments of aging hydropower facilities. ORNL/TM-2015/698. Oak Ridge, TN: Oak Ridge National Laboratory. Accessed July 12, 2016: *http://hydropower.ornl.gov/research/hydropower/.*

[51] Hadjerioua, B.; Y. Wei; and S.C. Kao. An Assessment of Energy Potential at Non-powered Dams in the United States. April 2012. GPO DOE/EE-0711, Washington, DC. Accessed July 12, 2016. *http://nhaap.ornl.gov/sites/default/files/NHAAP_NPD_FY11_Final_Report.pdf.*

[52] Sale, M. J., N.A. Bishop, Jr., S.L. Reiser, K. Johnson, A.C. Bailey, A. Frank, and B.T. Smith. 2014. Opportunities for Energy Development in Water Conduits: A Report Prepared in Response to Section 7 of the Hydropower Regulatory Efficiency Act of 2013. ORNL/TM-2014/272. Prepared for the U.S. Department of Energy by the Oak Ridge National Laboratory Water Power Technologies Team.

[53] Kao, S. C.; R. M. McManamay; K. M. Stewart; N. M. Samu; B. Hadjerioua; S. T. DeNeale; D. Yeasmin; M. F. K.; Pasha; A.Oubeidillah; and B.T. Smith. 2014. New Stream-Reach Development: A Comprehensive Assessment of Hydropower Energy Potential in the United States. GPO DOE/EE-1063. Washington, DC. Accessed July 12, 2016. *http://nhaap.ornl.gov/sites/default/files/ORNL_NSD_FY14_Final_Report.pdf.*

[54] Hadjerioua, B.; R. Uria-Martinez; A. Witt; and N. Bishop. 2014. Evaluation of the Feasibility and Viability of Modular Pumped Storage Hydro (m-PSH) in the United States. ORNL/TM- 2015/559. Oak Ridge National Laboratory. Oak Ridge, Tennessee. Accessed July 12, 2016. *http://info.ornl.gov/sites/publications/files/Pub59307.pdf*.

[55] Jager, H.I.; R.A. Efroymson; J. Opperman; and M. Kelly. Spatial design principles for sustainable hydropower development in river basins. Renewable and Sustainable Energy Reviews 45: 808-816. Accessed July 12, 2016. *http://www.esd.ornl.gov/~zij/mypubs/Waterpower/Jager2015-RiverBasinDesign-Reviews Renewable.pdf.*

[56] U.S. Department of Energy. 2016. Biologically Based Design and Evaluation Initiative for Hydropower: Multi-Year Research Plan (2016–2018). Prepared by the Pacific Northwest and Oak Ridge National Laboratories for the U.S. Department of Energy, Water Power Program.

[57] Whitehead, M. and R. Albertani, "How Composite Materials Can be Used for Small Hydro Turbines," Hydro Review and HydroWorld.com, Vol. 34, No. 2, pp. 56-63, March 2015. Accessed July 12, 2016. *http://www.hydroworld.com/articles/hr/print/volume-34/issue-2/articles/how-composite-materials-can-be-used-for-small-hydro-turbines.html*.

[58] P.L. 109-58. Energy Policy Act of 2005. Public Law No: 109-58. 42 U.S.C. § 931 (a)(2)(D) Hydropower and 42 U.S.C. § 931 (a)(2)(E)(i) Miscellaneous Projects.) Accessed July 12, 2016. *https://www.gpo.gov/fdsys/pkg/PLAW-109publ58/content-detail.html*.

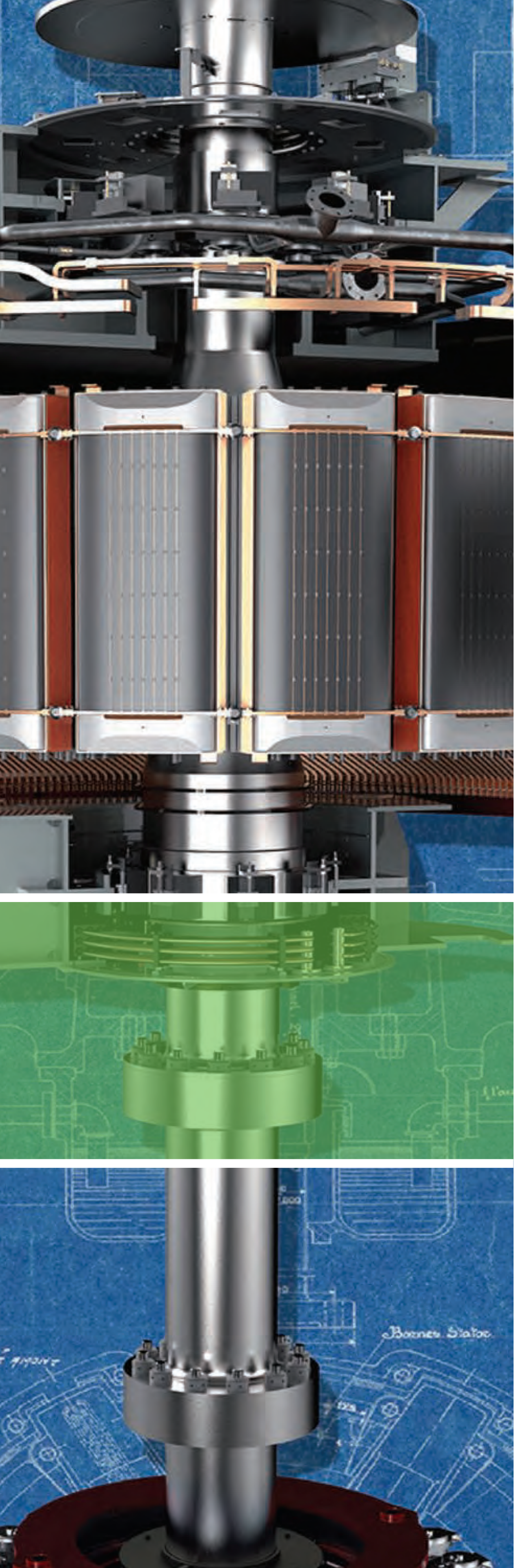
[59] Geist, D.R., Colotelo, A.H., Linley, T.J., Wagner, K.A., and Miracle, A.L. Forthcoming (2016). *Journal of Fisheries and Wildlife Management*. "Physical, physiological, and reproductive effects on adult fall Chinook salmon due to passage through a novel fish transport system."

[60] International Energy Agency. Energy security. International Energy Agency. Accessed November 15, 2015. *http://www.iea.org/topics/energysecurity/*.

# 2 STATE OF HYDROPOWER in the United States

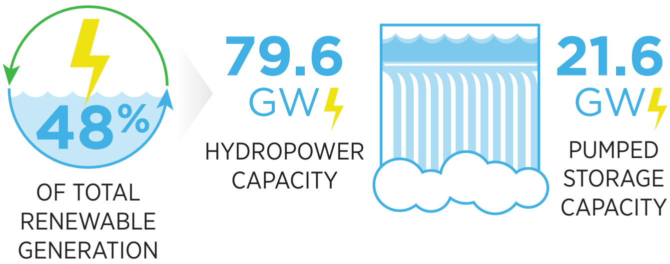
U.S. DEPARTMENT OF ENERGY

Photo from 65681751. Illustration by Joshua Bauer/NREL



# Overview

Hydropower is the primary source of renewable energy generation in the United States, delivering 48% of total renewable electricity sector generation in 2015, and roughly 62% of total cumulative renewable generation over the past decade (2006-2015) [1]. The approximately 101 gigawatts[1] (GW) of hydropower capacity installed as of 2014 included ~79.6 GW from hydropower generation[2] facilities and ~21.6 GW from pumped storage hydropower[3] facilities [2]. Reliable generation and grid support services from hydropower help meet the nation's requirements for the electrical bulk power system, and hydropower provides a long-term, renewable source of energy that is essentially free of hazardous waste and is low in carbon emissions. Hydropower also supports national energy security, as its fuel supply is largely domestic.




**Hydropower is the largest renewable energy resource in the United States and has been an established, reliable contributor to the nation's supply of electricity for more than 100 years.**

In the early 20th century, the environmental consequences of hydropower were not well characterized, in part because national priorities were focused on economic development and national defense. By the latter half of the 20th century, however, there was greater awareness of the environmental impacts of dams, reservoirs, and hydropower operations.

As a result, the federal government passed laws that have led to safer and more environmentally aware operation of dams, reservoirs, and hydropower facilities throughout the nation.

Decades of evolution in engineering technologies, environmental mitigation and protection methods, and regulatory frameworks provide a foundation for future hydropower. Five primary potential resource classes[4] exist for new hydropower capacity in the United States:

1. **Upgrades and optimization, i.e., rehabilitating, expanding, upgrading, and improving efficiency, of existing hydropower facilities;**
2. **Powering non-powered dams (NPDs);**
3. **Installing hydropower in existing water conveyance infrastructure, such as conduits and canals;**
4. **Developing hydropower projects on new stream-reaches (NSD); and**
5. **Increasing pumped storage hydropower (PSH).**

Development of these potential resources will require sustainable[5] development and operations practices. Future hydropower must integrate environmental stewardship, economic performance, and availability of critical water resources for production of clean energy.

Chapter 2, *State of Hydropower in the United States,* summarizes the status of hydropower in the United States as of year-end 2015 within eight important topic areas: history, contributions, and context; role in the grid; markets and project development economics; opportunities for development; design, infrastructure, and technology; operations and maintenance; pumped storage; and economic impact.

These eight topic areas provide key contextual and technical information— including trends, opportunities, and challenges—that was used in developing the *Hydropower Vision* and that is fundamental to the future concepts, growth potential, and roadmap actions explored in Chapters 1, 3, and 4.

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1. As of 2014.
2. Hydropower as discussed in this report includes new or conventional technologies that use diverted or impounded water to create hydraulic head to power turbines, and PSH facilities in which stored water is released to generate electricity and then pumped back during periods of excess generation to replenish a reservoir.
3. Throughout this report, the term "hydropower" generally encompasses all categories of hydropower. If a distinction needs to be made, the term "hydropower generation" distinguishes other types of projects from "pumped storage hydropower," or "PSH."
4. This report does not address marine (wave, current, and tidal) and river hydrokinetic technologies, as marine and hydrokinetic technologies are defined by Congress as separate and distinct from hydropower (Energy Policy Act of 2005. Public Law No: 109-58. 42 U.S.C. § 931 (a)(2)(D) Hydropower and 42 U.S.C. § 931 (a)(2)(E)(i) Miscellaneous Projects. *https://www.congress.gov/109/plaws/publ58/PLAW-109publ58.pdf*).
5. In the *Hydropower Vision,* the term *sustainable hydropower* describes a hydropower project or interrelated projects that are sited, designed, constructed, and operated to balance social, environmental, and economic objectives at multiple geographic scales (e.g., national, regional, basin, site).

# 2.0 Introduction

## *History, Contributions, and Context of Hydropower*

The world's first hydropower plant began to generate electrical energy in 1882 in Appleton, Wisconsin. The boom years for construction of hydropower facilities—from 1940 to 1970—responded to a rapidly growing economy with intense electricity demands. Hydropower development has waned since the 1990s due to rebalancing of water use priorities, market conditions, deregulation in the electricity industry, and other factors. As a result, the existing fleet of facilities—owned and operated by federal, public, and private entities[6]—is aging. Many of these facilities, including their dams and reservoirs, have multiple purposes beyond water storage and hydropower generation, including recreation, flood management, navigation, irrigation, municipal and industrial water supply, fish and wildlife, and cooling water for thermal plants.

Hydropower's effects on the environment[7] are recognized by facility owners and operators and, working with resource and regulatory agencies, they implement measures to avoid, minimize, or mitigate these effects. Balancing the needs of society in a manner that leads to more sustainable hydropower requires advanced planning that incorporates potential effects of climate change on water availability patterns and encompasses multi-stakeholder approaches.

## *Role of Hydropower in the Grid*

Hydropower is capable of the full range of services required by electricity transmission grid, including system regulation and supply/demand balance, voltage and frequency support, stability, and black start capability. In particular, hydropower's flexibility to rapidly ramp generation up and down in response to changes in the balance between electrical loads and generators facilitates integration of renewable variable generation, such as wind and solar energy, into the grid. The contribution of hydropower to grid planning and operations is expected to increase through improved quantification and valuation of hydropower's flexibility. In addition, small hydropower (defined in the *Hydropower Vision* as 0.5 to <10 MW) has the potential to increase deployment of distributed generation resources. As variable generation increases in the foreseeable future, the use of hydropower's flexibility—accounting for multiple water use requirements—to reduce system operating cost is an important trend.

## *Markets and Project Economics*

Compensation for hydropower generation comes from two primary sources: power markets and environmental markets.[8] In power markets, value is derived from power production and from flexibility to provide a wide range of power market services. Increasing penetration of variable generation, however, is changing how hydropower is compensated. Ownership also plays a key role in determining access to revenue streams and the investment perspective underlying how hydropower is valued. The structure and operation of hydropower markets varies regionally across the nation; some power markets are are organized day-ahead type markets, while others are bilateral, based on longer term agreements. Improved alignment of hydropower valuation across power and environmental markets could decrease market variability and uncertainty. Electricity markets in the United States are also influenced by the increasing role of Canadian hydropower.

## *Opportunities for Hydropower Development*

Opportunity exists to support growth of hydropower as an economically competitive source of low-carbon renewable energy. The challenge, however, is to incorporate environmental performance[9] and sustainability principles, while balancing public energy needs and water resources—especially in the context of multiple

6. Federal agencies operate about 49% of the total installed hydropower capacity, with about 10% of the total number of installations. Public ownership, such as public utility districts and rural cooperatives, comprise about 24% of total installed U.S. capacity and 27% of the total number of hydropower facilities. Private owners, including investor-owned utilities and independent power producers, control about 25% of total installed capacity and 63% of the total number of plants.
7. Hydropower facilities can affect flow regimes, water quality, sediment transport, habitat connectivity, fish passage, and other factors.
8. Environmental markets include renewables markets, such as Renewable Portfolio Standards, and emissions markets, such as those associated with trading of allowances for certain pollutants.
9. Environmental performance refers to hydropower's effects on ecosystem structures, processes, and functions.

objectives for water use. Toward this end, improved communication and collaboration during the hydropower development process could help expedite the process and achieve desired outcomes for all parties. In addition, basin-scale or multi-basin watershed approaches to hydropower development could benefit all stakeholders through improved collaboration and application of advanced technologies.

### *Design, Infrastructure, and Technology*

Research and design of hydropower facilities enhances civil structures, turbines, electrical components, and governors. Instrumentation, control, and monitoring equipment are also advancing technologically. Cost and construction time for civil structures can be reduced through technology advancements that include modular and segmented design, precast systems, smart concrete technology, and rock-bolted underpinning systems. Advances in technologies for power trains, shaft turbines, oil-free operations, battery and other storage capabilities, as well as equipment manufacturing and project design, can also improve the economic viability of hydropower generation. In combination with minimum in-stream flow levels, environmental protection technologies—such as fish screens, upstream passage facilities, aerating turbines, fish-friendly turbines, and surface flow outlets—help avoid or minimize the environmental impacts of hydropower operations.

### *Operations and Maintenance*

Hydropower operations and maintenance (O&M) is the suite of activities that bring particular generating units online, monitor and control water releases, safely shut down units, service the components of hydropower facilities in a reliable manner, and generally help ensure dam safety. Decision making processes for O&M at individual plants are closely linked to river system and power grid operational requirements so that impacts of O&M activities on system operations are coordinating and minimized. An increasingly important element of O&M is ensuring environmental compliance through facility enhancements, including modeling of hydrologic cycles, refined operating procedures, and system monitoring.

Refinement of O&M methods can support hydropower growth through development of best practices and fleet-wide benchmarking, and by incorporating environmental mitigation measures into operations scheduling and planning.

### *Pumped Storage Hydropower*

Pumped storage hydropower (PSH) is a proven, reliable, and commercially available large-scale energy resource that provides 97% of the total utility-scale energy storage in the United States [2]. Many PSH plants were constructed to complement large baseload nuclear and coal power plants, thereby providing increased loads at night when pumping and peaking power during the day through generation. In helping balance grid operations, PSH plants reduce overall system generation costs and provide a number of ancillary and essential reliability services to the grid, including frequency regulation and voltage support. PSH plants are also supporting integration of variable generation into the grid, helping avoid or minimize stability issues due to over-generation. Advanced PSH technology, such as adjustable or variable speed units, provides additional capabilities beyond those of older units. There is significant resource potential for new PSH development in the United States, especially closed-loop PSH. Realizing this potential will require overcoming economic, market, and regulatory challenges, such as fully optimized day-ahead and real-time markets.

### *Economics of Hydropower*

Hydropower is a demonstrated economic driver, supporting jobs from engineering and construction to O&M, offering other economic benefits, and providing electricity to help businesses compete globally. Construction and O&M for hydropower plants supports approximately 143,000 jobs[10] in the United States (2013 data). The median age for the hydropower workforce is higher than the national average, however, indicating a need to focus on educational and training programs for workers entering the industry. Beyond jobs, hydropower facilities can offer multiple benefits, such as recreational use, transportation, drinking water, flood management, and hydropower. Each of these uses can provide net economic benefits to the region surrounding a hydropower facility.

10. According to analyses presented in this report (Section 2.8).

# 2.1 Hydropower History, Contributions, and Context

Hydropower[11] helps meet the United States' basic need for electrical energy. Hydropower's generation flexibility helps stabilize the electrical grid by balancing energy from various sources, including variable renewable energy from wind and solar power systems. Hydropower has a long life cycle and a renewable[12] fuel source that does not produce hazardous wastes and emissions. U.S.-based hydropower enhances national energy security, because its fuel supply (water) cannot be controlled by foreign governments or groups. Hydropower development and operations necessarily are conducted within a multi-purpose context where adverse environmental, social, and cultural effects must be avoided, minimized, or mitigated, because hydropower's water supplies are public resources protected by state and federal laws.

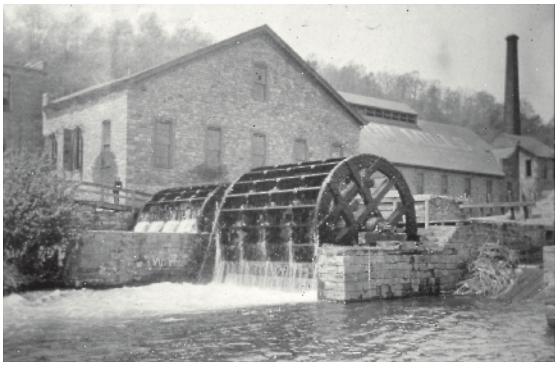


Photo courtesy of the National Canal Museum, an affiliate of the Delaware & Lehigh National Heritage Corridor, Easton, Pa

**Figure 2-1.** Water wheel for generating hydropower (Union Mills, New Hope, PA)

This section of the *Hydropower Vision* introduces the present state of hydropower in the United States by offering a brief history of hydropower, describing general characteristics, explaining environmental aspects, and providing foundational material for advancing sustainable hydropower. The overall objective of Section 2.1 is to provide context for subsequent sections of Chapter 2 that detail fundamental features of the state of U.S. hydropower in 2015 and offer a framework for the *Hydropower Vision* and its roadmap. Chapter 2 sections include: 2.2 *The Role of Hydropower in the Grid*, 2.3 *Markets and Project Economics*, 2.4 *Hydropower Development*, 2.5 *Design, Infrastructure, and Technology;* 2.6 *Operations and Maintenance;* 2.7 *Pumped Storage Hydropower,* and 2.8 *Economic Value of Hydropower*.

## 2.1.1 Historical Perspective

Hydropower has a long history in the United States. The technology was used in the 1700s and 1800s to convert the kinetic energy of flowing water to mechanical energy for industrial activities such as grinding grain into flour, sawing wood into lumber, and powering textile mills (Figure 2-1). Hydropower was the first source of *electrical* energy ever used in the United States, which became possible with the invention of the electric generator by Michael Faraday in 1831 and the hydro-turbine by James Francis in 1849. The world's first hydropower plant to generate electricity began operating in 1882 in Appleton, Wisconsin [3]. The first long-distance transmission of electricity from hydropower was in 1889, from the Sullivan Plant at Willamette Falls to streetlights in Portland, Oregon, 14 miles away. Along with wind and solar, hydropower can claim to be one of the first *renewable* energy technologies. Hydropower was fundamental to the electrification of America during the first three decades of the 1900s. By 1912, hydropower accounted for 30% of U.S. electrical generation, increasing to a high of 36% in 1932, dropping back to 29% in 1950 [4, 5]. In the 1930s and 1940s, hydropower development was critical to raising the nation out of the Great Depression and fostered industrial production during World War II supporting rapid expansion of the country's energy output (Figures 2-2 and 2-3).

11. As used here, hydropower means hydroelectricity. Hydropower technologies discussed in the *Hydropower Vision* include conventional technologies, where diverted or impounded water creates hydraulic head to power turbines, and pumped storage hydropower, where stored water is released to generate electricity in a similar way, but is then pumped back up to replenish the storage reservoir. Marine and river hydrokinetics, which convert the energy of waves and tides, and ocean currents and rivers, respectively, into electricity, are not included in this report.

12. For purposes of the *Hydropower Vision*, hydropower is renewable in the sense that water is replenished through the hydrologic cycle.

For example, between 1937 and 1944, the U.S. Bureau of Reclamation (Reclamation) more than quadrupled its hydroelectric capacity [6]. The early era also included development of multi-purpose projects to provide irrigation water and flood control, with hydropower often a secondary objective. Major hydropower dams constructed during this pivotal period in U.S. history include the Bonneville and Grand Coulee dams on the Columbia River, Hoover Dam on the Colorado River, and the majority of the Tennessee Valley Authority (TVA) system.

Installation of new hydropower capacity in the United States increased from the early 1900s through the 1950s, peaked in the 1960s, and then declined in the 2000s (Figure 2-3). Most PSH capacity was installed in the 1960s, 1970s, and 1980s to complement operation of large, baseload coal and nuclear power plants and to help balance the grid by providing peaking power during daytime generation and load during nighttime pumping. Construction of new PSH facilities has declined since the 1990s (Figure 2-3). This decline in new construction resulted from a rebalancing of water use priorities, market conditions, and other factors [7]. While development subsided, environmental statutes instituted in the 1960s and 70s resulted in modifications to hydropower operations for environmental purposes at hundreds of hydropower plants in the 1980s and beyond. The statutes helped raise existing projects to new standards of environmental protection to maximize net public interests, because hydropower installation had altered natural river systems.

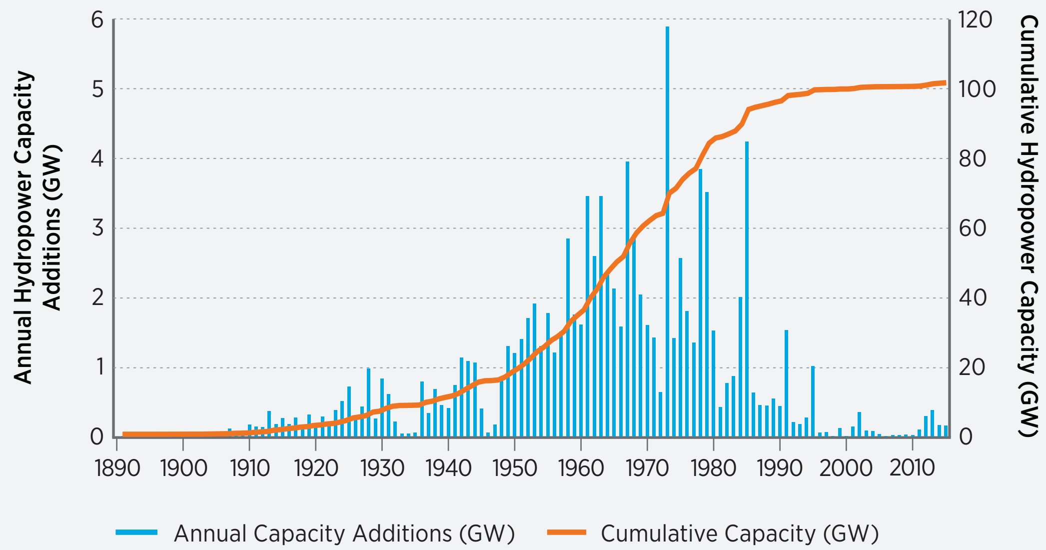

Poster by Lloyd Hoff, courtesy of Bonneville Power Administration Library

**Figure 2-2.** World War II era poster promoting hydropower

Hydropower generation in the United States increased 175% between 1950 and 1970, from 100 terawatt-hours (TWh) to 275 TWh (Figure 2-4). Since the 1970s, average total energy produced by hydropower plants has remained consistent, at around 275 TWh per year. The amount of net total United States electricity generation contributed by hydropower has decreased, from 30% in 1950 to 7% in 2013, as nuclear power, coal, natural gas, and other sources have been added to the nation's energy portfolio to meet increasing demand. In terms of generation, hydropower is the primary source of renewable energy in the United States, delivering 48% of total renewable electricity sector generation in 2015, and roughly 62% of total cumulative renewable generation over the past decade (2006-2015) [1].

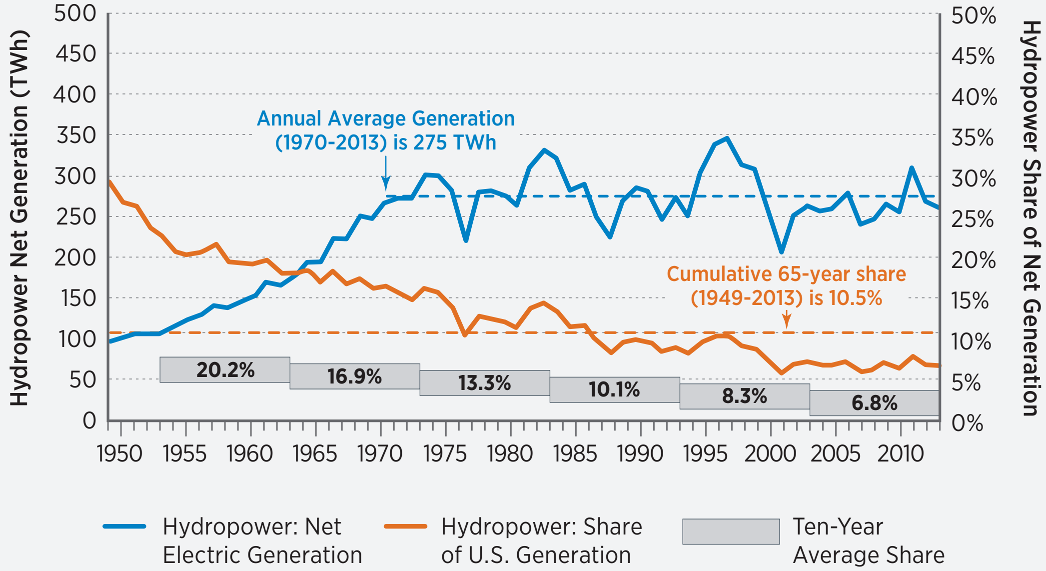
## 2.1.2 General Characteristics of Hydropower

Hydropower involves the physical process of directing flowing water through turbines to generate electricity. The amount of power generated is a function of the head (difference in height between the upstream pool and tailwater) and flow (volume of water passing a location per unit of time). Water is conveyed from an upstream pool created by a dam, or from a diversion to a powerhouse containing one or more turbines (Figure 2-5). At the turbine, energy is transferred via the turbine runner or other rotating element to spin a shaft connected to an electric generator. Water, after passing the turbine runner, enters a draft tube or other outflow structure into the tailwater. The electrical energy produced by the generator exits the powerhouse via a transformer, which "steps up" (increases) the voltage



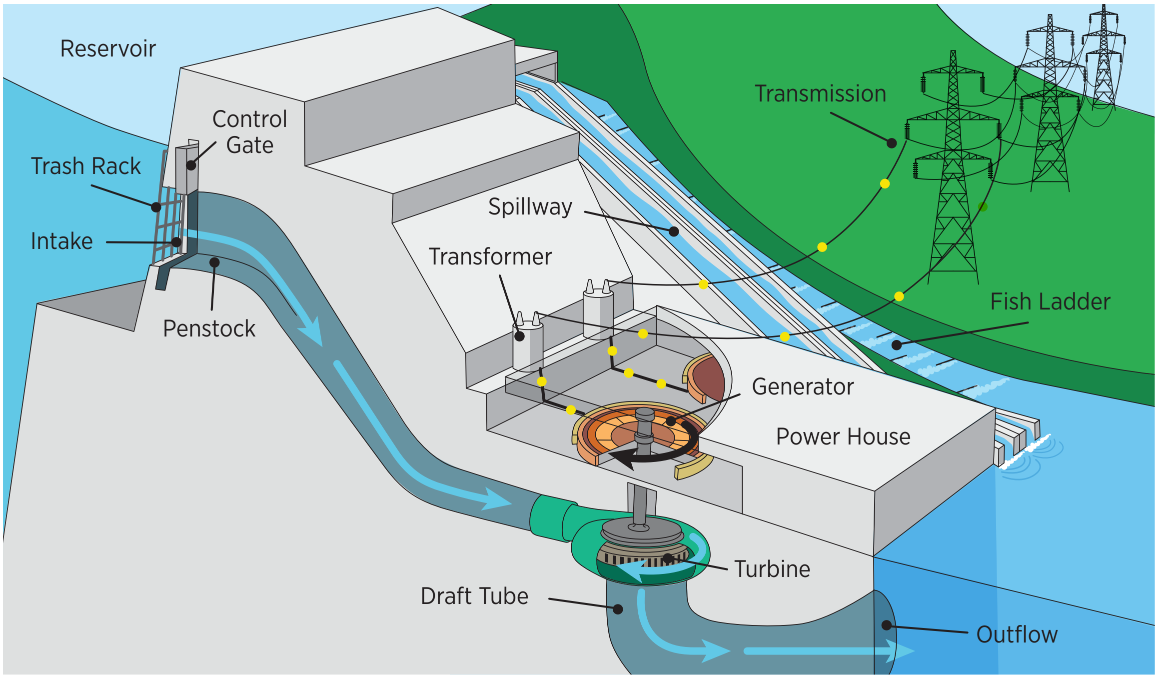

Sources: Energy Information Administration (EIA) Form 860 2011 [8], EIA Monthly Energy Review [4], Federal Energy Regulatory Commission Energy Infrastructure Updates [9]

**Figure 2-3.** U.S. hydropower and pumped storage hydropower annual capacity additions and cumulative capacity from 1890–2015 (GW)




Sources: EIA Annual Energy Review [10] and EIA Electric Power Monthly [11]

**Figure 2-4.** Net hydropower generation and share of United States generation, 1950-2013




Source: U.S. Department of Energy [12]

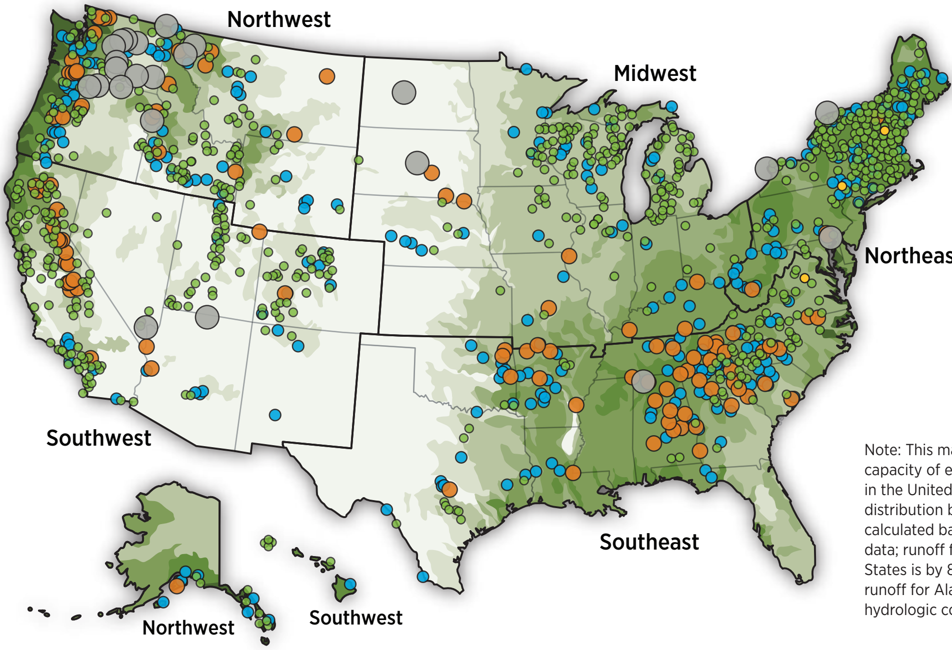
**Figure 2-5.** Three-dimensional cross-section showing the components of a typical hydropower project (water flow is from left to right)

of the electricity flowing through transmission lines of the electrical grid. At substations and power poles, the voltage is "stepped down" (decreased) for delivery via distribution lines to end-use customers. For the *Hydropower Vision,* hydropower is classified based on capacity: micro (<0.5 megawatts [MW]), small (0.5 to <10 MW), medium (10 to <100 MW), large (100 to 500 MW), or very large (> 500 MW).

### Existing Hydropower Facilities

Forty-eight states have hydropower facilities, and ten of these states generated more than 10% of their electricity from hydropower in 2014 [13]. As of the end of 2014, the U.S. hydropower fleet contained 2,198 active power plants with a total capacity of 79.6 GW, and 42 PSH plants totaling 21.6 GW [2] (Figure 2-6).[13] There are three main classifications of hydropower facility ownership: federal, public, and private. There are also ownerships through public-private and public-federal partnerships. The three main federal agencies authorized by Congress to own and operate hydropower plants are the U.S. Army Corps of Engineers (Corps), Reclamation, and the TVA. These agencies operate about 49% of the total installed hydropower capacity through ownership and operation of about 10% of the total number of hydropower facilities (Figure 2-7). Public ownership includes public utility districts, irrigation districts, states, and rural cooperatives, whose hydropower resources consist of about 24% of total installed U.S. capacity and 27% of the total number of hydropower facilities. Private owners, including investor-owned utilities, independent power producers, and industrial companies, control about 25% of total installed capacity and 63% of the total number of plants. These data include private owners of hydropower plants located at federal dams. For example, there are 90 privately owned power plants at Corps-owned dams [14] and 28 at Reclamation-owned dams [15].

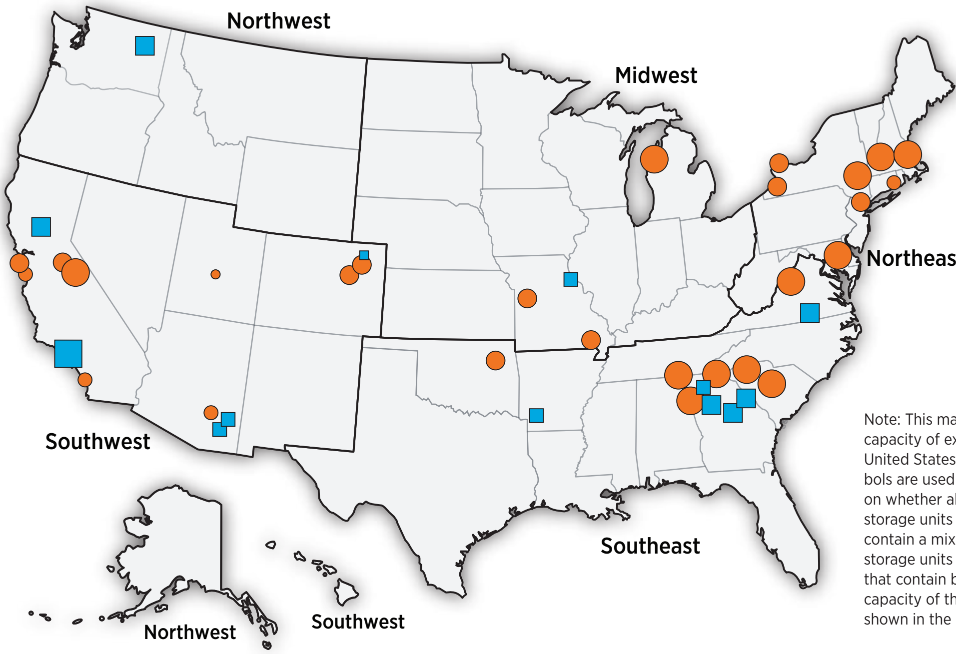
13. Figure 2-6 includes an overlay of runoff distribution. The relationship of runoff to hydropower is discussed in more detail in the Multi-Purpose Dam Uses and Water Management discussion in Section 2.1.2.




Note: This map displays the location and capacity of existing hydropower projects in the United States in relation to runoff distribution by watershed. Runoff was calculated based on the best available data; runoff for the conterminous United States is by 8-digit hydrologic code, and runoff for Alaska and Hawaii is by 4-digit hydrologic code.

**Runoff (mm/yr)** ≤ 10 > 10–150 > 150–300 > 300–400 > 400–600 > 600–1,000 > 1,000

**Hydropower Plant Capacity (MW)** ≤ 0.1 > 0.1–10 > 10–100 > 100–500 > 500




Note: This map displays the location and capacity of existing PSH plants in the United States by region. Different symbols are used for PSH plants depending on whether all their units are pumped storage units (dedicated PSH) or they contain a mixture of regular and pumped storage units (hybrid PSH). For plants that contain both types of units, only the capacity of the pumped storage units is shown in the map.

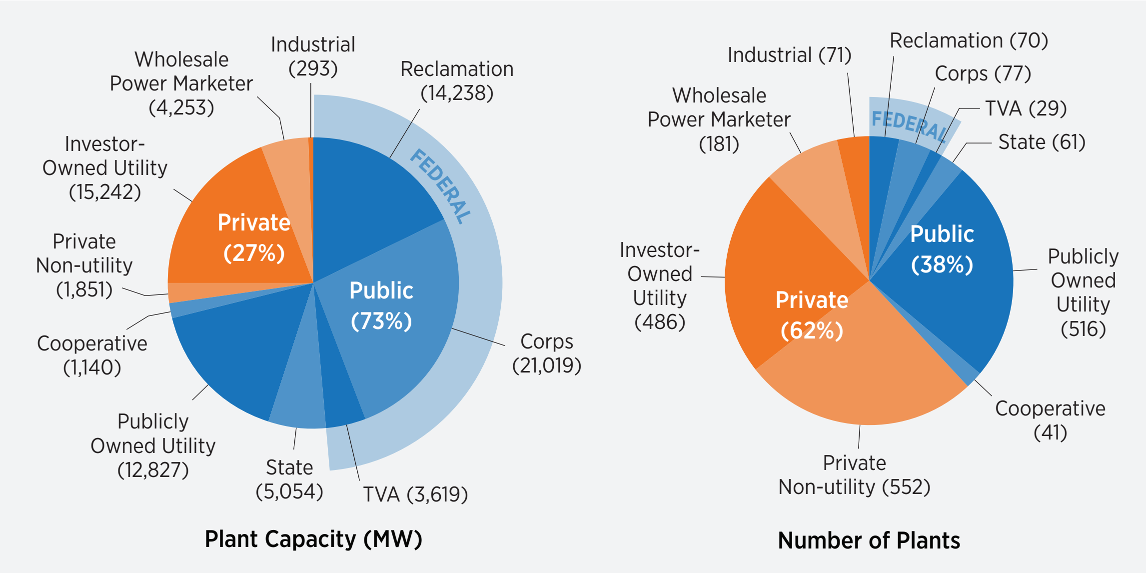
**PSH Plants by Type & Installed Capacity (MW)**

Dedicated PSH ≤ 10 > 10–100 > 100–500 > 500

Hybrid PSH ≤ 10 > 10–100 > 100–500 > 500

Source: Uría-Martínez et al. 2015[2]

**Figure 2-6.** Map of facilities in the existing U.S. hydropower fleet: conventional hydropower (top) and PSH (bottom)




Note: The region delineation is based on Federal Energy Regulatory Commission hydropower regions.

Source: Uría-Martínez et al. 2015[2]

**Figure 2-7.** U.S. hydropower plant ownership mix: capacity (left) and number of plants (right)

The states of California, Oregon, and Washington have the most installed hydropower capacity (~40 GW in 565 plants) of all areas of the country. Many of the region's hydropower facilities have capacities of more than 50 MW and are federally owned. In fact, hydropower plants in the Columbia River basin in the Pacific Northwest produce more than 40% of total U.S. hydropower generation. The Northeast region of the United States has the highest number of hydropower plants (~600), most of which are 0.1–10 MW. The Southwest region has low capacity (< 5 GW) and few plants (< 50 plants). In all regions, more plants are in the small size category (0.1–10 MW) than the other size categories. The generating facility with the highest capacity in the United States is the 6.9-GW Grand Coulee Dam on the Columbia River.

The existing United States fleet of hydropower plants is aging. For instance, as of 2014, the average age of Corps hydropower facilities was 49 years, and, as of 2015, the average age of Reclamation hydropower facilities was 58 years [7]. At the beginning of 2011, hydropower plants comprised 24 of the 25 oldest operating power facilities in the United States, with 72% of facilities older than 60 years. While the basic civil works of hydropower facilities are considered safe and reliable, the turbines, generators, and other mechanical and electrical equipment require increased maintenance and refurbishing to maintain existing generation capacity. This often includes equipment upgrades, turbine efficiency improvements, and modifications that ensure environmental protection and mitigation. At existing plants where environmentally improved designs for new turbines were employed, e.g., new turbine runners at Wanapum Dam on the Columbia River, broad-scale upgrades and efficiency improvements have contributed to increasing hydropower capacity in the United States (see Section 2.5).

When costs to modernize or to meet environmental objectives outweigh the potential economic benefits of continued operation, hydropower facility owners may choose to decommission facilities. Examples include the Condit Dam in Washington and the Marmot Dam in Oregon. Other situations involve dam decommissioning where the primary purpose is to alleviate environmental impacts, e.g., Glines Canyon Dam and Elwha Dam, both in the state of Washington. Factors influencing decommissioning also include costs of replacement energy, changes in water availability, and public interests. Decommissioning has generally been limited to older (mean age 87 years), small capacity projects (0.4–10 MW) [16]. About 168 MW of hydropower were decommissioned during 2005–2013 [2].

In addition to the lower 48 contiguous U.S. states, existing hydropower contributes to electricity supplies in Hawaii and Alaska. As of 2015, there were 22 operational hydropower projects in Hawaii with a total installed capacity of nearly 40 MW [17]. In 2014, hydropower across the state generated 85,444 megawatt hours (MWh), which accounted for 0.9% of all electricity sold by Hawaii's electric utilities to their customers [18]. In Alaska, hydropower contributes 25% of the statewide electrical energy [11], with 47 existing hydroelectric projects and a combined capacity of 474 MW. Development of local, non-distributed hydropower is of interest in Hawaii and Alaska, and elsewhere in the United States.

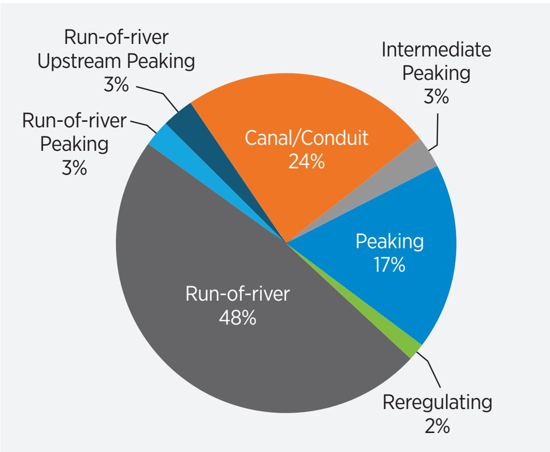
### Operational Modes

In terms of operating modes (as defined by McManamay et al. 2016 [19]), the majority of hydropower facilities in the United States *by number of facilities* are peaking or canal/conduit (Figure 2-8), while the majority *by capacity* are peaking and run-of-river (Figure 2-9). Peaking plants release water to produce energy when electricity demand is high (peaking), typically during weekday mornings and afternoons. If there is limited storage capacity, storage dams upstream, or both, run-of-river projects can also serve peaking purposes. These operating modes range in operating flexibility[14] from least flexible (canal/conduit) to most flexible (peaking).

Figure 2-10 illustrates the installed capacity for typical types of hydropower (as defined by Uría-Martínez et al. 2015 [2]), broken down by region.

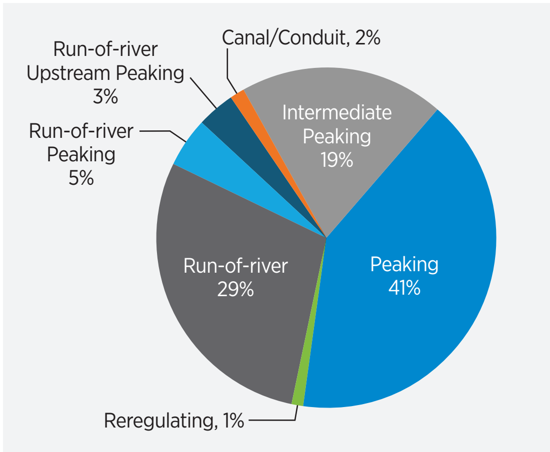
### Multi-Purpose Dam Uses and Water Management

Dams and reservoirs have multiple purposes beyond storage and flow regulation for hydropower generation (Figure 2-11).[15] Since hydropower is a non-consumptive use of water, water flowing through a turbine can be used again for other purposes. For powered dams, recreation is the most common secondary purpose of reservoirs. Other purposes




Source: National Hydropower Asset Assessment Program FY15 Plant Database [15]

**Figure 2-8.** Distribution of operating modes for hydropower facilities, by number of projects



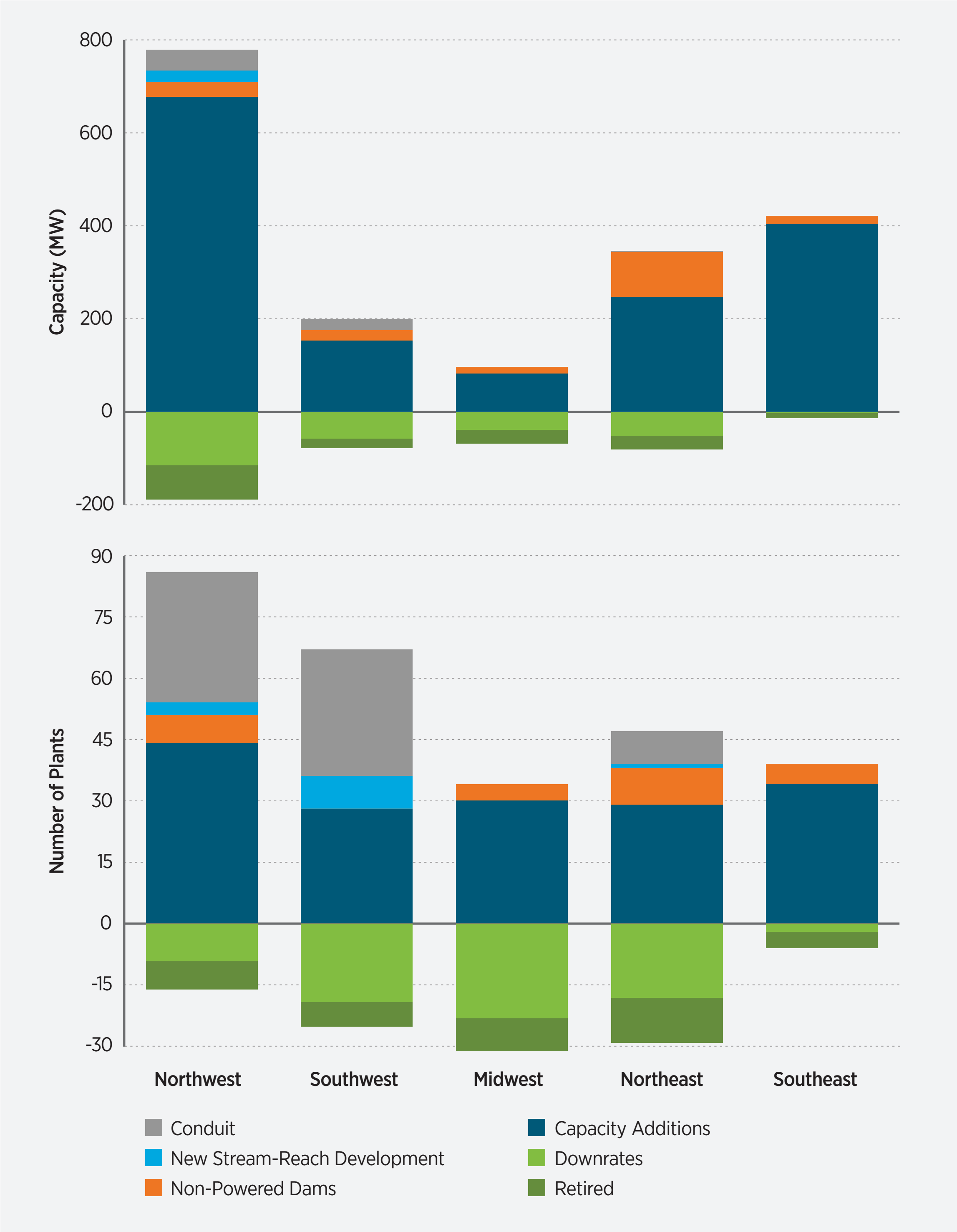

Source: National Hydropower Asset Assessment Program FY15 Plant Database [15]

**Figure 2-9.** Distribution of operating modes for hydropower facilities, by capacity

Note for Figures 2-8 and 2-9: The values are based on the most updated plant information available. Retired and pumped storage plants were removed from the analysis. Also not included are 813 plants for which the Mode of Operation field was "null". The data thus represent 65% of total number of plants and 78% of total capacity. Source: NHAAP FY15 Plant Database [15]

14. The "flexibility" of a hydropower plant is the capability to choose the optimal timing of power production, to provide reserves, and to respond quickly to changing market and power system needs. The extent to which a plant has flexibility is dependent upon plant technology and design characteristics, regulations governing operations, and the priority of power production and ancillary grid services provision amongst the other multiple water uses of a facility. Limitations on flexibility can include constraints on the maximum or minimum amount of water allowed to be discharged through a facility as well as the speed with which that rate of flow can be changed ("ramp rate"). Prescribed ramp rates are also a matter of safety for boaters and anglers.

15. Note that, in Figure 2-11, the use categories are not mutually exclusive; a given dam can be included in more than one category. The data include only powered dams that also have purposes other than hydropower generation.



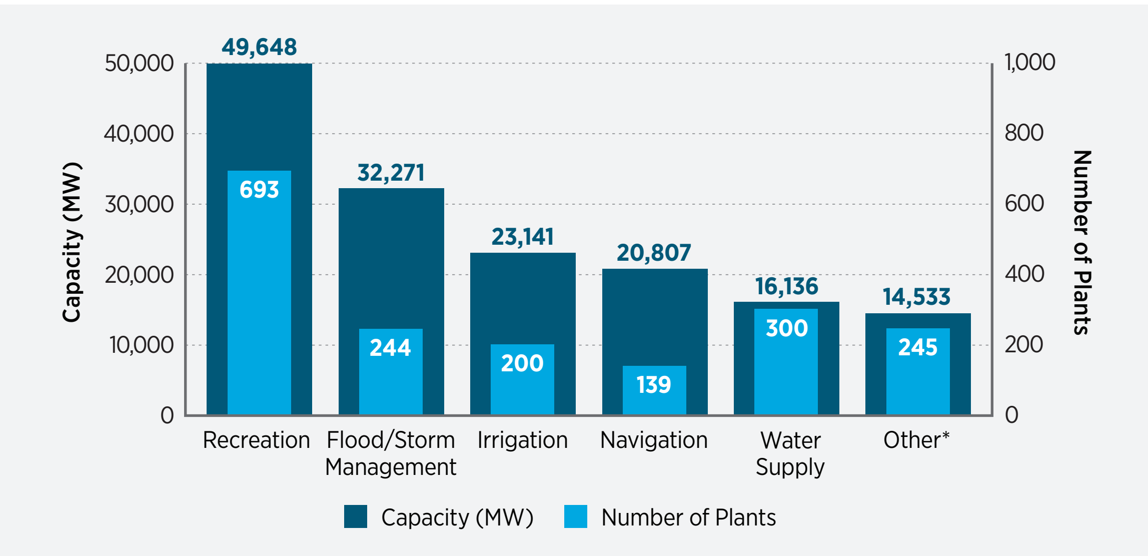

Source: Uría-Martínez et al. 2015 [2]

**Figure 2-10** Comparison of regional differences in hydropower capacity by project type (2005-2013) include fish and wildlife, flood management, navigation, agricultural irrigation, drinking water supply, and cooling water for thermal plants. Hydropower is the primary authorized purpose at only 2.5% of the approximately 87,359 federal dams across the country [20]. Many are not suited for hydropower because low head (<15 feet) or low flow limits potential energy production, or there are other limiting factors such as those related to environmental concerns, dam integrity/safety, proximity to load centers and transmission, and multiple use conflicts [21]. Prioritization of uses can be mandated in Federal Energy Regulatory Commission (FERC) licenses for non-federal projects, and in Congressional authorizations for federal projects. The overarching intent is to operate the projects in a given basin(s) as a system, in an economically and environmentally responsible fashion.

General water management practices include monitoring and managing surface water runoff into streams, rivers, lakes, reservoirs, and other waterways. Hydropower generation is generally positively correlated with runoff in upstream watersheds [22]. Water management can employ forecasts of water supply (predictions of the volume of runoff over a given time period) and rate-of-flow (predictions of stream flows) using weather predictions (precipitation), accumulated snow measurements, and other information. Multiple agencies and entities have a role in making and applying runoff and stream flow forecasts, including project owner/operators, power marketers, the National Weather Service, the U.S. Geological Survey, and the Natural Resources Conservation Service. Dependable forecasting allows water managers to optimize beneficial uses and minimize unnecessary costs. Water management planning for hydropower operations and other uses is complex and on-going.

Water availability is determined by hydrologic processes, which are affected by climate, geology, and landforms. Water availability varies temporally (seasonally and annually) and spatially (longitudinally and regionally). For example, runoff patterns in the eastern United States are determined primarily by rain, while snowpack drives runoff patterns throughout most of the West.

Water availability patterns are influenced by changes in climate, including those considered possible under global climate change models. Climate modeling generally suggests that dry regions are likely to get drier and wet regions wetter [23]. Hydropower managers can use predictions of future water supplies produced by climate models to prepare contingency plans for weather emergencies and disasters. Hydropower resources would be affected by runoff patterns that are changing due to variations in typical temperature and precipitation patterns, both spatially and temporally. These




Note: The use categories are not mutually exclusive; a given dam can be included in more than one category. The data include only powered dams.
Source: Uría-Martínez et al. 2015 [2]

**Figure 2-11.** Total capacity and number of plants for six separate uses (illustrated by the blue bars) of existing hydropower dams and reservoirs changes could affect water quality (e.g., temperature, dissolved oxygen), and stream flows, as well as timing and level of energy demand, seasonal pricing, and rates for electricity. In the Pacific region, for example, warmer air temperatures would cause increased evaporation and more precipitation to fall as rain than snow.

Water scheduling for hydropower generation takes into account runoff forecasts, energy markets, environmental objectives, and other factors. In some cases, long-term power contract commitments come into play during scheduling. On a temporal basis, scheduling is performed for short-term (minutes, hours, days) and long-term (weeks, months, years) horizons. On a spatial basis, scheduling occurs at scales ranging from a given turbine unit (turbine level or turbine scale), to a full hydropower facility (site level or site scale), to a given region with multiple watersheds (basin level or basin scale). Sophisticated computer models have been developed to aid hydropower schedulers. Sensor networks, data assimilations, visualization, and other elements are all part of decision support systems used in most river and power control centers. Text Box 2-1 provides an example of scheduling and planning for one complex hydropower system.

### *Transmission and Markets*

Hydropower transmission and markets involve interconnections and balancing authority areas, coordinating entities, wholesale markets, cost and pricing trends, and incentive programs.

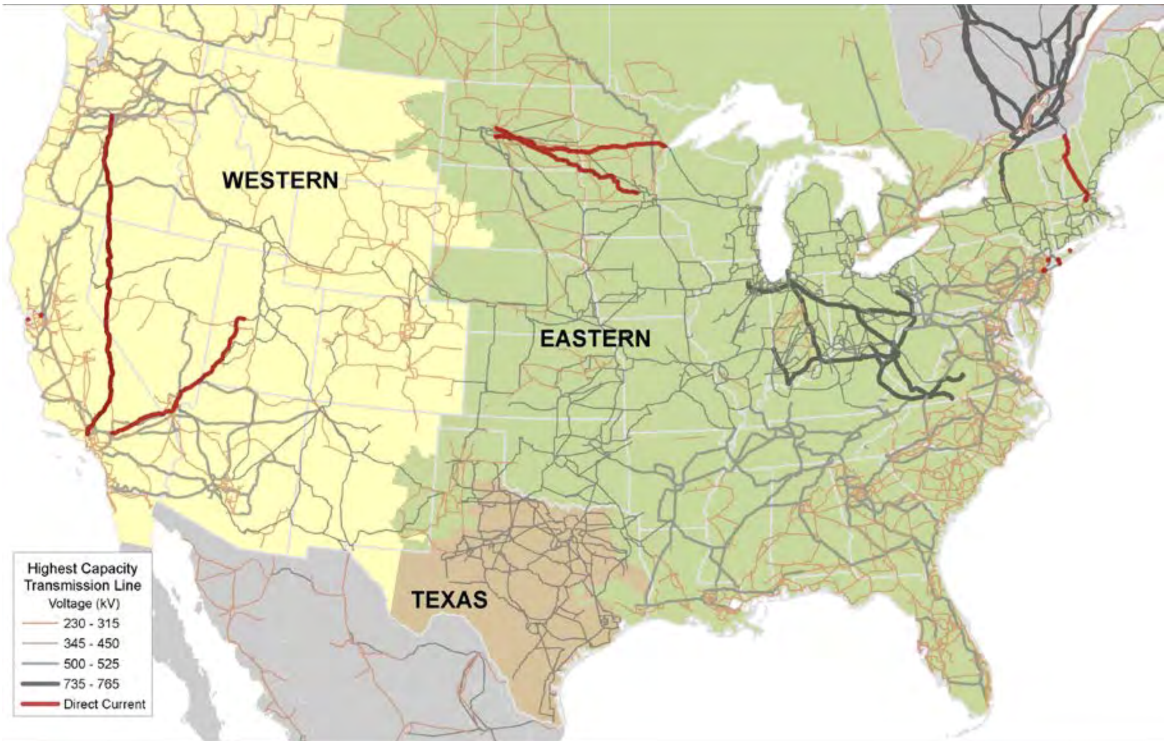
**Interconnections and Balancing Authority Areas.** Three primary transmission grids, called "interconnections," serve the United States: the Eastern Interconnection, the Western Interconnection, and the Electricity Reliability Council of Texas (ERCOT), which is also called the Texas Interconnection (Figure 2-12). A fourth major North American grid is the Quebec Interconnection. A given interconnection comprises segments called balancing authority areas (BAAs). Within a BAA, supply (generation) must be exactly matched to demand (load). If a BAA fails to have balanced generation and demand, it either forces excess generation onto adjacent BAAs, or more commonly, draws power from them. Balance may be achieved through imports and exports of power; however, these must be scheduled and coordinated between adjacent BAAs. Maintaining this balance within and across BAAs is critical for system reliability. If a BAA is significantly out of balance, even momentarily, and adjacent BAAs do not have sufficient flexible generation to respond, there may be a load interruption.

**Coordinating Entities**. Multiple entities oversee the flow of electricity from generation sources to consumers, each with specific responsibilities. Under Section 215 of the Federal Power Act, FERC certified the North American Electric Reliability Corporation (NERC), a not-for-profit membership corporation, to serve as the electric reliability organization responsible for developing and enforcing Reliability Standards for the electrical bulk-power system. These standards set

Text Box 2-1.

**Real-Time Modeling of Hydropower System Operations Across Multiple Objectives**

The Federal Columbia River Power System comprises 31 hydropower facilities that are operated under a complex mixture of power and non-power objectives and constraints related to multi-purpose uses. Although the objectives and constraints are typically well understood, there is uncertainty in fundamental elements, such as stream flows, load obligations, intermittent generation resources, and balancing reserves. Therefore, it is important to accurately model Federal Columbia River Power System operations to manage uncertainty and optimize use of water. Federal Columbia River Power System managers use modeling technologies to develop probabilistic views of capacity, power inventory, and operations as well as to support risk-based operational and marketing decisions. The models provide feasible, stable results and have robust solution algorithms, high resolution, and quick execution times. A range of operational possibilities are modeled to make risk-informed decisions for successful operations and marketing strategies to meet the multiple purposes of the Federal Columbia River Power System .



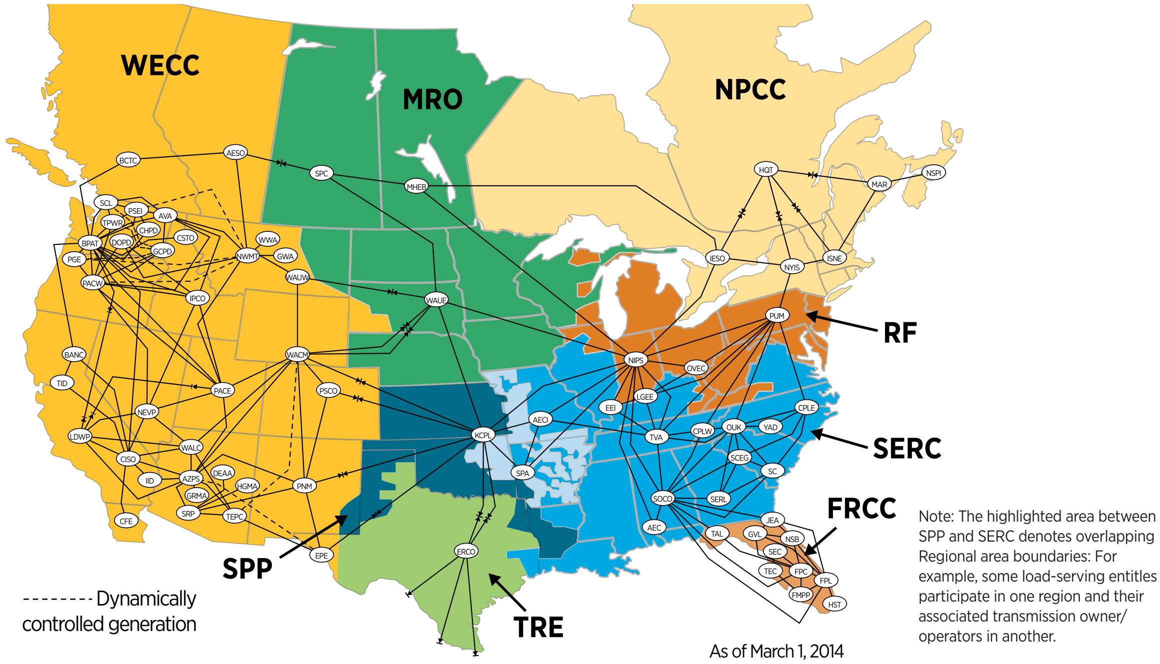

Note: In this map, the Quebec (Canada) Interconnection is part of the Eastern Interconnection.
Source: National Renewable Energy Laboratory

**Figure 2-12.** Transmission systems and three main grid interconnections in North America

mandatory requirements for generator owners and operators, transmission owners and operators, balancing authorities and other entities having a role in bulk-power system reliability. NERC's Reliability Standards have been adopted by the Canadian provinces, and also apply in the northern portion of Baja California in Mexico. NERC has delegated certain authorities to eight regional entities (Figure 2-13) that enforce compliance with agreed-upon standards and procedures. NERC's role is to provide oversight with regard to operation of the electrical bulk-power system.

A registered Balancing Authority (BA) is generally the entity responsible for ensuring balance and reliability within a given BAA. System operations within a BAA are conducted by BAs, such as Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs), where they exist. In the absence of a registered BA, transmission owners, utilities and federal Power Marketing Administrations (PMAs) coordinate the dispatch of generation and transmission according to rules established by FERC in a manner consistent with procedures and responsibilities of entities within the NERC region or sub-region. Failure to demonstrate load and generation resides within a BA can result in mandatory fines and sanctions from NERC. Failure to adequately perform BA functions when an entity is a registered BA will also result in mandatory fines and sanctions and could potentially result in losing BA registration in the NERC registry.

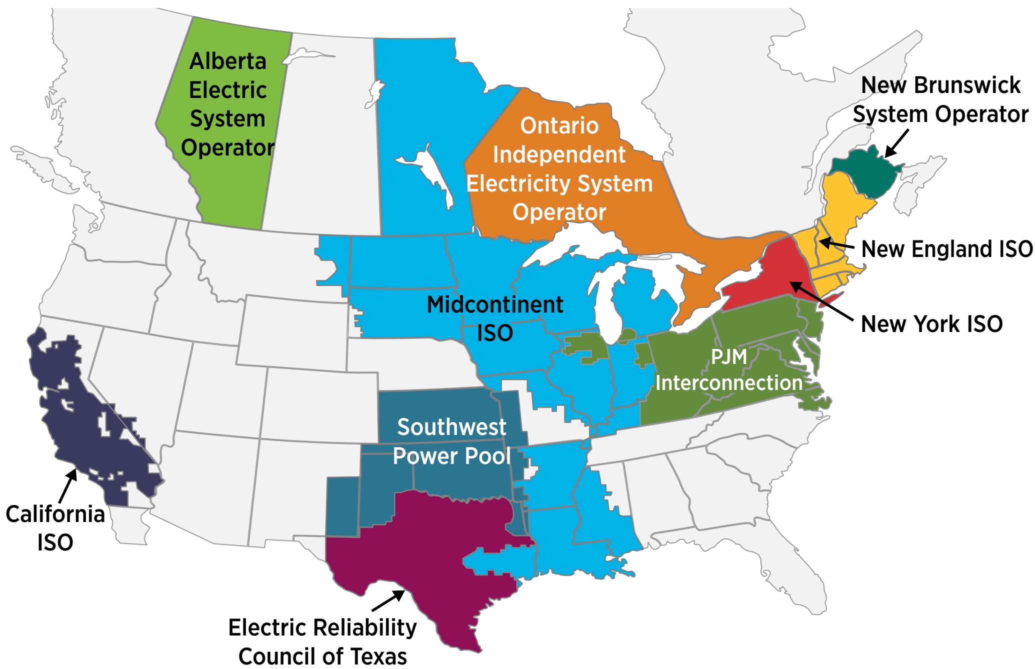
The various entities involved in electrical bulk-power can overlap. For example, the state of California has eight BAs. Electricity service in the state is dominated by three large investor-owned utilities (IOUs) and two large municipal utilities. At one time, each was a BA. After the state deregulated investor-owned utility service, a state-wide ISO (CAISO) was established to manage the transmission assets of the three IOUs, thereby combining three BAs into one. The state's other utilities were encouraged to join CAISO, but few agreed to do so. As a result, the two large municipal utilities are each a BA, and collections of other, smaller utilities make up the remaining five BAs. Each BA maintains system balance by controlling output




Note: FRCC = Florida Reliability Coordinating Council; MRO = Midwest Reliability Organization; NPCC = Northeast Power Coordinating Council; RF = Reliability First; SERC = SERC Reliability Corporation; SPP = Southwest Power Pool; TRE = Texas Reliability Entity; WECC = Western Electricity Coordinating Council

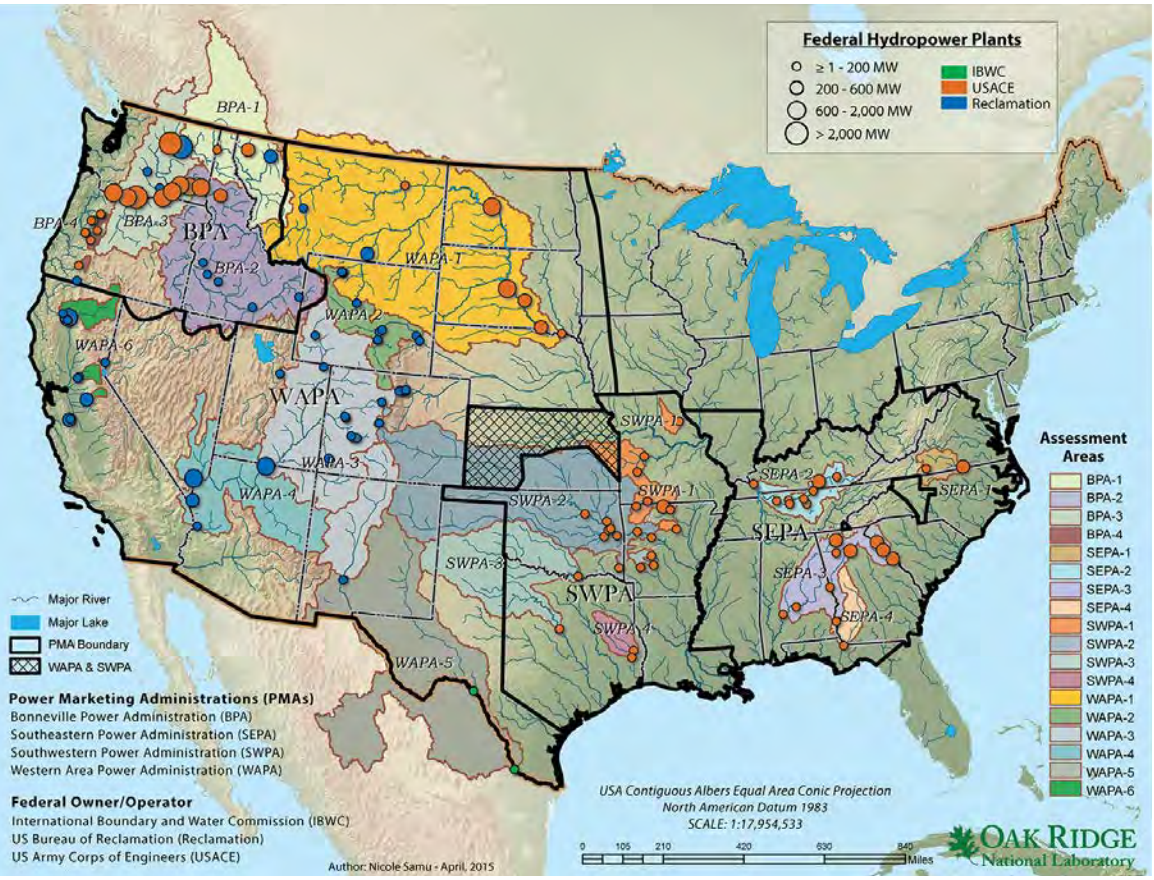
Source: NERC [25]

**Figure 2-13.** Map of coordinating entities organized under the North American Electric Reliability Corporation




Source: Western Area Power Administration [26]

**Figure 2-14.** Map of North American Regional Transmission Organizations




Source: National Hydropower Asset Assessment Program [27]

**Figure 2-15.** Map of federal Power Marketing Administration regions

levels of generation units, and by scheduling the import and export of electricity to and from neighboring BAAs. ISOs and RTOs (Figure 2-14) are formed upon approval by FERC and operate much of the nation's electrical bulk-power system. As noted, some regions of the United States do not have ISOs or RTOs. Transmission functions in those regions are performed by other entities, such as vertically integrated utilities or municipal utilities.

The federal PMAs transmit and market the electricity generated at federal hydropower projects owned and operated by the Corps or Reclamation (Figure 2-15). The four PMAs—Bonneville, Southeastern, Southwestern, and Western Area power administrations—are all part of the U.S. Department of Energy (DOE). The PMAs market hydropower at cost-based rates to "preference entities" such as public utility districts, but may also sell surplus energy to other utilities. PMAs sell wholesale electricity to various BAs, ISOs, RTOs, and utilities. They also have BA responsibilities in many of their operating areas. Although PMAs operate across state and BAA boundaries, power deliveries to load-serving entities, such as a municipal utility, are often included as generation within each respective entities' BAA. In the California example above, power delivered by the Bonneville Power Administration (BPA) or the Western Area Power Administration to utility customers in California is managed by CAISO or the individual receiving utility as part of its BAA responsibility. While TVA is not a PMA, it is a corporate agency of the United States, transmitting and marketing electricity produced at TVA power plants.

**Linkages with Canada.** Canadian hydropower is linked with U.S. hydropower and the bulk-power system electricity grids in North America. More than 60% of Canadian power is generated by hydropower, with a 2012 installed capacity of about 75 GW [24].

In 2012, net export of electricity from Canada to the United States was 47 TWh. In the eastern and central United States, energy supplies include hydropower from Ontario Hydro (7 GW capacity), Hydro-Quebec (35 GW capacity), and Manitoba Hydro (5 GW capacity). In the northwestern United States, a key factor in operation of the Federal Columbia River Power System is water storage at Canadian dams that were constructed as a result of the Columbia River Treaty between the United States and Canada. Three Canadian dams operated by BC Hydro—Mica, Hugh Keenleyside, and Duncan—provide almost half of the storage capacity in the Coordinated Columbia River System. These projects help control flooding; optimize energy generation; and provide water for environmental purposes, such as flows to aid downstream migration of juvenile salmon and steelhead.

**Wholesale Electricity Markets.** Wholesale electricity markets for hydropower vary in purpose, structure, and complexity. Markets also differ based on factors such as whether the hydropower is generated by a federal or non-federal entity, or whether it is transmitted and marketed in a region run by an ISO/RTO or through bilateral arrangements, such as a long-term power sales contract between BPA and Alcoa, Inc., a direct service customer. Markets also exist for hydropower as renewable or low-carbon energy, the most common of which are found at the state level in the form of Renewable Energy Credits (RECs). Hydropower's eligibility to generate RECs varies by state [28].

**In 2014, electricity prices in the Pacific Northwest were lowest in the nation [32], a region where low-cost hydropower is the predominant source of electricity.**

**Cost and Pricing Trends.** Once construction and other upfront costs are accounted for, costs to produce hydropower are low because the "fuel" is essentially free and operations and maintenance (O&M) costs are relatively low. The Energy Information Administration [93] reported the fixed and variable O&M costs for hydropower at $14.13/kilowatts (kW)-year[16] and $0.00/kW-year, respectively. The next lowest fixed and variable O&M costs were for combined cycle natural gas at $13.17/kw-yr. and $3.60/MWh, respectively [29]. Total installed costs can range from $500/kW to $3,500/kW or more depending on plant size, civil structures, and electro-mechanical equipment [30]. Wholesale prices for hydropower vary by market, region (Figure 2-16), season, and other factors. In the West, where snowpack is a major determinant of water supply, electricity prices can fall as a result of increased hydropower generation during the spring snowmelt period [31].

**Incentive Programs.** Incentives can be a factor in project development decisions. This was demonstrated during the early years (1981–1986) of the Public Utility Regulatory Policies Act (Pub. L. 95-617) when projects could earn predictable revenues, which resulted in an increase in investment in new hydropower projects [33]. A variety of state-level renewable portfolio policies, federal production tax credits, federal incentive programs, and federal investment tax credits are intended to provide an incentive for hydropower development. Most states have Renewable Portfolio Standards (RPSs) (Figure 2-17). Of these, a subset includes hydropower in RPSs and other renewable programs [28] (Table 2-1). State RPS programs vary in terms of hydropower capacity limits, eligibility of new hydropower, and whether certification by the Low Impact Hydropower Institute (LIHI)[17] is required. In general, incentive programs are expected to affect the market for existing hydropower and financing for new development.

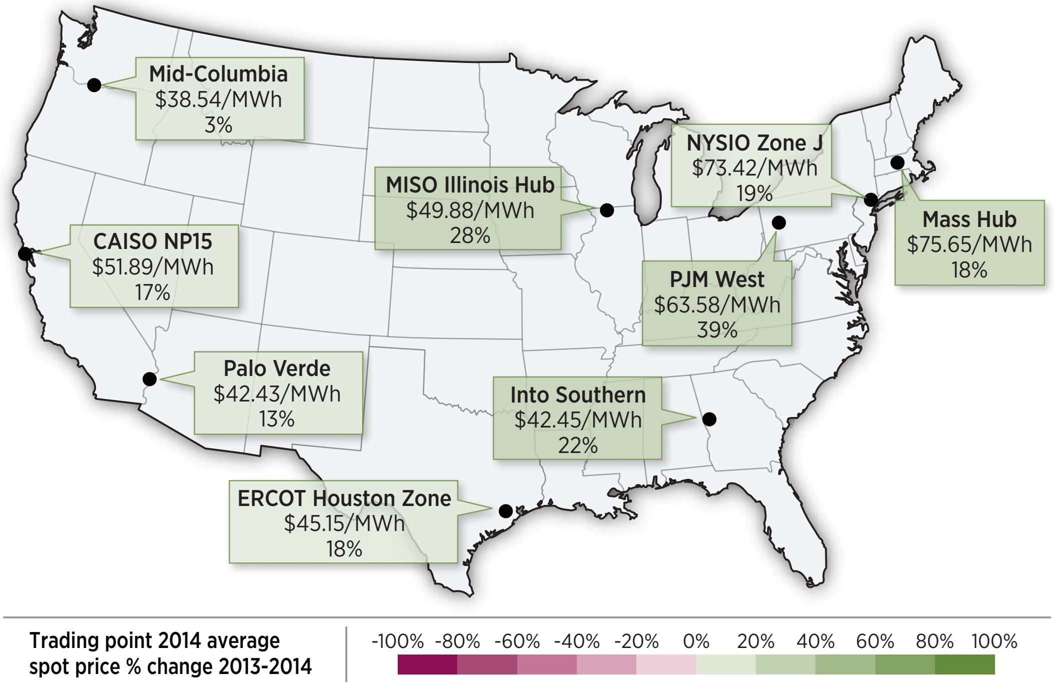
### *Regulatory Setting*

The regulatory environment for hydropower includes numerous laws at federal, state, and tribal levels. Regulations vary depending on whether a facility is federally or non-federally owned. Several key regulatory developments and trends influence hydropower and, consequently, the *Hydropower Vision.*

While many laws have affected hydropower operation and development (Table 2-2), two provide a basis for the modern regulatory setting: the Reclamation Act of 1902 (Pub. L. 57-161) and the Federal Water Power Act of 1920 (FPA) (41 Stat. 1353). The Reclamation Act authorized development of irrigation projects, including dams and reservoirs, in 17 western states. The FPA established federal regulation of hydropower

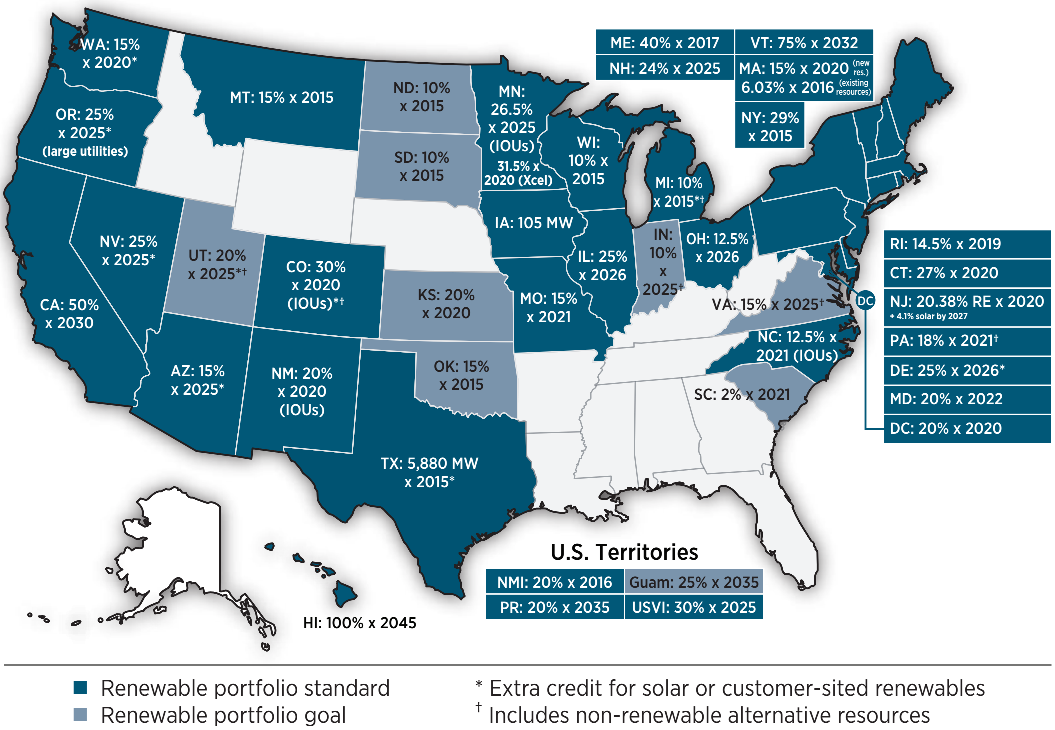
16. One "kW-year" is 1 kW of generation over a 1-year period.

17. LIHI, a non-profit corporation, established a certification process for existing hydropower plants that have avoided or reduced their environmental impacts pursuant to LIHI criteria.




Source: EIA 2015 [32]

**Figure 2-16.** Average wholesale prices for 2014 electricity as of January 12, 2015




Source: Database of State Incentives for Renewables and Efficiency [34]

**Figure 2-17.** Renewable Portfolio Standard policies across the United States development in the United States and provides FERC with the statutory basis for regulatory decisions related to hydropower. The early years of hydropower regulation focused on regulating projects for multiple uses, including navigation, flood control, and irrigation.

The Fish and Wildlife Coordination Act (16 U.S.C. § 661 et seq.), as amended in 1946 (60 Stat. 1080), required consideration of wildlife in federal actions. The Coordination Act was followed by several major environmental laws in the 1960s and 1970s. Additional laws that are most relevant to hydropower include the Wild and Scenic Rivers Act of 1968 (16 U.S.C. § 1271 et seq., Pub. L. 90-542), the National Environmental Policy Act (NEPA) of 1969 (42 U.S.C. § 4321 et seq., Pub. L. 91-190), the Clean Water Act of 1972 (33 U.S.C. § 1251 et seq., Pub. L. 92-500), and the Endangered Species Act (ESA) of 1973 (16 U.S.C. § 1531 et seq., Pub. L. 93-205). In addition, several laws—especially the Electric Consumers Protection Act of 1986 (16 U.S.C. § 791a et seq., Pub. L. 99-495) and the Energy Policy Act of 2005 (42 U.S.C. § 15801 et seq., Pub. L. 109-58)—influenced the regulatory and permitting processes under which hydropower has been developed. Individual states have laws related to hydropower, addressing parameters such as fish passage, dam safety, and renewable energy incentives. Tribes and other parties also have significant regulatory roles pertaining to hydropower. Table 2-2 highlights some key laws relevant to non-federal and federal hydropower.

**Table 2-1.** Hydropower in State Renewable Portfolio Standards

| State | Capacity Limit (MW) | New Hydropower Allowed? | LIHI Certification Required? |
|---|---|---|---|
| Arizona | 10 MW (for new hydro) | Yes | No |
| California | 30 | Yes | No |
| Colorado | 10 MW (Tier 1),<br>30 MW(Tier 2) | Yes | No |
| Connecticut | 5 MW, online July 2003 or after (Tier 1),<br>5 MW, online before July 2003 (Tier 2) | Yes | No |
| Delaware | 30 | Yes | Yes |
| District of Columbia | none specified | Yes | No |
| Hawaii | none specified | Yes | No |
| Illinois | none specified | No | No |
| Iowa | "small" but no explicit limit | Yes | No |
| Kansas | 10 | Yes | No |
| Maine | 100 MW, online September 2005 or after (Tier 1),<br>100 MW, online before September 2005 (Tier 2) | Yes | No |
| Maryland | 30 MW, online January 2004 or after (Tier 1),<br>no limitation if before January 2004 (Tier 2) | Yes, but no new dams | No |
| Massachusetts | 30 MW, online after 2007 (Tier 1),<br>7.5 MW, online 2007 or before (Tier 2) | Yes | Yes |

*Continued next page*

*Table 2-1. continued*

| State | Capacity Limit (MW) | New Hydropower Allowed? | LIHI Certification Required? |
|---|---|---|---|
| Michigan | none specified | Yes, but no new impoundments | No |
| Minnesota | 100 | Yes | No |
| Missouri | 10 | Yes | No |
| Montana | 10 MW (existing), 15 MW (if online after April 2009) | Yes, but on existing reservoirs or irrigation systems | No |
| Nevada | 30 | Yes, but no new diversions or dams | No |
| New Hampshire | 5 | No | No |
| New Jersey | 3 MW, online after July 2012 (Class I), 30 MW (Class II) | Yes | No |
| New Mexico | None specified | Yes | No |
| New York | None specified | Yes | No |
| North Carolina | 10 MW (primary schedule), no limitations (secondary schedule) | Yes | No |
| Ohio | None specified | Yes | No |
| Oregon | None specified | Yes, but must not be located in “protected areas” | Yes |
| Pennsylvania | 50 | Yes | Yes |
| Rhode Island | 30 | Yes | No |
| Texas | 10 MW for small hydro, 150MW for repowered hydro | Yes | No |
| Washington | None specified | Yes, but no new diversions or impoundments | No |
| Wisconsin | None specified | Yes | No |

Notes: 1) There may be additional limitations on hydropower eligibility beyond those described above. 2) State rules vary on whether PSH facilities qualify under the hydropower provision. 3) This table does not describe eligible capacity or efficiency gains at hydropower facilities.

Source: Stori 2013 [28]

**Table 2-2.** Chronological List of Some Key Laws Relevant to Hydropower

| Year | Legislation | Description |
|---|---|---|
| 1899 | Rivers and Harbors Appropriation Act | Required that dams proposed for navigable streams obtain approval from Congress, the Chief of Engineers (Corps), and the Secretary of the Army prior to construction. |
| 1902 | Reclamation Act | Funded irrigation projects for the arid lands of 17 states in the U.S. West and established the Reclamation Service (later to become the Bureau of Reclamation). |
| 1920 | Federal Water Power Act | Established the Federal Power Commission (FPC) to centralize the planning and regulation of hydropower within one agency and coordinate hydropower projects. Provided for hydropower projects on federal tribal reservations, development of waterways, and consideration of additional interests such as fish and wildlife. |
| 1933 | TVA Act | Created the TVA to provide economic development, flood control, navigation, and electricity generation in the Tennessee Valley. |
| 1935 | Federal Power Act (FPA) | Originally the Federal Water Power Act of 1935. Extended FPC's authority to all hydroelectric projects built by utilities engaged in interstate commerce. Amended numerous times. |
| 1935 | Public Utility Holding Company Act (PUHCA) | Facilitated regulation of electric utilities. |
| 1936 | Flood Control Act | Authorized the Corps and other federal agencies to build flood control projects such as dams, levees, and dikes. One of numerous flood control acts. |
| 1939 | Reclamation Project Act | Extended to 40 years the contract term for hydropower sales or lease of power privileges, with preference to public utilities. |
| 1977 | Department of Energy Organization | Abolished the FPC and created FERC to implement the license approval process. |
| 1978 | Public Utility Regulatory Policies Act | Promoted energy conservation, greater use of domestic energy, and waste/cogeneration/renewable energy sources, including hydropower development at small existing dams. |
| 1986 | Electric Consumers Protection Act | Amended the FPA to require equal consideration of fish and wildlife habitat, and generally increased the importance of environmental considerations in FERC licensing processes. |
| 2005 | Energy Policy Act | Provided tax incentives and loan guarantees for various types of energy, repealed PUHCA, and provided more opportunity for parties to challenge the underlying facts resource agencies use to base any mandatory conditions submitted to FERC. |
| 2013 | Bureau of Reclamation Small Conduit Hydropower Development and Rural Jobs Act | Authorized small conduit hydropower development (<5 MW) at Reclamation-owned facilities and streamlined the regulatory process for this development through the Lease of Power Privilege process. The legislation has the potential to affect hydropower development at a minimum of 373 sites, as identified in the Reclamation's conduit resource assessment [63]. |
| 2013 | Hydropower Regulatory Efficiency Act | Directed FERC to explore possible 2-year licensing process for powering existing non-powered dams and closed-loop PSH projects; increased the FERC small hydro exemption from 5 to 10 MW; excluded certain conduit projects <5 MW from FERC jurisdiction; and increased FERC exemption for conduit projects to 40 MW, among other provisions. Included a directive that DOE assess PSH opportunities, as well as hydropower potential using existing conduit infrastructure. |

Note: Key environmental laws applicable to hydropower are referenced elsewhere in the text.

As previously noted, regulation of hydropower has two broad categories depending on ownership—non-federal and federal. Non-federal covers the development and regulation of hydropower by public and private utilities, independent power producers, and power marketers. As the main regulatory body for non-federal hydropower, FERC is responsible for licensing new projects, relicensing existing projects, and providing environmental and safety oversight for more than 2,500 non-federal hydropower dams. During licensing and relicensing processes, FERC is required to give equal consideration to multiple factors when issuing a license. As stated in section 4(e) of the FPA, "The Commission, in addition to the power and development purposes for which licenses are issued, shall give equal consideration to the purposes of energy conservation, the protection, mitigation of damage to, and enhancement of, fish and wildlife…the protection of recreational opportunities, and the preservation of other aspects of environmental quality."

Development of federal hydropower projects requires authorization and appropriation from Congress. For example, Corps hydropower development is authorized through Water Resources and Development Acts. Reclamation's Lease of Power Privilege process is applied to develop hydropower at Reclamation dams and canals. To guide operation of hydropower facilities, the Corps, TVA, and Reclamation adhere to specific requirements in applicable Congressional authorizations, which can include natural resource protection and conservation; respond to interactions with various state agencies, tribes, and other stakeholders; and comply with applicable federal laws (e.g., NEPA and ESA). Federal hydropower operators must produce a NEPA Environmental Assessment/Environmental Impact Statement to change operations or modify facilities, and a subsequent Record of Decision.

The hydropower regulation process involves numerous stakeholders and participants. Environmental laws require that federal and state agencies be involved in the hydropower regulatory process. Indian tribes also have an important role, as do non-governmental organizations representing a variety of interests such as industry, the environment, fishing, and recreation. Tribes and non-governmental organizations can influence the outcome of hydropower regulatory processes. Participants in regulatory processes, for example, may help develop mitigation actions for non-federal and federal projects.

### 2.1.3 Environmental Aspects

As with other types of energy development, construction and operation of dams can cause serious environmental impacts. During the early 20th century, national priorities were not focused on environmental issues. By the latter half of the 20th century, however, there was increased understanding of the impacts of dams on ecosystems and greater interest in environmental concerns. As a consequence, the federal laws discussed in Section 2.1.2 require mitigation measures to address environmental effects on natural resources related to operation of existing and proposed dams and hydropower facilities. Some of the important of laws are NEPA, Clean Water Act, and ESA.

Dam construction affects riverine ecosystems, from the physical characteristics of the river and its floodplain to the composition and viability of biota and ecosystem function. For instance, dams can alter channel geomorphology [35], connectivity of habitat [36], sediment supply [37], water quality [38], flow regimes [39], nutrient transfer [40], and fish habitat, health, and survival [41]. Regulations to address environmental impacts at the project level are in force. Regulatory provisions addressing the adverse effects of dams should help, for example, to recover ESA-listed species. Planning at the "whole system" level or "basin scale" is relevant both in the siting of new hydropower facilities and in considering whether existing facilities that are obsolete or uneconomical can be removed and replaced with new hydropower capacity. Moreover, cumulative impact and strategic environmental assessments can provide a broad scoping of environmental impacts. Some potential environmental concerns associated with dam construction (with or without hydropower) and with operation of hydropower facilities are described here, along with potential methods to avoid or mitigate them.

**Flow Regimes.** Dam operations can alter the fundamental hydrologic properties of rivers, such as the magnitude, frequency, duration, timing, and rate of change of river flows. This alteration of natural runoff patterns has ecological significance, because healthy riverine ecosystems have natural dynamics of flows to form and maintain habitats and species (e.g., Poff et al. 1997 [42]). For example, storage dams can hold back water when it naturally would be flowing downstream as runoff, creating unnatural decreased flows. This stored water can be released at a later time for hydropower generation during typically low flow periods, creating unnatural increased flows. This can beneficial during droughts when stored water releases can help maintain riverine habitats. One approach to mitigate for altered flow regimes can be for hydropower facility operators to target specific hydrologic attributes, e.g., maintaining flows above seasonally adjusted minimums. In addition, variations in daily hydropower operations, such as ramping rates or timing of releases, is used in attempts to provide improved flow regimes for sensitive species or critical stages in species life cycles. Maintaining habitat availability and conserving habitats that function effectively over a range of flows (termed persistent habitat) is another way to protect affected species [43].

**Water Quality.** Construction and operation of dams can affect water quality in impoundments and downstream rivers in a variety of ways. Direct effects include spatial and temporal changes in water temperature, dissolved oxygen, nutrients, turbidity, dissolved gases, and more. Indirect effects include the responses of riverine organisms, populations, and communities to these changes in water quality. Measures to address concerns about water quality and toxins include tools that can assess and predict concerns, allowing hydropower operators to avoid or mitigate these effects. One example is an auto-venting turbine developed to increase the concentration of dissolved oxygen in water exiting hydropower plants, especially plants in the southeastern United States where low dissolved oxygen levels can exist due to deep withdrawals of low-oxygen water from the forebay or decaying organic matter and warm water temperatures [44].

**Sediment Transport.** Dams alter the sediment transport process by decreasing sediment loads. This in turn affects water turbidity and bank erosion rates, as well as channel formation, aggregation/degradation, complexity, and maintenance. These changes to natural sediment transport in a river influence habitat-forming processes, such as bars and shoals [39]. In general, sedimentation is increased in the dam's reservoir due to relatively slow water velocity. In contrast, sedimentation downstream of a dam is decreased due to lower sediment load and relatively high water velocities. Additional detrimental downstream effects may include channel constriction and substrate coarsening. One approach that has been pursued to address the effects of decreased sediment transport on riverine habitat formation has been to attempt to physically build up sediment in sediment-starved areas downstream of hydropower dams [45]. In addition, a sediment sluiceway might be designed into a dam to pass impounded sediments during high flow periods [46].

**Barriers to Movement and Loss of Connectivity.** Dams impede the movement of organisms, nutrients, and energy in a river network and reduce or block connectivity between habitats upstream and downstream of the structure [47]. This is an important concern for fish species whose life cycle requires migration between freshwater and marine environments, and for resident fish species whose life stages involve movements among different riverine habitats. Lack of connectivity also inhibits natural gene transfer among populations of resident fish [48]. Methods to improve fish passage and connectivity include construction of collection facilities or passage structures, such as surface flow outlets and fish ladders, to help facilitate downstream and upstream movement of fish past a dam. Basin-scale planning during the siting phase can also help avoid or minimize the effects of barriers (e.g., Larson et al. 2014 [49]; McNanamay et al. 2015 [50]).

**Dam Passage Injury and Mortality to Fishes.** Downstream passage through a turbine, spillway, or other route can injure or kill fish [51, 52, 53]. Impacts can be direct (e.g., strike by a turbine blade) or indirect (e.g., predation while disoriented post-passage). Dams can also affect upstream fish passage by causing migration delays and increasing vulnerability to predation by concentrating fish at entrance to upstream passage facilities. In rivers with multiple dams, impacts may be cumulative from one dam to the next, depending on species behavior. One area of research on this topic is the evaluation of accelerated deployment of new or refurbished hydropower turbines employing "fish-friendly" turbine designs [54], such as minimum gap[18] runners [55]. Other approaches include installing passage structures or devices to bypass downstream-moving fish around turbines [56] and intake screens to prevent entrainment of fish [57].

Addressing environmental impacts has become a critical part of the hydropower development or relicensing process. Some of the most common strategies to avoid or mitigate environmental impacts are minimum streamflow requirements, dissolved oxygen

18. According to Hogan et al. 2014 [55], the minimum gap runner is, "a modification of a Kaplan turbine in which the gaps between the adjustable runner blade and the hub, and between the blade tip and the discharge ring, are minimized at all blade positions."

> **Balancing the needs of society and the environment in a way that creates environmentally sustainable hydropower of the future requires advanced planning, technical, and legal approaches. For a given basin, new and innovative approaches to achieve balanced hydropower development can be pursued within an adaptive management* framework instituted by and with active participation of stakeholders (e.g., Irwin and Freeman 2002 [58]). Importantly, systematic sharing of case studies emerging from application of new approaches may facilitate "learning by doing" and increase the rate of adaptation and innovation.**
>
> *Adaptive management involves a systematic, rigorous approach for learning through experiences and results from management actions [59].

abatement, fish passage structures, improved operations, recreation enhancements, and ecosystem restoration. Dam removal can also be used as a mitigation strategy in a "trade-off" or optimization situation at the basin scale, where environmental, economic, and social values are treated as co-equal objectives during new hydropower development. An example is the Penobscot River basin, where stakeholders reached an agreement to add hydropower in some areas and remove dams in others [60]. Successfully avoiding or mitigating environmental impacts is essential to hydropower of the 21st century.

## 2.1.4 Advancing Sustainable Hydropower

Growing hydropower in general will require refurbishing the existing fleet, adding new hydropower capacity, and balancing multiple water use objectives. Sustainability is essential to this growth, because hydropower of the 21st century will need to integrate principles of environmental stewardship and water use management that balance societal needs for energy with protection of the environment. Potential resources for additional capacity have been identified, and some are under development as of 2015. Principles and practices of sustainable hydropower provide a foundation for hydropower development. They also set a context for actions in the *Hydropower Vision* roadmap, which will need to include sustainability considerations to ensure balanced hydropower development.

### *Resource Potential*

Five main potential resources exist for new or added hydropower capacity,[19] including PSH, in the United States:

1. **Refurbishment**—rehabilitating, expanding, upgrading, and improving efficiency and capacity of existing hydropower facilities. Also termed modernizing or maintaining, this avenue is being pursued in response to an aging fleet of hydropower facilities as well as other factors. Hydropower capacity that might be added through refurbishment is about 7 GW (based on information from Reclamation 2011 [61], Corps 2009 [62]).

2. **Non-Powered Dams**—powering non-powered dams (NPDs). This avenue contains the greatest opportunity for adding hydropower capacity on a per-dam basis (not including PSH). NPDs have the potential to add about 12 GW of new capacity [19].

3. **Conduits and Canals**—installing hydropower in existing water conveyance infrastructure, such as canals and conduits. Many of the potential projects would be considered small (< 10 MW) or micro hydropower (< 0.5 MW). The resource potential for Reclamation-owned canals is about 104 MW [63]. Beyond this, there have been no national resource assessments for conduits and canals [64].

4. **New Sites**—developing new hydropower projects. These new stream-reach development (NSD) projects would be new projects on previously undeveloped sections of waterways. Excluding only areas protected by federal legislation that limits the development of new hydropower, the hydropower capacity that might be added from NSDs is about 66 GW [65].[20]

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19. The capacity values in this section represent technical potential capacity, which is not necessarily the same as the amount of hydropower that can be sustainably or feasibly developed. See Chapter 3, Table O3-3, for discussion of how these technical resource potential estimates are used to inform the modeled resource potential of the *Hydropower Vision* analysis.

20. Kao et al. [65] noted, "These potential high-energy-density areas should be regarded as worthy of more detailed site-by-site evaluation by engineering and environmental professionals; not all areas identified in this assessment will be practical or feasible to develop for various reasons." See Chapter 3, Table O3-3, for discussion of how these technical resource potential estimates are used to inform the modeled resource potential of the Hydropower Vision analysis.

5. **Pumped Storage Hydropower**—increasing PSH. Developers are pursuing new PSH resources, in the 200–2000 MW range per plant, as well as technology upgrades at existing PSH plants. As of February 2015, about 50 PSH projects had been proposed, representing about 40 GW of new capacity [66].

### *Principles and Practices for Sustainable Hydropower*

A sustainable water and energy future is one in which the entire water-energy system, with its multiple components—economic, social, and ecological—can be made to function in the present as well as into the years ahead. Hydropower facilities need to be resilient to changes in system state (e.g., changing climate and hydrologic regimes), as well as responsive to scientific discoveries and new technologies that improve the potential for meeting long-range system factors.

**For purposes of the *Hydropower Vision,* sustainable hydropower is a project or interrelated projects that are sited, designed, constructed, and operated to balance social, environmental, and economic objectives at multiple geographic scales (e.g., national, regional, basin, site).**

Hydropower is closely linked to the multiple uses and values of the water-energy system in which it operates. The future of hydropower, therefore, is linked to the future of various, sometimes competing uses of both water and energy. Sustainable hydropower fits into the water-energy system by ensuring the ability to meet energy needs without jeopardizing the function of other components or the overall system. Where hydropower can be added to new and existing infrastructure in a way that satisfies environmental and economic objectives, it can enhance the societal value and long-term viability of that infrastructure. To be considered sustainable, the use of America's hydropower resources for low-carbon energy production and the long-term economic viability of individual projects must be integrated with other water uses, stakeholders, and priorities.

Sustainability is often evaluated based on a project's performance with respect to a set of objectives that reflect the interplay among economic, environmental,

**Table 2-3.** Examples of Sustainability Objectives Related to Hydropower[21]

| Environmental objectives include: |
|---|
| • Avoiding risk to sensitive and high value freshwater and coastal systems |
| • Mitigating loss of riverine connectivity |
| • Maximizing persistence of native species and communities |
| • Supporting natural flow, sediment, and water quality regimes as appropriate |
| • Mitigating dissolved oxygen concerns |
| • Maintaining geomorphic equilibrium |
| **Social objectives include:** |
| • Ensuring public health and safety |
| • Ensuring provision of water supply for local communities |
| • Honoring tribal treaty rights |
| • Supporting cultural heritages and archeological resources |
| • Providing reservoir and downstream recreation opportunities |
| • Respecting land owner rights |
| **Economic objectives include:** |
| • Providing low-cost, reliable energy |
| • Minimizing development and operating costs |
| • Maximizing market/economic values |
| • Providing generation flexibility and long-term viability |
| • Providing job opportunities |

21. Based in part on International Hydropower Association [67] and Sale et al. [68]


**Figure 2-18.** Factors to be balanced in developing and growing sustainable hydropower

hydropower development and operation [67, 68] (Table 2-3 and Figure 2-18). While the *Hydropower Vision* is not intended to provide a new set of objectives for hydropower sustainability, this report offers a representative list of examples of economic, environmental, and social objectives that provides a broad-scale context of sustainable hydropower. It is not possible to "maximize" all of these objectives simultaneously, so sustainability focuses on taking individual values into account and optimizing across them. Figure 2-18 illustrates consideration for multiple factors.

## 2.1.5 Unique Value of Dams and Hydropower

As explained in this section, hydropower operates within a distinctive set of conditions, market structures, and environmental contexts. The distinctive values of hydropower to the nation's energy supply create momentum for refurbishment of existing facilities and development of new facilities, i.e., renewed vigor of the industry in a sustainable manner that balances societal, environmental, and economic objectives. These unique values are summarized in this section, starting with the multiple purpose context in which hydropower operates.

Dams provide benefits to the public beyond low-cost, renewable hydropower. Dams protect public safety and economic well-being from flooding of downstream communities and lands; in fact, the primary authorized purpose for many dams is flood management, not hydropower. Storage dams improve resiliency in water supplies for downstream interests during drought conditions. Dam reservoirs enable recreational opportunities for people to canoe, fish, water ski, camp, bird watch, and more. Agriculture in many western states relies on irrigation water from reservoirs. Dams divert water to municipal water facilities to be treated for people to consume. Water is a public resource that is used for many purposes, one of which is hydropower.

Hydropower has a long life cycle and provides critical generation and ancillary grid services to help ensure the reliability of the national electrical bulk-power system, including energy for base load and for load following (energy balancing) as system demands fluctuate. Additional services include frequency regulation, reactive supply and voltage control, spinning and non-spinning operating reserves, replacement services, black start capability, and firm capacity for system planning (see Text Box 2-2a and Text Box 2-2b for more information on these services). Quantifying and monetizing these ancillary and essential reliability services appropriately will help support the long-term viability of hydropower.

Hydropower's value may also be monetized in renewables markets (compliance and voluntary markets) and emissions markets (federal clean air and greenhouse gas markets). Hydropower's eligibility and treatment in these markets, however, varies widely across the United States. Increased market demand for renewable energy and an enhanced understanding of hydropower as a renewable energy resource could particularly motivate hydropower growth.

**Planning for 21st-century hydropower will likely include scenarios for climate change. In particular, owners of existing hydropower operations and developers of new hydropower facilities need to consider the projected effects of runoff patterns altered by climate change. To address this challenge, planning scenarios for hydropower operations may incorporate climate change predictions. In the future, utilities are also likely to establish processes to deal with climate change in long-term planning. For example, water storage has a role in mitigating adverse effects of global warming. While there remains much uncertainty about climate change and its effects on water resources, many inhibitive risks to future hydropower might be addressed using an adaptive management approach.**

The public economic value of hydropower is underscored by the number of skilled jobs that the industry supports. Positions to support hydropower include mechanics, electricians, operators, transmission line workers, dispatchers, schedulers, engineers, analysts, and marketing specialists. Growth of hydropower projects is expected to increase the number of jobs in the sector.

Hydropower has national security value as part of the nation's critical infrastructure and as a domestic contributor to energy supply. A robust, modernized fleet of hydropower facilities will help ensure maintenance of critical infrastructure including storage reservoirs for water supply and flood management, dams for power production, and a reliable electrical transmission grid.

Maintaining the capacity of the existing fleet of hydropower facilities and multi-purpose dams can help ensure public safety as well as availability of hydropower to support the electrical grid and serve the diverse energy mix that will be needed in the future. In order to serve the public's best interests, future hydropower development and generation must be balanced with environmental stewardship and multi-purpose water use management. The opportunities for growth in hydropower capacity and PSH flexibility must consider and attempt to optimize economic, environmental, and social parameters, which can vary by hydropower resource type, location, and regulatory environment.

Considering the future of hydropower requires understanding the long history and complex structure of the United States hydropower industry. The objectives of hydropower have not always been pursued within a context that balances outcomes with environmental and social objectives. More than 100 years of hydropower evolution, however, provide a solid foundation for a future hydropower industry that offers long-term viability by integrating environmental stewardship, economic performance, and availability of critical water resources for production of clean energy.

# 2.2 The Role of Hydropower in the Grid

Hydropower is a valuable generation resource within the U.S. electrical bulk-power system, including being linked to all three of the transmission interconnections comprising the system. In addition to providing cost-competitive, low-carbon electricity, hydropower's flexibility further supports the power system by contributing such services as system balance, voltage support, and stability. This section examines how hydropower fits into the national electric generation and transmission system; the role it plays in grid operations and planning; and the opportunities and challenges for hydropower to have an increased grid presence in the decades to come.

## Highlights:

- Hydropower is a cost-competitive and low-carbon energy source that provides the full range of services required by the electrical bulk-power system, or grid.
- Hydropower is a flexible energy resource, but the limits of its flexibility are not widely understood and vary from plant to plant and region to region.
- The flexibility of hydropower generation can support integration of other variable renewables such as wind and solar energy. The value of hydropower to the integration of wind and solar will depend in part on the limits of its flexibility, as well as competition from other flexible resources.

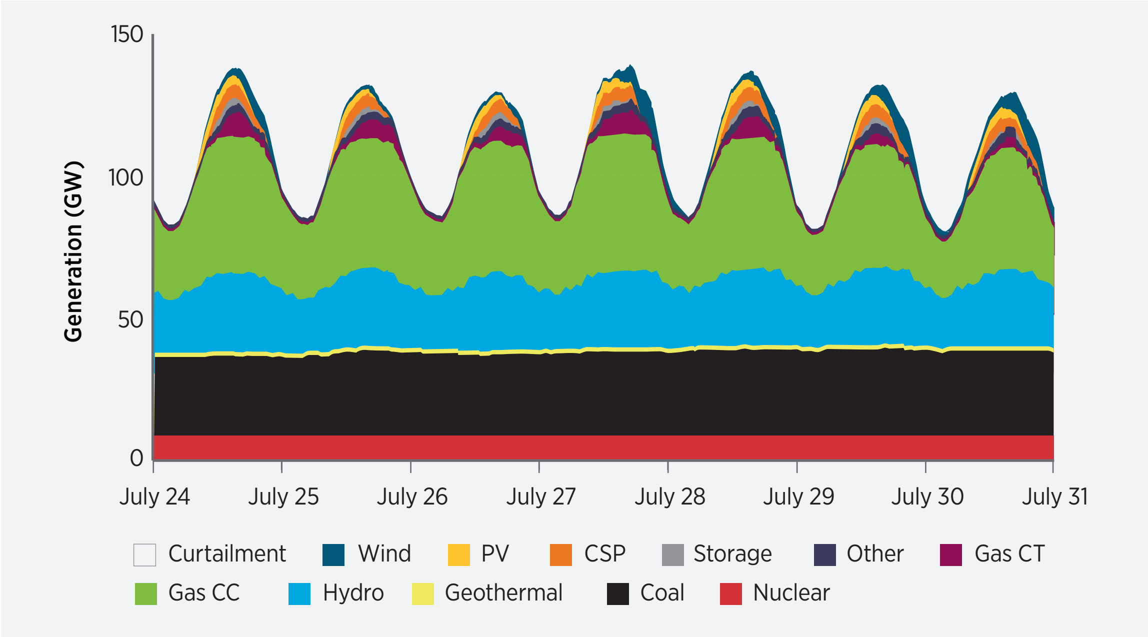
## 2.2.1 Transmission System Overview

Large transmission grids can be operated as a single system or, as is more common, can be broken into several smaller transmission "balancing authority areas." In these BAAs, reliability requirements are met while balancing load with generation and interchanges with neighboring regions. When a balancing area is well connected to neighboring areas, balancing the electrical system is typically easier because the transmission system permits the exchange of power and other services.[22] This requires transmission interconnection between areas that have available transfer capacity. For instance, hydropower facilities in the Pacific Northwest sell energy to utilities in California and the Southwest to help those regions meet their summer peak demand. This exchange is facilitated by market mechanisms that enable purchases and sales, or frequent economic dispatch (the process of changing generation output to meet changing conditions). The U.S. markets perform economic dispatch every five minutes [69].

The high-voltage transmission network in the United States is divided into three interconnections. The first two are the Western and Eastern Interconnections, located generally west and east of a line running north-south along the eastern Wyoming border (see Figure 2-12). The third interconnection is located in Texas, although it does not conform precisely to the state boundaries. Although each of these three regions is synchronized internally, they are not synchronized with each other. This means that there is limited ability to move power between these three synchronous regions using transmission interconnection ties (which convert and transmit power, in an AC-DC-AC[23] pattern), each of which has a capacity ranging from 100 MW to 200 MW. Total generating capacity in the United States exceeds 1,000 GW, and therefore the ability to transfer power among interconnections is quite small relative to the size of the system [70].

The objective of power system planners and operators is to provide a reliable supply of electrical energy at the lowest possible cost. Because demand fluctuates over all time scales, from seconds to decades, the mix of resources has evolved such that different types of resources provide specific types of services and energy to the power system. Traditionally, baseload generators (often coal or nuclear) have the lowest variable cost, and provide energy at all times with limited changes in output levels and subject to their availability. Mid-merit (intermediate) generation sources, which may consist of higher-variable cost natural gas[24] combined cycle or low-variable cost hydropower resources, operate based on their capabilities and the relative need of the system; these plants often provide high output during the day and lower (or even zero) power levels at night. Peaking power plants typically operate for limited periods of extremely high demand; such plants may consist of combustion turbines or PSH. PSH has traditionally been operated by pumping water at night when costs and prices are low, then releasing the water during the day when costs and prices are higher. This provides a form of arbitrage that can provide both economic and reliability benefits.

22. Such services consist of the various balancing and reliability functions necessary to keep the grid in a stable operating mode. These services are discussed in more detail in Text Box 2-2a.
23. Alternating current–direct current–alternating current.
24. When coal prices exceed gas prices, gas generation tends to be used more as baseload power, and coal as intermediate power, subject to physical constraints.




Source: Lew et al. 2013 [71]

**Figure 2-19.** Example of simulated power system dispatch for a week in the Western Interconnection

Although it is often used as intermediate generation, some hydropower operates as baseload generation. Wind and solar energy do not easily fit into these categories of generation. Because their variable cost is near zero, it is always economic to use as much wind/solar energy as possible, subject to various operating constraints. Figure 2-19 illustrates a typical week in the Western Interconnection with the use of hydropower generation to help meet peak demand during the day.

Most river basins offer at least some opportunity for water storage, typically as impoundment. This storage can be used to plan the timing of water release through the turbines—and thus the hydropower generation—to some degree. This timing depends on the size and other characteristics of the storage relative to the overall river system, as well as on the number of storage facilities within a given river basin. The amount of storage present in a river system as compared to the annual runoff greatly increases the flexibility and dispatchability of its associated hydropower.

## 2.2.2 Grid Services from Hydropower

To maintain system balance and stability, several elements of the power system must be managed so that the primary product—electrical energy—can be delivered safely, reliably, and economically. Doing so requires support from ancillary grid services, which FERC defines as: "those services necessary to support the transmission of electric power from seller to purchaser given the obligations of control areas and transmitting utilities within those control areas to maintain reliable operations of the interconnected transmission system" [72]. FERC defines six overall ancillary services,[25] many of which are now provided via markets in areas where RTOs or ISOs operate the grid. There are also some grid services that are necessary, but are not explicitly defined as ancillary services by FERC. Collectively, these services contribute primarily to maintenance of system balance on time scales ranging from sub-second to many minutes or even hours.

25. FERC defines the following ancillary services: (1) Scheduling, System Control and Dispatch Service, (2) Reactive Supply and Voltage Control from Generation Sources Service, (3) Regulation and Frequency Response Service, (4) Energy Imbalance Service, (5) Operating Reserve – Spinning Reserve Service, (6) Operating Reserve – Supplemental Reserve Service. See *http://www.ferc.gov/legal/maj-ord-reg/land-docs/order888.asp*. Other grid services may not fall under FERC's definition. In this report, we refer to the overall collection of services as "grid services," and indicate designated ancillary and essential reliability services where appropriate.

Text Box 2-2a.

## Grid Ancillary Services Relevant to Hydropower

**Regulation and frequency response:** *The ability of a resource or a system to respond to changes in system frequency, which must be maintained close to a constant level (60 Hertz).* NERC establishes control performance standards to ensure that each control area maintains reliability. This response can be provided by generators through three mechanisms:

- Inertia: A passive response, typically due to rotating masses in generators
- Primary frequency response or governor control: An active, unmanned response implemented through an electronic, digital, or mechanical device
- Frequency regulation: An active response to adjust an area's generation from a central location in order to maintain the area's interchange schedule and frequency

Hydropower generators can provide these regulation services. While hydropower turbines are able to respond to sudden changes in system frequency, the relatively large mass rotating in hydropower turbine generators and the dynamics of the water column in the penstock mean hydropower may have a lower response time than do gas or steam [75]. This larger inertia can, however, be an advantage in smaller or islanded power systems as it contributes to system stability [76].

**Load-following and flexibility reserve:** *The ability of the power system to balance variability existing in the load over longer timeframes than regulation and frequency response, from multiple minutes to several hours.* This function is typically accomplished by mid-merit (intermediate) and peaker units. Most U.S. hydropower units are able to and do effectively provide load following to an hourly schedule, as well as following ramps that occur within the hour time scale. This flexibility is not without impact, however. Increased variation in hydropower generation can impact riverbank erosion and aquatic life, as well as increase operating costs and decrease system lifetime. In order to determine optimal use of hydropower for load-following services, these impacts must be considered against the cost of providing load following from other types of generation.

**Energy imbalance service:** *The transmission operator provides energy to cover any mismatch in hourly energy between the transmission customer's energy supply and the demand that is served in the balancing authority area.*

**Spinning reserve:** *Online (connected to the grid) generation that is reserved to quickly respond to system events (such as the loss of a generator) by increasing or decreasing output.* Except when already running at full load, hydropower offers an excellent source of reserve because it has high ramping capability throughout its range.

**Supplemental (non-spinning) reserve:** *Offline generation that is capable of being connected within a specified period (usually 10 minutes) in response to an event in the system.* Offline hydropower generation is capable of synchronizing quickly, and can provide non-spinning reserve to the extent that sufficient water supply is available to the unit for generation.

**Reactive power and voltage support:** *The portion of electricity that establishes and sustains the electric and magnetic fields of AC equipment.* Insufficient provision of reactive power can lead to voltage collapses and system instability. All hydropower facilities are operated to follow a voltage schedule to ensure sufficient voltage support. Reactive power is typically a local issue. Because hydropower facilities are often located in remote areas, their ability to provide reactive power in such locations can be essential.

**Black start (restoration) service:** *The capability to start up in the absence of support from the transmission grid.* This capability is of value to restart sections of the grid after a blackout and can typically be provided by hydropower.

The provision of these services has economic value above and beyond the value of the energy produced while generating, and increases the flexibility of the electrical system to accommodate load changes. Text Box 2-2a describes a number of grid services typically required by the grid [72, 73, 74] and that can be and are provided by hydropower. Certain key grid services are considered by NERC to be critical to maintaining the operations and stability of the national grid, and have been designated by them to be essential reliability services (Textbox 2-2b).

In theory, grid services can come from any resource that is physically capable of performing as needed to provide the service or services—i.e., a power plant, demand response, or storage device. In practice, some resource types may be constrained physically or economically from providing certain services. The result is that not all power plants provide all services, but it is also unnecessary to have these services from all plants. For example, large nuclear units do not generally supply regulation or other forms of reserve because it is expensive and time-consuming to change plant output and control the fuel supply to the reactors. Large coal units may provide regulation through automatic generation control, but may not

Text Box 2-2b.

### ***Essential Reliability Services:*** Grid Services Designated As Critical to National Power System Reliability

In its role as the Electric Reliability Organization of the United States, NERC has designated the services of frequency response, ramping, and voltage support as essential to reliable operation of the national power grid.

In December 2015, NERC issued its "Essential Reliability Services Task Force Measures Framework Report," [79] to help stakeholders and policymakers understand and prepare for a changing energy resource mix. Subsequently, NERC issued a public statement [103] emphasizing key points regarding essential reliability services:

- *North America's resource mix is undergoing a significant transformation at an accelerated pace with ongoing retirements of fossil-fired and nuclear capacity and growth in natural gas, wind, and solar resources.*
- *A key priority for our energy future is to ensure that reliability is maintained as the generation resource mix changes.*
- *NERC has identified three essential reliability services (ERS) that warrant attention—frequency response, ramping, and voltage support. While these three services are among the first to manifest, we see other issues such as inertia beginning to emerge.*
- *For this reason, policy makers need to include provisions for essential reliability services of the grid: ramping, frequency control, voltage control, and also to address emerging issues, such as inertia.*
- *ERS are necessary to balance and maintain the North American BPS [bulk-power system]. Conventional generation (steam, hydro, and combustion turbine technologies) inherently provides ERS needed to reliably operate the system.*
- *It is necessary for policy makers to recognize the need for these services by ensuring that interconnection requirements, market mechanisms, or other reliability requirements provide sufficient means of adapting the system to accommodate large amounts of variable and/or distributed energy resources (DERs). Policy makers are increasingly recognizing these needs, which will become more significant as larger penetrations of renewables and retirements of base load coal (and some nuclear) occur.*

be as flexible or accurate as natural gas combined cycle plants. Inertial response will differ between large and small units because of differences in their rotating mass. There might also be instances in which the capability is available but not provided, e.g., units that have disabled governor control (e.g., Eto et al. 2010 [77] and Ela et al. 2014 [78]).

Because of the wide range of operational flexibility offered by most hydropower resources, hydropower is often used to provide various types of reserves and has demonstrated suitability for services that involve changing output on relatively short time scales (seconds to hours). There may be institutional constraints that result from market design and/or operating practice that prevent access to some of this latent flexibility; however, hydropower provides most, if not all, grid services. For example, Key [80] demonstrated that all grid services are provided by hydropower in varying degrees across the United States. This includes capacity and energy as well as designated ancillary services (e.g., regulation, spinning and non-spinning reserve, and voltage support). Hydropower is generally capable of providing frequency response and inertia. Not all resources may be needed to provide the electricity and balancing/support services needed by the grid, but many types of power plants with differing characteristics can operate as a system to provide all necessary services.

### 2.2.3 Hydropower and Electrical System Flexibility

Hydropower is a flexible system generation resource, but its generation is subject to many competing objectives and varying priorities—such as water deliveries, navigation, and others—that have an impact on minimum/maximum flows and minimum/maximum ramp rates. These constraints arise due to the numerous functions served by multi-purpose dams, as well as the environmental and regulatory constraints that govern hydropower facility operation. While these constraints vary from region to region and in differing hydrologic environments, environmental considerations include protections for fish and wildlife, water temperature, water quality and supply, and shoreline protection. Regulatory considerations that may impact generation include flood management; navigation; recreation; land rights; hydraulic coordination between upstream and downstream dams; and any applicable federal, state, or local policies. The level of flexibility after these considerations are accounted for varies considerably, as illustrated in Text Box 2-3.

Despite the fact that hydropower operations are constrained in some respects, there is flexibility available for use in scheduling generators, for buying/selling energy, and for providing ancillary services. The availability of these services may vary by time of day, month, or year. Hydropower operators must consider how to quantify and use system flexibility; the value of this flexibility in the interconnected grid and market or utility systems; and how to best integrate physical infrastructure, governing bodies, and regulations to maximize utility and benefits of hydropower while meeting priorities and complying with regulations.

Hydropower's operational flexibility can be constrained by other functions of the facility or by regulatory issues. It can also sometimes be limited by the lack of available transmission capabilities to other regions or other constraints on the power system that do not allow the full provision of available services from hydropower. These constraints are unique to each hydropower system. For many electrical systems that include hydropower, considerations include how much flexibility is available from the hydropower and whether any further flexibility can be accessed through reasonable changes in operation, infrastructure development, or organization/regulation. For example, during periods of high water runoff during the spring when demand is low and wind energy is high, hydropower may contribute to over-generation because there is insufficient storage relative to run-of-river. The potential value of the flexibility services is not straightforward, in part because some aspects of flexibility are not properly valued by electricity/ancillary service markets (Section 2.3.1.2). The value is also likely to fluctuate as the electricity generation mix evolves.

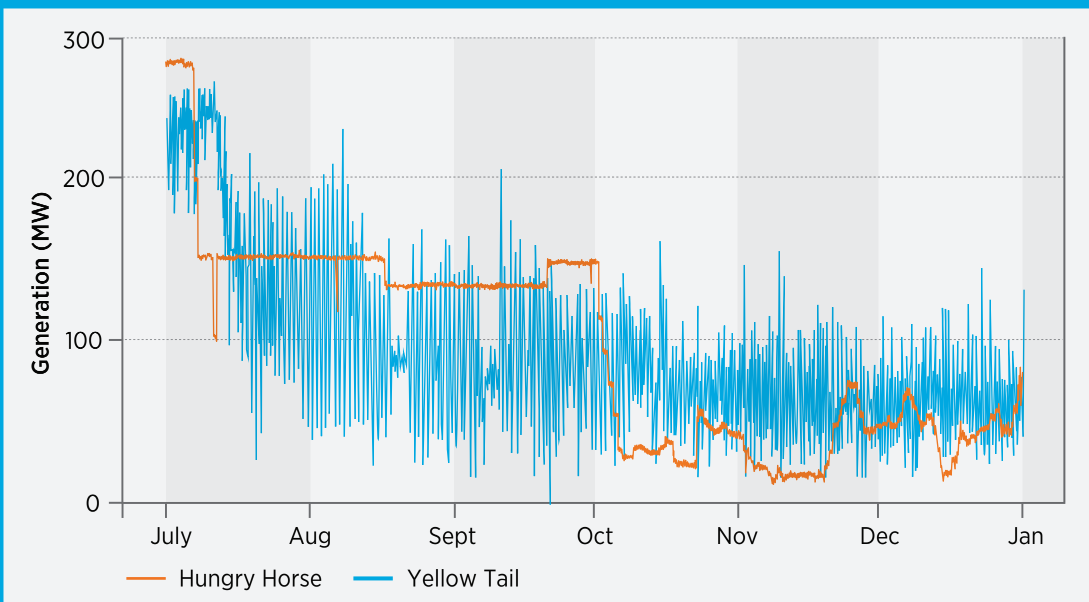
Text Box 2-3.

## Flexibility and Free-Running Streams

Free-running streams downstream of hydropower dams limit flexibility because rapid discharge decreases can cause undesirably large increases in water flow in a small amount of time. Smaller dams (called re-regulation or "rereg" dams) can be built just downstream of a larger dam. By impounding all or part of the water released, these smaller dams can often relieve issues such as stranding fish and imperiling people on the river banks. The effects on flexibility can be substantial. For example, the Hungry Horse and Yellowtail projects, located in separate river basins in Montana, have characteristics similar to hydropower dams, but they discharge into a free-running stream and a rereg dam (Yellowtail Afterbay), respectively. The degree of flexibility, which is reflected as generation, is illustrated by these two dams' respective generation patterns.



Hungry Horse dam (left), Yellowtail dam (center), and Yellowtail Afterbay dam (right) *Photo credits: U.S. Bureau of Reclamation*




Hourly generation from Hungry Horse (red) and Yellowtail (blue) dams in the second half of 2010

*Sources: Army Corps NWD Database [81], Western Area Power Administration Transmission Expansion Planning Policy Committee [82]*

## 2.2.4 Pumped Storage Hydropower Capabilities

Compared with other hydropower facilities, PSH facilities typically have fewer operational and environmental constraints.[26] PSH facilities have traditionally served two primary functions in the electrical system: (1) providing energy storage and shifting system demand from peak to off-peak periods; and (2) providing backup capacity in case of outages of large thermal or nuclear generating units. PSH plants are able to start quickly and have high ramp rates, characteristics that allow such plants to provide high generating capacity in a short time period. These operational characteristics contribute to greater flexibility and reliability of power system operation [83]. A common use for PSH is to perform a type of arbitrage—storing electricity when prices or operational system costs are low, and producing electricity when prices/costs are high.

The operational flexibility of PSH facilities makes it possible for these systems to provide key ancillary grid services, such as a combination of spinning and non-spinning reserve components of contingency reserves. Most PSH plants can increase output (ramp up) quickly and reach maximum installed capacity within 10 minutes. PSH plants can also provide frequency regulation and other ancillary services. While fixed-speed PSH plants can provide regulation reserve only in the generating mode of operation, advanced adjustable-speed[27] PSH units can provide regulation service in both generating and pumping modes of operation. Most PSH technologies can switch from full pumping to full generation in several minutes [84]. See Section 2.7 for more information on these designs.

In addition to energy and grid services, PSH plants also provide a number of other benefits to power systems. For example, PSH plants provide a flatter net load for thermal generating units, allowing the units to reduce cycling and operate for longer periods of time at more efficient set points, especially in small systems [83]. PSH plants can also provide the load and storage for excess variable generation (VG), thus reducing the curtailment of this generation.[28] This supports integration of a larger share of variable renewables into the power grid by storing energy when energy has a low value, and releasing energy during periods of high value.

## 2.2.5 Transmission Aspects Specific to Hydropower

By its nature, hydropower generation is constrained to be located along river basins with sufficient characteristics to support impoundments and power generation equipment. Transmission is necessary to deliver electricity from hydropower in these river locations to demand centers. Figure 2-20 illustrates that the greatest period of transmission expansion coincides with the development of hydropower and baseload units in the 1960s and 1970s. The figure also shows that the level of overall transmission expansion in the United States has increased slightly relative to the period 1990–2005.

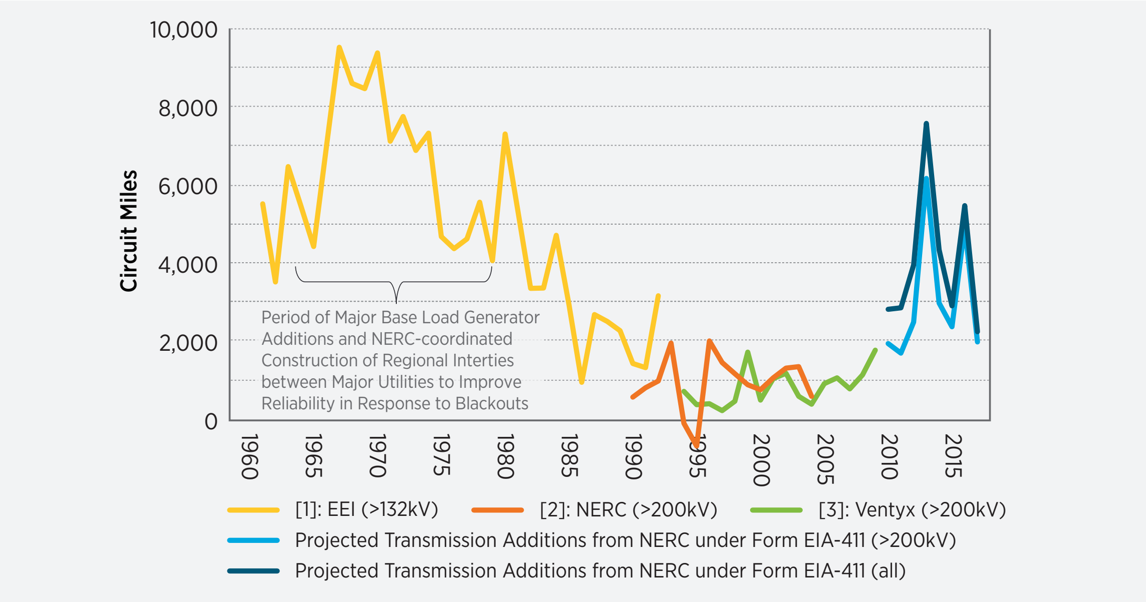
This section describes the geographic distribution of electricity demand in the United States, along with the overall structure and characteristics of the transmission network relative to demand centers and the location of existing hydropower facilities. New transmission is built primarily to provide a combination of the following functions and benefits:

- **Connecting new sources of generation.** Some new generation is located far from load centers, and transmission must be developed to deliver energy over these potentially large distances.
- **Connecting new or growing load areas.** Growing cities or new sources of demand may need new transmission to connect with the grid or support higher demand.
- **Increasing or maintaining reliability.** In some cases, new transmission can strengthen the grid, resulting in better performance and/or higher reliability (i.e., fewer consumer outages or better system balancing as measured by resource adequacy, frequency excursions, or NERC control performance standards).

26. For instance, many PSH facilities use at least one reservoir that is not part of the normal hydrologic system. This enables relaxation of some of the constraints that challenge typical hydrologic systems.

27. There are no adjustable-speed PSH units located in the United States as of the end of 2015.

28. In cases where curtailment can be reduced, periods of excess generation can be mitigated by storing excess energy through pumping water at the PSH facility.




Note: Most of the existing grid was built 30-50+ years prior to publication of the *Hydropower Vision.* Even relatively high recent and projected circuit miles additions are below levels of additions in 1960s and 1970s.

Source: Pfeifenberger 2012 [85]

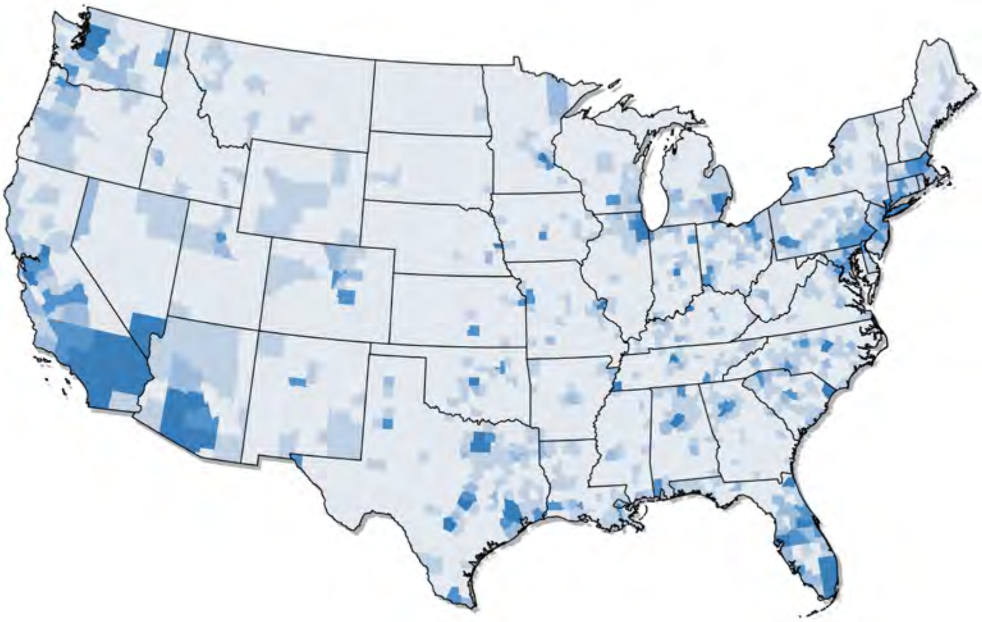
**Figure 2-20.** Historical high-voltage transmission additions in the United States

- **Reducing system-wide operating cost.** Connecting neighboring systems with a strong transmission tie may result in better use of less costly generation sources, and can link together markets of the electrical bulk-power system.

In some cases, new transmission can deliver a combination of these functions and advantages. In all cases, rigorous cost/benefit analysis is needed and must be accompanied by public stakeholder processes that address transmission development in cases of public opposition, environmental considerations, and controversial allocation of new transmission costs. Expanding the transmission system has become increasingly challenging because of environmental and cost allocation concerns; thus, the issue of limited transmission expansion is widespread. There are examples of approaches that have been used effectively to determine the value of new transmission, and methods that have helped ensure that incremental transmission additions do not prove inefficient in the long run. For instance, the Midcontinent ISO (MISO) Multi-value Project process does not directly attempt to place an economic value on reliability. Instead, potential new transmission is analyzed in Multi-value Project using extensive production cost modeling.[29] The resulting benefit calculations are compared to costs so that cost-effective solutions can be pursued [86].

Another approach, with different objectives, is Competitive Renewable Energy Zones, known as CREZ. In 2005, the Texas Legislature passed a law requiring the Public Utility Commission of Texas to designate Competitive Renewable Energy Zones as locations in which renewable energy would be developed. The Commission was also required to approve transmission improvements that would connect these selected zones with load centers. The Public Utility Commission selected five Competitive Renewable Energy Zones for wind power development in 2008 and defined the transmission improvement plan required to bring the generated power to consumers. The primary objective was to reduce costs over the long run by avoiding the need for multiple lower voltage lines to the same region over time, as compared to capturing economies of scale by building a line of sufficient capacity to serve future needs in addition to current needs [87].

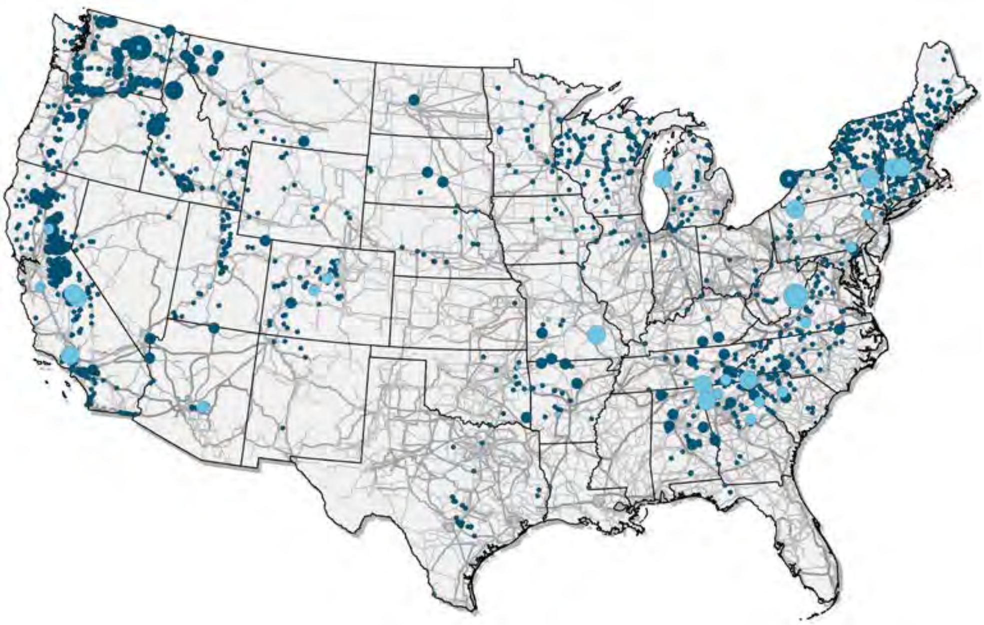
29. Production cost modeling involves a simulation of the power system operation, usually for one year or more, and provides a large number of outputs and metrics. These can be used to help assess the cost or benefit of any change to the system, and to evaluate congestion, the operational impact of deferred generation, and many other potential changes to the power system.



**Load (TWh)** < 1 | 1 – 3 | 3 – 5 | 5 – 10 | > 10

Source: National Renewable Energy Laboratory. Data extracted from ABB Energy Velocity Suite [88]

**Figure 2-21.** Distribution of electricity demand by county in the United States



**Existing Hydropower Capacity**
Pumped Storage: < 50 MW | 50–200 MW | 200–500 MW | > 500 MW
Hydraulic Turbine: < 50 MW | 50–200 MW | 200–500 MW | > 500 MW

Source: National Renewable Energy Laboratory. Data extracted from ABB Energy Velocity Suite [88]

**Figure 2-22.** Location of existing hydropower capacity in the United States, along with the transmission network

Figure 2-21 illustrates how electricity demand is distributed around the country. The density of demand is generally a function of population, and the map illustrates population centers along the East Coast, parts of the South and Midwest, and along the West Coast as having the highest demand.

Existing hydropower facilities are partially reflective of demand patterns, but are more closely aligned with the availability of potential hydropower resource (Figure 2-22). As shown, hydropower generation is greater in California and the Pacific Northwest, in and near the Tennessee Valley, and in parts of the upper Midwest and Northeast. The map distinguishes PSH from other hydropower, and shows the relative size of the units. Because PSH is dependent upon elevation differences between upper and lower reservoirs, such facilities are more common in (but not entirely confined to) mountainous regions. Figure 2-22 also overlays the transmission network with hydropower locations.

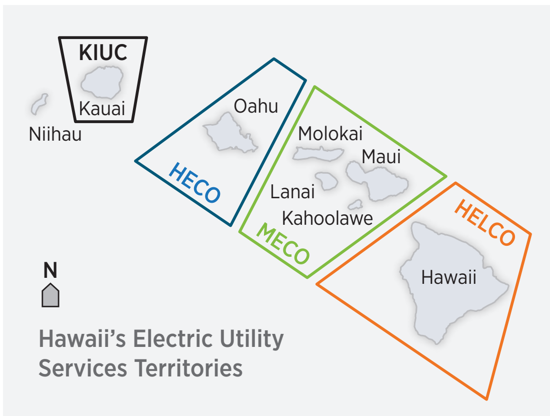
## 2.2.6 Transmission Interactions with Canada

Canadian hydropower development and the country's transmission system are integrated with the U.S. power system. Hydro Quebec has interties[30] and energy transactions with New York and New England, while Manitoba Hydro is part of the MISO market area (Figure 2-14) and is integrated into bulk-power system market operations in that part of the country. The amount of transmission capacity interconnecting the two countries varies as a function of geography. BC Hydro and PowerEx have extensive hydropower and interconnection into the northwestern United States, although the operational coordination is somewhat less than in MISO because there is no organized wholesale power market in that region of the United States.

Canadian hydropower resources have similar characteristics to U.S. hydropower. The multiple uses of water in Canada, however, do not appear to constrain electric operations to the same extent as in the United States. In the Canadian system, power generation is the priority at many Canadian multi-purpose water resource (or dam) projects. The Canadian system also has more hydropower storage, which increases the ability of these resources to manage inter-annual or other shorter term weather fluctuations that influence the hydrology—and, therefore, the energy available from the dams. This greater availability of energy, coupled with better ability to manage this energy, makes Canadian hydropower resources more flexible than those in the United States. This suggests the potential to help manage the variability and uncertainty that is part of power systems operation [89], particularly in the United States. These factors are likely to increase as new variable energy sources, such as wind and solar power, are added to the resource mix, and hydropower can play a role in integrating these sources. In regions of the United States and Canada that are already integrated via bulk-power system markets, much of this coordination is implicitly in place. In regions that lack organized markets spanning parts of the United States and Canada, this coordination is less developed, limiting the ability of Canadian hydropower to help balance VG.

## 2.2.7 Transmission in Hawaii and Alaska

Each of Hawaii's six islands with utility services has its own electrical grid and must supply its own power (Figure 2-23). Kauai Island Utility Cooperative services Kauai; Hawaiian Electric Company services Oahu; Maui Electric Company services Maui, Molokai, and Lanai; and Hawaii Electric Light Company services Hawaii island. Hawaiian Electric Company, Maui Electric Company, and Hawaii Electric Light are known collectively as the Hawaiian Electric Companies, and




Source: Hawaii Department of Business, Economic Development, and Tourism [91]

**Figure 2-23.** Division of Hawaii's electric utilities

30. An intertie refers to a transmission link that joins two (or more) neighboring electrical areas of the grid. This connection allows for varying level of operational coordination between neighboring entities, which can often reduce cost, increase reliability, or both.

provide power to about 95% of the state's population. Hawaii's electric utilities generate and distribute electricity from their own power plants and purchase energy for redistribution from numerous independent power producers (IPPs) statewide [90], including hydropower producers.

In Alaska, approximately 80% of the population resides in the geographic area known as the Railbelt. This region stretches from Fairbanks through Anchorage and to Homer at the tip of the Kenai Peninsula. The Railbelt is electrically connected via utility and state transmission assets that provide a means of conveying electricity from the state-owned Bradley Lake Hydroelectric project near Homer, Alaska, to the six regulated public Railbelt utilities.

Generation sources for the Railbelt include hydropower from Bradley Lake, Eklutna Lake, Cooper Lake, and South Fork. These hydropower sources are supplemented by thermal generation using coal at Healy, coal and diesel at Fairbanks, and natural gas-fired combustion turbines in Nikiski, Soldotna, Anchorage, and Eklutna. Wind farms add energy from Fire Island near Anchorage and Eva Creek near Healy. Integrated Resource Plan modeling of the Railbelt electrical system has been conducted, with the assumption of load growth of approximately 1% per year. This projected load growth could be affected by resource development projects, including mining and a pipeline to transport natural gas from the North Slope to tidewater for export.

Southeast Alaska relies on hydropower for nearly 90% of its electric generation. The communities of Ketchikan, Wrangell, and Petersburg are connected electrically through a transmission system owned by the Southeast Alaska Power Agency, with hydropower resources meeting a large portion of electrical needs. Projects have been undertaken on this system to add water storage capacity to the existing hydropower generation.

A predominantly hydropower-based interconnected electric system with diesel backup serves the eight communities on Prince of Wales Island, in southeastern Alaska. The capital city of Juneau and the city of Sitka are separate hydropower-based communities that have added capacity to their systems. Juneau accomplished this through construction of new generation at Lake Dorothy, while Sitka raised the height of the existing dam at Blue Lake.

The Upper Lynn Canal sub-region receives its electric power via a single contingency transmission system that connects the utilities serving Haines and Skagway. The source of electric power for this area is primarily hydropower generation, with diesel augmentation that carries a greater part of the load when run-of-river hydropower is not possible. The governments of Alaska state and Yukon Territory evaluated an electric connection with the islanded electric system serving Whitehorse and smaller communities in the Yukon Territory. The study concluded this connection could provide cross-border benefits if business development, such as shore-side power for cruise ships, is negotiated. An interconnected system would provide the means for additional renewable hydroelectric resources to deliver energy to customers.

The balance of the state, rural Alaska, consists of a patchwork of mostly isolated communities with limited infrastructure. The communities use primarily diesel generation for their power supply. In fiscal year 2015, the 184 largest communities in rural Alaska had a combined population of 83,400 residents [92]. For the most part, village centralized power systems are isolated grids that are not interconnected due to the low loads, topography, and long distances that separate them. Through the Alaska Energy Authority, the state provides economic assistance via the Power Cost Equalization program to communities and residents in rural Alaska burdened with high power costs. Other Authority programs include rural power systems, bulk fuel upgrades, and village energy efficiency. Alaska Energy Authority also provides technical assistance with operations issues (reliability and efficiency) of the power plants for these remote villages; training for bulk fuel and power plant operators; and more advanced training for hydropower facility operators.

In some cases, hybrid micro-grids containing hydropower generation and at least one alternative energy resource are proposed or in place where Alaska Energy Authority assists with the integration of local renewable energy resources. Hydropower is used where available, such as in Kodiak, where the electric utility is supplied by 80% hydropower and 19% wind. The Copper Valley Electric Association's mix of hydropower and diesel in Valdez is connected via transmission to the utilities' diesel generation in Glennallen. Gustavus, Chignik Lake, Larson Bay, and Atka all have small run-of-river hydropower that provides most electricity, augmented by standby diesel.

## 2.2.8 Power System Planning

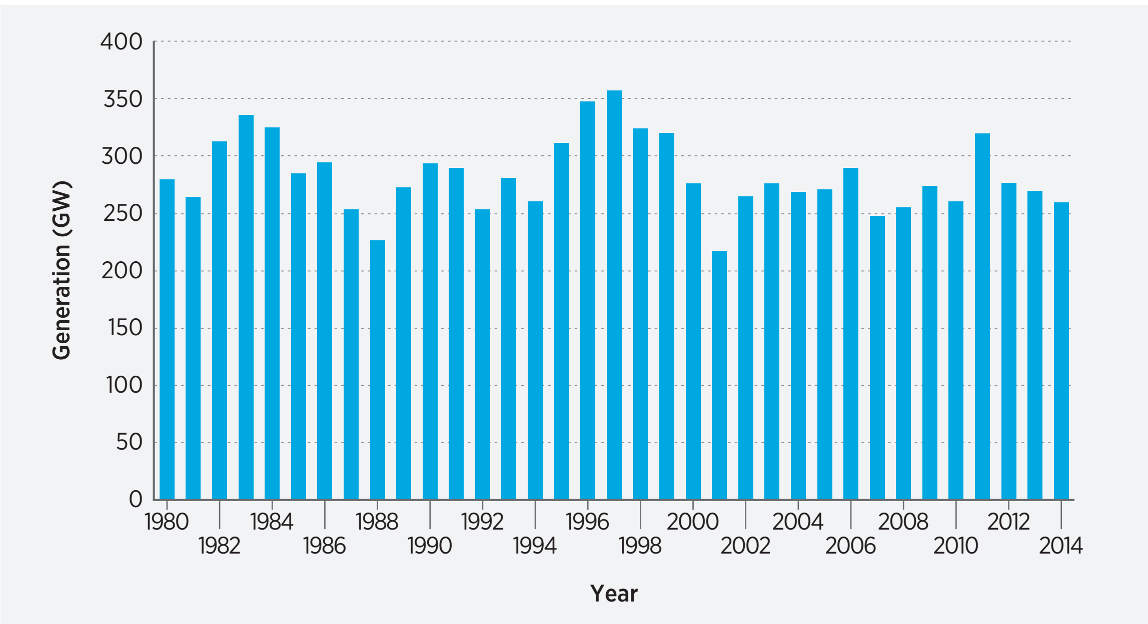
Power system planning involves predicting the future state of electricity demand and using this information to design and invest in sufficient, cost-effective generation, transmission, and distribution so that the power system can operate reliably. Although there is no uniform approach across the United States, the general planning process typically involves analysis of potential future resources needed to satisfy future demand (resource planning) and new transmission that may be needed to deliver energy to load centers (transmission planning). Because of the interplay between resource planning and transmission planning, they necessarily overlap.

The characteristics of the generation portfolio must match electricity demand, and hydropower may in some cases be a good match. In other cases, hydropower may not be the best choice to supply new generation or may be infeasible for development. These issues are discussed further in Section 2.4.

When evaluating suitability of new generation resources, questions that are considered include:

- Will the resource help meet the anticipated future demand?
- What is the relative economic value of the capacity and energy that this resource can provide relative to alternatives?
- What characteristics in terms of flexibility are needed for the power system to be balanced and reliable, and which of these characteristics can the candidate resource provide?
- What is the timing of the energy delivery from the resource?
- What is the likely inter-annual and long-term variability around the energy and services that the resource can provide?
- What is the net environmental impact of the resource relative to other alternatives?
- What are the risks associated with all of these factors (and perhaps others)?

These questions represent the types of issues that must be considered for any new power resource. Hydropower facilities can generally provide flexibility in power systems operation. Runoff can vary significantly from year to year, however, and the potential variations and timing of both energy delivery and grid services must be considered. The value of the energy and grid services that hydropower can provide can be




Source: data from EIA 2013 [93]

**Figure 2-24.** Annual generation by hydropower in the United States from 1980–2014 evaluated by using electricity production simulation tools to compare the operational and economic value of hydropower against other options.

Historical data of operations exist for most hydropower locations and can help support planning studies. Figure 2-24 presents total generation from hydropower in the United States between 1980 and 2013. Variances across years can include the influence of weather and precipitation, and can be greater when examining individual balancing authority areas or river systems.

## 2.2.9 Emerging Issues Related to Transmission

Opportunities for hydropower could not only enable a higher level of participation of the technology in electric systems, but may also potentially increase plant operating revenues earned from selling energy and ancillary grid services. This section discusses changes in the electrical bulk-power system and ways in which hydropower may be able to support those changes.

**Evolution of the Power System.** As of 2015, there has been a transformation in how the grid and power system are operated, influenced in large part by the integration of variable renewable generation, e.g., wind and solar energy. In the future, electric vehicles, distributed generation, smart grid functions, and other changes could further affect grid operations. These shifts may challenge hydropower facilities to operate in ways that were not considered when the facilities were designed. To support new functions, hydropower facilities may not physically change, but their operations might. A vision of future hydropower resources needs to be robust with respect to the myriad of possible future changes to the electricity system.

Renewable resources such as wind and solar are low marginal cost energy resources because they have no fuel cost (as compared to resources like natural gas or coal generation), and are frequently incorporated into utility systems via "take or pay" contracts. Because VG is often not dispatchable in the traditional sense because the associated fuel—wind or sunlight—is not always available,[31] it essentially appears as negative load in the system. During times of low wind and/or solar energy generation, the remaining generators make up the difference, providing the remaining generation required to meet demand. This residual demand is called net load, or net demand. This means that dispatchable generators are tasked with balancing the *net load* of the system; that is, the load minus VG. As the penetration of VG energy increases, the character of the net demand changes—sometimes dramatically—compared to the demand alone.

Both wind and solar can, however, be dispatched down. In addition, the power electronics embedded in the wind turbine or solar inverters can respond to automatic generation control signals. These capabilities make it possible for VG to be included in market operations and are now in use by MISO, New York ISO, and others.

Past studies and operating experience have shown that introducing variable renewable generation such as wind and solar power into a balancing area will increase the regulation requirements and need for reserves due to the inherent variability and uncertainty associated with such resources (e.g., GE Energy 2010 [94], Acker 2011a [95], Ela et al. 2011 [96], Exeter et.al. 2012 [97], Palchak and Denholm 2014 [98]). Reserves are provided by the more agile generation (or load) resources on the electrical system, and these resources serve to make the system more "flexible" and capable of adapting to both expected and unexpected changes. When there is significant VG in a given system, hydropower can provide significant value if it can contribute towards meeting the net demand (demand minus VG). The net demand has more variability and uncertainty than demand itself. If this net demand can be met without curtailing VG, this is generally the most cost-effective way to integrate VG.

Studies have also determined that systems with greater flexibility can more easily incorporate higher levels of VG penetration. In fact, flexible use of hydropower can reduce system operating costs in the presence of high VG penetration while accommodating primary hydropower constraints (e.g., competing uses) [99, 100]. Wind and solar penetration—perhaps ranging up to 10%–20% of demand—can sometimes be accommodated with little or no changes to system operational practices, but operational coordination between balancing authority areas—especially small

31. The use of power electronics in power inverters, coupled with power markets or operational practice that can incorporate this capability, can allow for VG to provide limited dispatchability in some conditions.

ones—can improve integration effectiveness.[32] As wind and/or solar energy penetration levels exceed 20% of annual energy demand, it is possible that changes to the standard practice of system balancing will be required (e.g., increased frequency of scheduling, balancing area coordination).

**Potential Opportunities to Enhance the Value/Use of Hydropower.** Hydropower contributions to system flexibility are typically represented in a simplified fashion in VG integration studies, because the complex interactions between hydropower generators in the same river basin do not always fit within the modeling framework. While hydropower is an inherently flexible generation resource, the estimation of available flexibility under radically different operational conditions is an arduous task and is often beyond the scope of such studies. More details about VG integration in systems with hydropower can be found in several resources (e.g., Acker 2011a [95], Acker 2011b [101], GE Energy 2010 [94], Acker and Pete 2012 [99]). These studies show that utilizing the ability of controllable hydropower generation (including PSH and dispatchable), the timing of hydropower generation can help maintain system balance while reducing operational cost. This operational cost reduction is compared to operational cost that would be incurred if the hydropower generation were totally inflexible compared to a scenario with no VG.

It is also possible that, at least in some cases, the level of flexibility that hydropower can provide—even considering the many non-power constraints—may not be accurately captured in some modeling frameworks. A 2014 study by Ibanez et al. [102] found that detailed modeling of the Columbia River Basin for a selected week identified additional flexibility available from hydropower, as compared to what is found by more traditional electric power production simulations. While this study included only a week of simulation on a single river basin, the findings indicate that additional work applied more broadly to hydropower will likely be able to further identify and capture a more accurate representation in a hydropower system. Results from this limited study cannot be reasonably extrapolated to other cases, but they do indicate that there may be more flexibility available than is generally captured in traditional modeling approaches. It seems reasonable to conclude that the potential exists to better understand the flexibility of hydropower and how it can support VG integration.

In some regions, it may be possible to increase the flexibility in hydropower operations by modifying operational procedures and/or wholesale energy market designs. This potential improvement is constrained by physical operational limits and by the competing priorities on river flow. For example, 2013 research by the Electric Power Research Institute (EPRI) found that hydropower facilities in both structured market and non-market areas[33] have opportunities to improve plant efficiency [103]. Wholesale energy markets are discussed further in Section 2.1.2 and Section 2.3.1.

The EPRI study also demonstrated that upgrades to plant equipment for PSH can add value by increasing the operating range. This can be done through mechanical changes, without installing new hydropower units, and can increase PSH revenue by 61%. In addition, advancements to variable-speed or adjustable-speed drives have enabled PSH facilities to be more flexible and offer grid services while pumping, which allows for increased revenue from ancillary grid services. This also allows for provision of frequency regulation, reduced cycling of thermal fleet, and an increase in the amount of time the unit can be operated at its maximum output under a wider range of head conditions. These additional changes, which facilitate lower minimum load and higher efficiency, can increase revenue by up to 85% at a fraction of the cost of new PSH development [103].

## 2.2.10 Trends and Opportunities

Trends and opportunities for hydropower related to hydropower's Role in the Grid include:

- Development of future hydropower resources will occur in the context of a myriad of possible changes to the electricity system.

32. Increasing the coordination between balancing areas improves system economics (regardless of VG penetration) by enabling access to more diverse generation assets and load behavior, and reducing the need for reserves. Simultaneous incorporation of greater amounts of VG and increased coordination of balancing areas enables offset of additional flexibility required for VG by the flexibility gains acquired. California has adopted a 50% renewable generation requirement by 2030, and is part of the expanding Energy Imbalance Market in the west that is a good example of operational coordination across wider geographic and electrical areas.

33. "Non-market areas" refers to the parts of the United States that do not have large coordinated markets. These non-market areas are outside of RTOs and ISOs (see *http://www.isorto.org/about/default*).

- Quantifying the flexibility in hydropower is a prerequisite for determining the value of hydropower-provided flexibility. This will become increasingly important as the development of VG continues for the foreseeable future. This is a dynamic process and will change as hydropower and VG capabilities evolve, and weather and climate vary.
- Improvement in the deployment of hydropower flexibility to reduce system operating costs in the presence of high VG penetration, while accommodating competing uses.
- Integration of physical infrastructure, governing organizations, and regulations to maximize utility and benefits of hydropower while meeting priorities and complying with regulations.
- Utilization of electricity production simulation tools to determine the value of the energy and grid services that hydropower can provide can be pursued by comparing the operational and economic value of hydropower against other options.

## 2.3 Markets and Project Economics

Hydropower facility owners realize value from two primary sources: power markets and environmental markets (e.g., RPSs). While the structure and operation of power markets vary across the nation, common roles for hydropower are electricity generation and flexibility to provide various grid services. Environmental markets such as those created by RPSs can provide additional value to hydropower owners, but are based on market- and region-specific considerations of hydropower as a sustainable, renewable, or "green" power resource. Federal and state incentive programs also play a role in project economics by valuing existing and new hydropower assets, with the availability of these incentives based on asset ownership and resource characteristics.

### Highlights:

- Increasing penetrations of variable renewable generation are changing the way the grid is operated and the way hydropower and other generation is compensated.
- Facility ownership plays a key role in determining access to revenue streams and the investment perspective underlying how hydropower is valued.
- Treatment of hydropower as a renewable resource is not consistent from state to state, which complicates hydropower marketing.
- Canadian hydropower is playing an increasing role in U.S. electricity markets.

Ultimately, the combination of power markets, environmental markets, and project economics create the revenue streams upon which hydropower facilities are developed and operated. This section explains hydropower's role in power and environmental markets and discusses project economics.

### 2.3.1 Power Markets

Supplying electricity, balancing the power system, and responding to system emergencies are the primary roles of hydropower—and, coupled with providing peaking capacity to ensure the grid has adequate capabilities to meet peak electricity demand, are the technology's primary sources of value. The manner in which non-federal plants operate and are compensated within the power system is highly dependent on the structure of the market and regional factors influencing and constraining the supply of electricity. With respect to federal hydropower projects, operations are highly dependent on both existing power sales contracts and market dynamics although operations can be influenced by other authorized purposes such as flood control. Within the continental United States, hydropower facilities can operate as part of formally structured competitive markets of ISOs and RTOs; be operated external to these market areas by an electric utility or independent power producer; or—in the case of the federal hydropower fleet—produce power in an explicitly multi-purpose context to be sold by PMAs. The isolated Alaskan and Hawaiian markets have unique economic and technical constraints on their power systems, which in turn create unique circumstances for electric generation sources.

### *Bilateral Markets/Non-Market Areas*

In vertically integrated[34] markets (that is, where generation, transmission, and distribution are all owned by the utility), utilities source power to meet customer demands through self-supply, bilateral contracts with other utilities, short- and long-term purchases from IPPs, or purchases from other individual market participants as necessary. Within this context, hydropower can be a cost-effective asset given the low cost of production [104] and the possibility for portfolio savings, such as those from decreased wear and tear facilitated by reduced need for stops and starts in thermal generators. These portfolio benefits[35] could ultimately be reflected in the internal valuation of hydropower as a rate reduction tool by utilities.

In the long-term resource planning context, hydropower's low variable O&M costs [104] can stabilize future prices for ratepayers. Renewable power is often considered a hedge against future fossil fuel price volatility. This value is documented in the structure of bilateral wind power purchase agreements (PPAs), and is present even in an era of low gas prices [105]. The additional flexibility of hydropower facilities builds upon this energy value by reducing the need for fossil fuel capacity to provide reserves and ancillary and essential reliability services to the grid. However, major climatic and weather variability—such as extreme drought conditions—can reduce the certainty of water availability for power production.

From an operations standpoint, the presence of flexible hydropower resources in mixed hydro-thermal systems can enable utilities to keep coal, gas, and nuclear facilities generating at stable operating points that are more efficient than they would be without hydropower included. This type of system efficiency can lower fuel costs and reduce wear and tear on thermal assets by eliminating excessive ramping. The strategic water management capabilities provided by hydropower storage furthers co-optimization of hydropower and thermal generation through the release of colder water for use in thermal cooling at plants further downstream, and the maintenance of adequate reservoir levels at thermal water intakes. These benefits from integrated operations are another example of the portfolio benefits potentially afforded by hydropower.

### *Markets Administered by Independent System Operators and Regional Transmission Organizations*

Outside traditional vertically integrated market structures in which utilities are able to directly use hydropower to optimize their power generation portfolio, the value of hydropower assets depends on the extent to which restructured ISO/RTO markets efficiently reward generators for the full value they provide to the power system. The range of capabilities provided by hydropower resources can allow projects to maximize value in competitive markets through generation during times of higher energy prices as well as participation in markets for more highly valued ancillary and essential reliability services. The ability of hydropower to extract maximum value from markets is often constrained, however, by regulation and market mechanisms, technical design limitations, and competing non-electricity water uses. Varying market structures, participation opportunities, and prices introduce a regional component into the extent and magnitude of compensation that hydropower assets receive for contributions to the power system.

**Value from Energy Production.** The market for energy has historically been a primary source of the value available in wholesale markets. The magnitude of this value for hydropower is dependent on the ability of a hydropower facility to generate during predictable system conditions as well as unpredictable ones, the latter of which can create higher prices. Shifting or withholding water releases for generation during higher value times of the day ("peaking") is contingent on a project's storage capability and the

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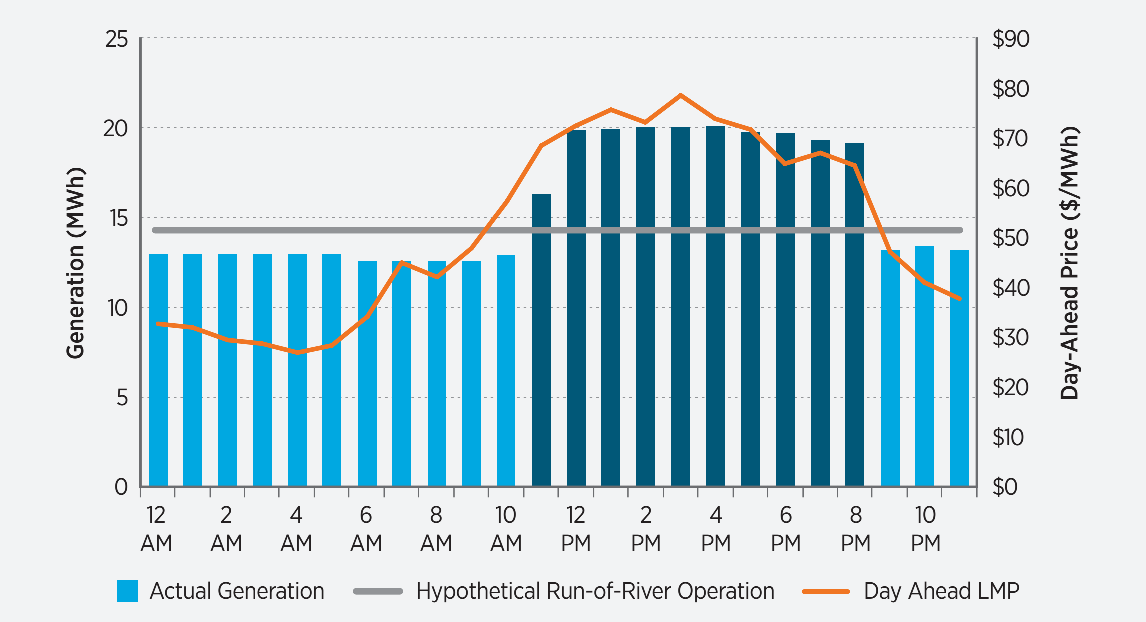
34. Electricity markets were subjected to a national wave of reforms in the late 1990s and early 2000s, focused on introducing more competitive mechanisms to the traditional vertically integrated, investor-owned utility model. By 2012, more than a third of U.S. generation was produced by IPPs, essentially the generation facet of a traditional IOU, uncoupled from the transmission business components. Many of the markets in which these IPPs operate collectively formed larger centralized markets (ISOs/RTOs) that oversee regional operations and help to manage the grid [106]. These ISO/RTO markets typically cover areas where generation and distribution services are procured on a competitive basis. Areas in which generation, transmission, and distribution services are provided by state-regulated entities are referred to as "vertically integrated" or "non-market" regions. The footprint of some formally organized markets, however, such as MISO and the Southwest Power Pool, include fully regulated, "non-market" states.

35. It is important to note that portfolio benefits are still realizable in competitive markets, but that these benefits accrue separately to generation, transmission, and load. In theory, these benefits can be factored into market resource planning processes, but are at risk of being ignored or undervalued if products for these benefits do not exist.




Notes: Shaded hours (11 AM – 8 PM) show the preference for generation during the highest value time periods; a facility with complete operational flexibility would shift all generation to these hours. LMP is "locational marginal price" (i.e., price at a specific location).

Source: FERC, 2014e [107]

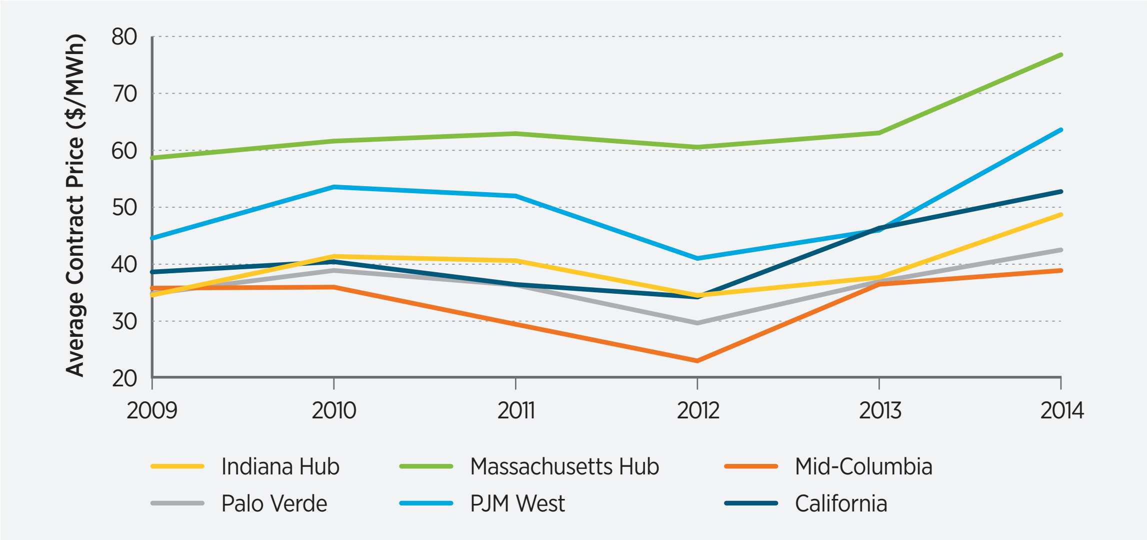
**Figure 2-25.** Example participation of a hydropower plant in ISO New England energy markets (example date: September 2, 2014)

regulatory requirements governing its operations. The operation of many hydropower plants also is subject to alternative water use demands, such as off-peak water releases for environmental or recreational purposes; municipal, industrial and agricultural water supply; ramp rate restrictions; or limitations in up-stream reservoir level fluctuations.

Whereas peaking plants have usable storage from the project's reservoir, run-of-river facilities have little to no ability to time-shift water releases. This rigidity can be the result of either technical constraints (e.g., no storage capacity) or regulatory mandates that water releases must closely match water inflows into a reservoir. Run-of-river facilities receive less compensation compared to projects with storage, since more of their generation occurs during less valuable time periods (i.e., such facilities cannot take advantage of any price changes in the market). As an illustration, Figure 2-25 captures the actual daily operation of a hydropower facility in ISO New England and a hypothetical run-of-river operational scenario where the plant's generation is flat throughout the day. This example facility's high minimum operation throughout the day indicates the facility is not a purely peaking project. Even with its limited operational flexibility, however, the facility earns at least 16% more by shifting generation to peak hours than would be possible under pure run-of-river operations.[36]

No matter the operational flexibility of hydropower resources, the value of energy production varies regionally based on market-specific structure and the resulting prices for energy, ancillary services, and capacity products. Figure 2-26 plots representative wholesale annual average energy prices for various

36. Separate from run-of-river operations, hydropower facilities added retroactively to federal water resource infrastructure (such as the powering of Corps or Reclamation non-powered dams and conduits) operate under a unique set of circumstances. In such cases, the ability to generate power is contingent on the infrastructure owner's decision to release water. When FERC regulation applies, these projects are generally licensed as "run-of-release." When developed under the Reclamation Lease of Power Privilege process, Reclamation's operating guidelines apply. Many of these projects have the capability to generate during periods of peak demand and prices, but this can only occur if the dam or canal owners are willing to schedule water releases during these times. Often, original dam purposes such as water supply or navigation require carefully timed releases, and operational flexibility is minimal. However, some dam purposes such as flood management may offer more flexibility in the timing of releases to improve value opportunities for facility owners.




Source: EIA, 2014 [112]

**Figure 2-26.** Example of six regional U.S. wholesale energy prices, annualized 2009-2014

regions throughout the country, which in 2014 ranged from approximately $40 to $80/MWh [108]. Local fuel mix and transmission constraints influence the value received by generators for producing energy, and price differentials within a single ISO can be equivalent to the differences in average prices between ISOs.[37]

U.S. markets are increasingly driven by natural gas prices, as combustion turbines or combined cycle gas turbines are often the marginal generation technology in several ISOs [109]. One exception to this is the Northwest Power Pool, a sub-region of the Western Electricity Coordinating Council, where the power system is 60% hydropower [110]. This hydropower can become the marginal generation technology during periods of high flow, resulting in the lower energy prices at the region's Mid-Columbia hub (Figure 2-26).

**Value of Grid Service Markets.** In addition to value derived directly from generating power, the fast response and storage capabilities of hydropower facilities allow for extraction of additional value through the provision of ancillary grid services, including designated essential reliability services (see Text Box 2-2a and Text Box 2-2b). The value an individual plant can generate in ancillary service markets can vary from facility to facility based on technical capabilities and market needs and arrangements. Most facilities in the United States possess the physical ramp rates and response times necessary to bid into spinning and non-spinning reserve markets,[38] although maximizing value from energy and ancillary services may not be possible due to regulatory operating constraints. Despite this, even run-of-river/run-of-release facilities are capable of providing frequency regulation services, although doing so may require appropriate stipulations in their FERC operating licenses.[39] Hydropower projects are also capable of supplying black start services.[40] During the 2003 blackout, large hydropower stations anchored some islanded areas that maintained power and served as the basis for restoring services to larger areas, including Ontario and New York [113].

37. As an example, New York ISO 2013 wholesale energy prices in the Long Island zone were approximately $75/MWh, compared to the $40/MWh seen in western New York [111]. Of note, hydropower plays a major role in western New York through the energy supplied by the New York Power Authority's Niagara Power Project.

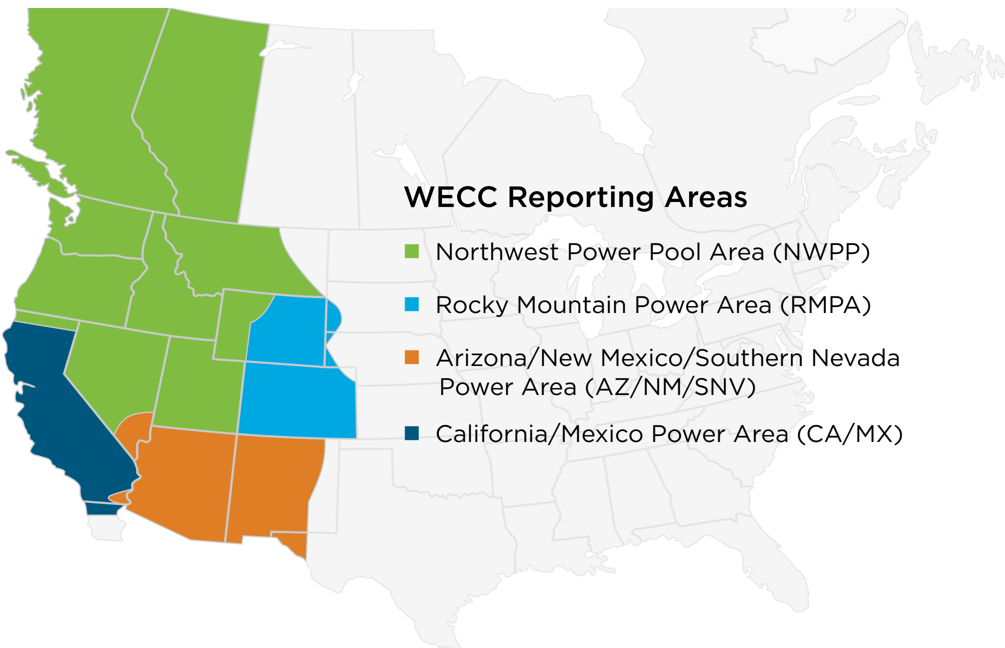
38. In an update to the EIA's Form 860, more than 80% of reporting hydropower capacity (inclusive of PSH) is listed as capable of ramping from cold shutdown to full power within 10 minutes. In an update to the Energy Information Administration's Form 860, more than 80% of reporting hydropower capacity (inclusive of PSH) is listed as capable of ramping from cold shutdown to full power within 10 minutes.

39. For example, some developments within the Missouri Madison project (FERC No. 2188) have run-of-river explicitly defined to only exclude peaking, loadfollowing, and the provision of non-spinning reserves.

While there is no systematic national scale data on hydropower's provision of ancillary grid services [116], the results of simulation studies have illustrated potential contributions on a regional basis. For example, value from simulated market operations identified in a 2013 EPRI study [80] suggested that, on average, hydropower in the Western Electricity Coordinating Council (Figure 2-27) would obtain only 4% of its revenues from ancillary services. This value, however, varied regionally, from a low of 2% in the hydropower-dominated Northwest Power Pool up to 20% of total revenue in the Rocky Mountain Power Area.

Regional-scale analyses can capture aggregate trends in hydropower ancillary service revenues and highlight key issues of market scale where ancillary services can comprise relatively small amounts of overall power system production costs. For example, FERC has required ISOs to structure frequency regulation markets such that better performing generators are compensated appropriately [118]. While such market changes are ongoing, initial results from the PJM Interconnection suggest that improved market designs better compensate high performers,[41] such as existing fast-responding hydropower generators, while shrinking the quantity of reserves necessary to ensure grid stability because of improved certainty in regulation performance [119].

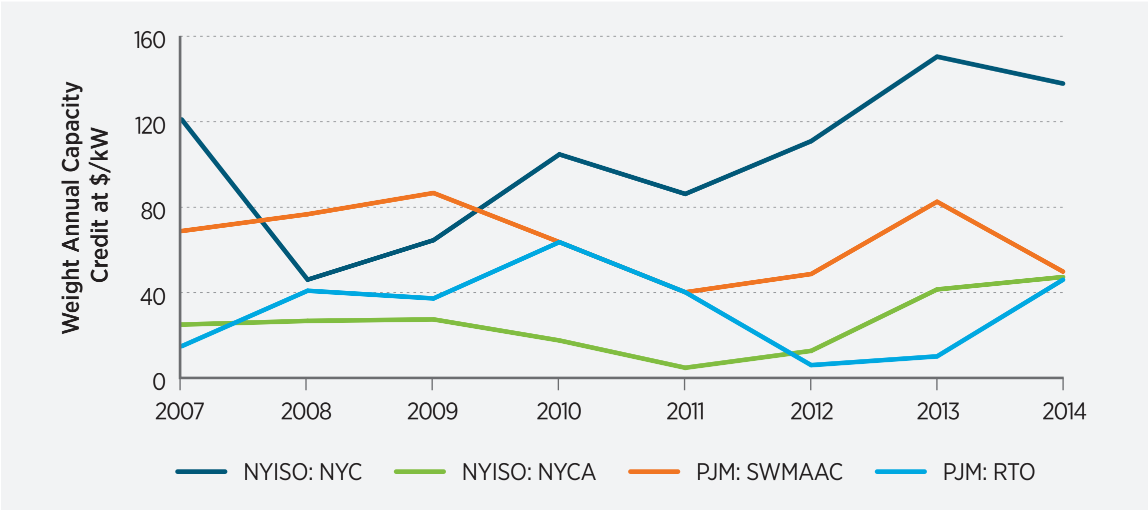
**Value of Capacity.** Capacity markets are intended to provide an additional source of revenue to ensure supply adequacy in markets. These markets can be particularly important for hydropower—which requires long-lived, capital-intensive investment in what amounts to core power system infrastructure. Capacity procured in forward markets must be available when called upon to meet periods of high demand; otherwise, generators or face underperformance penalties. Because of this, hydropower facilities with reliable storage and flexibility are able to commit larger portions of their generation capabilities, increasing the amount of value captured in these markets. Given its inherent nature as a storage technology, PSH in particular can rely on much of its capacity to be available; hydropower facilities with less operational flexibility may bid less capacity to




Source: FERC [117]

**Figure 2-27.** The four Western Electricity Coordinating Council reporting areas

41. That is, those generators that can respond quickly and effectively in a variety of situations, or flexible facilities that can come online and ramp up or down quickly.




Sources: NYISO 2014 [120]; PJM [119]

**Figure 2-28.** Capacity market clearing prices for four selected markets, annualized 2007–2014

avoid overcommitting. The revenue available from capacity markets supplements that from energy and ancillary service markets, with high capacity prices found in transmission-constrained markets, such as certain zones in New York ISO and PJM (Figure 2-28).

While compensation values can reach or exceed $100/kW per year, the value of capacity markets is volatile and uncertain on a year-to-year basis (Figure 2-28). The volatility illustrated in Figure 2-28—combined with the lead times necessary to plan, obtain approval for, and build hydropower facilities—can hinder the use of capacity market revenue to justify or source funding for capital expenditures. Long-term bilateral contracting with a utility could make the capital outlay for a facility more attractive, but also suffers from issues related to the long lead times because the timing of project completion may extend beyond utility planning horizons.

Experiences in 2014 with gas supply shortages during record cold events in Midwest [121] and northern markets [122] have motivated modifications to capacity markets for transmission authorities to more heavily penalize underperformance (i.e., not meeting capacity commitments) and ensure supply adequacy, such as the recent revision of PJM's capacity market mechanisms [123].

Within the U.S. competitive markets, the Southwest Power Pool, CAISO, and ERCOT do not maintain centralized forward markets for ensuring future resource adequacy. CAISO ensures resource adequacy through regulatory mandates from the California Public Utilities Commission to California's load-servicing entities. Utilities bilaterally procure capacity, and CAISO retains the authority to procure backstop capacity if needed. ERCOT does not have an equivalent forward capacity procurement construct and instead relies on high ($9,000/MWh) scarcity pricing caps to incent resource adequacy through energy market price signals [124]. In the absence of a capacity market, scarcity prices are much higher than day-to-day prices in day-ahead markets, so that generators are adequately rewarded during times of critically high demand. For context, the average weighted price at the ERCOT North 345KV Peak price hub was $41.56/MWh [125].

**Challenges and Constraints.** While ISO/RTO markets attempt to provide the structures and mechanisms by which energy generators are rewarded for contributions to the power system, the full accounting, optimization, and compensation for hydropower generation and ancillary services is difficult. In particular, the value (and accompanying opportunity cost) of bidding and deploying hydropower into a market has inter-temporal and non-market environmental and recreational considerations that complicate estimating the true "value" of the water used to generate power. Some attempts to remedy this concern exist; for example, PJM calculates hydropower lost opportunity costs on an inter-temporal basis when compensating the provision of frequency regulation. The complexities associated with explicitly co-optimizing hydropower generation, ancillary service provision, and environmental benefits, however, is an active field of research within hydropower operations [126, 127].

Co-optimization is acute for PSH and hydropower facilities with reservoir storage that requires long-term resource optimization to maximize the value and use of water in the power system. PSH facilities can be challenged in the day-ahead bidding process as separate bids must be placed for generation and pumping—resulting in financial penalties if pumping and generating bids are not cleared in such a way as to allow for the planned operations. This and other PSH-specific market issues are discussed in Section 2.7.

An additional challenge arises in the coordination among multiple owners on hydrologically interconnected (cascaded) river systems. This coordination becomes even more difficult in a market context. In non-market regions, coordination is possible through an apportionment of the benefits of coordination, such as that which occurs as part of the Mid-Columbia Hourly Coordinating Agreement.[42] In a hydropower-dominant and coordinated system, the addition of a market construct—such as potential regional energy imbalance or economic dispatch markets being investigated by the California ISO and the Northwest Power Pool—would need to be designed and managed to ensure that hydropower operations intended to optimize all water uses are not seen as anti-competitive, and that the flexibility from hydropower resources is not used by market participants without compensation.

**Unvalued and Undervalued Services.** In addition to hydropower assets not being optimally used or valued in organized wholesale markets, not all benefits provided by hydropower facilities are readily quantifiable or easily attributable to hydropower in a market framework. In some cases, market rules undervalue operational flexibility in general—e.g., with the exception of New York ISO, Southwest Power Pool, and CAISO, real-time markets are settled on an average hourly basis. Fast response resources such as hydropower and PSH, however, have the ability to follow 5-minute price deviations in real-time markets; settling on this real-time basis would more accurately value this capability by tying compensation to prices in the 5-minute interval instead of an hourly average. Markets are trending towards faster settlements. ISO New England anticipates moving to 5-minute settlements in 2016, and MISO is working to implement sub-hourly settlements. Additionally, FERC has recognized and is seeking to reform the mismatch between dispatch and settlement timeframes [128].

It's possible that no value or inadequate value may be placed on some services, such as those provided by hydropower generators with characteristics that allow for rapid and precise responses to instability in the grid. Large hydropower generating facilities with storage and fast ramping ability can react quickly to system disturbances. One example is the participation of some facilities in grid operator Special Protection Schemes and Remedial Actions Schemes. Under these Schemes, pivotal large generators can be dropped from the system to relieve emergent transmission congestion and reliability issues. This capability defers or obviates costly system upgrades, such as transmission expansion, but this value may not be captured by the participating facilities [129].

Hydropower is also one of the major sources of power system inertia and a key provider of primary frequency response, potentially supplying a majority of primary response in the Western Electricity Coordinating Council [130][43]—yet there is no direct market compensation mechanism for either function. In that sense, existing competitive market structures have evolved around some elements of stability in the power system that hydropower and other technologies provide, and have started to respond with market changes that reward stabilizing performance. Examples of this include "Pay for Performance" regulation services, and evolving capacity and black start market designs. Revisions to address primary frequency response may be possible in the future, as reflected by interest expressed by FERC [131].

42. The Mid-Columbia Hourly Coordinating Agreement is a management program for the dams of the Columbia River system that seeks to balance usage across the projects in an efficient manner. By managing this coordination on an hourly basis, the water is used more effectively across the regional portfolio than longer timeframes would allow, helping to smooth out the natural variability in river flow. The seven dams that comprise this system have been coordinating operations since 1973 [132].

42. "Non-market areas" refers to the parts of the United States that do not have large coordinated markets. These non-market areas are outside of RTOs and ISOs (see *http://www.isorto.org/about/default*).

**Emerging Market Issues.** Several national trends are changing the value proposition for hydropower in non-market areas and competitive markets alike; most notably, the increasing penetration of variable renewable energy sources into the power system. While IOUs and generators in non-market areas are generally better equipped to optimize system operations, their strategies for integrating variable renewables are still subject to regulatory scrutiny. Related experience of BPA is discussed in this chapter in context of integrating renewables with federal hydropower. Wholesale markets, in consultation with market participants, react to the new operating realities imposed by variable renewables by developing appropriate market products and structures to maintain cost-effective grid stability.

High levels of renewables can affect traditional wholesale market values, particularly energy prices, as well as create increasing needs for fast response and flexible resources [133]. Periods of renewable energy oversupply have forced localized prices into negative territory [134]. When this occurs, hydropower projects may be forced to spill water, which goes unused for generation to avoid negative prices (vs. generating power with that water)—or, in cases where flows must be directed through turbines to meet mandated environmental goals such as water temperature or dissolved gas concentration targets, hydropower generators are forced to operate at a loss.

With RPS goals of 33% of generation from renewables by 2020 and 50% by 2030, California is one of the first markets in the United States that is forced to respond to increased levels of variable generation resources with year-over-year increases in negative prices caused by high amounts of non-dispatchable solar and wind generation [135]. Quarterly reports from CAISO demonstrate a new paradigm in energy markets, in which negative prices occur during daytime hours when the sun is shining but mild weather keeps load levels low. This creates the need to ramp generation quickly as the sun sets and peak loads are reached in the evening [136].

In the Midwest, high (and increasing) levels of wind supply within MISO's footprint have led to a series of reforms to address the economic and reliability impacts. Transmission expansion and a move to a market-based economic wind curtailment mechanism (the Dispatchable Intermittent Resource protocol) have held levels of wind curtailment steady [137]. Additional storage and fast-response capability (such as that provided from hydropower) could reduce further the cost of integrating wind. To this end, Manitoba Hydro and the MISO have been exploring the potential for enhanced market integration to use Manitoba's cascaded hydropower system as a "battery" to absorb this excess wind power [89]. This created a new market mechanism in 2015 [138].[44]

With growing amounts of bulk energy provided by renewables, electricity markets—including existing ISO/RTO footprints and proposed new mechanisms such as Energy Imbalance Markets in the West—will continue to evolve and expand, both in terms of physical footprint and in the suite of market products created to deal with changing grid conditions. In light of these new realities, the economic and grid services value of hydropower and other generating assets will be increasingly tied to how flexible they are in responding to variability by ramping capacity up or down quickly.[45]

## Federal Hydropower

Federal hydropower is unique in terms of the purpose of the fleet and the requirements under which its power must be sold. Reclamation (14,112 MW; 18% of U.S. capacity), the Corps (20,959 MW, 26%), and TVA (3,619 MW; 5%) comprise a combined 49% of the U.S. hydropower fleet [2], and this ability to capture value is a core determinant of how this near-majority of U.S. hydropower invests and optimizes its power operations.

**Corps and Reclamation Funding Context.** By law, generation from the federal fleet is sold at cost by the respective Power Marketing Administration with first right of refusal of that power given to public power entities, including municipal utilities, public utility districts, and electric cooperatives. Electricity generated

44. Specifically, MISO added bilateral price-sensitive exports to its External Asynchronous Resource structure in March 2015.

45. Structural changes in California to procure flexible resources include flexible ramping constraints in CAISO's real-time market process (flexible resources are compensated for their additional opportunity costs), an additional flexible capacity resource adequacy requirement for load-serving entities [139], and the planned development of a formal market product to procure flexible ramping capabilities in real time [140].

by Corps- and Reclamation-owned hydropower facilities is sold by the PMAs, which market power in excess of project needs to outside customers.[46]

Different PMAs and regions within each PMA offer different products to customers. Most production is marketed through 10–20 year contracts signed with the preference customers.[47] At some PMAs, power in excess of those long-term contracts can be sold in bilateral arrangements with other interested third parties, or bid directly into ISO markets. For most PMAs, revenues from these sales are generally remanded to the U.S. Treasury to cover O&M and service the debt and interest from the construction of the hydropower facilities, and for an allocation of the multi-purpose costs. From the perspective of value capture, this creates an indirect flow of funding back to the generating assets. Reinvestment of the value that hydropower generates through the PMAs must come through the O&M and capital funding that the Corps and Reclamation receive as appropriated by Congress in any given year.

This funding context has led to a situation in which monetary flows to the asset owners and operators do not reflect the market value of their power system operations—or even cover the costs of modernization and general maintenance. For the Corps in particular, production from its facilities is sold by the PMAs for approximately $3 billion–$4 billion in annual revenues from at-cost sales, but, in 2010, for example, only $230 million total was appropriated and allocated to O&M and capital expenditures.[48] Of this, only $30 million could be used for major equipment replacement and upgrades. The aggregate impact of this limited funding has led to a steady decline in the performance and availability of the Corps fleet across all divisions [141].

However, PMAs do have some additional funding mechanisms to supplement O&M and capital appropriations to the federal owners.[49] The Water Resources Development Act of 2000 allows direct customer funding agreements for all PMAs. While Corps and Reclamation facilities are not valued directly in a market context, these direct agreements do allow for some additional monetization of the value of federal power operations, at least as determined by the preference customers.

**Alternative Federal Fleet Funding Arrangements.** The value and funding issues faced by the Corps and Reclamation are not new, and it is generally believed that a status quo, flat, or declining Congressional appropriations environment will have deleterious effects on the performance of the federal fleet [143]. Solutions to these issues have been proposed by an array of interested parties, with proposals along a spectrum of market and political philosophies. Proposals include legislative actions that generally maintain market arrangements, such as increasing direct appropriations or altering statutes to allow all PMAs to directly fund O&M, rehabilitations, and modernizations; allowing for public-private partnerships similar in concept to federal Energy Savings Performance Contracts; and even privatizing the federal power generation infrastructure [142].

**TVA as a Federal Utility.** As a federal utility that owns and operates multi-purpose water resource projects in a manner analogous to the Corps and Reclamation, TVA operates under a different mandate and with more financial autonomy than the other federal owners. As a federal utility, TVA's generation and transmission operations are more analogous to a vertically integrated utility in a non-market area. Similar to vertically integrated utilities, TVA internalizes the value of its hydropower system operations, coordinating scheduling and generation to minimize the cost of supplying power from a fleet that includes coal, nuclear, and gas power assets. TVA has received no federal appropriations for its power functions since 1959 (appropriations for environmental stewardship and economic development activities stopped in 1999) and the utility generally operates autonomously. It finances itself fully from its power sales and by issuing bonds; however, TVA's borrowing authority is subject to a statutory limitation of $30 billion.

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46. Some of the multiple purposes of Corps and Reclamation facilities, such as operation of irrigation infrastructure and navigation locks, require electricity. Only the power remaining after accounting for these activities is marketed by the PMAs.

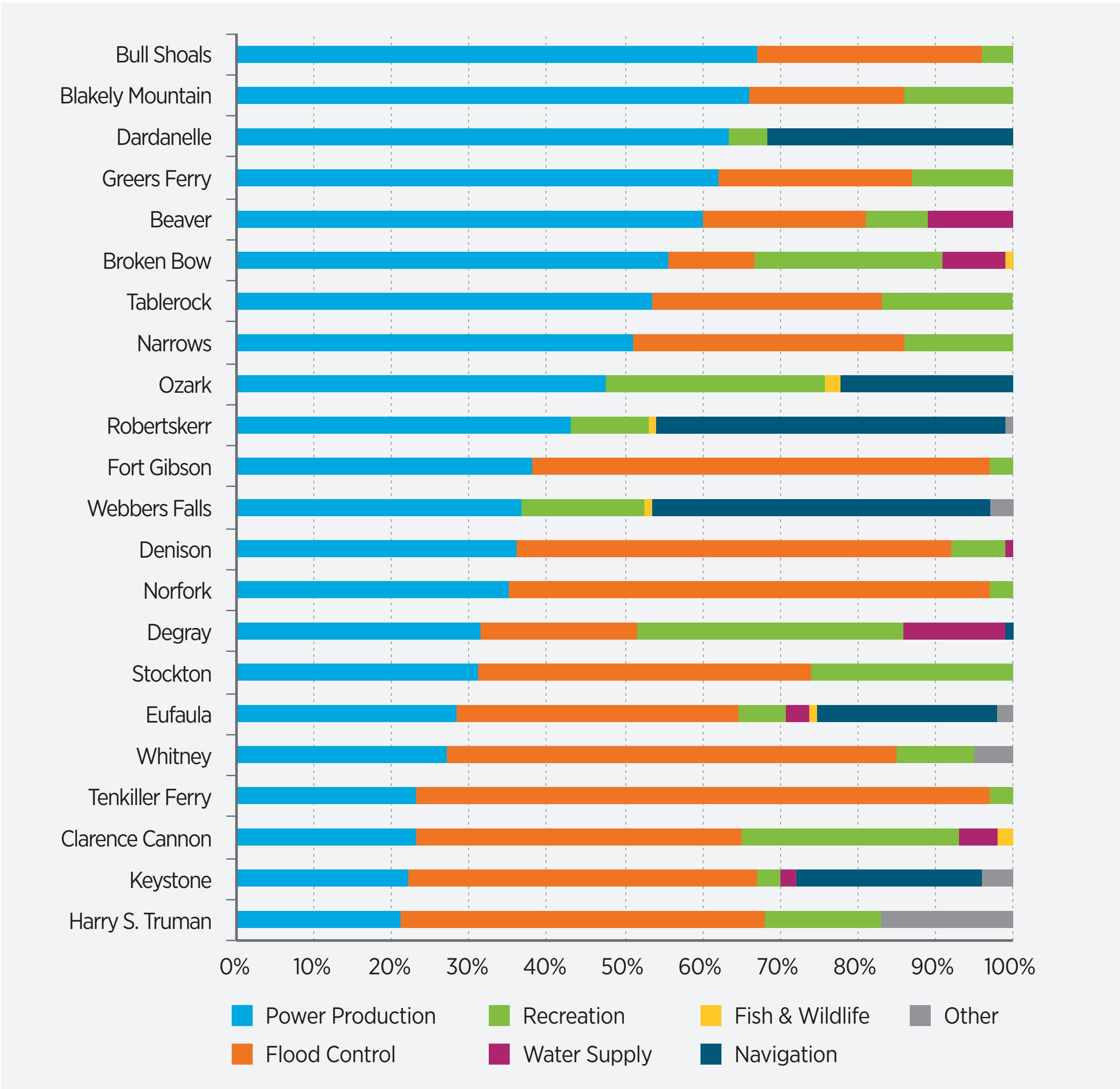
47. The degree of certainty regarding the volume and timing of generation under these contracts varies, including being marketed "as available" (Western Area Power Administration's Central Valley Project), in "slices" of annual generation (one BPA product), or on a purely firm basis (Southeastern Power Administration).

48. As such, hydropower is fourth in priority at the Corps— owner and operator of 26% of the U.S. hydropower fleet—with recreation and behind navigation, flood control, and ecosystem restoration) [141].

49. BPA retains its revenues and has the authority to fund capital improvements for the hydroelectric projects for which it markets power. BPA also has Direct Service Industry customers who have preference to federal generation at an established rate which is above their Tier 1 rate.

While TVA is better positioned than other PMAs to value and optimize the use of its hydropower assets, it has historically been subject to strategic reviews of its continued operation as a federal entity [144]. The 2014 review [145] found that TVA was operating successfully under a status quo arrangement, and recommended against divestiture of TVA assets by the federal government.

**Multi-Purpose Role of Federal Hydropower.** The multi-purpose nature of federal hydropower results in a complex set of operating considerations (Figure 2-29). These bounds affect both operational flexibility and the extent to which these facilities can maximize the power system value of their power production function. Even though non-federal projects also have to comply with licensing conditions to protect fish and wildlife or to coexist with other purposes, competition from other uses can be greater for federal facilities. Power production at federal facilities is often viewed as a "by-product" of other project functions. This dichotomy is due to the origin of federal hydropower capabilities as components of integrated water




Source: Southwestern Power Administration, 2009

**Figure 2-29.** Allocation of capital costs for multi-purpose Corps projects based on Congressionally authorized use within the Southwestern Power Administration resource infrastructure. For the Corps, the primary functions of dams have been inland navigation and flood control, while for Reclamation, dams have been used for irrigation and water supply.

Figure 2-29 illustrates this multi-purpose use by showing the portions of project capital costs assigned to the Corps facilities from which Southwestern Power Administration markets power. While in most cases the hydropower purpose was not assigned a majority of the original project cost allocation, it is often allocated the largest or second largest share of the cost.

The federal hydropower purpose has full repayment responsibility, through PMA rates, for 100% of the hydropower costs, including the original capital investment allocation and any reinvestment in the project, as well as for a hydropower assigned percentage of joint-use costs specific to each project. This includes interest on all of the investment costs. Additionally, the PMA rates that provide for repayment include annual O&M costs that recover 100% of the hydropower O&M costs and the hydropower assigned percentage of joint-use O&M costs specific to each project. Other purposes do not have repayment responsibility and in some instances, federal hydropower is footing the bill, directly and indirectly, for some of these other purposes. Therefore, the value or revenue fractions of the various purposes do not necessarily correlate with the cost fractions. For instance, in many Reclamation projects, power production is authorized to repay other purposes (e.g., irrigation) and has been essential to overall project repayment. This pattern is also clear in the Southwestern Power Administration's allocations, although the Corps receives appropriations for flood control and navigation. In the case of BPA-marketed power, 30% of preference customer rates are composed of charges associated with environmental mitigation and stewardship of fish and wildlife [142].

**Emerging Issues—Renewables on PMA Systems.** Increased penetration of variable generation in the western portion of the United States may pose challenges for PMAs. Maintaining system balance while accommodating large amounts of variable output requires keeping more reserves with various response times (regulating reserves, following reserves, imbalance reserves). Rather than rolling the additional cost of maintaining reserves into customer rates, PMAs translate the expenses into integration charges for third-party variable renewable generators connected to the PMA transmission systems.

In 2013, wind and solar generation represented 24% of total installed capacity in BPA service territory. The level of wind penetration in the BPA system forces grid operators to manage seasonal generation oversupply. During spring months with high river flows due to snowmelt, the environmental requirements governing operations along the Federal Columbia River Power System often require that hydropower managers address high dissolved gas concentrations produced by unforced spill by operating at maximum hydraulic capacity to pass as much water through turbines as possible. High hydropower generation, coupled with low loads and high wind during the spring months, forces Federal Columbia River Power System operators to take corrective actions, limiting flexibility in an otherwise flexible system. The actions and appropriate compensation in a market context (such as environmental redispatch or wind curtailment) were disputed among PMA customers, BPA, and VG owners. The disputes were settled through a 2014 FERC approval of BPA's proposed Oversupply Management Protocol, which allows BPA to recover costs incurred while managing oversupply issues [123].

Though levels are not comparable to BPA, the Western Area Power Administration is also experiencing an increase of renewable generation on its system. At the Western Area Power Administration's Colorado Missouri Balancing Authority, 9.8% of total generation came from intermittent renewables. To prepare for future required flexibility related to renewable energy generation, the Power Administration has integrated its Upper Great Plains Region into the Southwest Power Pool. This increases access to generating resources that can provide the additional reserves needed.

### *Unique U.S. Market Segments*

The value of hydropower is substantially different in the unique markets outside of the continental United States. Alaska and Hawaii are smaller markets in which access to electricity is limited and more costly relative to the continental United States.

In Alaska, the potential for new hydropower development is limited by the market, not the resource; the 4.7 GW potential from previously identified hydropower sites [65] is double the entire state's installed electric generating capacity as of 2014. Alaska is home to three distinct types of power markets, each with their own unique grid issues and relation to hydropower: the Southeastern region; the Railbelt; and isolated, rural communities.

In the non-remote communities of Alaska's southeastern region, hydropower is the dominant source of electricity, comprising 96% of generation in 2011 [147, 148]. While undeveloped hydropower resources are available, the region's non-isolated local power markets cannot accommodate additional hydropower. Because of this, exploration of hydropower development in the region has focused on the potential to export to British Columbia and the Pacific Northwest. Both of those markets are already served by hydropower projects with similar or lower levelized electricity costs. Developing new hydropower for export would require additional transmission and infrastructure investment, rendering most such projects economically infeasible [149].

The Railbelt is the grid-interconnected region stretching from the Kenai Peninsula to Anchorage, and north to Fairbanks. This region is home to roughly three-quarters of both Alaska's population and its electricity demand. Hydropower is a relatively small contributor (8%) to power supply in the Railbelt. The Railbelt is not an integrated, single energy market similar to traditional utility footprints in the continental United States. It is composed of six electric cooperatives and municipal utilities with relatively weak interconnections, often over single lines between service territories. This limited level of interconnection limits the integration of variable renewables, constrains optimal output from existing hydropower facilities, and prevents centrally coordinating the operation of generating units throughout the Railbelt interconnection [150].

The third Alaska power market comprises rural communities scattered across the state without formal grid access. These communities rely on diesel generators, and maintain low power consumption in order to avoid high prices ($0.30–$1.00/kWh in 2011) [148]. For isolated communities (and remote commercial operations, such as mining or fossil fuel extraction), even small, comparably expensive hydropower plants can be a cost-effective alternative to diesel-fired generators. Hydropower development also adds storage capacity for remote locations. This allows for the potential to couple hydropower with renewables to further offset dependence on diesel fuel, which is typically more costly and may need to be flown in via helicopter.

Hawaii has no single electricity market—each individual island is an independent, stranded market that relies largely on oil imports [151]. Hawaii has an aggressive plan to reduce both its oil dependence and greenhouse gas (GHG) emissions. The state's RPS law, passed in June 2015 (Act 97), requires each electric utility company that sells electricity for consumption in Hawaii to have 100% of net electricity sales come from renewable energy by 2045 [152]. Hawaiian Electric Companies customers who generate solar, wind, hydropower, or biomass energy on their own property, provided the system capacity is 100kW or less, may also be eligible for net energy metering to offset their own use.

### *International Issues*

The value of participation in U.S. electricity markets is not limited to U.S. generation resources; in particular, Canadian hydropower is playing an increasing role in formal U.S. markets along the Northern border. While Canadian utilities already participate in the Western Electricity Coordinating Council, and, by virtue of transmission interconnection, are key partners in NERC reliability standards, evolving market structures and needs within competitive markets may be changing the way in which Canadian hydropower is valued in U.S. markets. The case of increased cooperation in the Midwest between MISO and Manitoba Hydro was discussed previously in the context renewables integration, and additional considerations are at play throughout other U.S. and Canadian markets.

In the Northeast, New York ISO and ISO New England have strong interties to major hydropower producers in Ontario[50] (7 GW of hydropower) and Hydro Quebec (35 GW). Hydro Quebec borders both markets while Ontario is only interconnected into New York ISO. The New England states are considering stronger interties to Canadian hydropower producers in light of gas supply infrastructure concerns and the retirement of major nuclear generators. Expanded access to Canadian hydropower in the Northeast would require strengthening interties (either with new transmission capacity or upgrades) between the two countries. Policy discussions are ongoing with regards to whether large Canadian hydropower should be considered "renewable" for the purposes of state RPS standards.

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50. Ontario Power owns 7 GW of hydropower assets, and the power system in Ontario is managed by the Province's Independent Electricity System Operator.

In the Pacific Northwest, the interplay among value, hydropower operations, and power trade with Canada is treated differently. Of particular importance are the governing stipulations of the Columbia River Treaty. Signed in 1961 and implemented in 1964, the Treaty resulted in the cooperative development and operation of the Columbia River Basin to reduce flooding and increase hydropower generation. Under the Treaty, Canada receives half of the downstream power benefits—that is, additional generation in the United States—created by strategic water management at its upstream storage facilities. This provision for the return of power value is known as the "Canadian Entitlement," and its monetary value has been estimated at between $200 million and $350 million per year. The Entitlement is supplied by BPA's customers and the Mid-Columbia Public Utility Districts, split approximately 73% and 27%, respectively [153]. After September 15, 2024, either country has the option to terminate most of the Treaty provisions, including the Entitlement, by providing a 10-year advance written notice.

The Corps and BPA represent the United States in implementing the Treaty (collectively, the U.S. Entity); Canada is represented by BC Hydro. In 2013, the U.S. Entity filed recommendations to the U.S. State Department about the future of the Treaty [154]. Among these recommendations, they noted that the United States should pursue a rebalancing of the Treaty with respect to the Entitlement. At issue is whether the originally negotiated calculation of downstream power benefits is an accurate reflection of actual benefits to U.S. power customers. There are a number of reasons the existing calculation method is considered inaccurate, but they are all generally the result of power markets and U.S. hydropower operating realities looking much in different in the 21st century than they did—and were forecast to—when the Treaty was originally negotiated in the 1960s. In particular, the existing entitlement calculation is, by law, based on hypothetical optimal generation [155] and ignores changes in Columbia River operations necessitated by environmental regulations and increasing levels of variable generation interconnected into BPA's transmission system.

A related issue that may be addressed during a renegotiation of the Treaty is the transmission of Entitlement energy over lines running through the heavily-populated Puget Sound area. This has created transmission congestion events and threatened service reliability, and the U.S. Entity has recommended that the United States should seek a least-cost transmission strategy for any power returned to Canada after 2024, including reconsidering the flexibility of the return.

## 2.3.2 Environmental Markets

As a renewable source of electricity, some hydropower facilities have the opportunity to capture additional monetary value due to the low-carbon attributes of hydropower generation. The eligibility of hydropower to participate in environmental markets, however, varies across the country. Every segment of every market (e.g., state RPS, corporate sustainability initiatives, GHG emissions policies) has differing criteria under which hydropower is considered eligible. There are two types of environmental markets: renewables markets and emissions markets, both of which contain other market segments (Figure 2-30).

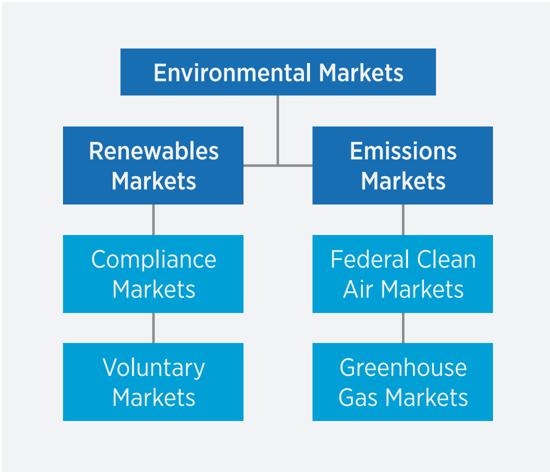



**Figure 2-30.** Hierarchical structure of environmental markets, including renewables markets and emissions markets

### *Renewables Markets*

Renewable energy markets are a potential major source of direct monetary value for hydropower projects. These markets capture and reward the renewable elements of electricity production in the form of RECs, which are produced in proportion to generated electricity. The monetization and value of these attributes (quantified in RECs) are defined on a market-by-market basis. The magnitude of value available to hydropower in a market is contingent on the stringency of a legal requirement (as in compliance markets), the value of sustainability to individual organizations (in the form of voluntary markets), and the eligibility of specific types of hydropower resources to participate.

Compliance markets related to renewable energy typically take the form of procurement requirements placed on utilities or load-serving entities by state-level government mandate. These requirements are reflected in RECs; i.e., entities are mandated to generate (or purchase) a required number of RECs. Twenty-nine U.S. states have compliance renewable energy markets, while another nine states and two territories have voluntary goals, which are not explicitly coupled to market structures [34]. The value of RECs in compliance markets varies based on renewable resource eligibility, resource availability, and the relative availability of RECs. In primary tiers,[51] it ranges from a low of approximately $1/MWh in Texas, to $15/MWh in states served by PJM, and increases to nearly $60/MWh in ISO New England states[52] [2]. Despite potentially attractive pricing (depending on market conditions), however, hydropower is not uniformly eligible for participation in renewable energy. Typical eligibility requirements placed on hydropower for participation in the most valuable, primary tiers of REC markets include [2]:

- Capacity limitations, with 30–50 MW being the range of common limits.
- Hydropower[53] resource and technology limitations that define or restrict eligibility based on whether the project in question is a new facility, incremental to an existing facility, the addition of power on an existing non-powered dam or conduit, or PSH. A typical restriction in the highest cost REC markets, such as in a state RPS, is that a facility be constructed on an existing dam or conduit, thus excluding development requiring new impoundment structures. Some states have unique RPS provisions with respect to PSH, which must often—but not uniformly—pump from energy generated by RPS-eligible resources in order to qualify for RECs.
- Age, online dates, or vintage, which typically restrict primary tier eligibility for projects constructed after the enactment of an RPS provision. This means the existing hydropower resource base is excluded. Explicit criteria that compare the operational, environmental, and public qualities of a hydropower project to standards that enable the project to be deemed eligible for participation. The most common such standard is the LIHI's certification program [68], used for RPS eligibility purposes in four compliance markets (Pennsylvania, Massachusetts, Oregon, and Delaware). LIHI does not include age or vintage restrictions, but its certifications do need to be renewed every 5–10 years.
- Asset ownership to define RPS eligibility (albeit less frequently). This includes restricting hydropower RECs to facilities owned by municipal or cooperative utilities (Pennsylvania), or legislating special provisions for energy from the federal fleet marketed by the PMAs (Oregon, North Carolina).

The immediate impact of this patchwork of eligibility is to render the RECs from hydropower projects substantially less liquid than those from other renewables, such as wind. This reduces their value overall, as it is more difficult to find off-takers at high value for RECs eligible in only limited markets.

There are varying motivations behind these eligibility restrictions. For example, many criteria with respect to age or vintage are intended to incent the development of new renewable resources or restrict the pool of RECs (by disqualifying existing hydropower) in order to raise the incentive value of RECs. Doing so, however, places existing low-carbon hydropower generation at an economic disadvantage relative to new sources of renewable generation—including, in some cases, new hydropower.

Many of the other eligibility requirements are attempts to limit the participation of hydropower to a subset of projects considered socially or environmentally acceptable by state RPS stakeholders. The potential efficacy of eligibility requirements in achieving these ends, however, varies. Where the use of LIHI certification (for example) as an eligibility

51. RPS resources are often separated into tiers based on their perceived "greenness" or a state's desire to incentivize development of a specific technology. A typical structure might include primary, secondary, and tertiary tiers of generating assets, with decreasing incentives at each step. If such a tier system exists, the primary tiers typically have the most stringent requirements [2].

52. PJM has partial and complete coverage of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and the District of Columbia. ISO New England comprises Maine, Vermont, New Hampshire, Massachusetts, Connecticut, and Rhode Island [156, 157].

53. A number of RPS policies explicitly allow for marine and hydrokinetic technologies such as wave, tidal, and in-stream turbines.

requirement is the *direct* incorporation of environmental and social criteria in determining the types of hydropower which should be allowable under RPS, other eligibility requirements such as size and resource/technology criteria are not necessarily tied to the actual impacts or performance of hydropower projects. The use of such *indirect* criteria creates inconsistencies in how—or doubts as to if—environmental and social aspects of hydropower development and operation are used to determine eligibility for REC markets. In addition to creating the liquidity and value issues discussed previously, the use of such indirect criteria also prevent the financial incentive of REC market eligibility from being a motivator to improve on social and environmental metrics. Where markets valuing these aspects of hydropower directly exist (as in select RPS provisions) they provide clear criteria, price signals, and funding sources that may incent environmental improvements. Where other indirect criteria are used, there can be no incentive for improvement. Ultimately, restrictions on facility size, and resource,[54] and the general restrictions on project age and vintage limit the opportunities to use renewable market price signals to incent a more sustainable breed of hydropower plants.

Another challenge is the ability to enter into long-term contracts with a credit-worthy entity due to the variability and uncertainty of REC markets—a problem that is exacerbated relative to other renewables by the long lead time for hydropower projects. As financing for new construction is often dependent on showing long-term expected revenue, long-term contracts are often vital to getting new projects developed. Some states overcome this challenge by having explicit compliance programs that allow for long-term contracts for new or existing facilities, such as the New York State Energy Authority's Main Tier Solicitation, or Rhode Island's Affordable Clean Energy Security Act. "Long-term" is defined by these programs, however, as 10–20 years, which is less than the typical full physical or economic life of hydropower assets. The oldest power plants in operation tend to be hydropower facilities and may continue operating beyond 100 years [158].

Though compliance markets create a legal obligation to purchase RECs, many organizations and individuals opt to purchase renewable (or "green") power directly through voluntary markets. Pricing in this market segment is lower than that in compliance markets; voluntary REC prices have traded at less than $1/MWh [159]. Eligibility criteria similar to those in compliance markets are applied to hydropower in voluntary markets as well.

Of the 24 national retail REC products known variously as tags, credits, certificates, or energy, only seven include hydropower. Hydropower is an eligible technology, however, for the well-known voluntary market REC verification organization, Green-e. Under the Green-e standard, U.S. hydropower is subject to an age/vintage requirement in which only new facilities (defined on a 15-year rolling window) are eligible. They must also meet either the explicit environmental criteria set out by LIHI, or a resource qualification restricting eligibility to powered conduits or canals. Repowered facilities are subject to the additional restriction of a 10-MW capacity cap [160].

Corporations may choose to directly procure renewable energy through the direct contracting or purchase of facilities—one recent example of this in the hydropower industry is Apple's partnership with Natel Energy to build a small hydropower project in Oregon [161]. More broadly, the U.S. Environmental Protection Agency (EPA) provides guidance on voluntary REC markets as guidance to potential corporate purchasers. Under this guidance, however, hydropower is only loosely defined as typically operated in run-of-river mode and having fewer environmental impacts than large-scale hydropower, while meeting river and ecosystem quality standards [162].

Most end-use electric customers can participate in voluntary markets through "green power purchase" agreements with their electric service provider, which allow customers to pay a premium for electricity generated from renewable sources. More than half of all electricity customers in the United States have direct access to green power pricing [159]. Under these programs, utilities acquire RECs and then make them available to customers through bundled PPAs with renewable projects, or through market or bilateral contracts for unbundled RECs. The role of hydropower in this environment depends on the specific REC products being sought. Hydropower comprised 4% of total green power sales in 2013 [159].

54. Even in the LIHI standards, greenfield development is not allowed, since dams and impoundments associated with a hydropower project must have been constructed prior to 1998.It remains at least conceptually possible, however, that development at new sites could in many ways be more sustainable than some existing projects eligible under existing RPS criteria.

Federal renewable energy procurement presents a unique situation. The federal government is, in aggregate, the largest single buyer in voluntary renewable energy markets. Federal agencies purchased 4.1 million MWh of renewable energy in 2013.[55] Hydropower—much of it from existing facilities—comprised 10% of this amount [159]. Existing hydropower, however, does not count towards the renewable electric energy consumption requirements the federal government must meet under the Energy Policy Act of 2005, as amended (42 U.S.C. § 15852, Pub. L. 109-58). Under this Act, for hydropower, only "new hydroelectric generation capacity achieved from increased efficiency or additions of new capacity at an existing hydroelectric project" counts towards the federal government's renewable electric energy consumption requirements (42 U.S.C. § 15852, Pub. L. 109-58).

#### *Emissions Markets*

In addition to direct value streams from compliance and voluntary renewable energy markets, the relative value of hydropower is also contingent on how regulations constraining environmental impacts from power plants change the value of fossil fuel generators as well as energy prices more broadly.

Some environmental regulations take explicit market form, such as the EPA's Cross-State Pollution Rule, which requires reductions in sulfur dioxide ($SO_2$) and nitrogen oxide (NOx) emissions in the eastern United States. Hydropower's lack of emissions relative to major $SO_2$ and NOx emitters (such as coal or oil-fired plants) make it a more attractive choice in terms of emissions; however, EPA analysis suggests its Cross-State Pollution Rule has minimal impact on overall electricity prices [163].

One potential source of a shift in the relative value of hydropower assets could come with attempts to regulate the emission of GHG from power generators. No current federal regulation or market exists, but California has established a state-level GHG market linked via a cap-and-trade mechanism to GHG reduction policy in Quebec and Ontario, and a regional market for Northeastern and Mid-Atlantic states (the Regional Greenhouse Gas Initiative) has existed since 2008.

While no federal GHG policy is in effect, EPA's Clean Power Plan highlights the unique issues for hydropower in potential future GHG markets and regulations. In particular, the Clean Power Plan illustrates the contrast between hydropower's capability to meet these goals and how it fares in terms of compliance [164].

For example, under the Clean Power Plan measures, GHG baselines are estimated from emissions in 2012—a year with abnormally high hydropower production in the Northwest due to favorable hydrologic conditions. Hydropower displacement of fossil fuel generation created a very low emission baseline from which the EPA determined interim and final reduction goals [165]. This treatment creates a more stringent target for the affected state, but also potentially higher value for hydropower plants from higher energy prices. Hydropower could also support Clean Power Plan compliance by lowering the cost of integrating variable generation.

While EPA considers new hydropower facilities as possible compliance options, state-level policy would ultimately determine the mechanisms by which targets are met. Under some approaches, the complexity that surrounds hydropower eligibility in state RPSs may come into play in situations where resources determined to be renewable are granted carbon dioxide ($CO_2$) offsets [166]. If hydropower is not counted as a comparable compliance resource when compared to other non-hydropower renewables, nuclear, or natural gas, existing hydropower assets and development of incremental and new resources could be at risk.

Under carbon constraints, hydropower's value relative to GHG-emitting resources can be enhanced, unless emissions targets fail to identify hydropower as a compliance tool. Assurance that hydropower is eligible as a low-carbon option can help ensure that hydropower resources are maintained and enhanced as part of a low-emission future.

### 2.3.3 Project Economics

The value the owner or developer of a hydropower project places on their facility, and its overall financial viability, is contingent on both investment philosophy and access to financing. The long-term value streams provided by hydropower are thus evaluated differently by different segments of the power industry. These varied investment perspectives combine with market value streams and a variety of federal and state incentives to drive the economics of hydropower projects.

55. This is in contrast to the top single private purchaser in these markets, Intel, with annual purchases of 3.1 MWh in 2013 [159]. In addition to renewable energy purchases, the Corps, Reclamation, and TVA also consume renewable hydropower generation on-site to support the operation of water resource infrastructure, such as pumping water for irrigation and controlling gates on navigation locks.

### *Project Ownership, Project Value, and the Cost of Capital*

Given its long life cycle, hydropower's full value is only captured across its physical life, which often exceeds 50 years. In the most basic terms, owners of hydropower assets with the lowest cost of capital (i.e., lowest discount or interest rate) are able to place higher value on long-term benefits. However, various players in the energy industry maintain their own development and investment philosophies across different timescales, requiring varying returns on investments:

- IPPs, which have accounted for much of new generation development [167] and the majority of renewables development [168], typically seek quick payback projects financed by non-recourse bank debt and high-cost equity. Prior to the recession, projects with longer PPAs were able to find commercial bank terms as long as 15 years, and deals with institutional lenders as long as 19 [169].
- IOUs take a longer term perspective and can internalize the benefits of hydropower to their power systems with lower rates of return than IPPs. This is because IOU projects are corporate-financed, using utility balance sheets with payback guaranteed through the customer rate base [169, 170].
- Public power entities ultimately employ even longer horizons and lower discount rates with which to value hydropower, and can fully finance projects using long-term revenue bonds [170]. Credit ratings for public power entities, including those that own and develop hydropower, are generally competitive. The hydropower-backed revenue bonds of the Mid-Columbia public utility districts and the municipal consortium Missouri River Energy Services, which is developing non-powered dams, have been rated as high, investment-grade (Aa3/AA- or above) [171].
- Conceptually, valuation of the federal fleet occurs at the lowest rates, with internal planning discount rates based on the yields of treasury bonds with long-term maturities (fixed at 3.375% for 2015) [172]. In the case of capital expenditures on the federal fleet funded by preference customers, however, such as the Corps Hydropower Modernization Initiative, federal hydropower has been effectively financed and valued at something more akin to public power rates. Similarly, when exercising its borrowing authority, BPA is rated as well as or better than large hydropower-backed public power entities [173].

The financial structure and valuation timeframe for each owner/developer paradigm is driven not only by investment philosophy (i.e., maximizing returns for IPPs, minimizing cost of service under fair rate of return for IOUs, minimizing cost of service for public power), but also by the available sources of financing for each. The solid investment grade ratings of public power bond issuances can be marketed to a variety of fixed-income institutional investors, such as banks or pension funds, with investment philosophies that align to the long-term value streams of hydropower projects. IOUs can access medium- to long-term financing through stock market equity and corporate bond issuances, while project financing for IPPs must obtain relatively high-cost investors willing to accept higher risks, such as private infusions of equity and non-recourse bank loans.

These disparate valuation and financing perspectives intersect with a core difficulty in hydropower project development—the fact that formal market value streams send price signals that do not align with either the development or operation timeframes for projects. Since 2005, the median hydropower project has taken more than 12 years from inception to commercial operation [2]. In that same timeframe, electricity and REC market prices have vacillated with natural gas prices and varying policies.

Many, but not all,[56] centralized markets procure capacity three years in advance, which often may not cover the construction timeframe of a typical hydropower facility. IOU and public power investors, with their ability to internalize hydropower's benefits and finance project development on balance sheet, are better able to justify pursuing hydropower projects. IPP developers, however, must undertake the lengthy and risky portions of the project development process while dependent on equity funding. Conventional debt sources of project finance are typically inaccessible until lenders have adequate certainty in developers having resolved regulatory (e.g., FERC license) and revenue (e.g., PPA, capacity market, REC contract) risks [174].

56. Some markets have extended this timeframe, such as ISO New England's move to a 7-year lock-in period. This change may improve hydropower financing options in the long term.

Developers of small projects face additional challenges based on the limited scale and relative small dollar value of their projects to potential investors. Large hydropower owners ensure investor interest through bond issues or loan prospects for which smaller projects do not have sufficient leverage. In cases where small projects *are* able secure the interest of large, conventional financing sources (such as commercial banks), their financing costs are usually higher on a relative basis (per MW) [175]. While all hydropower projects are subjected to rigorous due diligence, the cost of this process is spread across fewer MW for small projects relative to their larger counterparts. This suggests that innovative financing solutions are necessary in the small hydropower market.

One successful approach has been to pool smaller projects together for financing purposes [175]. A greater total investment opportunity will draw more interest and lower the relative transaction costs, while pooling assets in different geographic and hydrologic regions can also lower the risk profile of the project portfolio to investors by diversifying exposure to any single market or abnormal climate pattern. In the limited cases in which developers have had success getting small projects funded, many have done so through funding mechanisms uncommon in energy infrastructure investment. This includes long-term contracting of new hydropower generation by a municipality in exchange for preferential financing. An example of this is Bowersock Mills in Lawrence, Kansas [2].

### Federal Incentives and the Impact on Project Financing

Federal incentive policy has been a driver in hydropower and renewable energy economics, and has governed the manner in which many projects have been financed. While federal renewable energy tax credits have been attributed with helping drive the growth of wind and solar in the United States, the use and utility of incentives for hydropower development has been more varied. Still, nearly all developments of new hydropower facilities have leveraged federal and state incentives to finance development [2].

Similar to other renewables, hydropower has historically been eligible for the Renewable Electricity Production Tax Credit (PTC) and the Business Energy Investment Tax Credit (ITC). Hydropower has been eligible for only half the value of the PTC relative to other renewables, but it does receive full value of the ITC (30%). The use of the PTC and ITC in justifying a project often requires unique financial arrangements if the project developer does not have the tax burden ("tax appetite") to make use of the full credit. These arrangements, such as partnership flips, sale-leasebacks, and others, generally result in higher financing costs than if the credits could be used internally [176]. For a brief period after the American Recovery and Reinvestment Act of 2009 (ARRA), a shortage of tax equity prompted the extension of a "cash grant" provision to ITC-eligible projects, removing the need for third parties to make use of the credits.[57]

Each incentive measure values different aspects of hydropower's contribution to the grid. The PTC directly rewards hydropower generation, albeit at half value. The ITC (or cash grant) directly offsets investment; doing so in hydropower projects makes it less costly to build additional capacity that may ultimately be used in reserve or ancillary service roles (neither of which is necessarily incented by the PTC). Despite improving project economics, the PTC, ITC, and cash grant carried implicit eligibility criteria similar to many state RPS provisions; eligibility for the federal PTC and ITC is also restricted to upgrades at existing facilities and the powering of existing water resource infrastructure. Projects on undeveloped stream reaches are not eligible.

Incentives based on tax credits can help spur private development, but may be less effective for hydropower than other renewable energy industries on two fronts. First, the use of tax credits to improve project economics requires tax equity investors, who are generally focused on the short-term and more costly to secure. This locks out long-term, low-cost financing from institutional investors who lack sufficient tax

57. ARRA temporarily offered grants instead of tax credits due to a shortage of market appetite for equity following the economic downturn and the resulting immediate impact on tax equity investing institutions [177].

burden and offer traditional debt products [176, 178]. Both of these investment forms typically require a long-term contract, spanning several decades, for the private development. The contract's length acts to reassure the investor that they will be getting their desired return in a consistent, predictable manner. Second, the PTC and ITC are ineffective mechanisms for facilitating increased generation from the public fleet because these incentives are tax-based, and the federal fleet does not pay taxes [179]. This is important considering that 73% of all existing hydropower capacity is owned by public entities [2].

Some non-tax-based incentives exist, such as payments from Section 242 of the Energy Policy Act of 2005 (42 U.S.C. § 15881),[58] which established a production-based incentive for hydropower plants built on existing dams and conduits. However, the magnitude of incentives available under Section 242 is considerably lower than that from the PTC and ITC. Payments are capped at $750,000/year for an individual project, and annual funding has been inconsistent. Although the program was part of the Energy Policy Act of 2005, Congress only appropriated funds to the program in 2014, 2015, and 2016. Authorization for the program ends in fiscal year 2025. An additional program under Section 243 of the Energy Policy Act of 2005 provides for payments to incentivize efficiency increases at existing facilities, but this program has never been funded. Given the long lead times of hydropower development, incentives contingent on year-to-year funding such as the Section 242 payment or year-to-year eligibility extensions such as the PTC and ITC are not certain to be available by the time developers will be seeking to finance project construction, which introduces an element of risk.

Policy mechanisms in the form of bond subsidies offer support to non-federal public entities developing and expanding hydropower projects. These have included Clean Renewable Energy Bonds, ARRA-funded Build America Bonds, and Qualified Energy Conservation Bonds, among others. Eligibility for each mechanism and their precise nature varies, but these bond incentives generally allow public entities to finance hydropower and other qualifying projects at low rates using to federal payment of tax credits to investors, or cash payments to the issuing entity. Hydropower projects were eligible and received 24% of the 2009 Clean Renewable Energy Bond allocation of $2.2 billion [180], and Clean Renewable Energy Bonds and Build America Bonds have been used to finance some of the largest hydropower facilities under development. The most prominent example is the funding of American Municipal Power's 208 MW of Ohio River non-powered dam projects; the utility funded more than $1.7 billion of its $2 billion expenditures through the issuance of Build America Bonds and Clean Renewable Energy Bonds [182]. In general, Build America Bonds lowered the cost of municipal borrowing by an average of 54 basis points [183].

Bond incentives to public entities have also resulted in unique financing arrangements for small private developers. For example, the city of Lawrence, Kansas, issued a series of industrial revenue bonds to finance an expansion to the Bowersock Mills & Power Company hydropower project, in conjunction with a long-term PPA for project power through the municipal power company [184]. The entire $23.5 million was funded through different tax-advantaged bonds, with $8.7 million coming from the municipality's allotment of Qualified Energy Conservation Bonds [185]. This sale-leaseback measure [184] is similar in concept to the sale-leaseback arrangements made for tax equity investors to use the ITC. In this case, the city actually owns the project, but immediately leased it back to the developers. Municipal ownership facilitated availability of a more attractive financing package.

Federal loan guarantees may also play a role in securing low-cost financing for hydropower projects. In 2014, DOE announced that up to $4 billion would be available for its Section 1703 loan guarantee program. Eligible projects include the use of innovative technologies[59] at existing non-powered dams, and the addition of variable speed pump turbines into existing hydropower facilities [186]. Other federal loan programs have also been available for hydropower, such as the U.S. Department of Agriculture's Rural Energy for America Program.

58. Unlike the PTC and ITC, the Section 242 incentive is a direct payment for production and not a tax credit. Congress allocated funding for this incentive for the first time in 2014, with $3.6 million distributed among qualified applicants, based on their 2013 energy production [181].

59. For a technology to meet the DOE Loan Guarantee Program's threshold for being innovative, it must be in commercial operation and at fewer than three facilities in the United States.

### *Additional Incentives at the State Level*

Some states may offer additional incentives with relevance to hydropower. Some of these incentives are tax breaks and financing incentives similar to their federal counterparts, while others provide direct financial assistance. State-level incentives typically take the form of grants, tax credits, or low-interest loans. One example was Oregon's now-expired Business Energy Tax Credit, which was nonrefundable and could be applied against personal or corporate taxes [187]. While the Business Energy Tax Credit was primarily a tax credit, public power entities made use of it by passing the credit to a third party as a payment [187]. The Business Energy Tax Credit was partially responsible for a number of irrigation canal hydropower installations [188].

In addition to supplementing revenue or lowering financing costs, programs at the state level may seek to reduce costs by addressing regulatory barriers and financial risks that inhibit development, particularly for small projects. In 2010, the state of Colorado and FERC signed a memorandum of understanding to streamline the permitting process for small hydropower projects. Under the program, Colorado pre-screened qualifying, low-impact hydropower projects under 5 MW. For pre-screened projects, FERC waived the first and second stages of consultation otherwise required by 18 CFR sections 4.38(b) and (c) [189]. The state also worked as a permitting hub, providing technical assistance to applicants and channeling permitting requests to the state and federal offices involved in the process [190]. In 2008, Alaska created a renewable energy grant fund to provide assistance to utilities, IPPs, tribal groups, and municipalities for feasibility studies, permitting, and construction of renewable energy facilities, including hydropower. This program has been broadly successful in streamlining hydropower development for eligible projects [191].

## 2.3.4 Trends and Opportunities

Trends and opportunities in Markets and Projects Economics include:

- Improvement in the valuation and compensation of hydropower in power markets is being examined. Linkage of compensation to prices in the 5-minute interval instead of an hourly average should be considered. Since fast response resources such as hydropower and PSH have the ability to follow 5-minute price deviations in real-time markets, settling on this real-time basis would more accurately value this capability and help realize the full potential value of providing ancillary grid services and essential reliability services within power markets.
- Removal of barriers to the financing of new projects would help advance hydropower. Conducting outreach and education with stakeholders and institutional investors can improve access to financing, which is needed to advance hydropower, especially small hydropower.
- Improvement in understanding of and hydropower's participation in renewable and clean energy markets is being examined. An example is consideration of approaches to reduce the patchwork eligibility framework for RECs, while respecting state-specific concerns and needs.
- Improved consistency in how sustainable aspects of hydropower development and operation are incorporated and ultimately valued in the REC market may decrease the variability and uncertainty of REC markets, facilitating entry into long-term contracts. This will help efforts to increase acceptance of hydropower as a renewable energy source.

# 2.4 Hydropower Development

The main opportunities for growth in hydropower are refurbishing the existing fleet, adding generation facilities to NPDs and existing water resources infrastructure (primarily irrigation canals or conduits), NSD, and PSH.[60] Each opportunity area has unique elements, drivers, and challenges to developing additional hydropower capacity. For example, development of hydropower on free-running streams will require new approaches and involve a broad spectrum of stakeholders. This section provides an overview of hydropower development and includes an explanation of the context within which development occurs. The section closes with suggestions to improve the hydropower development process to the benefit of all stakeholders.

> **Highlights:**
>
> - Resources are available to support growth of hydropower as an economically competitive source of low-carbon renewable energy.
> - Improved communication and collaboration during the hydropower planning process could expedite the regulatory process and help achieve desired outcomes for all parties.
> - In the context of a multi-use, multi-value system of users and stakeholders, hydropower development should incorporate environmental protection measures and sustainability principles in balancing energy needs and water resources.

## 2.4.1 Overview of Development

U.S. hydropower is primed to increase its role in the future of low-carbon electricity generation. Industrialization, economic development, and wartime manufacturing needs drove the development of much of the existing hydropower fleet. This laid the foundation for the growth of hydropower as a keystone of the electrical grid in many regions and the nation's largest source of renewable energy, delivering about 65% of total renewable generation from 2004 through 2013 [192]. Future growth will be driven by an evolving set of needs and requirements, such as reducing carbon emissions, achieving reliable operation, and stabilizing an electric grid that is subject to new demands. The technology to generate low-carbon, renewable hydropower improves with time, as does understanding of how hydropower development interacts with the social and environmental values of a community. Developers seek to create value through hydropower projects that are viable to build within the regulatory, environmental, social, and economic frameworks that apply at the time development occurs and that will remain viable to operate into the future.

Given that hydropower development in the United States began more than a century ago, it might be assumed to be a mature technology with little opportunity for growth. This, however, is not the case. There is potential to generate additional electricity at existing dams; at existing non-powered dams, canals, or conduits; and at new sites, using new, low-head technologies. Developing this untapped hydropower potential requires addressing social, environmental, and financial uncertainties to the satisfaction of stakeholders, regulators, and financiers. Although many aspects of development are well defined, such as the FERC licensing process or state Section 401[61] water quality certification, it can be difficult to predict how much each process may cost, how long it might take, or what operations will ultimately be allowed. Project development involves iteratively resolving uncertainties and finding options that make the project viable.

To increase the likelihood that a project will be successful, a developer must identify whether the project will produce economic return without detrimental social or environmental effects that cannot be avoided,

60. Development of PSH is covered in Section 2.7.

61. Under the Clean Water Act, an applicant seeking a federal license or permit to conduct any activity that may result in a discharge to waters of the United States must provide the federal agency with a Section 401 certification. The certification is made by an authorized tribe and/or the state in which the discharge originates and requires reasonable assurance that the discharge will comply with applicable provisions of the act, including water quality standards. A state's water quality standards may specify the designated use of a stream or lake (e.g., for water supply or recreation), pollutant limits necessary to protect the designated use, and policies to ensure that existing water uses will not be degraded by pollutant discharges.

minimized or mitigated; can avoid complications that might stall or disrupt the development process or hinder the future operational performance; and that balances stakeholder objectives. Characteristics that drive the viability of a project vary somewhat depending on whether it is proposed by private industry, an IOU, or a municipality. Similarly, the criteria that drive development in one area of the United States might differ from those in another part of the country.

### *Primary Phases of Development*

The hydropower development process can be organized into seven broad phases, many of which overlap and during which applicable permitting, licensing and environmental review is initiated and pursued:

1. Site Identification (Origination)
2. Pre-Feasibility
3. Feasibility
4. Financing/Contracts
5. Detailed Design
6. Construction
7. Commissioning

In each phase, developers seek to identify unusual obstacles or costs before large capital investments are made. In the origination and pre-feasibility phases, site identification and initial screening occurs as an important first step, since the site must be broadly screened for its technical, environmental, social, political, and financial viability [193]. Figure 2-31 illustrates a typical or representative development process for hydropower, in which feasibility is evaluated more thoroughly before progressing to preliminary design and permitting.

Depending on the project size and capacity, ownership of the project site, and other political, environmental, and social considerations, the developer must determine which licenses and permits will be required. Early consultation with agencies, permitting authorities and stakeholders can increase the efficiency of this process. In general, the development pathways are similar regardless of ownership type. Primary differences between development undertaken by federal owners vs. that of non-federal owners relates to 1) FERC jurisdiction and associated licensing, 2) funding or financing mechanisms that affect cost structures, and 3) market access and revenue streams that affect revenue structures.

| Bank Perspective | Main Activities (Developer) |
|---|---|
| **Phase 1** | **Site Identification/Concept** |
| | • Identification of potential site(s)<br>• Funding of project development<br>• Development of rough technical concept |
| **Phase 2** | **Pre-Feasibility Study** |
| | • Assessment of different technical options<br>• Approximate costs/benefits<br>• Permitting needs<br>• Market assessment |
| **Phase 3** | **Feasibility Study*** |
| • First contact with project developer | • Technical and financial evaluation of preferred option<br>• Assessment of financing options<br>• Initiation of permitting process |
| **Phase 4** | **Financing/Contracts*** |
| • Due diligence<br>• Financing concept | • Permitting<br>• Contracting strategy<br>• Supplier selection and contract negotiation<br>• Financing of project |
| **Phase 5** | **Detailed Design*** |
| • Loan agreement | • Preparation of detailed design for all relevant lots<br>• Preparation of project implementation schedule<br>• Finalization of permitting process |
| **Phase 6** | **Construction*** |
| • Independent review of construction | • Construction supervision |
| **Phase 7** | **Commissioning*** |
| • Independent review of commissioning | • Performance testing<br>• Preparation of as build design (if required) |

*Involvement of financing institution begins with Phase 3

Source: International Finance Corporation, 2015 [194]

**Figure 2-31.** Representative project development process for a hydropower project

The Regulatory and Permitting Information Desktop, or RAPID,[62] Toolkit provides regulatory flow charts that provide overviews of the requirements a developer must address, along with links to permit applications, processes, manuals, and related information. Under certain circumstances, exemptions or exclusions from permitting may be possible. Consultation with the agencies and permitting authorities as well as stakeholders is typically done as the licensing and permitting plan is developed and initiated [193].

The final project design phase includes finalizing the FERC licensing process or Lease of Power Privilege Process; the Corps permitting process; securing of a PPA or equivalent revenue stream or power sales agreement, if applicable; financing or rate-making approval; and procuring major equipment. Once these steps are completed and authorizations have been granted, the project can move to construction and commissioning.

### *Key Aspects of Development*

Hydropower development requires regular examination of the balance between the risks and rewards throughout the development process. That on-going examination is often driven by economic considerations. For IOUs, the forecast project cost must remain competitive to other sources of generation. For municipal and private developers, lenders are interested in understanding the risks at each phase to ensure that financing is commensurate with the demonstrated progress. Key areas of interest can include but may not be limited to:

- **Land (Site Control)**—Are the long-term rights necessary to construct and operate the project available or reasonably obtainable?
- **Permits, Licenses and Environmental Requirements**—Can all material permits and licenses be obtained in a timely manner, or with sufficient certainty to obtain as scheduled? What studies are needed? Can requirements for environmental or resource protection be met within the desired timeline and at an acceptable cost?
- **Stakeholders**—Has, or can, alignment of all critical stakeholders to the project be achieved?
- **Engineering**—Do conceptual, pre-feasibility, and feasibility level engineering and technical assessments yield any fatal flaws? Can firm price, schedule, and contract with equipment suppliers and contractors be achieved?
- **Interconnection/Transmission**—What studies are necessary, what is the certainty of interconnection capacity availability, and what is the risk of applicable transmission upgrade costs? Are interconnect fees prohibitive or are contracts difficult to obtain in a reasonable timeframe?
- **Revenue**—What is the certainty on installed capacity, basis of annual energy generation, and associated revenue stream–e.g., long-term PPA, wholesale markets, changing policies or incentives, and relevant market prices and products?
- **Construction/Major Equipment Procurement**—What is the certainty of construction schedule, cost, and potential for delay, and what is the certainty of equipment supply and performance?
- **O&M and Capital Expenditures**—What is the certainty of O&M costs and major capital expenditures over time?
- **Financial Risk**—How are cost escalation, interest-during-construction, and exchange rates accounted for?
- **Commercial Operations Date Provisions**—What commitments (to host/ISO) are being made with respect to commencement of operation? What is the liability/cost of delaying commencement? Will the project meet deadlines of any incentive programs?

## 2.4.2 Context for Development

As noted earlier, approximately half of the existing hydropower fleet is federally owned (i.e., Reclamation, TVA, and the Corps). Development activities by such federal owners fall outside FERC jurisdiction. Although exemptions have been created for specific situations, most hydropower development will fall within FERC jurisdiction, even when proposed by a private developer at existing federal facilities. One exception would be private development at a federal Reclamation project where the Lease of Power Privilege process would apply. A memorandum of understanding between FERC and Reclamation detailing the circumstances under which each agency has authority can be found in the Federal Register (58 Fed. Reg. 3269, January 8, 1993). An overview and context of hydropower licensing and relicensing processes and regulatory framework are discussed in subsequent sections, and additional detail is available on FERC's website.

62. *http://en.openei.org/wiki/RAPID*

### *Key Laws Governing Hydropower Development*

Under the authority of the FPA (see Table 2-2) as amended, FERC authorizes nonfederal hydropower projects located on navigable waterways or federal lands, or connected to the interstate electric grid, or that use surplus water or water power from a federal dam. FERC comprises up to five Commissioners who are appointed by the President and confirmed by the U.S. Senate. The Commission is supported by a staff of environment, engineering, and legal experts who evaluate hydropower license applications, prepare environmental documents, and make recommendations to the Commission on hydropower licensing matters. The Commission may issue an original license, valid for up to 50 years, for construction, operation, and maintenance of jurisdictional projects. When a license expires, the federal government can take over the project; the Commission can issue a new license (relicense) to either the existing licensee or a new licensee for a period of up to 50 years; or the project can be decommissioned.

In certain instances, FERC may exempt a project from the licensing provisions of Part I of the FPA, such that the project is instead subject only to environmental conditions mandated by state and federal fish and wildlife agencies. This means that the project is not subject to the comprehensive development standard of FPA section 10(a)(1) (16 U.S.C. § 803(a)(1)), mandatory conditions under FPA sections 4(e) and 18 (16 U.S.C. §§797(e) and 811), eminent domain authority of FPA section 21 (16 U.S.C. § 814), and other provisions.

FERC's primary authority comes from the FPA, which has been amended over time. The most notable of these amendments was the Electric Consumers Protection Act of 1986, which added the "equal consideration clause" to section 4(e) (16 U.S.C. § 797(e)) and added section 10(j) (16 U.S.C. § 803(j)) giving fish and wildlife agency recommendations greater weight than they had previously been given. In general, implementation of FERC's authority relative to licensing, compliance, and dam safety is shaped by the Commission's regulations (primarily Title 18 of the Code of Federal Regulations) as well as by FERC policy statements, guidance documents, and handbooks available on FERC's website. Statutory change over time has also influenced the FERC licensing process. For example, the Energy Policy Act of 2005 contained key provisions addressing and shaping the regulatory framework, specifically section 241. This section (1) expedited resolution of mandatory conditions, e.g., fishway prescriptions, including timeframes for resolution; and (2) added new section 33 (16 U.S.C. § 823d) to the FPA, which allows the applicant or another party to a license proceeding to propose an alternative condition to an agency prescription that the agency involved must accept, if it is determined that the alternative provides for adequate protection at a significantly lower cost.

Two bills signed into law in 2013 are specific to small hydropower development. The first of these bills, The Hydropower Regulatory Efficiency Act of 2013, shaped the existing FERC regulatory landscape by (1) exempting certain conduit hydropower facilities from the licensing requirements of the FPA; (2) amending Section 405 of the Public Utility Regulatory Policies Act of 1978 to define "small hydroelectric power projects" as having an installed capacity that does not exceed 10,000 kilowatts; (3) authorizing FERC to extend the term of preliminary permits once, for not more than two additional years beyond the three years previously allowed under Section 5 of the FPA; and (4) directing FERC to investigate the feasibility of a 2-year licensing process for hydropower development at non-powered dams and closed-loop pump storage projects. The second of these bills, the Bureau of Reclamation Small Conduit Hydropower Development and Rural Jobs Act, encourages development of small conduit hydropower at all Reclamation-owned canals, pipelines, aqueducts, and other waterways [195].

FERC's authority is shaped further by several other laws and executive orders, most notably the eight federal laws described subsequently.

**National Environmental Policy Act.** NEPA establishes environmental protection as a major national policy objective. The Act requires all federal agencies to evaluate the environmental impacts of major federal actions, including the permitting of activities affecting the environment. The NEPA process requires the identification and assessment of reasonable alternatives to the proposed action, and federal agencies are to use all practical means to restore and enhance the quality of the environment and to avoid or minimize any possible adverse effects of their actions upon the quality of the environment. FERC adheres to the statutory requirements of NEPA.

**Fish and Wildlife Coordination Act.** The Fish and Wildlife Coordination Act requires federal agencies granting a license or permit for the control, impoundment, or modification of streams and water bodies to first consult with the U.S. Department of the Interior's Fish and Wildlife Service (FWS), the U.S. Department of Commerce's National Marine Fisheries Service (NMFS), and the appropriate state fish and wildlife agencies regarding conservation of these resources. A federal agency licensing a development project related to a water resource is required under the Fish and Wildlife Coordination Act to give full consideration to the recommendations of the FWS, NMFS, and the relevant state fish and wildlife agency on the wildlife-related aspects of such projects. FERC is directed under the Act to not only consult with the FWS, NMFS, and the state agencies, but also to include in each license conditions for the protection, mitigation, and enhancement of fish and wildlife. Those conditions are to be based on recommendations received pursuant to Section 10(j) of the FPA (16 U.S.C. § 803(j)) from the FWS, NMFS, and state fish and wildlife agencies.

**National Historic Preservation Act.** The National Historic Preservation Act requires the federal government to accelerate its own historic preservation programs and to encourage such efforts on state, local, and private levels. Compliance with the NHPA may be coupled with FERC's NEPA process where a federal licensing action affects a historical or cultural resource. FERC is bound in licensing decisions by the provisions of the National Historic Preservation Act, which requires the Commission to take into account the effect of the action on any district, site, building, structure, or object that is included in or eligible for inclusion in the National Register of Historic Places, and to give the Advisory Council on Historic Preservation a reasonable opportunity to comment on a proposed action.

**Endangered Species Act.** The purpose of the ESA is to protect and conserve endangered and threatened species, and to protect the ecosystems upon which those species depend. During the hydropower project licensing process, FERC must consult with FWS or NMFS to determine whether the permitting action is likely to jeopardize the continued existence of any endangered or threatened species or result in critical habitat destruction or adverse modification. Where endangered or threatened species may be present in the area affected by a hydropower project proposed for licensing, FERC may be required to prepare a biological assessment for the purpose of identifying any endangered or threatened species likely to be affected by licensing. This biological assessment may be undertaken as an integral part of NEPA compliance. Under their implementing regulations, FWS or NMFS must provide a biological opinion to FERC within 135 days of receipt of the biological assessment. FERC's general practice is to refrain from issuing a license until receipt of a biological opinion, and to include a biological opinion's terms and conditions as part of any issued license.

**Clean Water Act.** Under Section 401 of the Clean Water Act (33 U.S.C. § 1341), a FERC license applicant must obtain certification from a state, authorized tribe, or interstate pollution control agency that verifies compliance with the Act. Evidence of a request for water quality certification must be filed with FERC no later than 60 days after the Commission issues a Notice of Ready for Environmental Analysis or as otherwise directed by the Commission. Under the provisions of the Clean Water Act, a state water quality certifying agency must issue a water quality certificate within one year of receipt of the application, although this requirement is routinely extended. FERC is precluded from issuing a license until a water quality certificate is issued or waived (or is deemed waived), and FERC must include the terms and conditions of the water quality certification as part of any issued license. Terms and conditions by FWS and NMFS pertaining to fish passage must be included as part of any license issued.

Amendments to the Clean Water Act in 1972 created the National Pollutant Discharge Elimination System. The system, which is managed by EPA, helps address water pollution by regulating point sources of pollutants into U.S. waterways. A permit issued under the National Pollutant Discharge Elimination System usually allows a facility to discharge a specified amount of a pollutant into a water body, under certain conditions. Although hydropower does not result in such a specific continuous or regular discharge, this program adds extra protection relative to aspects such as lubricants in sealed systems or construction activities. EPA authorizes state, tribal, and territorial governments to execute the national system under individual State Pollutant Discharge Elimination Systems.

**Wild and Scenic Rivers Act.** The Wild and Scenic Rivers Act provides for the protection and preservation of certain rivers and their immediate environments by instituting a National Wild and Scenic Rivers System. Rivers may be included in this system either by an act of Congress or by the Secretary of the Interior, upon application by a state governor. Section 7(a) of the Act (16 U.S.C. § 1278(a)) provides that FERC shall not license the construction of any project on or directly affects any river that is designated as a component of the Wild and Scenic River System. Moreover, all departments and agencies of the United States are precluded from "assist[ing], by loan, grant, license, or otherwise in the construction of any water resources project that would have a direct and adverse effect on the values for which [a component of the Wild and Scenic Rivers System] was established." Section 7(a) of WSR does provide for licensing of or assistance to developments below or above a designated river if it can be determined the development "will not invade the area or unreasonably diminish the scenic, recreational, and fish and wildlife values" present when the river was designated as part of the System.

**Americans with Disabilities Act.** The Americans with Disabilities Act was created to protect the civil rights of persons with disabilities. The ADA requires public and private entities with public accommodations to ensure accessibility to persons with disabilities. Although FERC does not specifically require ADA-compliant facilities, FERC licensees must consider the disabled when planning recreational facilities, and new recreational facilities and access areas at hydropower projects must comply with the requirements of the ADA.

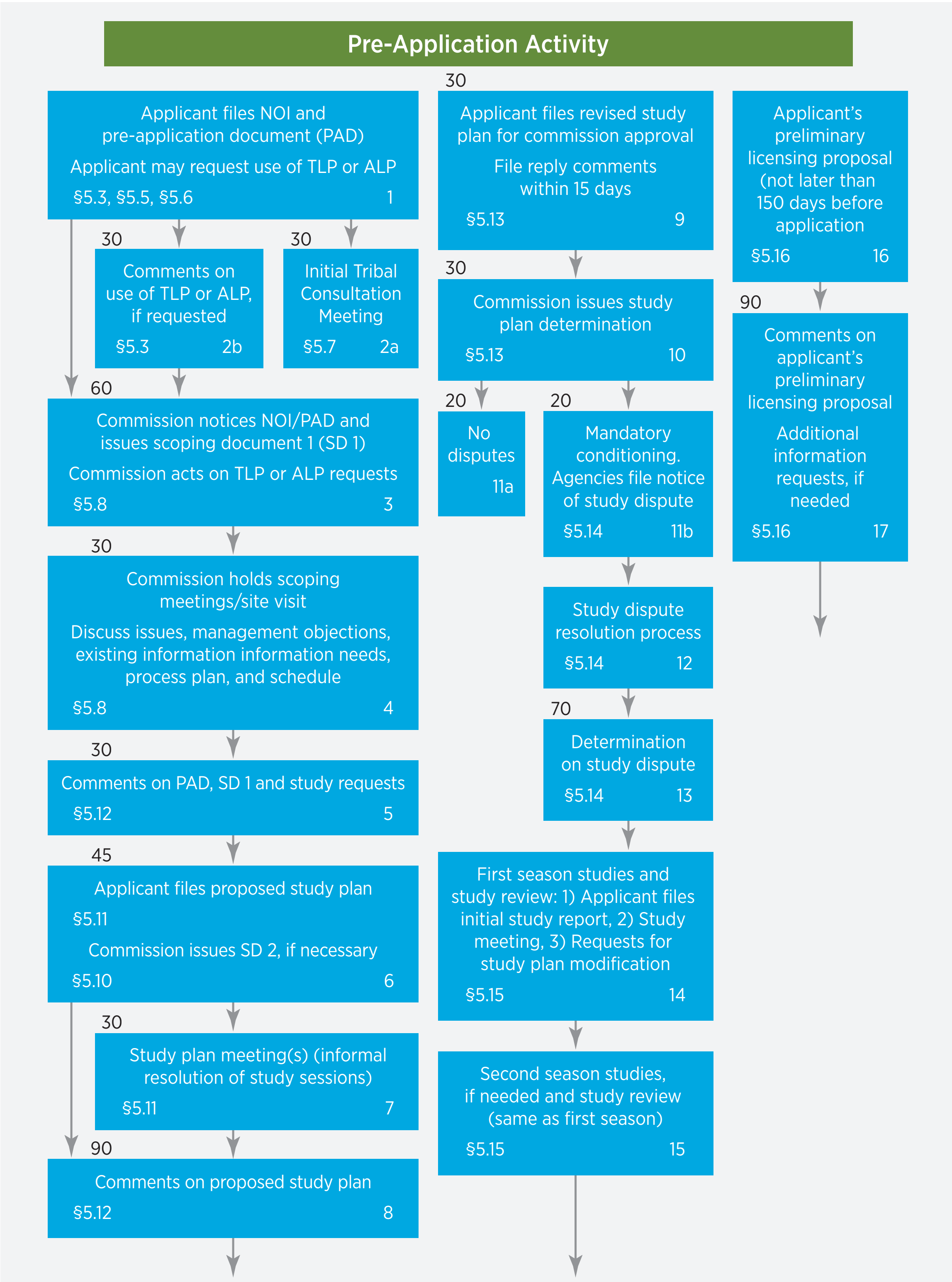
**Pacific Northwest Power Planning and Conservation Act.** Under Section 4(h) of the Pacific Northwest Power Planning and Conservation Act (or Northwest Power Act) (16 U.S.C. § 839b(h)), the Northwest Power and Conservation Council developed and updates every five years the Columbia River Basin Fish and Wildlife Program to protect, mitigate, and enhance the fish and wildlife resources associated with development and operation of hydropower projects within the Columbia River Basin. Section 4(h) of the Northwest Power Act states that the federal and state agencies with regulatory responsibilities for such projects should provide equitable treatment for fish and wildlife resources, in addition to other purposes for which hydropower is developed. These agencies must also take into account, to the fullest extent practicable, the Columbia River Basin Fish and Wildlife Program, which directs agencies to consult with federal and state fish and wildlife agencies, appropriate Indian tribes, and the Northwest Power and Conservation Council during the study, design, construction, and operation of any hydropower development in the Basin. Section 12.1A of the Columbia River Basin Fish and Wildlife Program outlines conditions that should be provided for in any original or new license, and designates certain river reaches as protected from development. If the project is not within the Columbia River Basin, Section 12.1A would not apply.

**FERC Licensing Processes.** Per FERC regulations, applicants for licenses may use one of three license processes: integrated, traditional, or alternative. In the Integrated Licensing Process (ILP, which is FERC's default process), Commission staff involvement begins during the pre-filing consultation process and is sustained throughout the licensing process. The ILP merges pre-filing consultation and the NEPA process, brings finality to pre-filing study disputes, and maximizes the opportunity for federal and state agencies to coordinate their respective processes with the Commission's licensing process. In the Traditional Licensing Process, FERC conducts scoping after an application is accepted for filing, and there is typically little Commission staff involvement during the pre-filing consultation process prior to when the application is filed. In the Alternative Licensing Process, scoping is done prior to filing the application with FERC, but Commission staff involvement during study plan development and other pre-filing activities is advisory in nature. The Alternative Licensing Process is flexible and collaborative, but lacks the scheduling structure and consistent Commission staff assistance offered by the ILP. The highlights of FERC's three processes are summarized in Table 2-4, followed by a flowchart depicting the key aspects of FERC's default ILP (Figures 2-32a and 2-32b).

**Table 2-4.** Comparison of Attributes of the Three Hydropower Licensing Processes of the Federal Energy Regulatory Commission

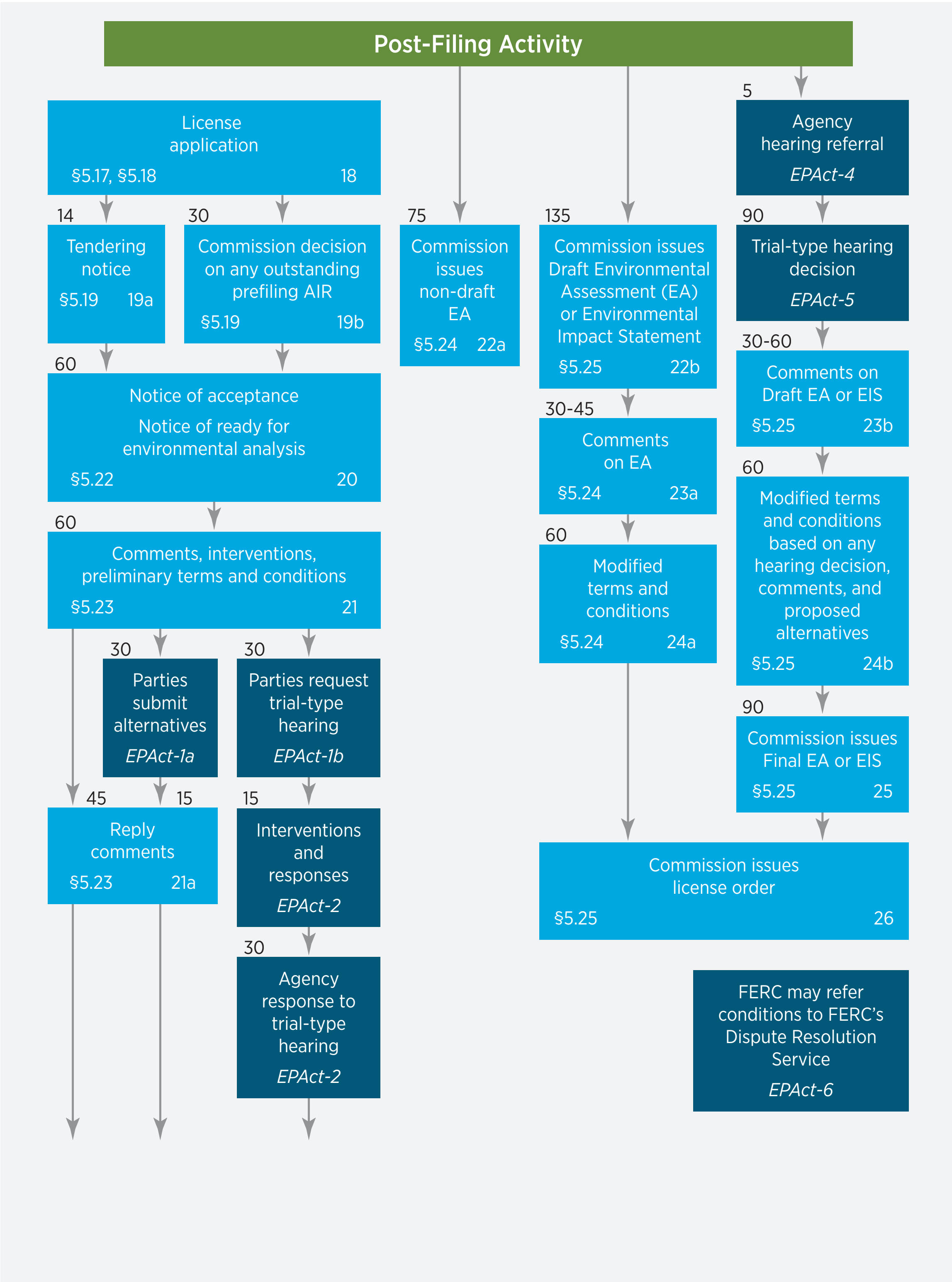
| | Traditional Licensing Process (TLP) | Alternative Licensing Process (ALP) | Integrated Licensing Process (ILP) |
|---|---|---|---|
| **Consultation with Resource Agencies and Indian Tribes** | • Paper driven | • Collaborative | • Integrated |
| **Deadlines** | • Pre-filing—some deadlines for participants<br>• Post-filing—defined deadlines for participants | • Pre-filing—deadlines defined by collaborative group<br>• Post-filing—defined dead-lines for participants | • Defined deadlines for all participants throughout the process, including FERC |
| **Study Plan Development** | • No FERC involvement<br>• Developed by an appli-cant based on early agency, tribal, and public recommendations | • FERC staff advisory assistance<br>• Developed by collabora-tive group | • Plan approved by FERC<br>• Developed through study plan meetings with FERC staff involvement |
| **Study Dispute Resolution** | • OEP Director opinion advisory | • OEP Director opinion advisory | • Informal dispute resolution available to all participants<br>• Formal dispute resolution available to agencies w/man-datory conditioning authority<br>• OEP Director opinion binding on applicant |
| **Application** | • Draft and final application include Exhibit E | • Draft and final application include applicant-prepared EA or 3rd party EIS | • Preliminary licensing proposal (or draft application) and final application include Exhibit E that has form and contents of an EA |
| **Additional Information Requests** | • Available to participants after filing of application | • Available to participants primarily before filing of application<br>• Post-filing requests available but should be limited due to collabora-tive approach | • Available to participants before filing of application<br>• No formal avenue to request additional info after applica-tion filed |
| **Timing of Resource Agency Terms and Conditions** | • Terms and conditions filed 60 days after REA notice<br>• Schedule for filing final terms and conditions permitted | • Terms and conditions filed 60 days after REA notice<br>• Schedule for filing final terms and conditions permitted | • Terms and conditions filed 60 days after REA notice<br>• Modified terms and conditions 60 days after comments on the single EA or draft NEPA document |

Source: FERC [196]




Source: FERC [196]

**Figure 2-32a.** Flow diagram for the Federal Energy Regulatory Commission's Integrated Licensing Process

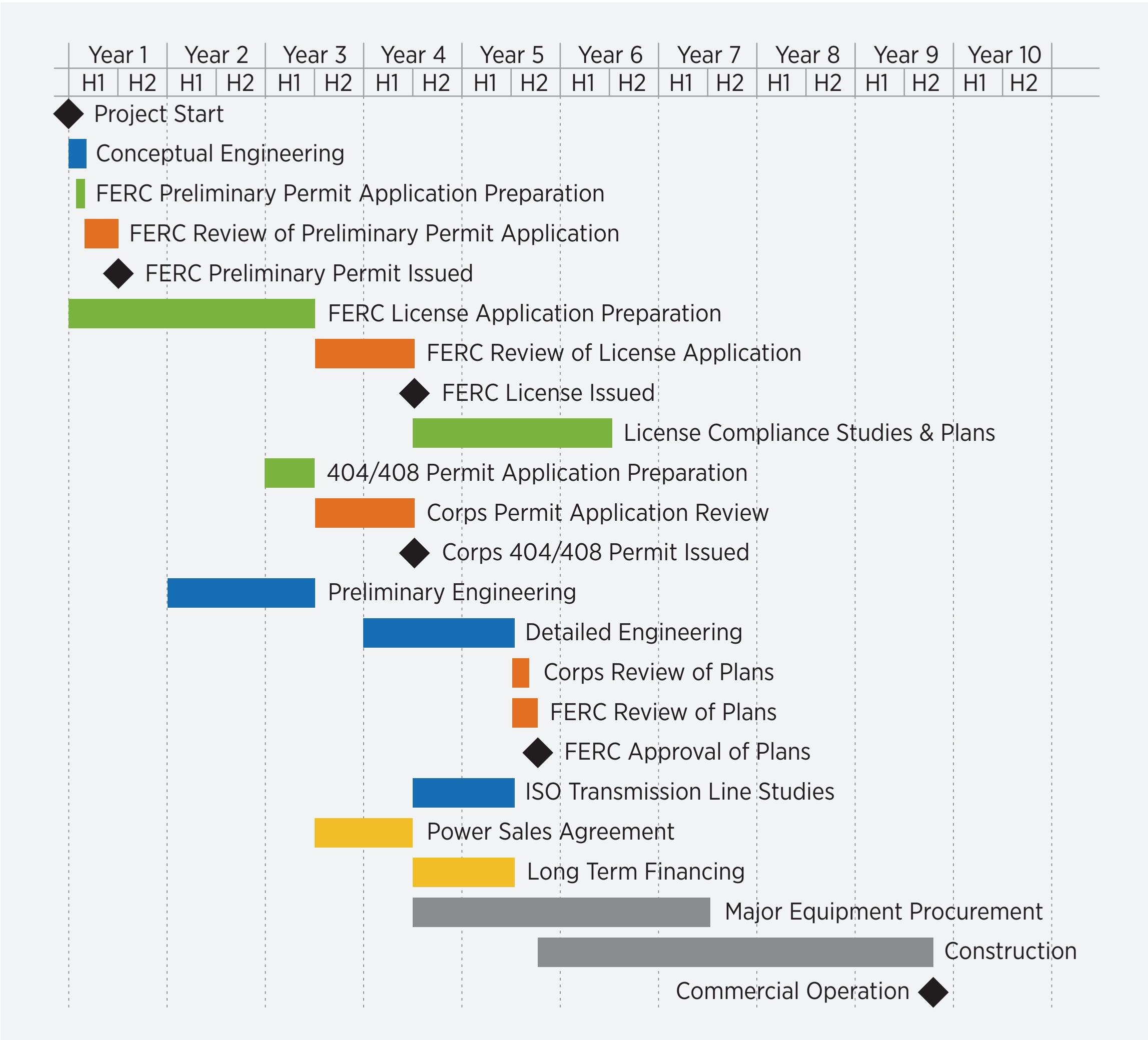



Source: FERC [196]

**Figure 2-32b.** Flow diagram for the Federal Energy Regulatory Commission's Integrated Licensing Process

### *The Timing of Development*

Hydropower development activities could accelerate if the scope of compliance requirements and timeline of the licensing and permitting processes were more predictable for developers, thereby reducing uncertainty in the development process. Even if requirements remained the same, decreasing the costs or time to commercial operation would increase the rate of growth in installed capacity, and decreasing uncertainty would make it easier to identify which potential projects would be viable. Accelerated development processes have been proposed in which all areas of concern can be addressed in a predictable timeframe. Figure 2-33 illustrates an example of a proposed "accelerated licensing and permitting" approach, in this case for NPD development at a federal facility. The goal of this approach is to obtain a FERC license in three-and-a-half years and achieve operation of the project in as few as five years after the FERC license is issued [197]. This timeline illustrates the complexity and interdependence of the development process; and, even when "accelerated,"




Source: Meier et al. 2010 [197]

**Figure 2-33.** Example of an accelerated development schedule for a hydropower project licensed under the Federal Energy Regulatory Commission the timeline spans a decade. That timeline can lead developers and utilities to favor other generation technologies with shorter times to achieve commercial operation, such as natural gas turbines.

### Reducing the Time and Cost of Licensing

Hydropower growth is occurring through upgrades and additions at existing facilities, with hydropower generating equipment being added to non-powered dams and conduits, as well as to low-impact NSD [2]. One factor in the growth of hydropower is interest in all types of renewable energy resources, such that 37 states and the District of Columbia have legislation mandating RPSs for utilities (see Section 2.1.2). A second factor relates to the applicable legislation noted previously, namely the Hydropower Regulatory Efficiency Act of 2013 (see Table 2-2). The FERC regulatory framework has and continues to evolve; the Commission's internal reviews [198] identified permitting and regulatory processes as the most commonly cited challenges associated with hydropower development in the United States. Permitting and regulation are important to ensure hydropower projects that meet multiple stakeholder priorities, but the process by which requirements are established can still be a source of uncertainty in the length and cost of project development timelines. This process can also be a source of uncertainty for the scope of facility operations, thus influencing the ongoing value available from hydropower generation.

FERC recognized the need for continual improvement in the licensing process in its 2001 publication, *Report on Hydroelectric Licensing Policies, Procedures, and Regulations Comprehensive Review and Recommendations Pursuant to Section 603 of the Energy Act Of 2000.* In this document, FERC examined the licensing of hydropower projects to determine how to reduce the cost and time of obtaining a license under the FPA. Key excerpts from the Executive Summary of this report, prepared before the aforementioned legislation in 2005 and 2013, are in Text Box 2-4 [198]:[63]

Text Box 2-4.

**Key excerpts from the Federal Energy Regulatory Commission's report:**

***Report on Hydroelectric Licensing Policies, Procedures, and Regulations Comprehensive Review and Recommendations Pursuant to Section 603 of the Energy Act of 2000***

*"The median time from the filing a license application to its conclusion for recent applications is 43 months. Many proceedings, however, take substantially longer. Many specific factors contribute to delays, but the underlying source of most delays is a statutory scheme that disperses decision making among federal and state agencies acting independently of the Commission's proceedings.* ***The most common cause of long delayed proceedings is untimely receipt of state water quality certification under the Clean Water Act."*** (page 5)

***"The same statutory scheme also ensures that the Commission has scant control over the costs of preparing a license application or of the costs of environmental mitigation and enhancement.*** *These expenditures are frequently mandated in state water quality certification or mandatory federal agency conditions required pursuant to FPA Sections 4(e) and 18, and override the Commission's balancing of all relevant factors affecting the public interest."* (page 6)

*"The most effective way to reduce the cost and time of obtaining a hydropower license would be for Congress to make legislative changes necessary to restore the Commission's position as the sole federal decisional authority for licensing conditions and processes. Alternatively, consideration should be given to requiring other federal agencies with mandatory conditioning authority to better support their conditions."* (page 6)

***"Changes in Commission regulations and policies may also assist in reducing the time and cost of licensing, although they are not an adequate substitute for legislative reform."*** (page 6)

63. Bolding in this section has been added by the *Hydropower Vision* authors. It is not included in the original FERC report.

Legislation issued since the issuance of this 2001 FERC report, and the introduction of the ILP as the default licensing process, has aimed to achieve greater efficiency and effectiveness. FERC and the hydropower community also continue to examine the regulatory framework. In 2005 and 2010, FERC explored the effectiveness of the ILP, as illustrated on the Commission's website[64]:

> *"When the Commission adopted the Integrated Licensing Process (ILP) on July 23, 2003, it committed to studying the effectiveness of the ILP in achieving its goal of providing a more efficient and effective licensing process.* ***In 2005 and again in 2010, Commission staff asked participants using the ILP about ideas, tools, and techniques that were being implemented (or could be implemented) to achieve the goals of the ILP within the framework of the existing regulations… The ILP Effectiveness Study confirmed that the ILP is achieving its purposes of providing an efficient and effective hydropower licensing process in most cases.*** *The study also brought to light areas where each constituency (applicants, agencies, tribes, NGOs) could focus attention to improve the process. Commission staff is providing the following Action Plan for areas in its purview. We encourage other constituencies to do the same."*

Based on feedback from these initiatives, FERC developed its 2011 report, *Ideas for Implementing and Participating in the Integrated Licensing Process (ILP), Tools for Industry, Agencies, Tribes, Non-Governmental Organizations, Citizens, and FERC Staff, Version 2.0.* In this report, FERC describes its collaborative outreach to gather input and feedback [208]:

> *"In 2005 and again in 2010, Federal Energy Regulatory Commission (FERC or Commission) staff explored with applicants, tribes, agencies, non-governmental agencies (NGO), and citizens how well the integrated licensing process (ILP) was achieving its goal of providing a predictable, efficient, and timely licensing process that ensured adequate resource protection.* ***We asked what was going well and what might be done better. This document contains those shared ideas, tools, and techniques that have been successfully implemented*** *(or could be implemented) to assist future ILP participants without unduly extending the licensing process or changing existing regulations"* (page 3).

Numerous suggestions were provided in the report for applicants, agencies, tribes, non-governmental organizations, and FERC staff. Many of those suggestions focused on improving communication, participation, and collaboration to facilitate the licensing process.

According to data provided by FERC in December 2015, there were 26 pending license applications where Commission staff has completed NEPA, but the Commission is unable to render a license decision because a state agency has not yet issued its water quality certification decision, or FWS or NMFS has not yet issued its biological opinion. As of December 2015, the average time the Commission has been awaiting water quality certification or biological opinions since completion of final NEPA is about 5.3 years.

To spur development of new sources of hydropower, it must be possible to establish economic viability with a degree of certainty early in the development process and increasing certainty as the process unfolds. Hydropower is a capital-intensive technology with long lead times for development and construction, due to the significant feasibility, planning, design, and civil engineering works required [30]. Project licensing and permitting are also costly and similarly lengthy. Payoff begins only after the project achieves commercial operation, often several years (5+) after initiation of the development process. Banks and other financial institutions require project development methodologies that appropriately manage risk, offer reasonable assurance for repayment of loans, and minimize the risk for capital cost growth [193].

The civil structures and electro-mechanical equipment are two major cost components for hydropower projects [30], but they can be more reliably estimated than some other components. Project development costs also include planning and feasibility assessments, environmental impact analysis, licensing, environmental mitigation measures, development of recreation amenities, historical and archaeological mitigation, and water quality monitoring and mitigation [30]. The initial and ongoing costs in those areas can be substantial as well as difficult to estimate at the early stages of project development.

Regulatory uncertainty in the duration and outcomes of the licensing process are important challenges for private hydropower developers. Another important challenge—perhaps the greatest challenge—for

64. See *http://www.ferc.gov/industries/hydropower/gen-info/licensing/ilp/eff-eva.asp*

private developers is revenue uncertainty. Lenders will generally not finance projects without a long-term (typically 10+ years) PPA with a creditworthy counterparty, yielding a revenue stream with an acceptable debt-coverage ratio and a PPA term length that is equal to or greater than the term of the debt [193]. In addition to PPAs, interconnection cost is essential to project financial viability, because these two factors together determine the price of electricity that will be received, any other ancillary grid service revenues, future price escalation, and the cost of interconnection and wheeling (moving) project power to a power purchaser. Interconnection costs can vary widely depending upon the modifications required to carry the project power to the power purchaser [193]. The grid interconnection process can be a barrier to hydropower development (see Section 2.2), particularly for small hydropower. ISO interconnection application processes are typically costly and time-consuming, with their own timetables and priorities that are not necessarily consistent with the timeline needs of small hydropower developers [193].

### *Perspectives on Sustainability*

Many values factor into hydropower development, and there is growing recognition that those values need to sum to an amenable whole for the affected communities as well as the project owners over the life cycle of a facility. Regulatory and permitting processes address certain aspects of sustainability, and the inclusion of multiple stakeholder viewpoints during licensing encourages broad consideration of the related elements and objectives. However, there are opportunities for stakeholders to address sustainability questions even in advance of the regulatory process (e.g., third-party certification processes or design criteria that recognize "environmental performance" as a project goal). Low-impact certification programs and sustainability assessment protocols from organizations such as the LIHI and the International Hydropower Association provide examples of how hydropower operation and development can incorporate a broader perspective of performance. The LIHI certification program, for example, includes criteria related to river flows, water quality, fish passage and protection, watershed protection, threatened and endangered species protection, cultural resource protection, recreation, and facilities recommended for removal. The International Hydropower Association protocol addresses more than 20 sustainability topics in areas such as environmental, social, technical, economic, financial, and cross-cutting. Although the process for incorporating sustainability into development is not always well defined, addressing a broader range of topics early in the process may make it possible to reduce uncertainty in the development timeline.

Stakeholders, including hydropower owners and developers, value a broad spectrum of multiple and even competing uses such as water supply, water quality, flood control, navigation, hydropower generation, fisheries, biodiversity, habitat preservation, fish passage, and recreation. Those values can extend beyond the boundaries of the project under development, and a basin-scale or watershed approach (even beyond that in the existing regulatory framework) can enable the evaluation of those values across multiple projects and in the context of other water uses. A basin-scale or watershed approach to hydropower development provides more options than a single plant approach, giving such approaches the potential to balance the competing needs of environmental resources, the project developer, and other interested stakeholders. For environmental resources, the benefits potentially include:

- Ability to coordinate for maximum effectiveness on efforts to protecting/restoring fish passage, improvements to fish habitat, and other ecological benefits; and
- Ability to institute watershed-wide protection and improvements sooner because they would not be contingent on licensing terms.

For the project developer and other interested stakeholders, the potential benefits can include:

- Greater collaboration among regulators, applicants, agencies, stakeholders, which has the potential to increase upfront certainty;
- The opportunity to create common settlement agreements, 401 water quality certifications, and other tools such as Habitat Conservation Plans and recreation plans for all projects in a basin at one time;
- A more comprehensive range of potential solutions in the basin, and opportunities that might not be apparent at smaller scales;
- Incorporation of integrated planning for climate change;
- Single process for consultations and environmental review (e.g., consolidated/coordinated NEPA); and
- Cost-effective collaborative studies, and more efficient mitigation and resultant reduction of overall project costs.

Text Box 2-5.

### Addressing Habitat Connectivity and Fish Passage Issues on the Penobscot River

Through an innovative FERC relicensing process, a multiparty agreement was signed in 2004 between the Penobscot Indian Nation, a hydropower company, conservation groups, and state and federal agencies. The agreement resolved decades of conflict over fisheries and hydropower. By considering a system of dams, the agreement supported increased power generation at six dams while increasing fish passage at five others. The agreement provided for the acquisition and decommissioning of three large main stem dams by the Penobscot River Restoration Trust, with the removal of the two lower-most dams in 2012 and 2013 and a planned river-like bypass around an upstream dam [200]. These improvements were designed to increase access to an estimated 1,000 miles of habitat, and overall energy generation is already greater than pre-project levels. This project illustrates the creative problem solving and shared decision making that permitted this approach to balancing energy production with ecological values in the lower Penobscot River [199].

In many cases, factors such as staggered license expirations, conflicting objectives, multiple owners, increased complexity, requirements for mitigation within project bounds, and cost sharing can make it challenging to initiate a basin-scale or watershed approach. Basin-wide settlements[65] have existed for a number of years, including at least a dozen river basin settlements developed in New York since 1990 (such as the 1998 Raquette River Projects settlement). There are a growing number of success stories that have demonstrated the benefits of such an approach. One instructive example is the Penobscot River in Maine, where stakeholders successfully applied a basin-scale framework to address long-standing fish blockage and passage issues on the Penobscot River (Text Box 2-5) [199, 60].

The Penobscot process was the impetus for DOE to investigate a process and tools to look for similar opportunities elsewhere. The Basin-Scale Opportunity Assessment was one of the activities called for in the 2010 Hydropower Memorandum of Understanding between DOE, the U.S. Department of the Interior, and the Army [207]. The goal of the BSOA was to identify pathways to improve both the value of hydropower generation and environmental conditions within a river basin simultaneously. A three-phased approach to assessing hydropower environmental opportunities was devised and piloted in the Deschutes River Basin, with subsequent work focusing on developing a geospatially driven methods and tools for conducting rapid scoping assessments (i.e., Phase 1). Basin-Scale Opportunity Assessment scoping assessment methodology was tested in three U.S. river basins (Connecticut, Roanoke, and Bighorn), and is being woven into an interactive Web platform that supports multi-scale association for any hydrologic drainage in the United States (e.g., Larson et al. 2014 [201]).

Basin-wide settlements[66] have existed for a number of years, including at least a dozen river basin settlements developed in New York since 1990 (such as the 1998 Raquette River Projects settlement).

## 2.4.3 Maintaining and Expanding the Existing Fleet

An important opportunity for additional hydropower development in the United States is through refurbishment and expansion of existing facilities. This can add incremental generation through efficiency increases and/or the addition of the ability to use water for generation that was previously spilled. The number of aging hydropower projects means that refurbishment will become an increasingly important way of boosting hydropower output and increasing capacity [30].

65. A negotiated agreement among stakeholders and the licensee(s) that requests FERC to include specific terms and conditions in the new license(s) for the project(s).

66. A negotiated agreement among stakeholders and the hydropower facility owner to FERC about relicensing, with a request to accept the terms as relicensing.

### *Overview of the Resource*

Hydropower plant refurbishment, which includes repowering and refurbishment, refers to a range of activities such as repair or replacement of components, upgrading generating capability, and altering water management capabilities. Most refurbishment projects focus on the electro-mechanical equipment, but can involve repairs or redesigns of intakes, penstocks, and tailwaters [30].

Refurbishment projects generally fall into two categories:

- **Life extensions** entail replacement of equipment on an "in-kind" basis, with limited effort made to boost generating capacity potential. This replacement will, however, generally result in increased generation (relative to what was being produced) as worn out equipment is replaced. On average, these repairs will yield a 2.5% gain in capacity [30].
- **Upgrades and expansions** reflect incorporation of increased capacity and, potentially, increased efficiencies into a refurbishment program. Typically, once the potential upgrade or expansion opportunity is identified, the owner will develop a business case to support the opportunity, such that costs incurred to accommodate these changes are offset or justified by increased revenues. These upgrades can be modest or more extensive in nature and, depending on the extent of the wear and tear and additional civil structures to try and capture more energy, yield increases in capacity of between 10% and as much as 30% at a given plant [30]. This can also include expansions to generate with minimum stream flow releases, or adding a new or larger unit to an underutilized facility (e.g., a facility with an unused bay or excess water).

Many hydropower projects in the United States are aging, with some facilities approaching the century mark. The median age for federal hydropower projects is approaching 50 years [2]. In the Columbia River Basin, for example, the Corps, BPA, tribes, and other stakeholders are working to replace aging turbines, generators, and associated equipment with new and more power-efficient designs that also address fish passage concerns. BPA and the Corps plan to replace more than 90 Kaplan units on the Columbia and Snake Rivers with newer units that both produce more energy and meet or exceed fish passage or other environmental mandates resulting from the ESA or Clean Water Act. Environmental performance is incorporated through computational and scale physical models during the design process. Once new turbines are installed, performance is evaluated at full scale using tools such as the fish sensor device illustrated in Figure 2-38 in Section 2.5.4 to measure hydraulic conditions and acoustic telemetry to estimate fish survival rates. The result of this intensive process is increased confidence in both the expected performance of new turbines and actual performance that produces both energy-related and environmental benefits. Aging equipment is not limited to any particular region or organization, and hydropower operators across the United States will continue to refurbish or replace turbines.

### *Key Issues and Challenges*

Whether proposed and performed as part of relicensing or during the term of an existing license, upgrades, expansions and other types of operational changes (by non-federal owners) need to meet applicable FERC regulations germane to the proposed action (e.g. non-capacity amendment proceeding, capacity amendment proceeding, relicensing proceeding). Project developers and facility owner/operators operate within that context and often seek to meet power and environmental goals concurrently. For example, replacing an aging turbine with a modern design and materials evaluated through modern tools and techniques may produce power more efficiently across a wider range of conditions, reduce O&M costs, and create turbine conditions more conducive to improved water quality or fish survival. At Wanapum Dam on the Columbia River in Washington, for example, the turbine replacement process has increased energy generation by an average of 3.3%, while reducing maintenance costs and allowing for safer fish passage alternatives [202]. The replacement of the powerhouse at the Bridgewater Hydroelectric station on the Catawba River in North Carolina incorporated multiple aeration options into the turbines to meet tailrace water quality requirements [197].

Sustainability and environmental concerns can also drive the need for upgrades and improvements in an effort to simultaneously improve power generation and environmental performance. In general, facility upgrades and improvements represent excellent opportunities to add energy benefits in a sustainable way, particularly when objectives for sustainability are incorporated into the project planning process at an initial phase. The primary issue or challenge, especially with respect to license amendments, is to strike the appropriate and needed balance in addressing the applicable power and non-power resources without the amendment becoming onerous or costly. Those costs may be offset if the incremental gains in hydropower are developed in such a way as to be eligible for renewable energy incentives and green certifications.

### 2.4.4 Non-Powered Dams and Existing Infrastructure

A second opportunity for additional hydropower development in the United States involves adding power generation capabilities to existing infrastructure, either at NPDs or in water conveyances such as irrigation canals and conduits. Such structures are initially constructed to provide other benefits and uses, so adding power generating facilities to them can often be achieved at lower cost, with less risk, and in a shorter timeframe than development requiring new dam construction. Similarly, canal and conduit hydropower takes advantage of existing infrastructure and can increase the energy efficiency of water delivery systems by replacing valves with generation. Although these water conveyance infrastructures were originally designed for non-power purposes, new renewable energy can often be obtained without affecting other purposes and without the need to construct new dams or diversions [193].

#### *Overview of the Resource*

The United States has more than 80,000 NPDs that provide a variety of services ranging from water supply to inland navigation (in contrast, there are only roughly 2,500, or 3%, of those dams that generate hydropower). The abundance, cost, and environmental favorability (due to utilizing an existing structure) of NPDs make these dams an attractive resource for hydropower development [21].

There are many thousands of miles of existing, man-made conduits in the United States that are used to transport and distribute water and wastewater. Conduit hydropower differs from more typical hydropower development in that it is not located on natural rivers or waterways, and therefore does not involve the environmental impacts that are associated with hydropower [193].

#### *Key Issues and Challenges*

Challenges to developing NPDs, canals, or conduits for hydropower generation include the need for additional comprehensive assessments associated with the existing infrastructure at canals and conduits; concurrence on the type and level of study necessary; complex regulatory processes at the federal, state, and local levels; difficulties in securing project financing; potential operational conflicts between power generation and the existing purpose of the dam; unavailability and costs of transmission and associated facilities; and technological uncertainties associated with the longer-term performance of newer, more innovative, and potentially more cost-efficient technologies [193]. Additionally, development of hydropower on previously unlicensed water management structures may trigger a more rigorous standard for the structure itself than was acceptable prior to the addition of hydropower generation, even if the development changes little about how the structure or the water resource is managed. If a non-federal dam is being equipped with facilities that require a FERC license, for example, the applicant may have to bring the entire development up to current environmental (and dam safety) standards, versus simply addressing the additive effect of, for example, a small turbine.

The design of most existing NPDs, canals, and conduits includes no provisions for adding hydropower at a later time. As such, one of the major challenges in NPD development is avoiding major civil and structural modification. This challenge is exacerbated for smaller projects that may not justify a custom-engineered solution.

Modern principles of clean energy production can be incorporated into the development, and projects can adhere to strict environmental standards. For example, the Mahoning Creek Dam hydro project added 6 MW of generation capacity to a flood control dam and was certified as a “Low Impact” facility by the LIHI Certification Program. Certifications may, in some cases, provide additional benefits in improving the marketability and price of power.

Because they are closely tied to water use infrastructure, development of hydropower projects on canals or conduits may also provide innovative opportunities to further other water management goals such as irrigation, water conservation, enhanced instream flow, and dissolved gas management. Opportunities associated with irrigation systems are often identified in conjunction with comprehensive system analyses looking for efficiencies and conservation opportunities. There are examples of in-canal and conduit projects being carried out throughout the western United States in ways that generate additional benefits, as illustrated by the projects discussed in Text Box 2-6.

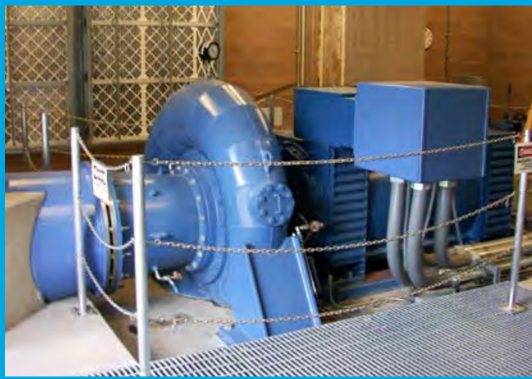
Text Box 2-6.

## Partnering for Successful Conduit Projects

The Juniper Ridge and Ponderosa hydropower projects are in-canal projects located north of Bend, Oregon. Both projects were completed in 2010 and FERC issued conduit exemptions from licensing. The Juniper Ridge Project was constructed by the Central Oregon Irrigation District in conjunction with a 2.5-mile-long canal lining project and has an installed capacity of 5 MW. The Ponderosa Project was constructed by Swalley Irrigation District in conjunction with a 5-mile-long irrigation canal lining project and has an installed capacity of 0.75 MW. Both projects generate power during the irrigation season when water is being conveyed in the canals.

The Juniper Ridge and Ponderosa projects both represent unique partnerships between irrigation districts, the environmental community, the state of Oregon (through state programs like the Allocation of Conserved Water Program and the now defunct Business Energy Tax Credit), and others. These partnerships meet multiple goals, including water conservation, stream restoration, enhanced flows, hydropower generation, energy savings, and more efficient operation for irrigation districts. Oregon's Conserved Water Program allows water rights holders who conserve water to lease or sell a portion of that water (75%, with 25% going back instream), creating a revenue stream to fund development projects like canal lining and piping [203].

The Deschutes River Conservancy worked closely with Swalley Irrigation District and Central Oregon Irrigation District through the Conserved Water Program to facilitate conserved water piping projects and put the saved water back into the main stem of the Deschutes River. Piping projects created head and an opportunity for small hydropower generation at the end of the pipe. Central Oregon Irrigation District and Swalley Irrigation District used



**Ponderosa Hydropower Project** *Photo courtesy Gary Johnson, Pacific Northwest National Laboratory*

funds from the sale of conserved water and assembled a financing package from loans, grants, and other means to fund piping and construction of hydropower facilities. Revenue from the sale of hydropower is now being used to pay back project debt over time.

When projects like this are successful, hydropower is one part of the equation, enabling improvements to irrigation infrastructure as well as conservation of water resources. There are challenges associated with these projects, however, including high utility wheeling costs, uncertainty around fish passage requirements, long payback periods, challenging local siting and permitting issues, and the need for strong coalitions and unique funding arrangements. In addition, funding from ARRA—a stand-alone (vs. recurring) investment—was important for both of these projects. Reducing costs of hydropower technologies, reducing costs of or the need to wheel power to the utility (using it onsite, for example, to offset pumping costs), and reducing siting and permitting costs will likely be needed for future successful project economics. Exploring new ways to fund projects through public/private partnerships and co-locating generation with load could present new opportunities.

## 2.4.5 New Stream-Reach Development

Developing new "greenfield" projects in water bodies with no existing dams or hydropower projects is known as new stream-reach development, or NSD. NSD can also consist of a new dam developed by a non-hydropower entity for drinking water supply or flood control; hydropower facilities can be co-located at such sites. Successful NSD requires consideration for environmental and social impacts that can result from this type of development.

In the United States, dams can provide numerous benefits, including hydropower. However, tens of thousands of non-hydropower dams across the country are obsolete and are no longer serving their intended purpose, and many are in a deficient condition and pose a threat to public safety. More than 1,000 obsolete dams in the United States have been removed in the last century, and with each successful removal the science supporting removal and recovery processes has grown. As a result, locally driven removals of non-hydropower, obsolete dams are occurring at an increasing rate and are reducing public safety risks while improving the health of our rivers. Building on these successes and advancing additional locally supported removals could help complement consideration of NSD potential, where together, the two efforts could increase energy yield while further addressing the widespread environmental and public safety problems of these obsolete dams.

### *Overview of the Resource*

Developers and researchers can use information about river morphology, hydrology, and the locations of existing dams to identify river reaches with untapped hydraulic head. Resource assessments have identified an array of sites with the technically recoverable potential for generating hydropower (Table 2-5; [65]). Assessments at the national scale account for factors that would preclude development, such as designation as a National Park, Wild and Scenic River, or Wilderness Area, but even sites that appear promising when evaluated at the national scale require comprehensive feasibility assessments at watershed or basin scales. More focused assessments direct developers toward the most promising sites, which can then be evaluated further for viability. Detailed assessment would need to consider, for example, the potential presence of threatened and endangered species, cultural sites, and other sensitive or protected resources.

### *Key Issues and Challenges*

To be successful, NSD must incorporate the lessons learned from earlier hydropower development in the United States and elsewhere. These lessons reflect primarily on the need to avoid or minimize environmental and societal impacts. Therefore, the benefits of new hydropower must be evaluated within the context of related impacts to the community, the environment, and other values with the participation of the stakeholders. It is also important to recognize that historical and new dam or conduit construction has not always been driven by hydropower development. As in the past, the purpose or need for new dams may be driven by non-power uses (e.g., water supply, flood control, navigation). The addition of hydropower can be considered in the context of the dam that is being constructed and operated to achieve other purposes. The existence of multiple use benefits could be revealed by conducting more detailed assessments.

NSD efforts are subjected to more scrutiny than refurbishments or NPDs because such development may require construction of a dam or diversion at a previously undeveloped location. NSD site characteristics must be documented and site suitability evaluated as required by the applicable regulatory framework and augmented by basin-scale approaches. Studies to address environmental concerns may have limited baseline information from which to draw, so developers may be forced to collect this information. Developers cannot assume that they can gain easy access to the transmission grid, so additional agreements with land owners and host utilities may be required. Coordination with other hydropower operations and water management activities in the basin may be needed to accurately estimate the timing and quantity of available flows.

The unique nature of NSD can add cost, time, and uncertainty to the development process. Developer costs must be offset by potential payback, which is usually driven by the amount and value of energy that will be generated. These factors have the effect of decreasing the feasibility of NSD in general, and particularly for smaller projects where the payback might not be sufficient to justify the costs. The ability to incorporate multiple uses and benefits could increase the potential payback and could increase the feasibility of development. Efforts to reduce uncertainty would reduce financial risks and help to identify the most feasible sites.

**Table 2-5.** Summary of New Stream-Reach Development Findings by Hydrologic Region

| Hydrologic Region | Capacity (MW) | Generation (MWh/year) | Capacity factor |
|---|---|---|---|
| **1. New England** | 2,025 | 11,791,000 | 66% |
| **2. Mid-Atlantic** | 4,144 | 22,721,000 | 63% |
| **3. South Atlantic-Gulf** | 2,439 | 13,494,000 | 63% |
| **4. Great Lakes** | 1,338 | 7,870,000 | 67% |
| **5. Ohio** | 3,795 | 19,986,000 | 60% |
| **6. Tennessee** | 1,228 | 7,229,000 | 67% |
| **7. Upper Mississippi** | 1,983 | 10,937,000 | 63% |
| **8. Lower Mississippi** | 2,067 | 12,044,000 | 67% |
| **9. Souris-Red-Rainy** | 142 | 737,000 | 59% |
| **10. Missouri** | 10,705 | 63,090,000 | 67% |
| **11. Arkansas-White-Red** | 5,771 | 32,687,000 | 65% |
| **12. Texas-Gulf** | 762 | 3,565,000 | 53% |
| **13. Rio Grande** | 1,103 | 6,237,000 | 65% |
| **14. Upper Colorado** | 1,914 | 11,481,000 | 68% |
| **15. Lower Colorado** | 622 | 3,761,000 | 69% |
| **16. Great Basin** | 547 | 3,008,000 | 63% |
| **17. Pacific Northwest** | 16,958 | 97,859,000 | 66% |
| **18. California** | 3,275 | 18,084,000 | 63% |
| **19. Alaska*** | 4,530 | (not estimated) | (not estimated) |
| **20. Hawaii*** | 145 | 699,000 | 55% |
| ***Total*** | 65,493 | 347,280,000 | 61% |

Note: Excludes stream-reaches in close proximity to national parks, designated wild and scenic rivers, and wilderness areas.
Source: Kao et al 2014 [65]

### 2.4.6 Bridging the Gaps in Hydropower Development

Hydropower development can contribute to advancing a low-carbon future energy system. Building upon Section 2.1 and the preceding portions of Section 2.4, this section discusses three primary concepts for bridging the gaps between the existing hydropower development process and the concepts discussed as part of the *Hydropower Vision Roadmap* (Chapter 4 of the *Hydropower Vision* report):

- Improved collaboration among developers, regulators, and stakeholders early in the development process;
- Planning at the basin or watershed scale to identify opportunities and address issues that may not be evident at individual projects;
- The importance of sustainability, interconnection, and revenue to the viability of a project;
- Consideration of the influence of climate change on water availability, variability, and competing uses; and
- The ability of the project to support grid integration of variable renewables.

Addressing these themes can help reduce costs and uncertainty associated with hydropower development requirements, and thus enhances the potential to accelerate development of additional sources of hydropower.

As an example of collaboration early in the development process, American Rivers has proposed a "Collaborative Development Process" that highlights and encourages the best practices of typical or existing development processes, and which addresses some of the common themes identified in this section [195]. These practices are based on American Rivers' experience in and assessment of hydropower licensing. The proposed development process is based on the idea that the societal value of rivers and watersheds, and the potentially competing uses of these resources, is often overlooked early in the development process. Examples of these societal values and competing uses include navigation, trade, manufacturing and transportation, riverine habitat, recreation, boating, tourism, waste disposal, flood protection, water storage, energy production, cooling and urban development needs [195].

One of the goals of the proposed development paradigm is to reduce uncertainty about a hydropower facility project early in the conceptual design stage, before significant amounts of time and capital have been invested in a design. Additional goals of this new paradigm include resolving as much conflict as possible, creating a focus on broader economic and community benefits versus purely financial returns of the project, identifying and promoting ancillary and grid reliability benefits, and generally easing the permitting process or identifying pitfalls early in the process [195].

American Rivers' proposed Collaborative Development Process includes water users and stakeholders as early as the prefeasibility phase. In doing so, the process facilitates the identification of more than one technical option for the system design, a description of operational alternatives, and more refinement of the elements in the feasibility assessment to incorporate the needs of relevant user groups. According to American Rivers, the permitting phase would no longer be a discovery process for regulators and community groups, but rather a confirmation of the work and efforts in previous stages [195]. Tackling uncertainties in a collaborative manner, early in the development process, holds the promise of reducing unexpected delay or expense during the permitting phase.

As discussed previously, basin-scale or watershed planning enables project developers and other stakeholders to evaluate various social, economic, and environmental values across multiple projects and in the context of other water uses. Such an approach facilitates the evaluation of a more comprehensive range of options and is more likely to identify the best means to achieve multiple goals over the entire basin or watershed. Although hydropower's environmental performance has been and can continue to be improved through project design and operation (e.g., environmental flow releases, fish protection and passage, water quality), other important potential impacts and benefits from hydropower development (particularly new dams) cannot be fully evaluated for mitigation strategies if examined only at the level of an individual dam. Without proper planning and siting at the river basin or "system" scale, opportunities for more optimal and balanced outcomes can be missed, such as meeting energy needs while maintaining and protecting other key environmental and social values in a river basin [204].

The Nature Conservancy has developed a simple framework that can build and compare development scenarios in an iterative fashion, seeking balanced outcomes across multiple values [204]. The framework focuses on the scale of a large river basin and is illustrated with analysis of a hypothetical river basin—though hypothetical, the data were adapted from real-world geographical information for three value sets: economic (hydropower capacity and cost of energy); indigenous/social values as represented by indigenous reserves; and environmental/ecological values, represented by a biodiversity "portfolio" and connectivity of the river system. The analysis compared twelve development scenarios [204].

The key result from Nature Conservancy analysis was that, for a given energy output, there was a fairly wide range in the output of other values. This example supports the hypothesis that, through river basin-scale planning, energy targets can be achieved with a more balanced output of other river values than can be achieved through individual project selection, with no significant difference in cost [204]. The Nature Conservancy's 2015 publication, "The Power of Rivers," discusses hydropower expansion scenarios that balance for community and environmental needs. The analysis discussed in the report models impacts to river flow patterns and connectivity networks to estimate potential impacts from hydropower expansion [205].

Interconnection and revenue are also important aspects in considering hydropower development. Various industry groups such as the Interstate Renewable Energy Council have been working with state public utility commissions to improve interconnection procedures by identifying and promulgating procedural best practices [206]. One such practice is to make available a pre-application report, which can enable project developers to better choose appropriate locations [193]. Related federal efforts to improve interconnection include FERC Order 792, issued in November 2013, which establishes new rules for small generator interconnection agreements and procedures. At the state level, California's Rule 21 describes the interconnection, operating, and metering requirements for generation facilities to be connected to a utility's distribution system [193]. If interconnection requirements are simplified and costs can be reduced, these factors can become less of a barrier to hydropower development.

## 2.4.7 Trends and Opportunities

Trends and opportunities for Hydropower Development include:

- Enhancement of stakeholder engagement and understanding within the regulatory domain and improvement in the predictability in scope and timeline, and collaboration among stakeholders, to aid licensing and permitting processes. These activities and others should help provide insights into achieving improved regulatory outcomes.
- Evaluation of the environmental sustainability of new hydropower facilities to increase appreciation of the importance of sustainability to the viability of a new project. Likewise, acceleration of stakeholder access to new science and innovation and analysis of policy impact scenarios should contribute to achieving regulatory objectives.
- Simplification and standardization of the grid interconnection process to aid development of small hydropower.
- Implementation of a basin-scale or watershed approach to hydropower development to offer more opportunities than a single plant approach and provide additional options for potential benefits to all stakeholders.
- Improvement in integration of water use within basins and watersheds. This might be achieved by identifying pathways to improve both hydropower values and environmental conditions within a river basin simultaneously, such as through basin-scale planning, especially in the context of resiliency to climate change.
- Increasing resilience of water management systems, hydropower generation, and ecological systems to climate alteration.

These trends and opportunities can help accelerate the development of new low-carbon hydropower generation.

# 2.5 Design, Infrastructure, and Technology

Hydropower facilities have a number of unique features, including certain structures, operating systems, and generating equipment. Though existing hydropower technologies are mature, advanced, and efficient, there are opportunities to increase hydropower potential through technology innovation and cost reduction. This section discusses opportunities for improvements in hydropower plant design and construction, technologies to increase generation efficiency, cost reductions, and designs that meet environmental obligations. Special attention is given to advanced and innovative technologies that facilitate hydropower development; e.g., the technology advances described in this section are relevant to hydropower refurbishments described in Section 2.4, Hydropower Development.

### Highlights:

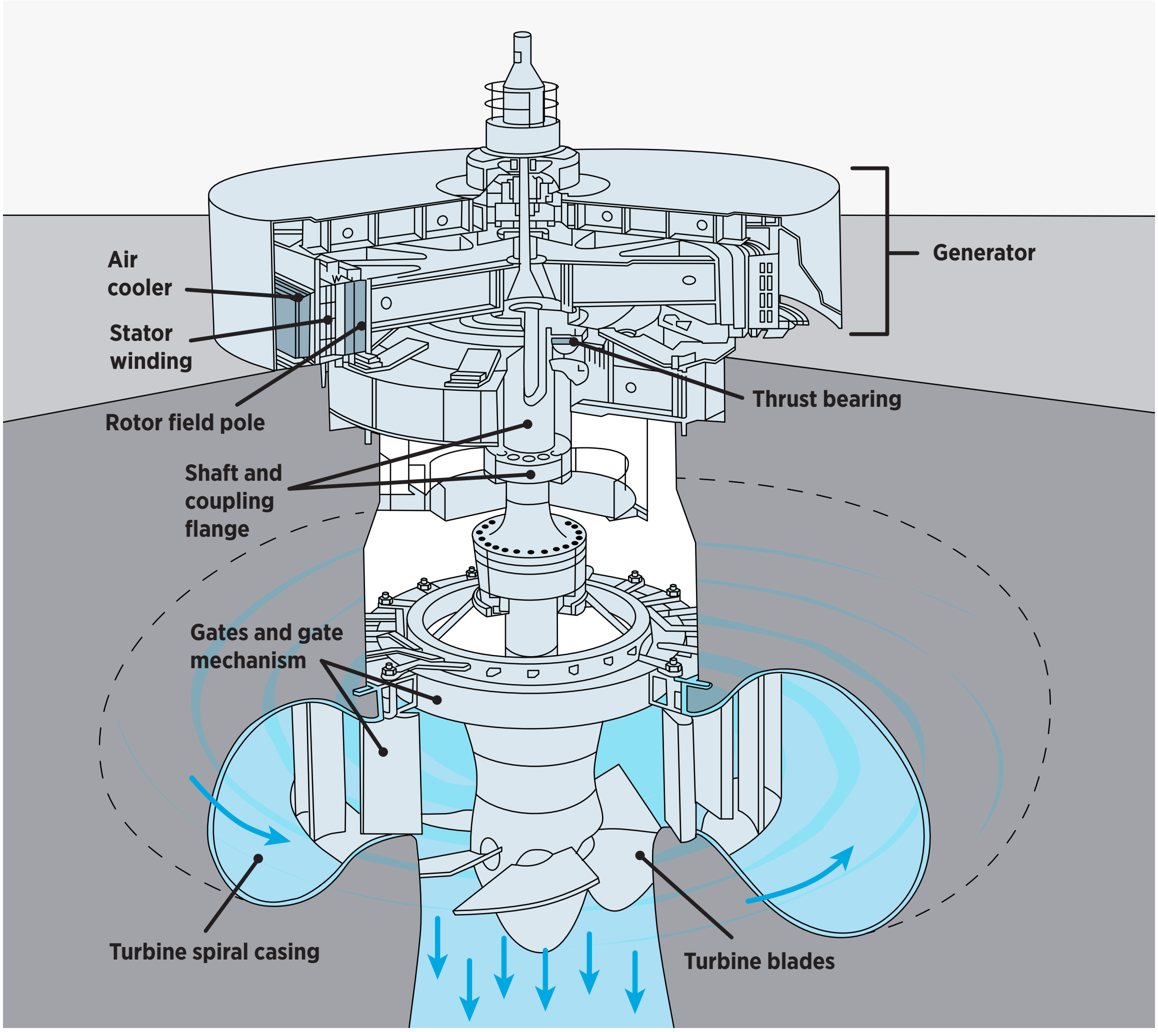
- Advances in research and design of hydropower facilities are ongoing, covering civil structures, turbines, electrical components, governors, and instrumentation, control, and monitoring equipment.
- Technology advances will reduce the cost and construction time of civil structures. Important advances include modular and segmental design, precast systems, smart concrete technology, and rock-bolted underpinning systems.
- Advancements in powertrain technologies, equipment manufacturing, and project design will also help reduce costs, thereby improving economic viability.
- Environmental protection technologies, such as fish screens, aerating turbines, and surface flow outlets, have been developed to avoid or minimize the impact of hydropower operations.

## 2.5.1 Uniqueness and Types of Hydropower Projects

Every hydropower facility is sited and designed in response to unique location-specific factors. Factors related to siting a hydropower facility include but are not limited to the local geography, topography and geology, characteristics of upper and lower reservoirs, elevation, distance between reservoirs, flow between reservoirs, environmental and competing use constraints, and transmission connections. Because any given site is characterized by a distinct combination of these factors, each facility is usually customized. Designs take into account civil issues related to site access; reservoir creation; water conveyance from one reservoir to another; powerhouse construction, including excavation issues; equipment design parameters such as number of units, unit size, unit speed, unit setting, and substation design; and issues related to environmental effects. The power train components that go into the design of a hydropower generating unit are shown in Figure 2-34. The optimum solution is often measured in economic terms, and a custom-engineered design must balance these factors against cost, construction time, and environmental considerations.

### *Types of Hydropower Facilities*

A wide variety of hydropower facilities exist, including small and large projects; facilities with dams, spillways, and impoundment reservoirs; facilities with a diversion system and no dams; facilities in conduits (canals and pipelines); facilities that are run-of-river with no active water storage; facilities with a variety of reservoir storage uses; and PSH (discussed in Section 2.5.1.2). A hydropower project can have a reservoir created by a dam, barrage, or diversion point that channels water into a tunnel, pipeline (penstock), or canal. Regulating gates and equipment are typically located at the point of diversion where water is transported to a powerhouse. In some cases, the powerhouse is a part of the dam, connected with a short water conduit or pipeline. The elevation difference from the water level at the point of the diversion to the water level on the downstream side of the powerhouse is often referred to as the gross head, and energy lost in moving water to the power plant from the upper reservoir is usually referred to




Source: Artinaid [209]

**Figure 2-34.** Example of the power train components of a representative hydropower plant

as head loss. It is the combination of the available net head (gross head minus the head loss) and water flow rate that provide the hydraulic power of water.

**Impoundment Systems.** An impoundment system contains and stores water. Impoundment systems can be entirely natural, such as a lake or river, or water in a cave or cavern. Man-made impoundment systems like large tanks or underground mines are also common. The most familiar man-made impoundment is the water behind a dam, normally constructed of earth, rock-fill, or concrete. Manmade impoundments have a spillway, which allows water to be transferred safely downstream when an excessive amount of water is flowing into the impoundment. This ensures that public safety is not jeopardized, nor is the safety and integrity of the structures forming the impoundment. Reservoir impoundments can be shallow (<10 feet) or deep (>100 feet). Depending on the size of the impoundment, the volume of water can range from one thousand gallons to billions of gallons.

**Diversion Systems.** The act of channeling water into a tunnel, pipeline, or canal is referred to as diversion. In these types of projects, water is diverted from the reservoir, lake, or river through a water conduit to the hydraulic turbines in the powerhouse for hydropower generation. Water can also be diverted for other purposes, such as environmental flows, irrigation, or municipal use. Diversion systems may include pump stations at the point of diversion to facilitate water distribution for the various uses. Water can also be diverted into a spillway or other man-made structure.

Diversion systems can include intake gates with hoists, trash racks, stop logs, or flow measurement devices. A newer type of diversion is the coanda screen, a stationary intake screen placed over a channel within a water overflow concrete structure that diverts water into a pipeline or canal. The screen is largely self-cleaning, using the natural flow of water, and the screen mesh is tight enough that it prevents trash, larger sediment, and fish from entering into the channel. Another type of diversion is created by a rubber dam or Obermeyer crest gate. During flood events, these structures can be lowered to allow flood flows to pass, and then raised again for storage and for directing the flow into diversion structure once the flood flows pass over.

**Conduit (Canal and Pipeline).** There are thousands of miles of canal and pipeline within the United States that convey water. Conduit hydropower could use existing infrastructure to manage the potential hydraulic energy. For canal installations, there is an intake structure, a conduit, and a powerhouse and substation. There are typically no reservoir impoundments in canal or pipeline systems, though there may be one upstream of the canal or pipeline. Such an impediment would be used for water delivery, and not for producing hydropower. All conduit hydropower development must incorporate a mechanism to bypass water and prevent any interruption in the water delivery system.

Conduit hydropower projects use the head between two water levels within a canal, or the available pressure within a pipeline system. These installations typically have relatively constant net head, flow, and water velocity. There are cases in which flow and water velocity can vary, but they are generally still predictable within an annual cycle. This makes the determination of installed capacity and energy estimates for a prospective hydropower installation more reliable, and reduces the climatological and flow variability risk associated with a typical run-of-river installation. These benefits are attractive from a development and investment standpoint, because, typically, the uncertainty regarding hydrologic prediction and climate change is a prime concern to investors.

**Run-of-River Projects.** Run-of-river hydropower projects are characteristically situated within a stream or river system, and pass water at roughly the same rate as it enters the reservoirs behind the dams to generate electricity. Typically, they are configured to minimize interruption of the natural stream and river flow conditions, often using water-level sensors to keep specific levels constant. A diversion structure guides river water into an intake, where it is transported through a penstock to a powerhouse and substation. An overflow structure allows large river flood flows to pass safely.

Run-of-river projects experience a range of flows that vary throughout an annual and year-to-year hydrologic cycle. Typically, the run-of-river flow rate is predicted using streamflow gauge measurements from prior years, but there is no guarantee that the flows experienced in one year will be consistent with the flows experienced in another year. In some cases, an existing reservoir upstream of a proposed run-of-river project can actually make flow estimates more predictable. The net head is also predictable for many run-of-river projects.

**Storage Projects.** The term “water storage” typically refers to the collection and storing of naturally flowing water and passing it at a later time. In hydropower facilities with storage capabilities, water is stored for a limited time and then released to meet energy demand. This type of storage is broadly classified as either peaking or pulsing. Storage projects are mostly used for peaking generation to meet water or energy demand at a given time by delivering stored water to the generating equipment during a shorter, concentrated period. Most peaking facilities will only generate electricity during certain hours of the day, when energy demand is highest. Water and energy peaking can vary widely to suit a variety of industrial, commercial, and residential requirements. Additionally, these projects are often used for pulsing to increase or decrease stream and reservoir flows within a set time period (day, week, month, or year). Typically, pulsing is a human-regulated operation in which reservoir storage is released to create a desired set of flow conditions downstream, but it can also be scheduled to coincide with naturally occurring flows, like a snowpack melt during the freshet (spring thaw) period. Pulsing can be used to enhance environmental conditions, meet social requirements such as recreational flows, and create favorable generation conditions in downstream hydropower facilities. Operating storage projects require an operating guide or "rule" curve which is function of the multi-purpose demands and requirements of the project, mainly flood control, recreation, irrigation, water supply, and others.

### *Pumped Storage Hydropower*

PSH is a unique type of hydropower that offers the ability to store and return large quantities of energy. The typical mode of operation for PSH is to pump water to an upper reservoir during off-peak times and use it generate later to meet peak grid requirements. PSH is the only grid-scale energy storage technology that has been used extensively for more than 100 years. PSH uses an upper reservoir to store energy in the form of water that has been pumped from a second reservoir at a lower elevation; this can be in either a closed or open loop. This stored energy is then released during periods of high electricity demand, in the same manner as a traditional hydropower station. The upper reservoir is recharged during periods of low energy prices by pumping water back into the reservoir when energy supplies are more abundant and the cost of energy is often much lower. This energy storage ability allows for a more optimal dispatch of all generating resources to meet the constantly changing electrical demands of consumers. Typically, PSH roundtrip efficiency is about 80%. PSH is discussed in detail in Section 2.7.

## 2.5.2 Primary Features of Hydropower Facilities

Hydropower facilities generally comprise civil structures; turbines; electrical components; governors; and instrumentation, control, and monitoring equipment. Advances in research and design in all areas are being pursued by the hydropower industry, as described below.

### *Civil Structures*

Hydropower dams impound water by forming an impervious barrier across a channel. The civil structures associated with hydropower developments are commonly the most extensive and costly components of a project, often 50% of total project costs. They are, however, essential to hydropower generation. "Civil structures" (sometimes also called "civil works") is loosely defined to include dams, spillways, powerhouses, water conveyance systems, and, where appropriate, facilities to protect or allow the passage of fish.

**Dams.** There are thousands of dams in the United States serving multiple purposes, including flood control, irrigation, water supply, navigation, and hydropower. These dams come in many shapes and sizes, and have proven to be reliable and safe. The rare cases of dam failure have most often been due to foundation failure or to a structure that was not engineered correctly.

Modern dams may be classified as gravity, embankment, arch, or a combination of these. Gravity dams are generally concrete or masonry structures that impound water using only the weight of the dam structure. Embankment dams comprise earthen or rock-fill embankments watertight by a central impervious core of clay or similar material, or an impervious upstream face of reinforced concrete, asphalt, or a synthetic polymer. Buttress dams use a series of concrete counterforts that support an impervious face. The buttresses transmit the water load to the foundation. Arch dams impound water, the forces of the impounded water compresses the arch dam, thus, transferring force to the dam abutments. The most well-known arch dam in the United States is probably the Hoover Dam. Structural configurations for dams include concrete arch, concrete gravity, roller compacted-concrete arch, and roller compacted-concrete gravity. Concrete-face rock-fill dams are a combination of rock and reinforced concrete.

**Spillways.** Dams include a structure to allow the discharge of river flows that cannot be passed through the turbines or other water works. These structures are generally referred to as spillways. Once the available storage capacity of the reservoir has been used, the spillway discharges flows that exceed the capability of the turbines. Spillways are sometimes used to discharge flows for environmental reasons ranging from fish passage to aeration of the water. Spills (flows) from the spillways of large, high dams may result in high levels of total dissolved gas (TDG), which is a significant environmental concern with regard to fish.

Since spillways must contain the flow of water without damage, they are generally concrete and may be incorporated into the dam structure. The simplest spillway has no gates or other regulating systems, and consists of a curved concrete shape in cross-section that passes flows when the elevation of impounded water exceeds the crest of the spillway. More complex spillways are equipped with various types of flow control systems, such as Tainter gates, slide gates, sluice gates, and drum gates, among others.

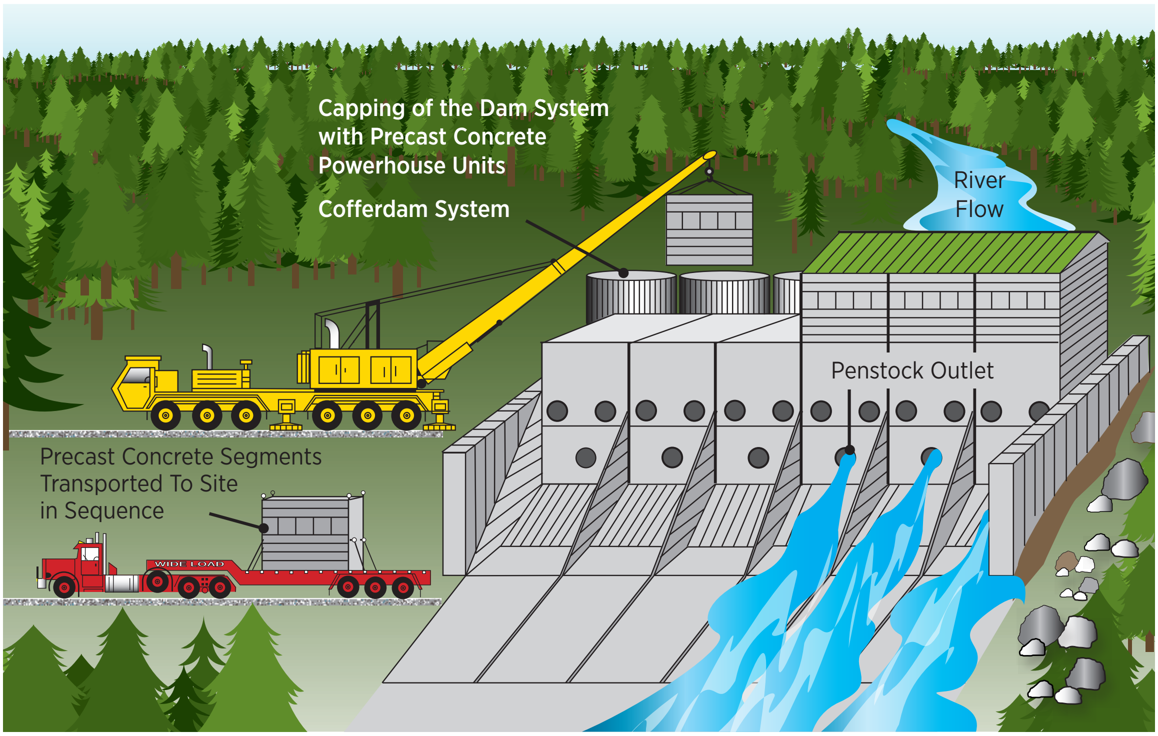
Spillways generally discharge water past the dam into the downstream river channel. Variations include spillways discharging into an underground water passage, or spillways built into side channels in the surrounding topography. Some spillways are gated and some are ungated.

**Water Conveyance Structures.** Water conveyance structures for hydropower plants, generally controlled by gates, carry flows from the reservoir or impoundment to the turbines. These water conveyance structures are typically a penstock connecting an intake structure in the reservoir to the turbines, or a canal extending from the impoundment to the plant's intake structure, or a turbine intake at low head project. A water conveyance system that discharges minimum flows for fish or habitat protection may also be built into the dam or reservoir.

**Powerhouses.** The powerhouse is the structure that contains the turbines, generators, and associated controls. Depending on the size of the system and number of turbines, the powerhouse may also have an assembly bay where equipment can be overhauled. For small hydropower plants, the powerhouse may operate remotely and contain only the turbines and generating equipment, with maintenance and inspection conducted by centrally dispatched teams as needed. Though less common, large multi-unit projects may also be operated remotely.

Powerhouses may be completely enclosed facilities, outdoor, or semi-outdoor facilities in which weatherproof equipment is outdoors or under hatches, or located entirely underground. The selection of design depends on the location, topography, and type of project.

**Fish Protection and Passage Facilities.** Fish protection and passage are important features at some hydropower projects, especially those where migratory species are present. To protect aquatic resources, projects may employ a variety of techniques, such as fish ladders that provide an upstream migratory path for fish to pass a dam, fish screens, and associated bypass systems and outfalls to reduce fish entrainment into turbines; and fish collection techniques to facilitate the physical transportation of fish around hydropower facilities.




Source: French Development Enterprises [210]

**Figure 2-35.** Conceptual depiction of a small hydropower construction operation involving an intelligent precast system

**Advancements in Research and Design of Civil Structures.** The following advancements in research and design of dams are being implemented to help reduce the cost of civil structures and minimize construction time:

- **Modular and Segmental Design:** Modular and segmental technology facilitates the development of a standardized family of structures designed to accept multiple equipment types, which facilitates flexible service and upgrade options. Onsite installation can be done in a fraction of the time needed for traditional methods and using standard construction equipment. Modular and segmental technology can be used for construction of the entire dam, including upper and lower stream spillways.
- **Precast Systems:** A precast modular system is a combination of factory-manufactured concrete segments that are connected together to become a larger structure (Figure 2-35). Precast concrete segments are prepared, cast, and cured at a specially equipped off-site location (i.e., not co-located with the hydropower facility). Once precast concrete segments pass quality controls, they are stored to await delivery and are transported as needed for onsite installation.
- **Glass Fiber Reinforced Concrete:** Glass fiber-reinforced concrete is a cement-based composite, with alkali-resistant fibers randomly dispersed throughout the product. The fibers serve a purpose similar to the steel in reinforced concrete, which is placed primarily in tensile stress areas. Using this advanced precast concrete method may result in an increased product lifespan of the structure.
- **Smart Concrete Technology:** Adding conductive carbon fibers to a precast concrete structure enables the material to provide real-time load information on the structure, thus allowing structural engineers to identify trouble spots long before stress or cracking is visible to the human eye.
- **Rock-Bolted Underpinning System:** A GPS-guided, rock-bolted underpinning system provides linkage to the riverbed, allowing for ease of installation and fastening of the structure into place. Each segment is secured to the riverbed or an existing retrofit dam by multiple rock bolts, each of which is capable of sustaining large loads.

### *Turbines*

In a hydropower facility, turbines harness the kinetic energy in flowing water. To do so, water is channeled into and through the turbine, which drives an electrical generator or other mechanical device (pump, grinding machine, saw, or grist mill). The power captured depends on the head and the flow rate (volume per unit time) of water through the turbine. Water passing through the turbines forces the rotational movement of turbine blades, which are attached to a shaft. This movement causes the shaft to rotate. The shaft is typically connected to a generator, which transforms kinetic energy into electricity. (Text Box 2-7)

Turbines usually consist of four parts:

- The inlet portion, or penstock, bringing water into the turbine;
- The turbine casing with flow regulation, which surrounds the runner;
- The runner being the moving part inside the turbine, which rotates a shaft; and
- The water conveyance or draft tube that returns water to the river below the dam.

Text Box 2-7.

#### Cavitation: Bubbles vs. Steel

Cavitation is a phenomenon that affects reaction turbines when, under certain operation conditions, vapor bubbles form and collapse due to rapid pressure changes in the water moving through a turbine. When the vapor bubbles collapse, they generate shock waves that create pits on the metal surface. Damages caused by cavitation include erosion of material from turbine parts, distortion of blade angle, and loss of efficiency due to erosion/distortion. Cavitation damage is usually the most costly maintenance item on a hydroelectric turbine because of the unexpected shutdowns and unplanned maintenance required for repairs. Design measures can be implemented to prevent cavitation damage, such as minimizing pressure variations, increasing material hardness, and using cavitation-resistant surface coatings.

All turbine components are selected based on the parameters of the site to both maximize power generation and assure economic and environmental feasibility. Typically, turbines are custom designed for to meet site specifics.

There are two general categories of hydraulic turbines: reaction and impulse. Reaction turbines convert the hydraulic head and flow passing by the turbine to rotational energy created by the airfoil shaped blades, whereas impulse turbines turn a runner by absorbing the impact of high velocity jets of water striking the runner buckets. There are many types of turbines, designed for use at sites with differing flows and heads. The three most common types are the Francis, Kaplan, and Pelton turbines (Figure 2-36). The Francis and Kaplan turbines are reaction-type turbines; the Pelton turbine is an impulse-type turbine.

The first modern turbine invented was the Francis turbine, which is used at sites with medium heads and flows. Francis turbines are high efficiency, allowing them to be used for a wide range of heads (from 10 meters to 600 meters). These turbines are usually customized for each site and can be configured either vertically or horizontally. Francis turbines also typically have adjustable wicket gates, which guide flow to the turbine runner in an optimized manner.

In a Kaplan turbine, both the blades and the wicket gates are adjustable. This unique adaptability allows for consistently high efficiencies over a range of flows and heads. In the 100 years since the invention of the Kaplan, a variety of configurations of the turbine have been developed, including the Z, S, pit, vertical, and bulb turbines. Each variation of the Kaplan turbine can be double regulated, meaning the turbine adjusts its runner blades and wicket gates to regulate turbine output for changing water conditions.

The Pelton turbine is best for high head sites and lower flow rates, such as in the mountains. A number of jets (1–6) direct water at high velocity towards the turbine buckets, causing the turbine to spin in air.

The primary factors critical for turbine selections are:

1. Site-specific considerations, such as available head, available flow rate, derived flow duration curves, site conditions, and environmental considerations;
2. Reliability and safety, which includes the turbine equipment as well as its operation and maintenance in order to prevent uncontrolled releases and possible mechanical issues; and

Photo credit: Mavel

**Figure 2-36.** Examples of Francis, Pelton, and Kaplan turbines

3. Economic feasibility, which will depend on turbine price, turbine performance, and civil structures requirement.

Turbine technology has evolved due to advanced computer-based design, analysis, manufacturing, and control methodology. Performance advancements include increased operating efficiency, effective control of cavitation as a wear mechanism, and improved operating range, operational quality (smoothness), and reliability. For waters with high levels of silt, special turbine designs have been developed to minimize erosion of components. Advanced turbine designs can also incorporate features that enhance environmental conditions, which can lead to improvements in fish passage survival and increases in dissolved oxygen levels in water flowing through the turbines. Significant capital investment toward modernizing and upgrading the fleet is consistently taking place, leaving potential for better use of water for power at existing dams and hydropower sites [2].

Many of the large international companies that manufacture turbines have subsidiaries which are adapting the efficient hydraulic designs of bigger turbines to cost-effective manufacturing, packaging, and installation. These solutions are being implemented in the small hydropower market, resulting in turbine systems that are affordable, efficient, reliable, and easy to install. For example, the vertical micro Pelton turbine applies the concept of a typical Pelton turbine and implements composite runner buckets into a package-type generating unit for small rivers with relatively low discharge and high head [211].

Innovative turbine technologies for small-scale hydropower have entered the market. Archimedes' screw turbines, for example, are becoming increasingly popular in low-scale hydropower. Screw turbines are used on low head/high flow sites, and can produce 5–500 kW of electric power. Due to their low rotational speed and wide diameters that prevent pressure buildup, screws allow better fish to pass downstream than for conventional turbine. Additional small hydropower (<10MW) turbine technologies were identified by the Small Scale Hydro Annex Task Force of the International Energy Agency.[67]

Research on additive manufacturing techniques holds promise for fast and efficient production of modular structures and turbine components. The term "modular" refers to precast, pre-assembled, and/or standardized components that would otherwise be site customized in traditional hydropower design. Additive manufacturing of modular components has the potential to reduce time and costs associated with fabrication and installation. Furthermore, composite materials used in additive manufacturing have the ability to make turbine components lighter and add a variety of properties, such as increasing material strength.

### *Electrical Components*

As water passes through turbines, the energy from the moving water is converted to a usable form, electrical energy. This section highlights the electrical components responsible for this conversion. Local conditions and the characteristics of the electricity grid are key factors in selection of the major electrical components for a particular hydropower facility. To make successful design decisions, developers must address several questions, including: What is the expected dependable power output capacity from the project, expressed over a 12-month water cycle and the expected ambient temperature? Will any local load service (disconnected from the main grid) be required? What type and magnitude of faults on the local grid will the generator need to be protected from, and are these expected to change over time? Will grid restoration by the generator be required? What method (dispatcher controlled, local operator) and requirement (start-on-demand, spinning reserve) will be needed for generator load response?

**Generators.** Generators connect to the hydraulic turbine and are used to convert the mechanical torque of the rotating waterwheel to electrical power. All large hydropower generators connect directly to the turbine shaft and thus have the same rotational speed as the turbine. Two types of generators are commonly used at hydropower plants: synchronous and induction. Virtually all hydropower generators are the synchronous type, where the generated frequency is synchronized with the rotor speed. Synchronous generators consist of a stator winding, field winding, and bearings for mechanical stability. The typical field winding of a synchronous generator is arranged on a series of poles around the periphery of the rotor and energized from a DC voltage source provided by an exciter.

Induction generators differ from synchronous generators in that the voltage frequency is regulated by the power system to which the induction generator is connected. Induction generators require reactive support from the grid and are thus more commonly used in locations with grid interconnections that do not require the machines to supply voltage support or black start. In cases where there is no grid interconnection, such as in rural distribution systems, induction generators can use step-up banks and distribution circuits to provide this reactive support.

67. These innovative technologies can be reviewed in more detail on the Small Hydro International Gateway of the International Energy Agency Small Scale Hydropower Task Force [211].

**Exciters.** Exciters supply the DC power necessary to energize the field windings of synchronous generators, as well as to control the generator voltage and reactive power to ensure stable operation of the power system.

Most modern generators use a static excitation system, while high-speed machines will often use a brushless exciter. In a static exciter, all components are stationary and the DC power results from the generator output itself. Brushless exciters are a form of rotating exciters where a rectifier (responsible for converting AC to DC) is mounted on a shaft that rotates to transfer the DC power to the generator field.

**Step-up Transformers.** Transformers are used in virtually all hydropower applications to step up (increase) the generator output voltage to the grid voltage; therefore, these components are the primary link between the power facility and the transmission network.

Mineral oil is commonly used for insulation in generator step-up transformers. Care needs to be taken to prevent accidental discharge of the fluid into waterways by using oil confinement techniques. As an alternative to mineral oil, insulating fluid derived from renewable vegetable oils can also be used to provide improved fire safety and environmental benefits.

**Advancements in Research and Design of Electrical Components.** Small, low-head hydropower projects have historically relied either on low efficiency induction generators that usually require some type of speed increaser or a synchronous generator. Both induction and synchronous generators have efficiency problems, since they operate at fixed speeds, while turbines need to operate at varying speeds at different heads to remain efficient. Variable-speed Permanent Magnet Generators (PMGs) offer higher efficiency over the entire range of optimum turbine speeds. Permanent Magnet Generators were developed for the wind industry, but are also being adapted and introduced into the small hydropower market.

The hydropower industry is increasingly examining ways to optimize the response of the excitation system to improve system stability under various types of disturbances. Excitation controls have historically been calibrated to respond to an expected system configuration and load flow, which is constantly changing. Industry is using new control techniques with neural network topology and fuzzy logic, a technique used for solving problems using pattern recognition of trained data sets, to optimize controller response to changing system conditions. Such optimizations will allow the system to operate more efficiently without compromising safe margins of system stability.

Sulfur-hexafluoride ($SF_6$) is being used as an alternative to insulating fluid, and custom insulation systems with temperature ratings to Class H[68] (180 degrees Centigrade total temperature) have also been developed. These custom systems allow self-cooled installations for sites with high ambient temperature. Industry is also designing shell form three-phase transformers that can be shipped in four disassembled packages. This allows for remote locations that would otherwise incur a cost penalty for use of single-phase tanks for a generator step-up transformer to use a three-phase installation.

### Governors

The speed governor is responsible for two critical functions in a hydropower facility. First, it controls the speed of the turbine-generator unit during start-up and shutdown, and automatically increases or decreases turbine output when the unit is on line in order to respond to grid frequency fluctuations ("grid responsiveness"). Second, it protects the power facility's civil and mechanical structures by controlling the opening and closing times of the wicket gate to limit under-pressure on start-up and over-pressure on shut-down, respectively.

Governor type refers to the methodology involved in detecting unit speed, comparing it to a reference set-point, and producing an error signal that is transmitted to the pilot control section of the hydraulic power unit, which produces the actual change in servomotor (or wicket gate) position and unit speed/frequency. All hydropower governors operate in a closed-loop manner, meaning they must have real-time feedback of both servomotor position and unit speed in order to perform adequately. All hydropower governor types perform the same primary functions and have similar sensitivity to speed and frequency changes. There are three primary governor types—mechanical, analog, and digital. The following descriptions highlight speed sensing in each governor type and identify similarities among the types:

68. The insulation rating is the maximum allowable winding temperature of a transformer. Insulation systems are rated by standard National Electrical Manufacturers Association classifications according to maximum allowable operating temperatures. Class H is the highest insulation class, with a maximum winding temperature of 180 degrees C.

- **Mechanical Governor:** Speed sensing is done using a Permanent Magnet Generator mechanically connected to the generator shaft, or, in some cases, by a Potential Transformer electrically wired to the generator stator. Some older units still have flyball speed detection governor. When actual speed deviates from the speed setpoint, the rod is moved up or down, which in turn causes the downstream governor mechanisms to process the error and produce a corrective hydraulic output from the pilot valve.
- **Analog Governor:** Speed sensing is done using a pair of magnetic pick-ups, which produce an AC signal of varying frequency. Electronic modules in the governor compare the actual speed with the speed setpoint and develop a corrective hydraulic output from the pilot valve.
- **Digital Governor:** Speed sensing is done using a Potential Transformer electrically wired to the generator stator, and/or a pair of magnetic pick-ups that produce an AC signal of varying frequency. Electronic modules in the governor compare the actual speed(s) with the speed setpoint and develop a corrective hydraulic output from the pilot valve.

Though mechanical governors are the dominant type of governors in service at hydropower plants, they are no longer manufactured due to their high cost. Analog governors have more functionality over mechanical governors but still have more hardware components than a modern digital governor [212]. As a result, digital governors—with their lower cost and versatility through software programmability—are the default governors for new installations or replacements. The key factors in governor selection relate to the location of the software algorithms (whether they are standalone controllers or integrated into a larger unit/plant controller) and the arrangement of the feedback devices to the controllers (whether they are direct-wired to the controller or wired to a remote input/output module that communicates to the controller indirectly over a plant communication network). Critical parameters like speed signals and position feedback signals must be direct-wired to eliminate signal latency and ensure that the governor algorithms are working with the most current speed, position, and turbine output data.

The underlying algorithms (known as Proportional Integral Derivative, or PID) that manage the response of a digital governor to speed and frequency deviations have remained largely unchanged for 50 years. Original equipment manufacturers and third-party governor providers typically supply setpoint algorithms that provide similar improvements in governor response to on-line setpoint changes. Other advances to increase the availability of digital governors are redundant speed sensing, position sensing, electrohydraulic control valves, power supplies, and programmable logic controller input/output modules.

### *Instrumentation, Controls, and Monitoring*

Instrumentation, Controls, and Monitoring (ICM) provide hydropower facility operators the ability to supervise proper operation of equipment. ICM functions like a “virtual” operator, allowing for the starting of generators or investigation of plant conditions without the delay of waiting for a roving operator. ICM allows operator responsibilities to be automated to a greater or lesser extent, depending on the need to attend to other plants or other process requirements (e.g., river flow control). For facilities controlled from a dispatch center, ICM provides remote capability to perform equipment supervision that would normally only be possible locally.

Programmable logic controllers, Supervisory Control and Data Acquisition (SCADA), and Distributed Control Systems each represent particular digital computer-based implementations of ICM. Programmable logic controllers are industrial control platforms adapted to specific machine control requirements of hydropower facilities. Programmable logic controllers provide distributed controllers at the hydropower facility, allowing control actions to be determined rapidly in response to local conditions, independent of operator intervention or communication with the main watershed controller.

SCADA systems provide for directed control of operations (starting, stopping, load changing) from a remote location (the master station) via operator actions. Alarm reporting and response are design features of SCADA systems that allow the operator to directly recover from abnormal plant conditions that might otherwise lead to generator shutdown. Other than automatic water flow control algorithms at the master station, operations via a SCADA system are manually controlled, requiring nearly continuous attendance by the operator at the master control console.

Distributed Control Systems are locally networked controllers, providing process- or machine-specific control capability along with remote communications and data archiving. Typical applications would include a multiple generator powerhouse with a local control room.

ICM systems were originally designed for attended (manned) hydropower facilities operating under local control. Remote visibility was typically not a design requirement for these ICM installations, meaning that even visibility in the plant control room may not have been available. Remote control actions in these settings were communicated via voice commands from a central control center and executed by the local operator. Critical variables that could normally be observed by a local operator should be considered when remote control capability is being added to hydropower facilities originally designed for local control in order to properly monitor plant performance and condition. Remote control may be desired as a means to allow centralization of operations personnel and dispatch functions. In cases where local control will still be allowed, coordination of controls design is critical for safety of personnel, equipment, and the public.

ICM systems for remote and automatic dispatch of hydropower generators must provide key safety features to prevent development of hazardous conditions for personnel, equipment, or water conveyance features. The local mode of control must prevent any remote operation of equipment, and local hardwired protective control functions cannot be disabled by the remote ICM system without creating a continuous alarm notification of the abnormal condition. The control system must also be designed to respond appropriately to avoid or reduce damage despite single component failures, considering the range of normal, abnormal, and emergency modes of operation. Appropriate ergonomic and cognitive features must be included in the ICM system design to avoid alarm fatigue and visual strain for personnel over 12-hour shifts.

Advances in research and design of instrumentation, monitoring, and control equipment include "Plug-and-Play" controls, and development and implementation of Generic Data Acquisition and Control Systems. Generic Data Acquisition and Control Systems are a computer-based industrial control system that automates operation of a system of devices used to control dispersed assets. The Generic Data Acquisition and Control Systems product contains commonly available building blocks for constructing scalable systems, and specializations for hydropower optimization and water control applications. Solar and wind energy both make increasing use of standardized equipment referred to as "plug-and-play." This standardization and ease of use can simplify and accelerate installations. Small, mini, and micro hydropower systems can benefit from this same approach. Equipment for each small hydropower system is historically custom designed. A standard control package that "plugs" into specific generators could make installation simpler, even for less experienced developers. Plug-and-play controls can be integrated into standardized modular turbine-generator systems for small hydropower, resulting in easier and less expensive project implementation.

## 2.5.3 Computational Tools for Hydropower

Advanced computational technologies are used by developers, engineers, and researchers in a wide variety of hydropower applications. These include hydraulic design, river forecasting, water quality modeling, and water use optimization. Often, super computers are used to run the models.

### *Hydraulic Design*

Hydraulic design for hydropower projects encompasses a variety of components such as turbines, spillways, intakes, draft tubes, outflow conduits, and fish passage systems. The primary design tools used by the hydropower industry are laboratory reduced-scale physical models and computational models. Laboratory models are based on alignment of laboratory measured quantities and the corresponding values in the full-scale system. Hydraulic models (both laboratory and numerical) are generally used to simulate conditions for three distinct hydropower activities: environmental enhancement, dam operation, and turbine design and optimization. Beyond the traditional hydraulic design applications, research has been directed towards using hydraulic models to quantify and identify measures to reduce fish mortality rates [219]. Computational fluid dynamics models use numerical methods to represent the physics of fluid in motion in the complex water systems of a hydropower facility. Rapid development and increased computing power have led to increased use of computational fluid dynamics models, which are commonly used by the hydropower industry as a first step in the investigative and design processes (Text Box 2-8).

Text Box 2-8.

**Biological Performance Assessment Toolset**

DOE has developed a method for estimating the risk of fish passage through hydropower turbines called the Biological Performance Assessment (BioPA) Toolset. BioPA uses computational fluid dynamics simulations of turbine designs to quantify the exposure of passing fish to four main stressors: nadir pressure, shear, turbulence, and blade strike. The Toolset calculates the probability of fish injury and combines these results with laboratory stress studies to produce a set of scores. These objective metrics can be used to compare relative performance between competing turbines or to refine a design, resulting in an increased number of fish successfully passing through turbines (see *http://availabletechnologies.pnnl.gov/technology.asp?id=373*).

### *River Forecasting, Water Quality, and Water Use Optimization*

Hydropower operators release water in a way that optimizes power generation while balancing economic, social, and environmental objectives. A variety of analytical tools have been developed to help operators in planning and scheduling on a spatial and temporal basis. River system real-time scheduling modeling tools have been developed for operational decision making, responsive forecasting, system optimization, and long-term resource planning. These real-time scheduling tools allow the user to compare several planning alternatives by modeling hydrologic and hydraulic processes, hydropower production, and water quality parameters such as dissolved oxygen, total dissolved gas, and temperature, among other factors. Hydrodynamic and water quality and optimization models capable of simulating and predicting how watershed management practices might affect the water quality of a reservoir. These models use several assumptions and approximations to simulate hydrodynamics and transport to predict variables such as water surface elevations, velocities, temperatures, and a number of water quality constituents.

In 2013, DOE funded a 3-year project to develop a set of tools to simultaneously optimize water management, energy generation, and environmental benefits from improved hydropower operations and planning while maintaining institutional water delivery requirements. The Water Use Optimization Toolset, or WUOT,[69] is a suite of advanced analytical tools to simulate key factors affecting hydropower operations, including water availability, short- and long-term water and power demands, and environmental performance. Instead of simply enforcing prescribed environmental requirements, the WUOT can discover new modes of operation that actually improve environmental performance without sacrificing water or power economics. The WUOT has been specifically designed for daily use by hydropower planners, schedulers, and dispatchers to assist in market, dispatch, and operational decisions.

## 2.5.4 Environmental Protection and Enhancement Technologies

Hydropower can have potential environmental impacts. Two of the main concerns are water quality and fish passage. Protection and enhancement technologies have been developed to address these concerns.

### *Water Quality*

Water quality and stream flows in waterways are typically affected by reservoirs that impound water for various uses, including hydropower generation. The effects of hydropower projects on water quality are site-specific and are an important consideration in the FERC relicensing process, as well as for State 401 Water Quality Certificates, which are required in order to prevent potential pollutant discharges to waters of the United States. Primary water quality concerns are ensuring adequate dissolved oxygen levels, water temperature, and minimum and/or environmental (water quantity and quality) flows for aquatic life.

Many environmental mitigation technologies are employed at key points in a hydropower facility upstream of a hydropower dam, temperature control devices are used for selective withdrawal of cold water for downstream fisheries, Garton pumps are used to push oxygenated water down to the turbine penstock intakes for aeration of releases, and line diffusers are used to increase the oxygen of water

69. Available on the Argonne National Laboratory website (*http://www.anl.gov/energy-systems/project/water-use-optimization-toolset conventional-hydropower-energy-and*).

in the forebay (i.e. the portion of a reservoir that is immediately upstream from a dam). At a hydropower dam, auto-venting turbines can add oxygen to hydropower releases; and mixing of warm water with cold water bypass releases can be used to provide a cooler downstream environment year-round. Aeration of turbine flows in the draft tubes is the one technology used to improve dissolved oxygen. Downstream of a hydropower dam, labyrinth weirs[70] can be used to increase oxygen concentrations in hydropower releases and to provide more steady-state flow conditions for the environment.

Considering the multitude of turbine system designs and the variation in water quality and hydrology from year to year, selecting the best approaches for water quality management at a hydropower facility can be challenging. Consequently, reservoir water quality models are commonly employed to simulate reservoir oxygenation using techniques such as oxygen diffuser systems, surface aeration, draft tube aeration, weir aeration, and forebay surface water pumps. Model output is used in combination with water quality management strategies to determine the most appropriate site-specific environmental technologies. Site-specific characteristics that may impact the TDG exchange at a hydropower facility include structural features of the spillway and stilling basin. The TDG exchange associated with spillway releases has been found to vary markedly from regulating outlet releases [213]. The interaction of highly aerated spillway flows with powerhouse releases may also play a prominent role in establishing the net TDG exchange in hydropower dam discharges.

Text Box 2-9.

### Advancements in Water Quality Technologies

Considerable effort has been devoted to addressing concerns for water quality standards and minimum flows. The following technologies have been developed or enhanced and applied at hydropower plants operating since 1990:

- Draft tube aeration added to turbine hub, blades or draft tube wall
- Surface water pumps that increase dissolved oxygen in hydropower releases
- Skimmer devices (e.g., skimmer curtains, skimmer walls, trashrack plates)
- Oxygen diffusers using porous hose to increase dissolved oxygen and/or fish habitat in reservoirs, and to reduce anoxic products (e.g., hydrogen sulfide, ammonia, methane)
- Aerating weirs (labyrinth, infuser) for tailwater aeration
- Upwelling air diffusers to reduce temperature in near-surface turbine releases
- Compressed air added to draft tube
- Pratt Cone valves
- Selective operations of turbine units that can increase tailwater dissolved oxygen

### *Fish Passage*

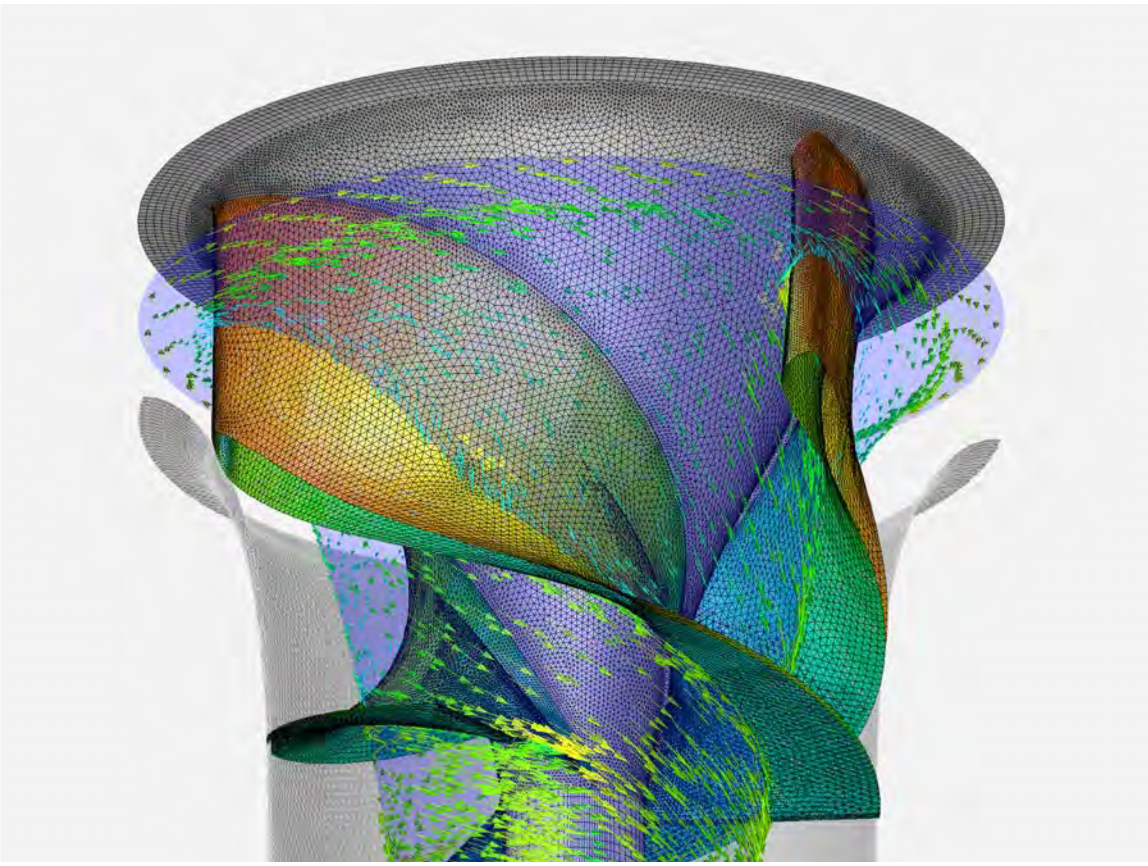
Safe passage of fishes through hydropower dams has been a topic of interest for decades. There have been numerous innovations across a broad range of technologies for reducing, evaluating, and monitoring the impacts of fish passage structures on fishes, including:

- **Upstream passage technologies.** Fishways for upstream passage have been around since the 17th century. The construction of hydropower facilities on the Columbia River in the 1930s accelerated the establishment of standards for entrance and exit locations, and attraction flows and velocities. Technologies for upstream passage are developed, and considered to be well-understood. On-going research continues in the United States and internationally to improve fish passage technologies for all fish species and under different river systems. There are six main types of fishways: 1) pool and weir fishway; 2) baffle fishway; 3) mechanized fish elevator; 4) rock-ramp fishway; 5) vertical-slot fishway; and 6) siphon fishway. There is no single general solution for designing upstream fish passageways. Effective fish passage design for a

70. A weir is a barrier built across a river or stream to alter its flow characteristics by raising or diverting water. Aerating weirs, such as the labyrinth type with its repetitive "W" shape, are specially designed to add oxygen to the water through air entrainment and increased oxygen transfer across the entrained bubbles.

specific site requires thorough understanding of site characteristics and fish population and fish behavior. Other technologies are being developed and tested around the world.

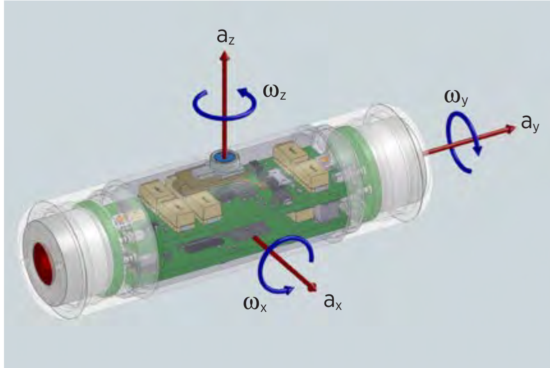
- **Downstream passage technologies**. There are six main technologies: 1) behavioral guidance devices; 2) physical barriers; 3) collection systems; 4) diversion systems; 5) surface flow outlets; and 6) fish-friendly turbines. Behavioral guidance devices use the avoidance response to external stimuli or natural behavior patterns to repel or attract fish. The most common of these are lights, electric fields, sound, air bubble curtains, water jet curtains, or a combination of these. Physical barriers are usually used with low water velocities; common types include barrier nets, porous dikes, bar racks, and infiltration intakes. Common collection systems include intake screens, fish pumps, and other bypass systems; while common fish diversion systems include angled screens, louvers/angled bar racks, Eicher screens, modular inclined screens, angled rotary drum screens, inclined plane screens, and guidance walls. Surface flow outlets include ice and trash sluiceways and spillway weirs. Fish-friendly turbines, such as the Alden turbine (Figure 2-37), have been specifically designed to address concerns about downstream fish passage. While not a passage technology per se, another common method to protect downstream migrant fishes is voluntary spill. Similar to upstream passage, there is no single solution for designing downstream fish passage. Effective design for a specific site requires thorough understanding of site characteristics and fish behavior, as well as good communication between engineers and biologists.



Source: DOE [214]

**Figure 2-37.** A computational fluid dynamics model simulation of the Alden Fish-Friendly Turbine

- **No-Dam Hydro**: Future hydropower development could be "no-dam hydropower," with a compact hydropower concept that would be installed either in one section of a river or adjacent to it, using only a portion of the river flow with fish diversion devices. This concept is still in the research and development stage. In 2012, Snohomish County (Washington) Public Utilities District received a preliminary permit from FERC to study and assess the potential of a 30-MW hydropower project on the South Fork Skykomish River that would require no dam, weir, or river barriers. This design is expected to reduce construction costs by $10 million and minimize environmental impact [215].




Source: Pacific Northwest National Laboratory

**Figure 2-38.** Three-dimensional drawing of a fish sensor device (dimensions: 89.9 × 24.5 mm)

Text Box 2-10.

## Mitigation of Environmental Conditions

Dams can have potentially adverse ecological impacts on fishes, aquatic wildlife, and botanical resources. Large impoundments impact the ability of aquatic organisms to move upstream and downstream within a river system, which may lead to population fragmentation and changes of spawning areas and habitats. Advancements in technology, however, have helped to mitigate these impacts.

Low dissolved oxygen is a common problem in reservoirs in the southern United States. At many existing hydropower facilities, the turbine intakes are far below the reservoir surface, where dissolved oxygen levels may be as low as 0 milligram per liter. When this water passes through the turbines and is discharged into the tailrace downstream of the facility, these low dissolved oxygen levels can have an adverse effect on water quality and aquatic life. Aerating turbines are an effective solution to this problem. Duke Energy, for example, demonstrated the opportunity to improve dissolved oxygen levels in water downstream from the Bridgewater Project in North Carolina. This mitigation was achieved through the installation of aerating turbines at a new powerhouse.

The Penobscot River Restoration Project consisted of the removal of two dams in the Penobscot River, and bypass addition of a third dam, which resulted in improved access to nearly 1,000 miles of habitat for eleven endangered species of sea-run fishes in Maine. Improved fish passage at four remaining dams and increased renewable generation at six means that these ecological benefits will be realized while maintaining or even increasing energy production.

In 2013, Grant County Public Utility District completed the installation of 10 new fish-friendly turbines at its existing Wanapum Dam hydropower facility to boost juvenile salmon survival rates and increase renewable energy generation by an average of 3.3%. The utility also installed a surface flow outlet, consisting of a 290-foot concrete chute, to ensure that young salmon migrating downstream to the Pacific Ocean can pass the dam unobstructed. This route achieves dam passage survival rates of greater than 98% for juvenile sockeye salmon and 99% for juvenile steelhead.

## 2.5.5 Costs and Equipment Optimization

Opportunities exist to reduce costs across a spectrum of hydropower equipment, ranging from small hydropower to large hydropower equipment, and components to support flexibility. These potential cost reductions in equipment and civil structures are a factor in expanding hydropower and keeping it competitively priced in the energy market. Small hydropower has high potential for expansion; however, these projects are typically customized for each application due to the numerous relevant variables in their application [216]. Head can vary across small hydropower projects, necessitating a range of different turbine types [212]. More modular equipment allows different turbine-generator packages to be available for a more inclusive variety of projects, and economies of scale are achieved by reusing the same turbine-generator design for different plant conditions. Adding variable-speed drives to generators at existing or new hydroelectric plants can result in increased power output. The speed of the generator adjusts to the speed of the turbine and operates at different head, thus keeping high generating efficiency without adverse effects on the electric grid interconnection or generation plant.

Hydropower facility operators monitor each piece of equipment and system in their facilities closely and typically delay replacing equipment as long as they are not experiencing recurrent failures or forced outages (non-scheduled outage). Since equipment replacement requires long lead time, however, factories strive to fabricate equipment quickly and reduce the cost of associated facility downtime. Orders may be placed based on paying a premium to shorten equipment replacement schedule, or based on the shortest firm delivery and assembly schedule. This can be done by shortening the design time and speeding up material deliveries necessary for emergency fabrications. While doing so can increase the cost of fabrication and installation, it can also generate larger net savings if a facility can be returned to revenue-producing energy generation more quickly.

Operators can have more operating flexibility, which can be translated in potential cost savings, if facility equipment is retrofitted to adjust to changing operating conditions. Due to renewable penetration, such as wind and solar, and the associated load following, hydropower and PSH operations are generally performing more starts and stops. This results in increased wear and shortens periods between major maintenance. Environmental requirements to meet river system targets such as water temperature, dissolved oxygen, minimum flow releases, and others force turbines to operate at different flows or heads. This results in rougher hydraulic operation and efficiencies lower than that for which systems are designed. These changes lead to increased maintenance and forced outages.

Grid interconnection is also a vital aspect in development of hydropower. Factors that must be considered include the market into which the generation will be sold, interconnection voltage, number of interconnecting lines, the magnitude of the local load service on the distribution network, and the ability of the system to reliably absorb the generation. A close match between generation and load should be maintained to ensure no voltage regulation issues arise. A lower voltage interconnection results in a lower cost of substation and transmission line. The location and size of the facility within the interconnected transmission system will determine the level of improvements and, consequently, costs to bring the generating plant on-line. These interconnection costs can be large enough to affect the viability of a hydropower facility project. Grid interconnection is discussed in more detail in Section 2.2.

### *Impact of Cost Uncertainty on Development and Financing*

On all hydropower developments, whether for a new facility or for an addition or refurbishment at an existing facility, the owners, developers, and financiers are concerned about net revenues as well as estimated costs vs. final costs. Investors need assurance that project debt payments will be paid and a project profit that meets their objectives will result. In early planning and feasibility studies, it is critical to properly estimate the project tariff and revenue, and to identify the interconnection cost. Projects that obtain higher tariffs can reduce owner or developer concerns and uncertainty regarding project revenue.

As noted previously, project cost estimators and financiers assign risk to each element of a hydropower cost estimate. Hydropower equipment costs can vary widely, and cost estimators often seek to obtain equipment bid prices as early as possible to reduce risk. Licensing or environmental study costs are not as predictable and these processes can take longer than planned, so costs may increase until the licensing is completed and required environmental mitigation is implemented. Such costs are often viewed as having moderate risk due to schedule and scope uncertainty, while below ground or underground construction such as that needed for hydropower facilities is often viewed as moderate to high risk due to vagaries of ground conditions present over large sites and within deep excavations.

Financiers attempt to mitigate project uncertainty through due diligence and the establishment of project requirements. These steps allow financiers to manage project construction-related expenditures and operating revenues. There are many techniques and methodologies used to remove uncertainty and risk from revenue prediction, construction cost estimates, and project construction schedules. If a project does not have adequate study development and site investigations, report documentation, a cost estimate with contingency for unknowns and risk items, a realistic construction schedule, predictable O&M costs, and comprehensible project tariffs with associated revenue predictions, an owner/developer will not invest equity and a financier will not finance the project.

### *Existing Equipment Optimization*

About 95% of the existing U.S. fleet of hydropower facilities was designed and built before 1995, with about 52% of plants built prior to 1965 and some using equipment that was designed more than 80 years ago [274]. Depending on the extent of maintenance programs, the equipment and water conveyance structures have likely degraded in ways that decrease energy produced compared to the original design. Many facilities have exhausted much of their useful life [217].

Hydropower design and manufacturing technology has advanced since the 1990s. Modern technologies use tools such as computer-aided flow analysis and structural analysis, computerized numerical control manufacturing, and advancements in materials science to produce hydropower component designs that can modernize an existing facility and improve compatibility with the surrounding aquatic environment. Incremental percentage increases in power generation from the same quantity of water, and higher energy capacities from the same powerhouse volume are commonly realized. It is typical to see plants realize operational efficiency improvements of 1% to 3%, and occasionally up to 10%, when modernizing older equipment. Unit capacity increases following upgrades have ranged from 5% to 15%, sometimes rising above 20% depending on the scope of the upgrade [218]. While energy generation improvements are related to efficiency and unit capacity improvements, they depend on the overall hydropower facility head and flow availability [212].

With the addition of updated control equipment and monitoring, units and powerhouses can operate in an informed and optimized configuration; the goal is to decrease the amount of water needed to produce a unit of energy. Agencies such as the Corps, Reclamation, TVA, and BPA are implementing efficiency programs that identify, design, and implement near real-time improvements on the hydropower system. The improvements fall into two categories: (1) making individual generating units more efficient by testing and tuning the operating parameters, improving measurement methods, and implementing controls to monitor the operations, and (2) operating generating units efficiently at a given facility through determination of the optimum number of units and configurations to be operated and the specific units that should be loaded [212].

The hydropower industry has invested at least $6 billion since 2005 in refurbishments, replacements, and upgrades to existing hydropower plants, with nonfederal owners spending more per installed kW than federal owners. These investments have ranged from replacing bearings to rebuilding dams. Most of the hydropower capacity additions in the United States have come from unit upgrades or additions to existing projects [2].

## 2.5.6 Technology Research and Design

Research and development are necessary to improve reliability, safety, efficiency, O&M, rehabilitation, and modernization of existing hydropower infrastructure.

Research into technologies for windings, including insulation systems and wedging systems, and into safety issues such as acceptable noise would help hydropower facility owners implement the most innovative technologies and continuously improve refurbishment outcomes. Research on transformers has focused on examining alternative insulation fluids that can improve personal safety and reduce environmental impact, such as ester oil and $SF_6$ gas. Guidelines for outage planning and management strategies, and their associated costs and saving opportunities, can help utilities understand different approaches and how those approaches might benefit utility customers. New methods for relay schemes or even new protection devices might be useful to help mitigate the often damaging results of arc flash. Research to identify the most common safety concerns and how to mitigate them in hydropower facilities could also prove valuable.

Through optimization and modernization, technology developed since the early 1990s is providing new opportunities for cost-effective energy production at nearly all plants. A comparison of optimization results might provide valuable information on what technology is available, as would research into the data that support these systems, such as performance curves, flow measurements, and cost. The industry could also benefit from cost-benefit analyses of modernizing existing hydropower facilities. A "smart" design process may be used to address facility life extension, water use optimization for energy production, O&M cost reductions, and environmental improvements, among others.

Finally, with many regions being asked to integrate variable renewable generation technologies such as solar and wind, an examination of operational changes to existing infrastructure might provide alternative solutions to building new infrastructure and another way to optimize and use hydropower units to produce additional revenue.

## 2.5.7 Trends and Opportunities

Trends and opportunities in Design, Infrastructure, and Technology include:

- Development of the next-generation hydropower technologies, through advances in research and design of dams that can help reduce the cost of civil structures and minimize construction time—modular and segmental design; precast systems; glass steel fiber reinforced concrete; smart concrete technology; rock-bolted underpinning system.
- Enhancement of the environmental performance of new and existing hydropower technologies, through activities such as adaptation of power efficient and fish-friendly hydraulic designs for cost-effective manufacture and installation for hydropower facilities.
- Comparison of optimization tools, and results and quantification of the benefits and/or added value to provide information on available technology; and research into the data that support these systems, such as performance curves, flow measurements, and cost.
- Implementation of cost-benefit analyses of modernizing existing hydropower facilities should benefit the hydropower community. A process of "smart" design may be conducted to address facility life extension, water use optimization for energy production, O&M cost reductions, and environmental improvements, among other issues.
- Examination of operational changes to existing infrastructure, which should provide alternative solutions to building new infrastructure.
- Addition of updated control equipment and monitoring, which can allow units and powerhouses to operate in an optimized configuration, thereby decreasing the amount of water needed to produce a unit of energy.
- Validation of the power performance and reliability of new hydropower technologies as well as assessment of the role and value of the federal hydropower fleet.

# 2.6 Operations and Maintenance

Hydropower O&M comprises the systematic activities that owner/operators undertake to maintain facility reliability to generate electricity. Facility operations involve selecting the appropriate generating units and bringing those units online; monitoring and controlling water releases and power generation; and safely shutting down units. Reliable operations cannot occur without proper, periodic maintenance of the components of hydropower facilities. Hydropower owner/operators maintain safety and reliability, and achieve operational objectives, by establishing hourly, daily, and weekly, and longer-term periodic operational procedures and best practices. Successful O&M is the achievement of pre-determined performance targets that are consistent with the overarching and established energy, environmental, and socioeconomic objectives for hydropower facilities. This section details basic O&M practices for hydropower.

### Highlights:

- Ensuring environmental compliance through facility enhancements, modeling of hydrologic cycles, refined operating procedures, and system monitoring is an increasingly important element of O&M.
- Decision making processes at individual plants are closely linked to full river system and power grid operational requirements to coordinate and minimize impacts of O&M activities on system operations.
- Evolving hydropower technologies and implementation strategies enhance operating reliability, flexibility, and responsiveness, thus increasing the market value of hydropower.
- Refinement of O&M methods will support hydropower growth through development of best practices, fleet-wide benchmarking, and improved incorporation of flexibility and environmental mitigation into operations scheduling and planning.

## 2.6.1 The Hydropower O&M Domain and Drivers of Change

Figure 2-39 illustrates hydropower O&M objectives in order of decreasing priority: Safety [of operations], Environmental Support, Reliability, and Maximizing Value and Performance. Hydropower owners employ multiple O&M implementation strategies to achieve these objectives, including models for staffing, control, and maintenance, along with a system of benchmarking and performance assessment, asset management, and a refurbishment strategy. Knowledge transfer and training play a critical role in O&M functions. This fact is especially true with the expected turnover of the workforce due to retirements. Owners typically choose one of several alternative strategies in each of these areas. The subsequent sections discuss these objectives and alternative strategies.

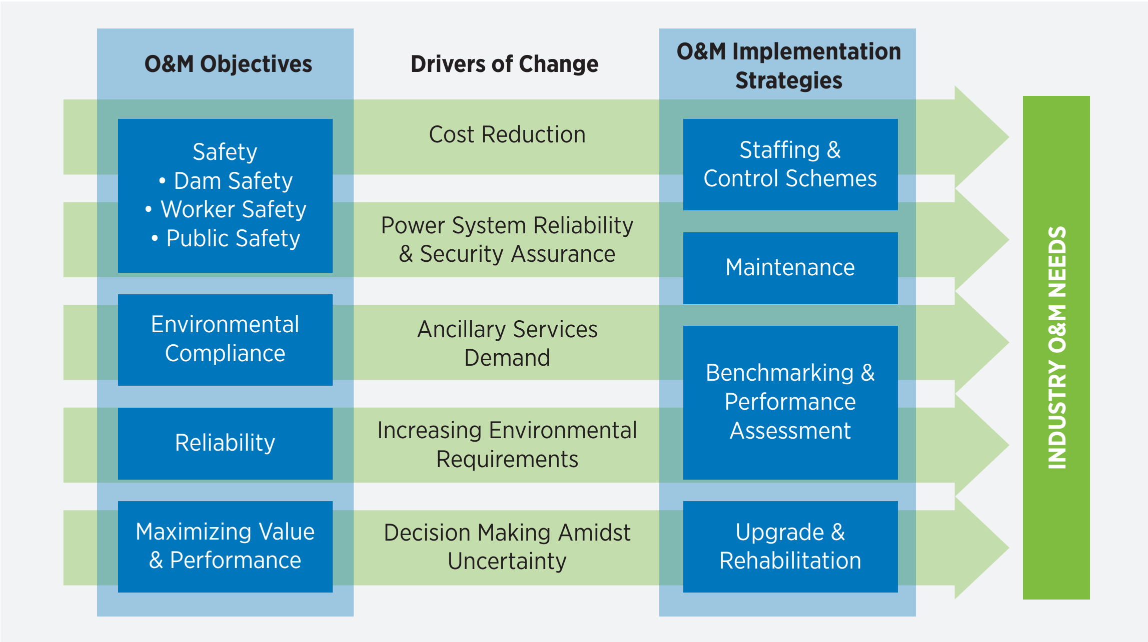
O&M methods are discussed separately in the *Hydropower Vision* for clarity, but this distinction is not always a natural one. Many activities accomplished by facility staff under management systems have related O&M objectives, with an overarching objective to ensure facilities are available to operate safely within environmental constraints and at the lowest cost possible to the benefit of the grid and its customers.

Hydropower O&M activities are evolving in response to multiple drivers of change, including cost reduction; power system reliability and security; ancillary grid services and flexible operation; increasing environmental needs; and decision making amidst uncertainty. O&M practices are intended to serve a range of objectives, detailed here.

### *Safety*

Hydropower facilities and dams have specific workforce cautions and are often located in areas used for public access and recreation. One area of focus for hydropower facilities includes safety—dam safety, public safety, and workforce safety.

The recreational use of reservoirs and streams adjacent to hydropower facilities is a benefit provided by all but the most remote or isolated facilities. For non-federal hydropower facilities, the FPA requires that the regulatory process give equal consideration to developmental and non-developmental (e.g.,




Source: Oak Ridge National Laboratory

**Figure 2-39.** The hydropower operations and maintenance paradigm

recreational use, protection of historical or cultural sites) values of public water resources. In addition to being a mechanism for facility owners to connect with stakeholders, recreational access may stimulate tourism and economic expenditure that benefits local economies. Over the term of hydropower licenses, non-federal hydropower operators must monitor and report public use associated with each facility and public access area. These operators are also responsible for making improvements and adding amenities or expanded public access, if required. In highly developed areas, these public use facilities may be a local and regional economic driver. Lands adjacent to hydropower reservoirs also tend to be desirable for private and commercial development. Recreational communities, private residential lots, and recreation-related commercial facilities have become fixtures of most reservoirs. The demand for private development needs to be balanced with providing access for reservoir users, including undeveloped natural areas, public access areas, formalized recreation areas, and mixed commercial uses that make each reservoir unique to the surrounding environment. Diligent public safety planning and management ensures owners have shoreline permitting programs that avoid the creation of public safety hazards (e.g., permitting docks and marinas, ensuring boat launches are appropriately spaced, enforcing local codes for electrical work, monitoring water hazards such as ski courses). Planning for and providing such features can ensure long-term benefits and opportunities for the public and local communities.

Many hydropower facility owners have public outreach programs that include education to schools, environmental groups, and the general public. These programs provide basic information on the hydropower plant's role and integration in the local environment. Proactive Emergency Action Plan training, community outreach, signage, and warning sirens are all mechanisms that can help educate the public about the dangers associated with dams and their aging infrastructure.

After the terrorist attacks of September 11, 2001, hydropower facility owners reviewed the level of public access to hydropower facilities and associated dam structures—many of which were previously open to the public—with regard to possible terrorist attacks. Since hydropower facilities provide support to the electric transmission grid for energy and specific ancillary and essential reliability services, including system restoration (black start), owners installed security fencing to limit access. Some of the larger hydropower facilities, including those owned by government agencies, also had security forces added.

**Dam Safety.** Dam safety is a consideration at both non-powered dams and hydropower facilities. FERC's Division of Dam Safety and Inspections, along with state dam safety agencies, requires all non-federal dam owners to prioritize the prevention of failure or any unintentional release of water. Instrumentation and monitoring programs are in place as an effort to prevent such events. A dam failure can result in loss of life, property damage, and unplanned expenditures for the facility owner. Aside from the need to maintain the dam structure in a safe condition for public safety in general, the owner would likely be subject to liability claims if the dam were to fail. Regardless of the size or type of entity that owns the dam, the owner has obligations to meet safety rules and will have defined roles for their personnel who support dam safety programs, such as a dam safety operator. Dam failures are most likely to occur for one of five reasons [220]:

- Overtopping caused by water spilling over the top of a dam;
- Piping caused when seepage through a dam is not properly filtered and soil particles continue to progress and form sink holes in the dam;
- Cracking caused by movements like the natural settling of a dam;
- Inadequate maintenance and upkeep; or
- Structural failure of materials used in dam construction.

Hydropower facility owners detect changes in dam structures and prevent failures using comprehensive monitoring plans that provide advanced public notice protocols as defined in each dam's Emergency Action Plan. Dam structures do decline over time, but signs of this deterioration such as seepage, settlement, and cracking are all detectable by routine inspection and monitoring. Common monitoring systems include piezometers to determine water levels in the dam, inclinometers, and other automated systems that provide engineers with data to continually assess the condition of a dam. Dam safety monitoring plans also include instrumentation and visual inspections. Inspections are essential to the stewardship of dams and associated facilities. FERC conducts periodic inspections of dams and other structures at FERC-licensed non-federal hydropower projects. Federal agencies have similar programs to assure the continued safe operation of federal hydropower infrastructure, dams, and waterworks. Visual inspection usually involves periodic checks, e.g. monthly/weekly checks by operating staff and annual inspections by engineering staff, which help detect unusual conditions such as cracking or piping. FERC-regulated hydropower facilities that are classified as high hazard and significant also include annual inspections by engineering staff from FERC's Division of Dam Safety and Inspections. Other dams are inspected at 3-year intervals. Additional inspections are made and audited by a third-party dam safety expert every five years.

These monitoring programs meet requirements of regulatory agencies, such as FERC's *Engineering Guidelines for the Evaluation of Hydropower Projects*. Dams belonging to investor-owned utilities are under the jurisdiction of FERC and state agencies, while structures owned by the federal government follow requirements in the *Federal Guidelines for Dam Safety.*

Dam owners also have maintenance programs to address abnormal conditions discovered in monitoring observations. For embankments, certain dam structures (i.e., earthen dams), should be covered with grass and shallow-rooted native plants, and regular mowing and maintenance schedules should be maintained. Trees and brush should be removed to facilitate inspection of the embankment and to prevent seepage paths (i.e., piping) due to their root structures [221]. Damage due to erosion, seepage, and cracks should be corrected when detected. For dam spillways, which allow passage of normal water flows, structures should be maintained and control equipment such as cranes, gates, and valves must be fully functional. Key maintenance activities include testing, lubrication, and correction of defects.

**Workforce Safety.** Hydropower facilities contain a number of energized components such as transformers, cables, switchgear, and generators, and the movement of heavy equipment and materials in such facilities is common. The safety of hydropower facility workers is of utmost importance, and owners have developed safety programs and procedures to prevent electrical shock, physical injuries, or death. These programs also include hazard awareness and safety procedures for water conveyance structures such as open flumes, channels, bulkheads, gates, and tunnels. Included are procedures to train workers about and reduce worker exposure to other hazards present in these facilities from compressed air, confined spaces, falls, material lifts and other dangerous situations. Reclamation has developed an extensive noise reduction program to prevent hearing loss in its facilities.

As industrial safety evolves, new regulations with worker safety requirements are issued to meet newly identified hazards. For example, in 1979, the National Fire Protection Association introduced NFPA 70E, Standard for Electrical Safety in the Workplace, which discusses methods to protect workers from harm due to exposure to electrical systems and devices. In 1995, NFPA 70E was revised to help protect individuals from arc flash dangers. Facility owners have made equipment modifications where possible, placed administrative controls, and provided new personal protective equipment to address the arc flash hazard.

Just as changes in maintenance approaches and safety have impacted hydropower facility owners, so have changes in workforce management. Some facility owners have incorporated human performance practices into their workplace management, e.g., the use of written procedures and checklists; ensuring the understanding of failure modes. Additional changes include the use of a maintenance management system to administer their work force and assets. The prime objective is eliminating equipment failures and accidents due to human error.

### *Environmental Stewardship in O&M Activities*

Hydropower facilities are located within complex aquatic and terrestrial ecosystems. In the presence of hydropower development and operations, these natural resources must be protected and restored to ensure their health and longevity. These stewardship activities require ongoing effort and expenditures by facility owners, regulators, non-governmental organizations, local governments, Indian tribes, and stakeholders. For facility owners, the environmental stewardship objectives embodied in policies, rules, and laws must be translated into operating procedures and best practices that can be implemented by facility staff and control systems.

Environmental stewardship requirements typically translate into minimum and maximum flow schedules, reservoir and tailwater elevation thresholds and rates of change, limits on the rate of change of flow releases from the facility, and changes in release schedules triggered by water quality conditions or the presence of fish that may be affected by operations. Facility or central staff must maintain environmental monitoring equipment; report monitoring data and analyses to regulatory authorities and to the public; and forecast, measure, and report the extent to which energy and environmental objectives and targets will be met. At the local facility level, these efforts center on monitoring and procedures, while compliance and tradeoff analyses for river systems and multiple facility fleets may be accomplished by dedicated environmental and performance staff.

When hydropower facility or support staff implements environmental stewardship activities, there are two effects on hydropower value. First, stewardship activities have direct costs that contribute to the life cycle and production costs for hydropower facilities. Examples include costs to install and maintain environmental mitigation equipment, perform biological monitoring and field data collection, and purchase bulk liquid oxygen for aeration systems. Second, stewardship activities may engender opportunity costs. For example, the majority of fishways that enable fish passage around dams require water to function. That water does not pass through turbines to generate energy and revenue for a facility owner. Operating spillways so as to route fish around turbines also has an opportunity cost.

A common example of opportunity cost is maintaining minimum flow releases through a facility even when the resulting energy generation is of low value in terms of revenue to the owner. In these cases, the minimum flow requirement has been established for the important objective of sustaining the health of downstream ecosystems, but the minimum flow release operation uses water that could otherwise be released during times of the day when energy prices are highest and would result in greater revenue for the facility owner. However, opportunity costs for minimum flow releases do not always accrue to the facility owner. In times of drought, maintaining minimum flow releases may mean that upstream reservoirs are depleted, with the reduced water surface elevation of those reservoirs resulting in diminished recreational opportunities or riparian habitat.

### Grid Reliability

As discussed in Section 2.1.2.4, NERC is a non-profit corporation that has been certified by FERC to develop mandatory reliability standards in the United States. NERC and its regional reliability entities[71] are charged with enforcement of these requirements. These reliability standards affect power facilities because they set guidelines within which operations must be conducted. Adherence requires documentation of generator capability, as well as testing of the protection circuits, station batteries, and other electrical functions required to maintain the electric grid. It also requires that facility operators respond to directives from transmission operators in order to support grid reliability. Failure to comply with these standards can result in monetary fines. In addition to providing a reliable source of electrical power to the electric grid, hydropower plants are ideally suited the black start function. The ability of hydropower units to quickly respond to these directives increases the value of hydropower resources to transmission operators and Reliability Coordinators. This feature was demonstrated in the 2003 Northeast blackout, when the flexibility of hydropower facilities and their ability to operate over a wide range of conditions allowed power to be restored and other types of generation to be brought back on-line [223].

Hydropower facilities also have enhanced abilities to quickly change operating points (i.e., respond to frequency disturbances and load following). These capabilities enhance contributions to the stability and reliability of the grid. While other generation sources can also perform these functions, the robust designs and simple mechanical systems of hydropower units mean they are minimally impacted by such changes and, as such, able to respond more quickly than fossil fuel generation units.

Hydropower units can operate reliably, meet environmental goals, and provide a range of grid services over a wide range of outputs. Few other units can provide this combination of services without considerable risk of equipment damage, especially at a MW size that can provide power restoration.

### Maximizing Market Value and Performance

Hydropower units are often the lowest production cost generators in an electric power system [224], so they are dispatched to replace higher cost generation resources that would otherwise be used (e.g., combined cycle natural gas generation). One strategy for economic dispatch in combined hydropower and thermal generation systems demands all of the hydropower generation (and water) that is available for the relevant period, so as to maximize the avoided costs of thermal generation. This demand for hydropower generation must be balanced against the future value of water for hydropower generation and other uses. Thus, the future value of water rewards efficiency in existing hydropower generation and limits the amount of hydropower available for meeting peak loads on a short-term (daily or hourly) time scale.

Other economic dispatch models use hydropower to meet load variability so that thermal sources can operate at an optimal base load setting. In this case, the value of water is balanced against the market demands and variable costs, including environmental costs, of operating thermal plants at less than optimal outputs (i.e., inefficient load points). Still another economic dispatch mode uses the flexibility of hydropower to follow the intermittent needs of the resource mix to meet variable load requirements and balance variable resource contributions. In order to maintain the reliability of the electrical bulk-power system, loads and resources must be balanced continuously and nearly instantaneously.

Operations of the river system—more than operations at the unit or project level—are the nexus of energy, water, and environmental policies. Ideally, those policies are sustainable and reflect the values of all stakeholders. Operational decision making for river systems typically reduces to hourly schedules of flow releases through each facility, which in turn controls reservoir elevations. In some cases, plants are used for inter-hour regulation of load/resources, which requires the same operational decision making. The tradeoffs that make decisions beneficial for one purpose and detrimental for another are often identified only by tracking the effects of releases and reservoir elevations though the multiple reservoirs that comprise a

71. NERC works with eight regional entities to improve the reliability of the electrical bulk-power system. The members of the regional entities come from all segments of the electric industry: investor-owned utilities; federal power agencies; rural electric cooperatives; state, municipal and provincial utilities; independent power producers; power marketers; and end-use customers. These entities account for virtually all the electricity supplied in the United States, Canada, and a portion of Baja California Norte, Mexico [222].

river system. Valuing multiple purposes and defining guidelines and policy for river system optimization and scheduling are issues that affect river system stakeholders and hydropower facility operators. Two examples of river system tradeoffs are:

- *The Columbia River Basin of the Pacific Northwest, where concern for resident and migrating fish species intertwine with needs for hydropower generation to support increasing penetration of wind and solar generation into multiple balancing authorities in the Pacific Northwest.* First, the releases of flows from the Columbia Basin headwater storage reservoirs provide salmon in the lower Snake and Columbia rivers with flows to enhance downstream migration. However, these releases may result in headwater reservoir water surface elevation variations that are not optimal for resident fish. Second, the optimal schedule of headwater reservoir flow releases to enhance either salmon migration or resident species habitat is not identical to the optimal schedule for hydropower generation at hydropower facilities downstream. By definition, less energy value is created when the optimal generation schedule is not followed. Third, increasing capacity for wind and solar generation in the region is making the flexibility of hydropower generation more valuable, but the need to avoid disrupting the timing of flows for salmon outmigration and to avoid excessive spill at Columbia River dams may limit such flexibility. Multiple study and research efforts are aimed at understanding the tradeoffs between aquatic environmental objectives and power system reliability and stability in systems with coordinated wind, solar, and hydropower assets.
- *The Tennessee River Basin, where keeping storage reservoirs full on the Clinch, Holston, and French Broad Rivers into mid-summer benefits recreational users, but also exacerbates water quality problems in those storage reservoirs and ponding reservoirs downstream on the main stem Tennessee River* [225]. Again, storage reservoir releases affect the overall value of system power production by altering the amount of water than can be released for hydropower. Maintaining water in headwater reservoirs through late summer also alters the system-wide storage available to reduce flood risks downstream in the Tennessee River Basin.

These examples are indicative of river systems in general because they include a mix of tributary storage projects and mainstem ponding projects. Run-of-river projects are often situated in the lower portions of river systems, but may also be found in upper portions due to historical development or unique environmental and regulatory issues. Wunderlich [226] states that river system optimization that accounts for linkages between projects is preferable to individual optimization of projects. Welt et al. [227] studied several river systems and concluded that the potential for economic gains from optimization increased with rising complexity of the hydropower system and electric power market. Labadie [228] points out that, “substantial technical challenges and rewards abide with integrated optimization of interconnected reservoir systems.”

When water control in a river system rests with multiple authorities, an explicit coordination agreement between the authorities can often provide greater value than independent operations. Public safety and reliable operation require at least a minimum level of coordination and communication among federal and non-federal authorities and multiple facility owners. However, there are institutional boundaries, regulations, authorities, and other administrative constraints that must be reconciled before operational coordination can yield increased efficiencies and value. Within water resources optimization, there are tradeoffs between the level of detail and time horizon that can be accommodated in prescriptive computational modeling. This results partly from limitations on computing power and data handling capabilities, but also because there is a limit to the amount of detail decision makers can consider beyond several seasons. As a result, decision support systems for water resources in general and hydropower in particular have been collections of generally interconnected models, differentiated by their time step and horizon. Typical scheduling activities within hydropower operations include the following:

- Long-term storage allocation: A storage allocation module prescribes optimal turbine release volumes and end-of-time-step reservoir elevations over a planning period of one to two years.
- Short-term dispatch optimization: A short-term dispatch module disaggregates weekly or monthly average flows and generation totals into daily or hourly dispatches for each project for the subsequent 24 hours to two weeks.

- Near-real-time optimization: A near-real-time module uses unit commitment and load allocation algorithms to disaggregate project discharge or generation dispatches from a short-term module into hourly unit operations.

Optimization notwithstanding, water management policy for individual projects constructed solely for power generation must be consistent with river system flood control policies established by state and federal agencies. While many constraints and decisions are considered, the primary decisions determined through optimization at the river system level are the daily and weekly releases and the elevations of the storage reservoirs.

Hydropower facility owners are challenged by regulatory authorities and customers to keep electric rates flat or lower than inflation. As a result, owners examine their operations to reduce O&M expenses, which are the primary driver for operators to control costs. Some examples of reductions hydropower facility owners may pursue include:

- Implementation of remote or automated unit operations that reduce labor costs and result in faster control and reduce the risk of human error, e.g., incorrectly synchronizing a generating unit to the transmission grid;[72]
- Using remote operations to eliminate non-productive travel time for employees driving between remotely located facilities to perform routine unit operations;
- Using remote operations to terminate the need for onsite operations employees and associated housing expenses for remotely located facilities;
- Transition from manual local control to remote automated operation of generating units, allowing for implementation of remote monitoring of critical monitoring and trending critical generator and turbine data;
- Identifying the optimal number of maintenance staff by evaluating the tasks required to keep the plant functioning and meet generation targets; and
- Use of computer maintenance management systems to prioritize work, optimize schedules, and make efficient use of plant staff.

## 2.6.2 Operations and Maintenance Implementation Strategies

The two key support functions of a hydropower facility are operations and maintenance. In executing these activities, hydropower facility owners aim to minimize risk so maximum generation can be achieved within operating constraints; to minimize forced outages; and to have hydropower available when called upon by the dispatch center.

### *Control Schema and Staffing*

In the early development of hydropower, plants were small in capacity and produced generation for local distribution; many hydropower facilities were redeveloped mills. Hydropower facilities consisted mainly of the generating unit and limited balance of plant equipment, and the generating unit was controlled locally by an operator.

As electrical demand grew, the generation required to meet this demand required new and larger capacity electrical plants. This included hydropower, though such facilities were typically built some distance from the loads that required the electrical energy. As hydropower capacity grew, so did control complexity.

Hydropower facility owners use a variety of staffing approaches depending on facility capacity, location, and functional requirements. Smaller facilities with limited generation most likely are controlled from a regional center, while those with larger capacity may be staffed with personnel. Control schemes can also involve a hybrid approach, with limited onsite personnel serving as a backup to remote control equipment. In the hybrid case, the onsite personnel will perform other tasks such as maintenance and inspections.

### *Facility Maintenance*

Hydropower facility maintenance programs are designed to reduce or eliminate unplanned equipment failures so the generating units can provide electricity generation and other ancillary services to the electrical grid as needed. This usually includes all routine and non-routine maintenance of the facility and equipment for water conveyance (e.g., spillway gates, water conduits, flumes), as well as maintenance of hydraulic equipment related to the turbine, the generator and associated equipment, switchgear, balance of plant, and the step-up transformer. Each facility owner establishes a maintenance strategy that

72. In this case, possible equipment damage from the human error would involve the generator breaker and generator stator windings.

provides the desired and most cost-effective balance of reliability, production costs, outage times, maintenance costs, and other strategic criterion.

The design features of equipment in early facilities (1880s to 1930s) were generally robust, the instrumentation was basic, and control systems relied on human action. Generating equipment in early facilities consisted of a turbine, shaft, and open frame air-cooled generator that were connected to the transmission grid through cables, a generator breaker, and a step-up transformer. Auxiliary equipment was limited to basics such as ventilation fans, lighting, and station drainage pumps. These facilities used corrective maintenance along with preventative strategy.

As industrial technology developed, many hydropower facility owners incorporated new equipment into the powerhouse during refurbishment or replacement projects. For example, the AC generator's excitation system was powered by a shaft-driven or separate DC generator, which in turn powered the main generator field. These rotating DC generators had carbon brushes, which required maintenance on a weekly basis. By contrast, the maintenance requirements of modern solid state exciters reduce maintenance to an annual check and are equipped with diagnostic equipment that identifies defects. Even with this change, brushes and slip rings are still required to transmit electrical current to the field poles. These brushes produce carbon dust as they wear, which must be collected and disposed of periodically. The sub-sections that follow describe several maintenance strategies used in modern hydropower facilities.

**Condition-Based Maintenance.** Condition-based maintenance consists of scheduling inspection and maintenance activities only if and when mechanical or operational conditions warrant, by periodically monitoring the machinery for excessive vibration, temperature and/or lubrication degradation, or by observing any other abnormal trends that occur over time [229]. Improved equipment reliability and availability can be achieved through a better understanding of evolving condition and fault mechanisms. Equipment manufacturers and third party suppliers continue to develop sensors that can detect changes in equipment performance and notify staff for needed maintenance.

As power and monitoring equipment are changing, so are maintenance strategies, due in part to decreasing funds, staff reductions, and high expectations of power availability. The development of monitoring and diagnostic technology supports implementation of condition-based maintenance. These improvements can be observed in plant equipment used in off-line tests as well as in-service data collection instruments, and provided through equipment communication ports. These data can be stored and analyzed in standard desktop computers in the facility. The interpretation of these data, however, requires special training, and oversight by experienced personnel is important in order to track performance trends.

In hydropower facilities, on-line sensor and diagnostic technology such as proximity probes focus on the turbine and generator. These technologies are used by engineering and facility staff to monitor anomalies that may require corrective maintenance. A comprehensive system could include a large number of probes, flow meters, partial discharge analysis, and other instrumentation [230].

The systems used to collect and analyze data must be able to detect deviations in select measurements, along with trending of collected data over a period of time. The systems must also be able to accommodate minor and random variations. More significant changes are brought to the attention of facility staff or technical experts who can further analyze the data and take appropriate action, such as scheduling an inspection and possible maintenance.

**Time-Based Preventative Maintenance.** Time-based (preventative) maintenance uses inspections performed on a schedule based on calendar time or machine run time. Such inspections are intended to detect, preclude, or mitigate degradation of a component or system, with the goal of sustaining or extending useful life by controlling degradation to an acceptable level [229]. Time-based maintenance is the most common method used by hydropower owners to manage their facilities. The defined time period and number of operations or machine operating hours is often determined based on operating experience, manufacturer recommendations, or regulatory requirements. Unlike condition-based maintenance, time-based maintenance does not require any sensor technology or monitoring systems, but may require test equipment.

A number of maintenance activities at most hydropower facilities are classified as time-based maintenance. Some of these are performed during planned outages, during which facility owners can conduct inspections, repair and cleaning activities, and diagnostic tests. These outages can be planned on an annual, biennial, or triennial basis, depending on the owner's assessment. During any equipment disassembly, facility owners work to mitigate inadvertent damage.

Some examples of time-based maintenance activities performed during planned unit outages are:

- **Waterways**—Major water conveyance systems and structures such as intake gates are inspected for integrity, leakage, and other structural elements during planned outages.
- **Turbines**—One major issue with turbines is damage to the runner surface due to cavitation erosion, abrasive erosion, and corrosion. If the damage is too severe, repairs are undertaken during the immediate planned outage; otherwise, repairs are incorporated into the next planned outage. Other turbine features examined during planned outages include the turbine-to-throat ring clearances, the wicket gates, the turbine guide bearing, head covers, wicket gate operating mechanisms, and monitoring systems.
- **Generators**—During planned outages, the generator stator and rotor are inspected for loose parts such as stator coils, slot wedges, field windings, or mechanical components. The high voltage stator windings, rotor field coils, and exciters receive diagnostic electrical tests which could reveal potential problems for continued reliable service. Generator bearings, bearing cooling systems, stator cooling systems, support brackets, stator sole plates, and other components are also inspected.
- **Generator Step-Up Transformers**—A number of maintenance tasks and diagnostic tests are completed on step-up transformers during planned outages. Prior to removal from service, the electrical connections are checked for overheating with an infrared device. The transformer bushings are also inspected for signs of cracks and chips, and for proper oil level. The electrical diagnostic tests include winding and core insulation resistance as well as power factor.

Time-based maintenance tasks during planned outages include other features of the hydropower facility, e.g., inspections of water control equipment such as spillway gates, Howell Bunger valves or similar equipment, cranes, raw water circulating pumps, safety equipment. Critical protection devices such as potential and current transformers, relays, and station batteries are tested and maintained on a periodic basis to comply with NERC Reliability Standards.

Many equipment manufacturers recommend time-based maintenance actions to extend the service life of their equipment, e.g., lubrication, filter change, and cleaning activities. While time-based maintenance offers advantages over other maintenance methods, it is not without limitations. For instance, the strategy cannot prevent catastrophic failures, but it can reduce their number [229].

**Corrective (Reactive) Maintenance.** Corrective maintenance, also known as reactive maintenance, is an approach that requires no preplanning actions; equipment operates until it ceases to function. It is commonly known as "run it till it breaks" [229].

The advantages of this approach are that it requires no monitoring systems or instruments, has no upfront expenses, and results in maintenance only when required. However, breakdowns or failures can occur at times of peak generation, and waiting until that happens can require increased labor expenses for outside staff to correct or replace the defective component so the system can be returned to operation. The failure can also result in the loss of electrical generation or the inability to release water from the reservoir, and the initial failure of one component can result in collateral damage to other equipment. Replacement components may not be stocked on-site at the hydropower facility, which would extend the downtime. Given these challenges, the intentional use of corrective maintenance in a hydropower facility is generally limited to components that are not mission-critical or that can be replaced within a few hours, including some balance of plant equipment such as small motors and bearings, electrical solenoids, etc. This approach could be used at the equipment's end of physical or economic life.

**Reliability-Centered Maintenance.** Reliability-centered maintenance is a combination of predictive/preventative maintenance techniques, in concert with root cause analysis [229]. Reliability-centered maintenance is a systematic approach to evaluate a facility's equipment and resources to best achieve the highest degree of facility reliability and cost-effectiveness [229]. The result of a successful reliability-centered maintenance program is maintenance strategies that can be implemented with regard to each of the facility assets in order to optimize asset values. These maintenance strategies are optimized so that the functionality of the plant is maintained using cost-effective maintenance techniques.

Reliability-centered maintenance involves gathering O&M data, performing analysis, and developing options for maintenance, and then using that information to prepare the maintenance tasks. Feedback is gathered following the first round of completed maintenance to see if the options were optimal and accurate, and adjustments are made as needed. This process is repeated on a periodic basis when potential improvements are identified. Facility owners have found success in using elements of the reliability-centered maintenance approach, working with available resources.

### *Planning, Benchmarking, and Performance Assessment*

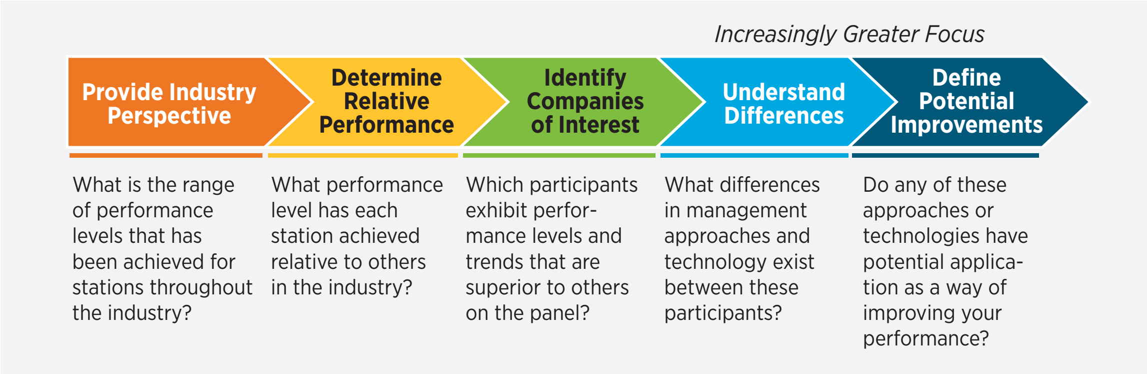
Hydropower facility owners seek optimal use of water for hydropower while maintaining environmental quality, preventing flood risk, and providing adequate municipal water supply and recreational activities. Accomplishing this requires accurate planning and optimization of available water. Planners use projected rainfall/runoff forecasts to determine expected generation. For facilities located in northern climates, snow pack levels are used in the planning process. Since these forecasts are developed at least a year in advance, the planning process is dynamic and requires revision over time. The process incorporates planned unit outages that can be executed during periods of low water availability. Planning for load-serving and system supply incorporates planned outages and maintenance using availability calculations such as Equivalent Availability Factor, Equivalent Forced Outage Factor, and facility electrical capacity.

Benchmarking compares the performance of hydropower facilities that perform similar functions. Understanding these differences allows a hydropower facility operator to quantify improvement potential relative to the practices of best performers, prioritize operating practices by their impact on performance, and consider ways in which prioritized practices may be applied internally to improve performance. The following data are typically included in a benchmarking program to compare hydropower facility operations:

- Pedigree data (facility type, capacity, age, unit size, type, configuration). These data are used to define peer groups of similar stations for comparisons.
- Cost data for all functional areas required to run a hydropower facility, including :
  - Operations
  - Maintenance (generating plant, waterways and dams, buildings and grounds)
  - Support (on-site and headquarters locations)
  - Public affairs and regulatory requirements
  - Investment, differentiated by long-term (7–10 years) projects in order to make routine O&M more comparable

  Cost data are normalized on a comparable unit-of-output basis, such as $/MW or $/MWh. The selection of the appropriate metric is best determined by the primary cost drivers for the functional area. For example, if the number of generating units is a primary driver of operations cost, then it would be useful to benchmark operations cost in $/unit.
- Performance data such as Generating Availability Data System data that are collected by NERC as required for 20-MW and larger units (smaller generating units do not have this requirement). Service-level measures are calculated to quantify how well the function is accomplishing its goals. In plant maintenance, for example, forced outage rate and availability factors are used as a measure of how well stations have been maintained. Several individual service-level measures may be combined to form a single composite index.
- Labor data, which are typically reported as the number of full-time equivalent employees, normalized on a comparable unit-of-output basis, similar to cost. These data are used to compare staffing levels in each functional area, as well as various components of labor cost such as wages, benefits, overtime, and the use of contractors.
- Safety data such as Recordable Injury and Lost Time Accident Rates, as defined by the Occupational Safety and Health Administration.

After the data are collected and the proper metrics are calculated, cost and performance data for a hydropower facility can be compared with the corresponding data for the facility's peer group (as defined by its pedigree data, e.g., size, type, age). The hydropower facility owner can determine whether the facility is above or below the peer group median (or some other desired metric). When reviewing benchmarking data, a holistic view is optimal; the relationship between measures is more important than superior performance for any particular measure in isolation.




Source: Navigant Consulting

**Figure 2-40.** Flow of benchmarking information to guide performance improvement

Hydropower facility owners can use benchmarking data for multiple purposes, including reporting to facility and executive management, setting and justifying annual budgets, setting cost performance targets and tracking progress, and establishing formal performance improvement programs. There is typically a performance trade-off between unit cost and availability; for example, high availability can sometimes be achieved only with high unit costs.

Performance improvement programs recognize that benchmarking is the first phase of an overall generation improvement effort. The key is to identify innovative practices that are being used by the leading performers. Benchmarking information is used to identify the areas in which a more in-depth investigation is warranted —i.e., where performance is below benchmark—as well as the performers of different functions performed at a hydropower facility. Facility owners can conduct interviews of leading performers and use those results along with performance measures to identify how the leading companies achieve superior performance levels. The innovative practices identified for each function allow each participant to identify its improvement potential and target areas where the innovative practices may be applied. This process is summarized in Figure 2-40.

### *Upgrade and Refurbishment*

Hydropower facility owners implement equipment condition assessment programs to understand which components are near the end of their service life and, as such, to better project replacement needs and related expenses. This understanding can also be used to revise the maintenance program to extend the equipment's service life and improve unit reliability. The condition of equipment can be determined through inspection by subject matter experts and enhanced with diagnostic instrumentation and periodic tests. Operating organizations use asset condition data to optimize expenditures by evaluating the opportunities and benefits for the greatest gain. These strategies seek to improve operational performance and prolong asset life.

Asset management is the systematic process of deploying, operating, maintaining, and upgrading assets cost effectively and in a prioritized way. It is also used to manage risk of equipment failure. In hydropower facilities, this is often also completed with limited resources. In the *Hydropower Vision,* "assets" are water control projects and components, including all equipment, structures, water conveyances, and reservoirs residing within the project boundaries. Assets also include the sensors and control systems that link physical projects to centralized dispatch facilities.

Hydropower asset managers contend with technical uncertainty and limited information, and they invest in research and collaborations within the hydropower industry to reduce technical uncertainty and to aggregate information for improved decision making. With an aging U.S. hydropower fleet and workforce, knowledge or inference about the condition of components is important to prioritizing limited funds for replacements, refurbishments, and upgrades, and to optimizing strategies for planned outages—within and among hydropower facilities. Facility owners use industry forums to share information on similar equipment and maintenance techniques, with the objective of extending service life and minimizing the risk of failure.

### 2.6.3 Trends and Opportunities

Trends and opportunities in Operations and Maintenance include:

- Development of best practices and justification for acquiring, validating, archiving, analyzing, and securing hydropower dispatch, cost, maintenance, condition monitoring, and performance data to maximize hydropower value.
- Movement of the industry and U.S. hydropower fleet to comprehensive benchmarking. It will be important to compile, disseminate, and implement best practices and benchmarking in operations and R&D.
- Understanding and creating parameters for the correlations and causalities among flexible hydropower dispatch, reliability, and O&M costs, and integrating such information into scheduling and planning processes.
- Development of best practices to include the effects of integrating environmental objectives into hydropower technology and operations decisions.
- Development of risk-based analytics to measure and manage dam safety, hydropower reliability, and hydropower scheduling.
- Assessment of benefits over a drainage area to determine the energy supply and market value impacts to environmental objectives and assess benefits over an entire drainage area (e.g., at the river system level) to achieve hydropower value while balancing regional environmental objectives (vs. just site specifics).
- Attraction of new workers into the hydropower industry along with the retention of the existing workforce. Training will be vital to the success of the industry in the future.

## 2.7 Pumped Storage Hydropower

The proven reliability, cost, and capacity potential of PSH demonstrate the technology's value as an energy storage resource for the United States. PSH functionality can be used to balance system loads and variable generation from other renewable resources on the grid. While existing PSH can provide operating flexibility, modern PSH technology represents an evolution from existing PSH facilities, with new technology development and design parameters that support rapid response capabilities. These capabilities can support power systems with a large share of variable renewable generation technologies, such as wind and solar. As explained in this section, PSH provides a number of services and contributions to the power system, such

### Highlights:

- PSH is a proven, reliable, and commercially available large-scale energy storage resource. PSH provides 97% of total utility-scale electricity storage in the United States as of 2015 [2].
- As of 2015, the PSH plants in operation in the United States had a total installed capacity of about 22 GW. Many PSH plants were constructed to complement large baseload nuclear and coal power plants, where PSH increases loads at night and provides peaking power during the day.
- By helping to balance the grid, PSH plants reduce overall system generation costs and provide a number of ancillary services, including frequency regulation and voltage support, and help integrate variable renewable generation technologies into the grid.
- New advanced PSH technology, such as adjustable-speed units, provides additional capabilities beyond those of existing units.
- There is significant resource potential for new PSH development in the United States, but inherent market and regulatory challenges must be overcome to realize this potential.

as frequency regulation, contingency reserves, voltage support, and others. This section describes the significant resource potential that exists for the development of new PSH projects and the challenges that need to be overcome for this potential to be realized.

## 2.7.1 History and Status of Pumped Storage Hydropower

One of the earliest known applications of PSH technology was in Zurich, Switzerland, in 1882, where a pump and turbine operated with a small reservoir as a hydro-mechanical storage system for nearly a decade. The first unit in North America was the Rocky River PSH plant, constructed in 1929 on the Housatonic River in Connecticut. These early units were relatively basic; each had a motor and pump on one shaft and a separate shaft with a generator and turbine. The TVA constructed the first reversible pump/turbine (Hiwassee Unit 2) in North Carolina in 1956. At 59.5 MW, Hiwassee was larger than previous PSH installations. Developments in technology and materials have continued to improve overall efficiency and allow increasingly larger units to be constructed.

As of 2015, there were 40 PSH plants in operation in the United States, with a total installed capacity of about 22 GW [231]. Many of these plants were constructed from the 1960s through the 1980s to complement large baseload nuclear and coal power plants, where PSH increased loads at night and provided peaking power during the day. These units also served as backup capacity in the case of outages.

Because most PSH plants operating in the United States as of 2015 were built at least three decades ago, many do not take full advantage of modern advances in PSH technologies. For example, improved fixed-speed technologies have faster responses (mode change and load change times) and wider operating range (lower minimum load, wider operating head range), while adjustable-speed units also have the ability to provide regulation service in the pumping mode of operation. These innovations improve the capabilities of PSH to support grid reliability and the integration of variable renewable generation resources, as discussed in more detail later in this section. While many proposed projects[73] in the United States are considering these more modern technologies, the innovations have been adopted more quickly by the rest of the world. For instance, more than 20 adjustable-speed PSH units have been placed into commercial operation since the 1990s—almost entirely in Japan and Europe—and several more are in design and construction phases [232].

Another PSH technology that provides flexibility is a ternary configuration with a hydraulic bypass. This type of ternary configuration has the motor/generator, turbine, and pump on the same shaft and rotating in the same direction, which allows for simultaneous operation of both the pump and turbine. Three 150-MW ternary units with hydraulic bypass have been installed at the Kops II plant in Austria, and several others are planned or in construction at other locations in Europe.

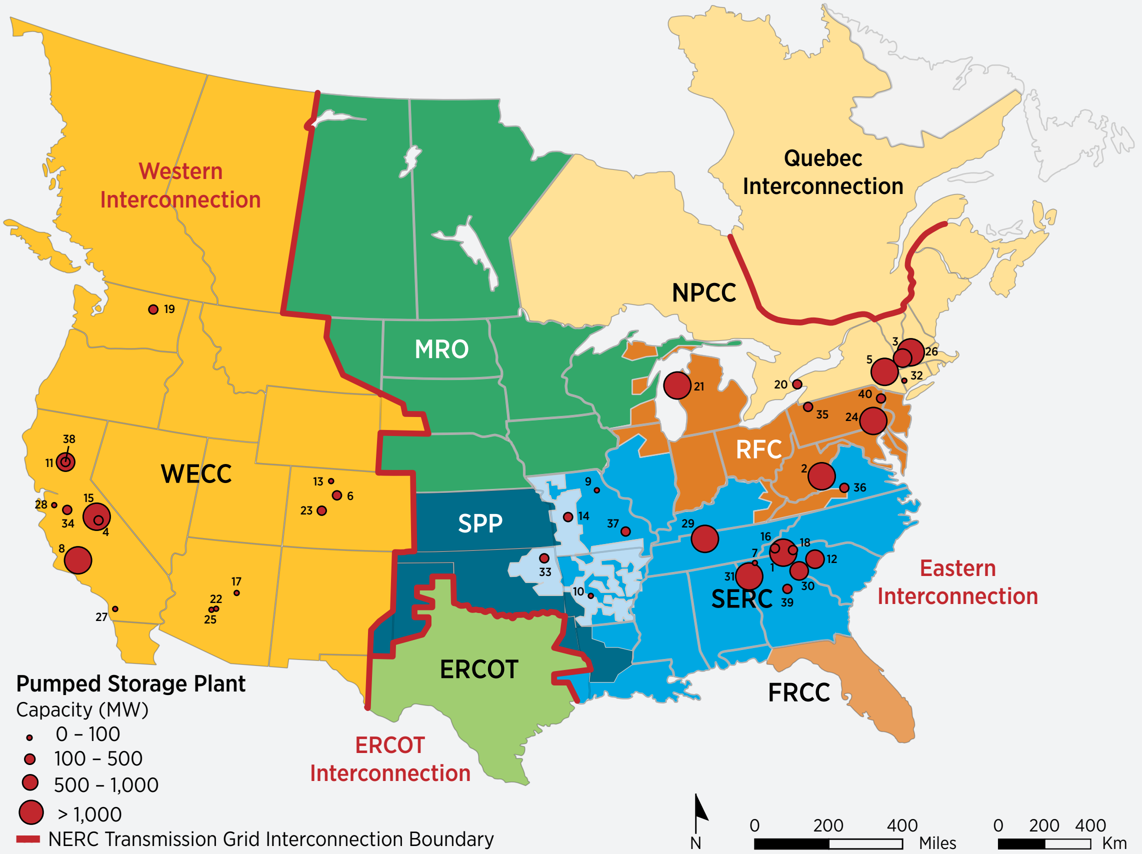
Worldwide, there are about 131 GW of PSH capacity in operation [233]. The regional distribution of global PSH capacity is presented in Table 2-6, while the locations and capacities of PSH facilities in the United States are illustrated in Figure 2-41.

**Table 2-6.** Global Pumped Storage Hydropower Capacity by Region

| Region | Capacity (MW) |
|---|---|
| Asia and Oceania | 55, 786 |
| Europe | 50,015 |
| North America | 22,545 |
| Eurasia | 2,840 |
| Africa | 1,864 |
| Central and South America | 974 |
| World | 132,360 |

Source: EIA International Energy Statistics [233]

73. Adjustable-speed PSH technologies are being considered by developers of proposed PSH projects, including the 1,300-MW Eagle Mountain projects in California, and the 390-MW Swan Lake North project in Oregon.




**NERC Regions**

ERCOT: Electric Reliability Council of Texas
FRCC: Florida Reliability Coordinating Council
MRO: Midwest Reliability Organization
NPCC: Northeast Power Coordinating Council
RFC: ReliabilityFirst Corporation
SERC: SERC Reliability Corporation
SPP: Southwest Power Pool
WECC: Western Electricity Coordinating Council

**Notes:** The Alaska Systems Coordinating Council (ASCC) is an Affiliate NERC member. Commercial electric power providers in Hawaii are not affiliated with NERC.

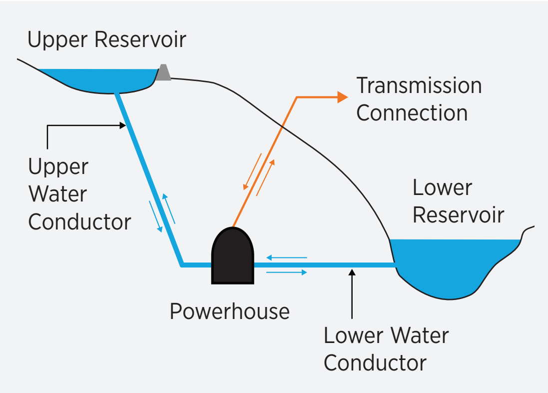
| No. | Name | Capacity (MW) |
|---|---|---|
| 1. | Bad Creek Pumped Hydro Storage | 1,065 |
| 2. | Bath County Pumped Storage Station | 3,030 |
| 3. | Bear Swamp Hydroelectric Power Station | 600 |
| 4. | Big Creek (John S. Eastwood) Pumped Storage | 199.8 |
| 5. | Blenheim-Gilboa Pumped Storage Power Project | 1,160 |
| 6. | Cabin Creek Generating Station | 324 |
| 7. | Carters Dam Pumped Storage | 250 |
| 8. | Castaic Pumped-Storage Plant | 1,247 |
| 9. | Clarence Cannon Dam Pumped Storage | 58 |
| 10. | DeGray Lake Pumped Hydro Storage | 28 |
| 11. | Edward Hyatt (Oroville) Power Plant | 819 |
| 12. | Fairfield Pumped Storage | 511.2 |
| 13. | Flatiron Powerplant | 8.5 |
| 14. | Harry S. Truman Pumped Hydro Storage | 161.4 |
| 15. | Helms Pumped Hydro Storage Project | 1,212 |
| 16. | Hiwassee Dam | 185 |
| 17. | Horse Mesa Pumped Hydro Storage | 97 |
| 18. | Jocassee Pumped Hydro Storage | 710 |
| 19. | John W. Keys III Pump-Generating Plant | 314 |
| 20. | Lewiston Pump-Generating Plant | 240 |
| 21. | Ludington Pumped Storage | 1,872 |
| 22. | Mormon Flat Pumped Hydro Storage | 50 |
| 23. | Mount Elbert Power Plant | 200 |
| 24. | Muddy Run Pumped Hydro Storage | 1,070 |
| 25. | New Wadell Dam Pumped Hydro Storage | 45 |
| 26. | Northfield Mountain Pumped Storage Hydroelectricity Facility | 1,119 |
| 27. | Olivenhain-Hodges Storage Project | 40 |
| 28. | O'Neill Powerplant | 25.2 |
| 29. | Raccoon Mountain Pumped Storage | 1,652 |
| 30. | Richard B. Russell Pumped Storage | 600 |
| 31. | Rocky Mountain Hydroelectric Plant | 1,095 |
| 32. | Rocky River Pumped Storage Plant | 29 |
| 33. | Salina Pumped Storage Project | 260 |
| 34. | San Luis (William R. Gianelli) Pumped Storage Hydroelectric Powerplant | 424 |
| 35. | Seneca Pumped Storage Generation Station | 440 |
| 36. | Smith Mountain Pumped Storage Project | 247 |
| 37. | Taum Sauk Hydroelectric Power Station | 440 |
| 38. | Thermalito Pumping – Generating Plant | 120 |
| 39. | Wallace Dam Pumped Storage | 208 |
| 40. | Yards Creek Pumped Storage | 400 |

Source: Argonne National Laboratory

**Figure 2-41.** Existing pumped storage hydropower plants in the United States

## 2.7.2 Characteristics of Pumped Storage Hydropower Technologies

PSH plants can be designed in many different ways, depending on the geologic and hydrologic constraints of a given location. The typical configuration of a PSH plant is illustrated in Figure 2-42. It includes two reservoirs connected with waterways (water conductors), a powerhouse with hydropower machinery and equipment (pump/turbines, motor/generators, excitation systems, etc.), transmission switchyard (transformers) and a transmission connection. Most PSH plants use "reversible" pumps/turbines, which can switch from pumping to generation by reversing the rotation direction. Some plants, particularly those with high hydraulic head,[74] may require separate turbines and pumps. The two reservoirs should be located close to each other and have a significant elevation difference, which increases the potential energy of water stored in the upper reservoir.




Source: Koritarov et al. 2014 [234]

**Figure 2-42.** Typical configuration of a pumped storage hydropower plant

Many PSH projects use reservoirs of existing hydropower facilities as their lower or upper reservoirs. Those PSH plants are typically referred to as "on-stream integral pumped storage" or "pump-back pumped storage." The latter uses two reservoirs located on the same river and can operate either as a typical hydropower plant, or, when the electricity demand is low, as a PSH facility.

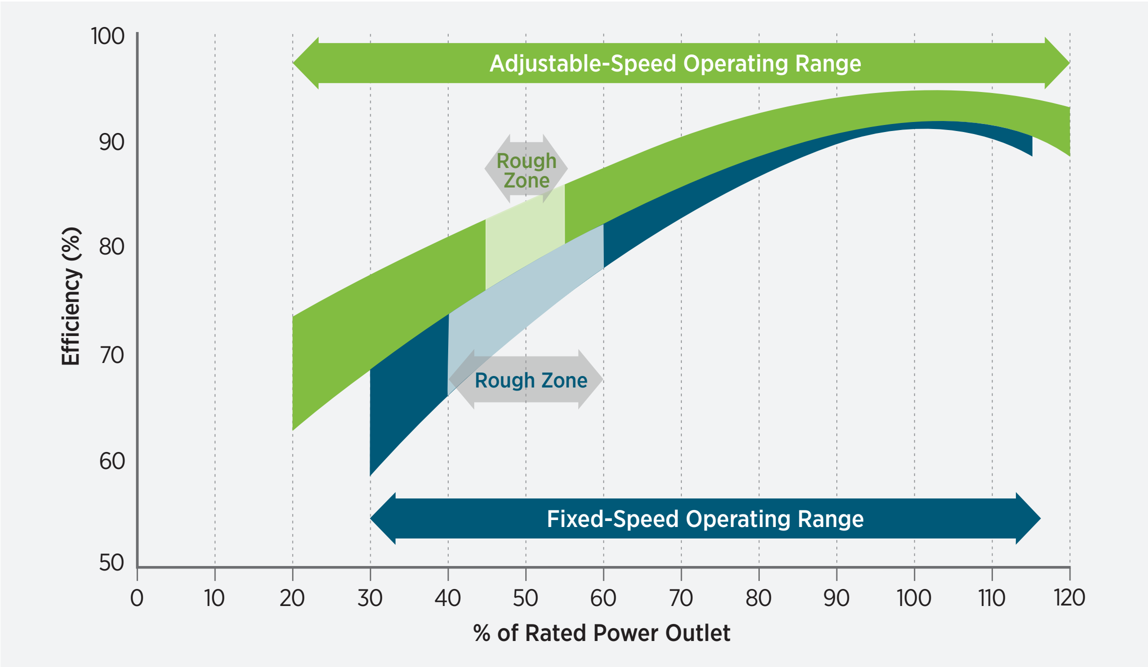
PSH plants that are continuously connected to a naturally flowing water feature are called "open-loop" projects. Conversely, "closed-loop" PSH systems typically consist of two man-made reservoirs that are not continuously connected to such water features. One advantage of this off-stream approach is that these artificially created reservoirs could be made devoid of fish and other aquatic life, so the environmental impacts of PSH plant operation to river and lacustrine (lake) ecosystems could be reduced.

PSH reservoirs are sized based on the storage duty and operating cycle (day, week). In Europe, the trend is to add additional units to existing PSH plants.[75] This shortens the storage cycle time of the reservoir, but allows more energy to be cycled in shorter time frames.

Most existing PSH plants use traditional single-speed (or fixed-speed) technology, where both the pump/turbine and the motor/generator operate at a fixed synchronous speed. A major breakthrough in PSH technology was the introduction of the doubly-fed induction machine motor/generator with adjustable-speed capability.[76]

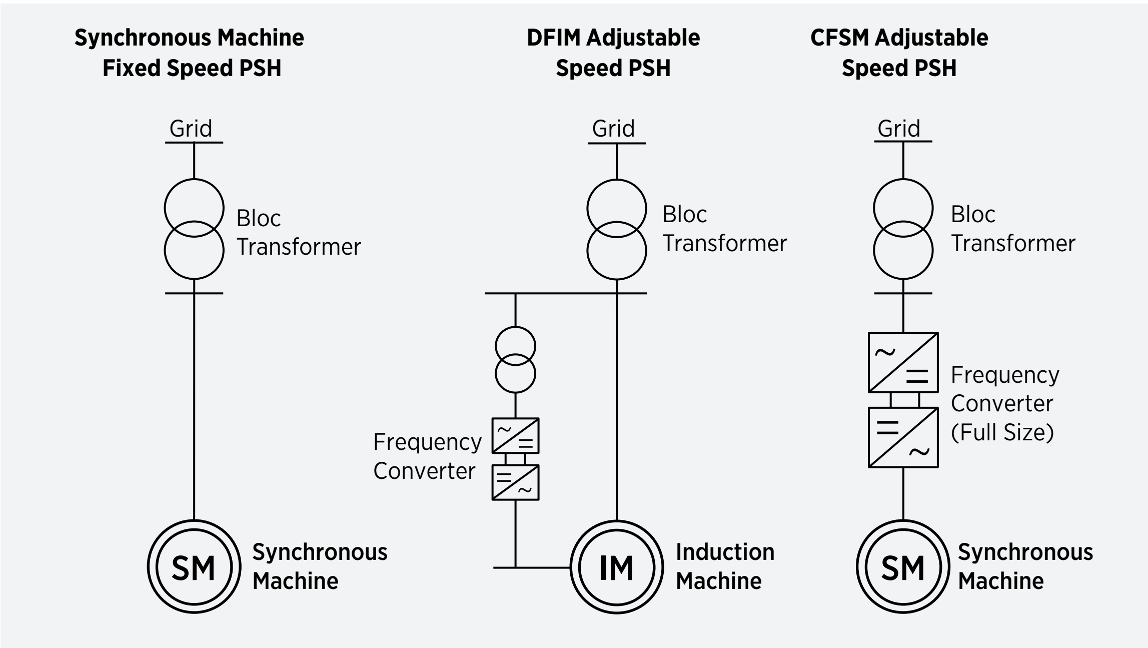
Adjustable-speed units provide a unique advantage in their ability to vary their power consumption during pumping, thereby providing frequency regulation in the pumping mode of operation [234]. Adjustable-speed units also operate with greater overall efficiency than fixed-speed units, especially when generating at partial load. This efficiency increase occurs because the rotating speed can be optimized for a given head and rate of water flow through the turbine. Depending on the design, adjustable-speed units may have a narrower rough zone[77] and the ability to generate at lower power levels—as low as 20%–30% of total installed capacity. These characteristics are illustrated in Figure 2-43.

74. For PSH plants, hydraulic head is the effective elevation difference between the upper and lower reservoirs.
75. For example, the new Kops II PSH facility in Austria, the planned 300-MW extension of Waldeck II in Germany, and PSH capacity additions at La Muela in Spain.
76. Unit 2 at Yagisawa PSH plant in Japan was the first adjustable-speed unit in operation. It was converted from fixed-speed to adjustable-speed by Toshiba in 1990.
77. Rough zones refer to operating ranges that need to be avoided due to excessive turbine vibrations and cavitation.




Source: Koritarov et al. 2014 [83], adapted from Corps 2009 [235]

**Figure 2-43.** Generation efficiency curves for fixed-speed (blue) and adjustable-speed (green) pumped storage hydropower units




Note: DFIM = Doubly-Fed Induction Machine, CFSM = Converter-Fed Synchronous Machine.

Source: Koritarov et al. 2015 [238]

**Figure 2-44.** Electrical single line diagrams of fixed- and adjustable-speed pumped storage hydropower technologies

An additional benefit of advanced adjustable-speed technologies is the electronically decoupled control of active and reactive power, which provides more flexible voltage support for the system. Compared to fixed-speed PSH units, adjustable-speed PSH technologies may provide even better capability to support the stability of the power system in the case of sudden generator or transmission outages.

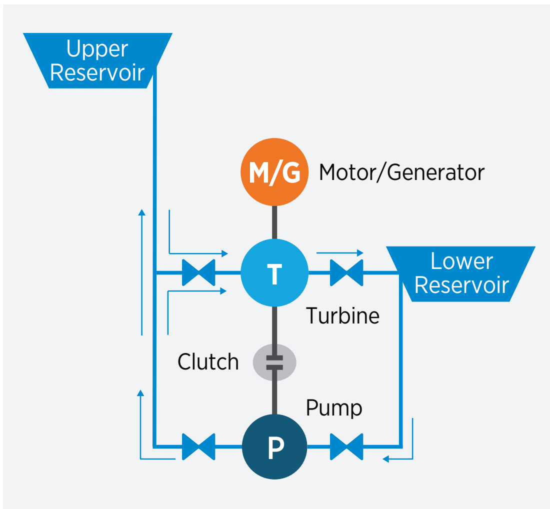
The adjustable-speed PSH technology was first developed in Japan in the 1990s, driven by the need for more flexibility in the country's nuclear-dependent power system. Since then, several adjustable-speed PSH plants have been built in Japan and Europe, and some existing fixed-speed PSH units have been converted to adjustable-speed technology.

The adjustable-speed operation of a PSH unit can also be achieved with a synchronous motor/generator if a full-size frequency converter is used to regulate the machine speed. This converter-fed synchronous machine technology was previously considered applicable only to smaller PSH units (less than 100 MW), but advances in converter technology may allow its applications to larger units [236]. Fixed- and adjustable-speed PSH units are diagrammed in Figure 2-44. In this figure, DFIM is doubly-fed induction machine and CFSM is converter-fed synchronous machine.

A ternary PSH unit uses a separate turbine and pump on a single shaft with the motor/generator, and provides greater operational flexibility than fixed-speed PSH plants. Ternary plants with hydraulic bypass can simultaneously operate both the pump and turbine, as they are on the same shaft (connected with a clutch) and rotate in the same direction. Such simultaneous operation is also known as "hydraulic short circuit" or "mixed mode." Ternary units can regulate the power that is supplied to the pump from the grid by varying the power output of the turbine. This allows them to operate across a wide range of power consumption levels, and to provide fast and significant regulation up and down service as well (i.e., full unit capacity for regulation). Figure 2-45 illustrates the typical configuration of a ternary PSH plant with a hydraulic bypass [237]. A comparison of main technical and operating characteristics of key PSH technologies is provided in Table 2-7.

### *Modular Pumped Storage Hydropower*

As of 2015, most global and domestic PSH development had focused on the construction of large (typically several hundred MWs), site-customized plants. A number of smaller plants and units do exist, however. The viability of alternative design paradigms for PSH technologies has been actively discussed by the industry and in research (e.g., Hadjerioua et al. 2012 [239], 2014 [240]). No reliable determinations on the viability of these concepts have been made, however. The development of smaller, distributed PSH systems incorporating elements of modular design (i.e., using commercial off-the-shelf pumps, turbines, piping, tanks, and valves) may drive down investment cost, compensating the loss of economies of scale with cost reductions achieved through component standardization; reduce development risk; and increase the ease of implementation. Small modular PSH (m-PSH) could be a competitive option for small and distributed energy storage applications. In addition, m-PSH could avoid many of the major




Source: Koritarov et al. 2013b [237]

**Figure 2-45.** Typical configuration of a ternary pumped storage hydropower with hydraulic bypass

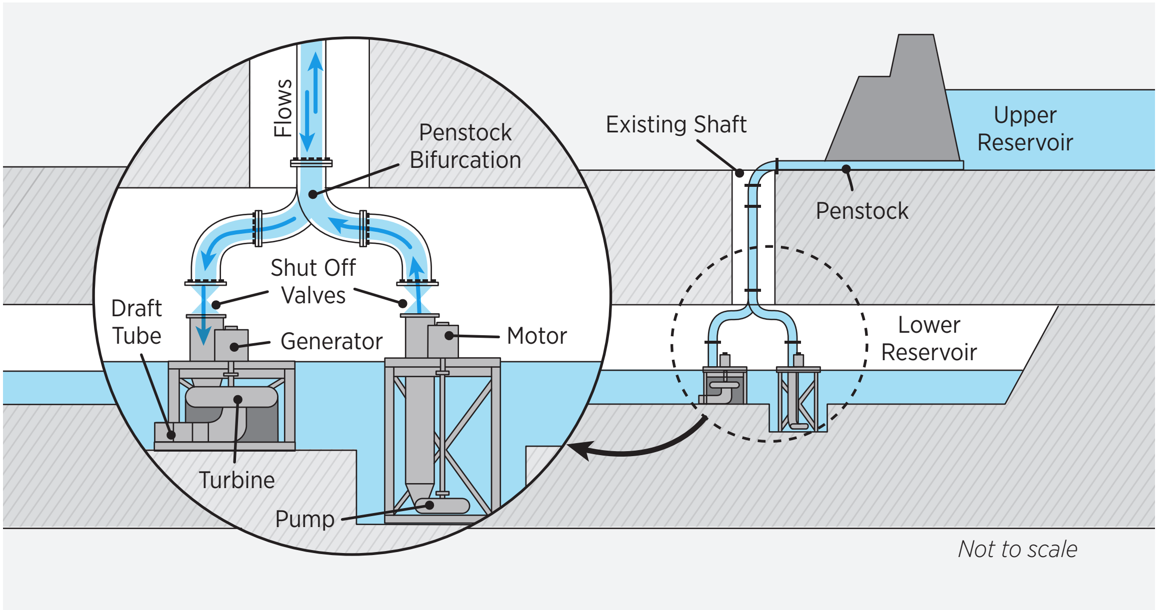
**Table 2-7.** Typical Operating Characteristics of Key Pumped Storage Hydropower Technologies

| Capability | Fixed-Speed PSH | DFIM Adjustable-Speed PSH | Ternary PSH with Hydraulic Bypass and Pelton Turbine |
|---|---|---|---|
| **Generation Mode:** | | | |
| Power output (% of rated capacity) | 30%[a]–100% | 20%–100% | 0%–100% |
| Standstill to generating mode (seconds) | 75–90 | 75–85 | 65 |
| Generating to pumping mode (seconds) | 240–420 | 240–415 | 25 |
| Frequency regulation | Yes | Yes | Yes |
| Spinning reserve | Yes | Yes | Yes |
| Ramping/load following | Yes | Yes | Yes |
| Reactive power/voltage support | Yes | Yes | Yes |
| Generator dropping | Yes | Yes | Yes |
| **Pumping Mode:** | | | |
| Power consumption (% of rated capacity) | 100% | 60%-100% (75%-125%)[b] | 0%–100% |
| Standstill to pumping mode (seconds) | 160–340 | 160–230 | 80 |
| Pumping to generating mode (seconds) | 90–190 | 90–190 | 25 |
| Frequency regulation | No | Yes | Yes |
| Spinning reserve | No | Yes | Yes |
| Ramping/load following | No | Yes | Yes |
| Reactive power/voltage support | Yes | Yes | Yes |
| Load shedding | Yes | Yes | Yes |

a. One of the key factors determining the minimum power output is the hydraulic head. While fixed-speed PSH with high head can have the minimum as low as 20% of rated capacity, 40% is a more realistic value for medium to lower head PSH units.

b. If a PSH unit is converted from fixed- to adjustable-speed and the same pump-turbine runner is used, the power consumption may range from 75% to 125% of the former fixed-speed power consumption (100%).

Source: Koritarov et al. 2015 [238]




Source: Hadjerioua et al. 2014 [83]

**Figure 2-46.** Pre-conceptual design of a potential modular pumped storage hydropower at existing coal mine

barriers commonly associated with large hydropower designs, including access to capital, a longer licensing process, and the potential impact to market prices (and subsequently revenues) caused by adding utility-scale storage to grid. Small m-PSH plants could potentially be developed at a variety of locations, including abandoned mines and quarries, many of them off-stream, thus avoiding a number of potential environmental issues. Figure 2-46 illustrates a potential m-PSH plant at an abandoned coal mine.

Ideally, m-PSH would be developed more rapidly, at lower risk, and with lower capital requirements than traditional large, site-customized plants. Some of the cost and design dynamics associated with this type of PSH development, however, are not well known, as the market for distributed energy storage has not developed. It is unclear, therefore, whether the benefits of modularization will be sufficient to outweigh the economies of scale inherent in utility-scale development, or if modular technology can be competitive with other alternative distributed storage technologies (i.e., batteries).

### *New PSH Concepts*

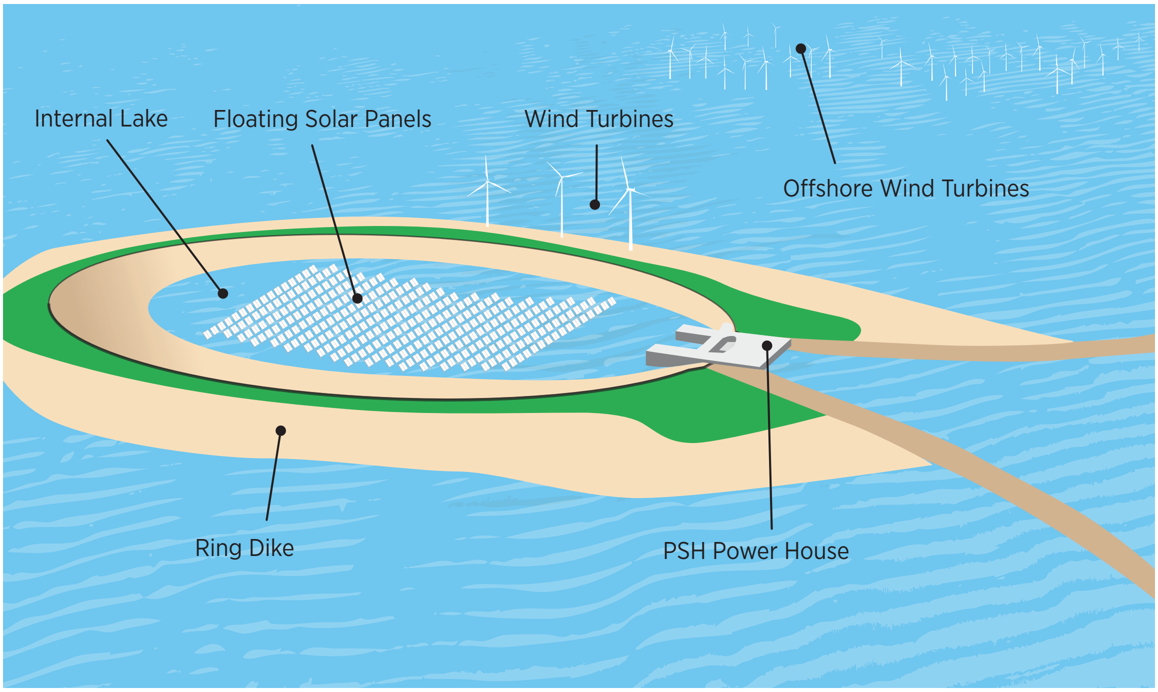
While PSH is one of the oldest energy technologies used for storing electric energy on a large scale, geological requirements for having two large water reservoirs at different elevations have often limited the locations where this storage technology can be applied. Many alternative PSH concepts are being explored to reduce or mitigate this challenge.

**Aquifer PSH.** Some aquifers can be used effectively as reservoirs in hydropower systems. Permeable aquifers have reservoir-like characteristics, and these can be exploited for hydropower generation. With aquifer PSH, water is pumped from the aquifer at off-peak times and stored above ground. When generation is needed, the water is allowed to fall back down to the aquifer to produce electricity. No large-scale aquifer storage project has been built as of 2015. Extensive research on the technology has been conducted, however, including a potential project at the Edwards Aquifer near San Antonio, Texas.

**Below-Ground Reservoir PSH.** Below-ground reservoirs such as old mine shafts, depleted natural gas formations, or tanks can be used as lower reservoirs for PSH. In such an application, water is pumped from the underground reservoir and stored above ground, then allowed to fall back down to the reservoir when generation is required. One such project is a potential 1,000-MW underground PSH facility in Granite Falls, Minnesota, for which a preliminary permit application was filed with FERC in 2010 by Riverbank Minnesota, LLC [241, 242].

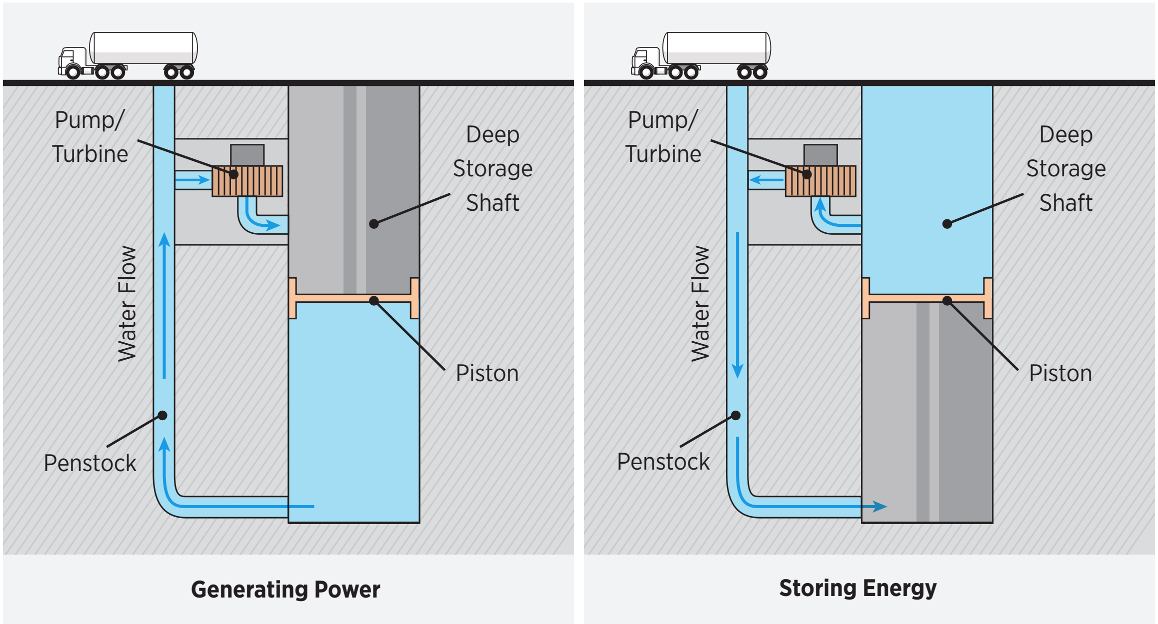
**Energy Island PSH.** Several concepts for a pumped storage "energy island" (Figure 2-47) have been proposed for storing energy from wind turbines in Europe's North Sea. These concepts generally include a ring dike encompassing an internal lake or lagoon that could be 100 feet or more below the surrounding sea level. During periods of excess available wind power, sea water would be pumped out of the island's interior lake, generating a differential in elevation between the sea water outside and inside the dike. When energy is needed during peak use periods or a lull in wind power production, sea water would be allowed to flow back in, generating electricity as in other types of pumped storage applications. Some concepts have incorporated turbines on the dike, and floating or fixed solar panels for additional electricity generation.

**In-Ground Storage Pipe PSH.** This hydraulic energy storage system consists of a storage shaft of 6–10 meters in diameter, housing a large piston built from pancakes of concrete and iron (Figure 2-48). Sliding seals surround the base of the piston. These seals allow the piston to move with minimal friction, and maintain the pressure differential above and below the mass. A return pipe of roughly two meters in diameter directs the water from the bottom of the shaft to the pump/turbine to generate electricity, or from the pump/turbine to the bottom of the shaft to raise the piston and store energy. Prototypical layouts allow for up to 2.4 GW per 2.5-acre footprint, with shafts extending 2,000 meters below the surface.




Source: National Renewable Energy Laboratory rendering, based on concepts proposed by the Belgian Ministry of Economy, Gottlieb Paludan Architects, and others

**Figure 2-47.** Energy Island pumped storage hydropower concept




Source: Gravity Power [243]

**Figure 2-48.** In-ground pipe pumped storage hydropower concept

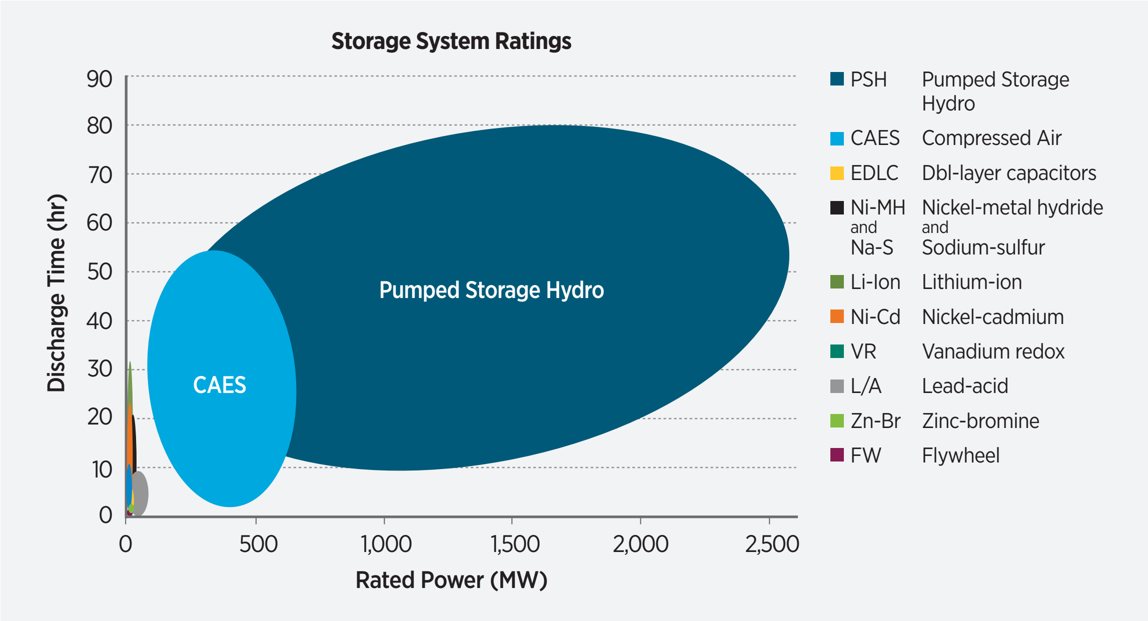
### *Comparison of Pumped Storage Hydropower to Other Energy Storage Technologies*

Growth in variable renewable generation has sparked renewed interest in energy storage technologies. As of 2015, research into the development of various grid-scale energy storage technologies, including batteries, flywheels, and compressed air energy storage was underway in the United States and internationally [244]. Figure 2-49 illustrates that PSH provides higher power ratings and larger energy storage capabilities than most other energy storage technologies. Compressed air energy storage is the only other technology that has facility generating capacity close to that for PSH. However, compressed air energy storage relies in part on fossil fuels for electricity generation (compressed air helps drive combustion turbines, thus reducing their use of natural gas fuel), and only a few compressed air energy storage plants are in operation. In contrast, PSH is a proven, commercially available, and reliable technology that compares favorably in terms of costs to most other energy storage solutions. As of 2013, PSH constituted 97% of the installed grid-scale energy storage capacity in the United States [2] and about 98% of the total energy storage capacity in the world [245].

## 2.7.3 The Role and Value of Pumped Storage Hydropower in Energy Systems

PSH facilities are versatile and provide benefits to the power system. These facilities were historically built to perform load shifting from peak to off-peak periods and to serve as backup capacity in case of forced outages of large thermal and nuclear generating units. As the penetration of variable renewable generation technologies has increased, PSH facilities are increasingly used to help manage the variability and uncertainty associated with wind and solar power generation, and to provide other benefits to the power system. PSH facilities also enable greater integration of wind and solar resources into the system by reducing the curtailments of excess variable renewable generation [83].

It has also been shown that that the value of PSH plants increases with higher penetration of variable renewable generation in the system [83]. PSH plants reduce overall system generation costs; provide flexibility and operating reserves; reduce cycling, ramping,




Source: HDR Inc.

**Figure 2-49.** Power rating vs. discharge time for energy storage technologies

and inefficient "part-load" operation of thermal generating units (Engels et al. 2010); reduce transmission congestion; increase the reliability of system operation; and provide other benefits [83]. Countries with a higher share of variable renewable generation, e.g., Germany, Austria, Spain, Portugal, are also the ones most active in constructing new PSH plants (Fisher et al 2012). A number of these new plants were designed to use advanced adjustable-speed and ternary technologies, as their additional flexibility in operation can compensate the fluctuations of variable renewable generation technologies. In addition, some existing PSH units, mostly in Japan, have been converted to adjustable-speed technology.

PSH technologies can contribute to operations and reliability requirements of the power grid [232, 83], including:

- **Inertial response:** The rotating masses in fixed-speed and ternary PSH units can provide inertial response to the power system (i.e., provide ride-through power and keep generating units synchronized). Adjustable-speed PSH units can provide inertial response through the use of power converters by controlling machine rotation speed.
- **Frequency regulation:** Adjustable-speed and ternary PSH can supply frequency regulation service in both pumping and generation modes, while fixed-speed PSH units can supply frequency regulation only when generating.
- **Contingency reserves:** All PSH technologies can provide contingency reserves.
- **Power system stability:** With respect to stability, fixed-speed and ternary PSH units have similar characteristics to other hydropower generators of the same size. The controls and capabilities of adjustable-speed units can be designed for improved performance under particular disturbances.
- **Voltage support:** As with stability, fixed-speed and ternary PSH units have substantial voltage support capabilities comparable to those of other hydropower generators of the same size. Adjustable-speed PSH units can be designed to provide enhanced voltage support beyond the capabilities of other generators.

- **Load leveling / energy arbitrage:** PSH facilities can earn revenues by storing energy when electricity prices are low and generating when prices are high. This reduces the peak power demand by shifting load to off-peak periods.
- **Generating capacity:** Capacity contributions from PSH contribute to meeting peak demand in a power system. Specifically, the ability of PSH to switch quickly between pumping and generation means that a PSH facility can either consume power or generate power as required by demand on the power system.
- **Large integration of variable renewables:** PSH provides flexible, fast-ramping generating and pumping capacity, as well as various ancillary grid services. These services support integration of variable renewable generation technologies into the grid. PSH can also store surplus variable renewable generation, thereby reducing curtailments.
- **Cycling and ramping of thermal generating units:** The flexibility of PSH units allows thermal units to operate in a steadier mode by reducing the need for ramping and frequent startups and shutdowns. This reduces the operating costs and wear and tear of thermal units.
- **Transmission congestion:** The operational flexibility of PSH units can help reduce transmission congestion and improve utilization of transmission assets, thus reducing or deferring the need for investments in new transmission capacity. This is heavily dependent on the locations of PSH plants in the power system.
- **Black start capability:** In the case of a widespread blackout in the power grid, system restoration must begin from generating units with the ability to start independently. Fixed speed and ternary PSH units are good candidates to provide black start service. Adjustable-speed units may also provide this service if equipped with an external power source (e.g., diesel generator) to energize the power converter.
- **Power quality and reliability:** PSH units provide reserve capacity that can be quickly dispatched during generation or transmission outages, thus improving the reliability and resiliency of system operations.

## 2.7.4 PSH Resources/ Opportunities

Based on applications submitted to FERC, electric utilities and PSH developers are showing renewed interest in developing new PSH plants in the United States. This interest is triggered, in part, by the recognition that the rapid expansion of variable renewable generation technologies into the electric grid will require increasing power system flexibility.

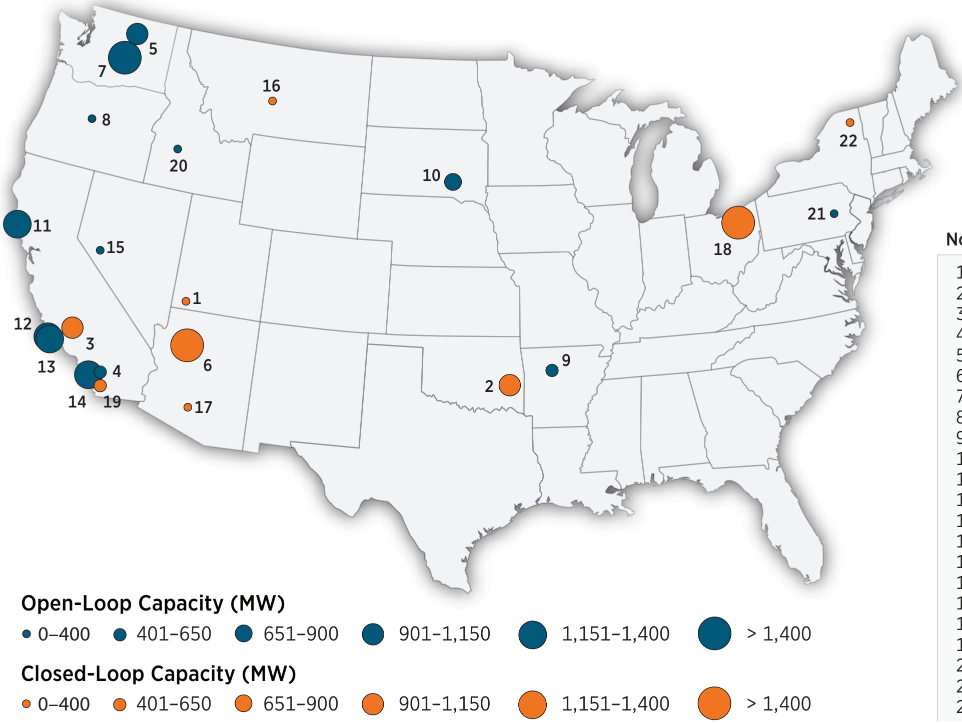
### *Preliminary FERC Permits for New Pumped Storage Hydropower Projects*

FERC has seen an increase in the number of preliminary permit applications filed for PSH projects. A preliminary permit does not authorize construction, but it does maintain priority of the application for a license (i.e., guaranteed first-to-file status) while the developer studies the site and prepares to apply for a license. As of April 2016, there were 23 active, FERC-issued preliminary permits for proposed PSH projects, representing more than 18,000 MW of capacity. More than 70% of these preliminary permits are for locations in the Western Interconnection, where the majority of existing and proposed variable generation technologies are located. Figure 2-50 illustrates proposed PSH projects in the United States with preliminary permits issued by FERC; nearly half of the preliminary permits propose closed-loop design. Many proposed projects (e.g., Eagle Mountain, Swan Lake North)[78] are considering the use of adjustable-speed PSH technology, which can be applied in open- and closed-loop designs. The Eagle Mountain project passed the preliminary permit phase and was issued a license in 2014.

### *Upgrading Existing Pumped Storage Hydropower with Advanced Technology*

Interest has also grown in converting existing fixed-speed PSH facilities in the United States to use advanced adjustable-speed technology. Adjustable-speed PSH facilities can provide regulation service in pumping mode, which helps facilitate renewable integration.

78. Eagle Mountain is a 1,300-MW PSH closed-loop project in California, and Swan Lake North is a 390-MW PSH closed-loop project in Oregon.




| No. | Capacity (MW) |
|---|---|
| 1 | 300 |
| 2 | 1,100 |
| 3 | 1,000 |
| 4 | 600 |
| 5 | 1,000 |
| 6 | 2,000 |
| 7 | 2,000 |
| 8 | 150 |
| 9 | 600 |
| 10 | 800 |
| 11 | 1,270 |
| 12 | 351 |
| 13 | 1,338 |
| 14 | 1,232 |
| 15 | 250 |
| 16 | 250 |
| 17 | 150 |
| 18 | 1,500 |
| 19 | 500 |
| 20 | 400 |
| 21 | 250 |
| 22 | 240 |

Note: Preliminary determination of open- vs. closed-loop classification based on preliminary permit application.

Source: FERC 2016 [246]

**Figure 2-50.** Preliminary permits for pumped storage hydropower in the United States

Not every fixed-speed PSH facility is a good candidate for conversion to adjustable-speed technology. A number of conditions related to civil structures and hydraulic, electrical, and mechanical systems need to be evaluated to determine if conversion is technically feasible and cost effective.

Internationally, several existing PSH plants have been converted to adjustable-speed technology. For example, in Japan, Unit 2 at the Yagisawa PSH plant was converted from fixed-speed to adjustable-speed in 1990. No conversions have been performed in the United States as of 2015.

## 2.7.5 New Pumped Storage Hydropower Development

New PSH can be developed by either the public or private sector. Most PSH facilities have been developed by electric utilities, both public and investor-owned. IPPs have shown interest in the development of new PSH facilities and have filed a number of applications for preliminary permits with FERC. IPPs hold more than 80% of the active preliminary permits for PSH projects, representing more than 15,000 MW of proposed capacity.

## Pumped Storage Hydropower Development Process

The PSH development process is similar regardless of the ownership types. This process involves the following considerations:

- **Determination of need.** Is there a need for the type of services that a PSH facility can provide? What are the projected types of services that will be needed in the long term, and what is the expected utilization of the PSH facility?
- **Market fundamentals.** The project business model must show that the PSH facility will be economically/financially viable given the regulatory and market environment. IPPs would want to know the conditions and/or requirements of long-term PPAs with a regulated utility before proceeding with development.
- **Site identification.** The characteristics of a potential site must be determined. These include:
  - *Technical aspects:*
    - The reservoirs, water conductors, and power plant must be designed to ensure that the resulting facility can perform as intended.
    - Developers must identify a water source for initial charge and make-up water for evaporative losses (closed-loop PSH), or identify an existing river or stream (open-loop PSH). An existing hydropower reservoir can also be used. The use of gray water from a waste treatment facility, storm water, sea water, and other non-potable sources are also possible options in some cases (typically for closed-loop PSH projects).
  - *Land ownership:*
    - Private lands: Projects may be sited on private lands in man-made or natural formations that could serve as lower or upper reservoirs, or use existing reservoirs/infrastructure. Abandoned coal surface mines and stone quarries are examples of man-made structures that could potentially be used as reservoirs for PSH projects.
    - Public lands: Projects may be sited within or adjacent to federal or state lands if they have features that are conducive to a PSH project.
  - *Environmental aspects:* The project needs to comply with all relevant environmental laws and regulations.
  - *Social and cultural aspects:* The project must comply with Section 106 of the National Historic Preservation Act and other similar laws and regulations at the relevant state and local levels of government.
  - *Geotechnical analysis:* The developer must confirm that a project is feasible with regard to geotechnical risk.
- **Transmission interconnection.** The developer must determine options for interconnection with the transmission system. Specific issues include the length of the proposed tie-line and coordination with FERC's jurisdictional interconnection process.
- **Permitting/licensing issues.** PSH projects require comprehensive environmental permitting at both the state and federal levels. If some or all of the land for the project is federally owned, additional time may be required for coordination among federal and state agencies. Potential impacts to recreational use, aquatic species, endangered species, and other issues require in-depth study similar to that for other types of hydropower.

## Role of Pumped Storage Hydropower in Sustainable Energy Development

PSH is a proven, reliable, commercially available technology that provides unique benefits (e.g., flexible capacity, energy storage, grid stability) for balancing variability of the load and variable renewable generation technologies, reducing their curtailments and increasing the overall reliability of power system operation. PSH can therefore help facilitate higher penetrations of variable renewable generation, which will result in an overall reduction in power sector emissions. PSH plants also improve the reliability and resilience of system operations by providing backup capacity that can be dispatched quickly during outages of large thermal units or other grid disturbances.

### *Environmental Impacts of Pumped Storage Hydropower*

Electricity generation by PSH facilities does not involve fossil fuels and thermal energy conversion processes. As with other storage technologies, PSH uses electricity from the grid to store energy. Net impacts on system emissions will depend on the generation mix that is used to provide energy for pumping at PSH units, and the generation mix that is displaced when PSH units are generating. In some systems, the net effect is positive, while in others it may be negative. Koritarov et al. [83] have shown that PSH impacts on emissions tend to decrease if more renewable energy is present in the system, as a larger share of pumping energy is provided by renewable generation and PSH plants also reduce curtailments of variable renewable generation technologies. In addition, PSH operation provides indirect emission benefits by allowing system operators to run fossil-fired plants more efficiently, with less ramping and unit cycling (start/stop operation).

In principle, PSH facilities are designed to have fast and flexible operating characteristics, so they are typically located at sites where the environmental impacts of such operation would be minimal. While open-loop PSH plants can have impacts on fish and other aquatic life, closed-loop PSH projects normally use two man-made reservoirs that are off-stream (not continuously connected to a naturally flowing water feature) and normally devoid of fish that could be affected by PSH operation. Typical PSH reservoir size is about one square mile, which is comparable to an average industrial site. Even closed-loop projects may have potential environmental issues, however, especially if they are constructed on brownfields (e.g., abandoned open pit mine lands) or other potentially contaminated areas. In addition, there are potential environmental impacts associated with activities that disturb the land during the reservoir construction process.

### *Regulatory Issues Influencing Pumped Storage Hydropower*

As with other hydropower projects, the licensing process for a new PSH project involves numerous activities and interactions with federal, state, municipal, and other authorities. There are also uncertainties because PSH projects need to obtain multiple approvals. Any delays in licensing or approval processes may affect overall project development costs, sometimes significantly.

Closed-loop PSH projects could reduce some challenges for developers, because they eliminate effects on fisheries and reduce effects on other resources (e.g., water quality and visual resources) that exist under open-loop PSH. This in turn can expedite permitting processes. The Hydropower Regulatory Efficiency Act of 2013 directed FERC to investigate the feasibility of a 2-year licensing process for closed-loop PSH projects.

Although the duration of FERC's licensing process can be dependent on the details of the proposed project and the existing resources that would be affected by it, PSH developers can take certain actions to shorten the licensing process. Developers can design the project to minimize the alteration of existing water flow and its use, and locate the project where there is minimal potential to affect threatened or endangered species and on sites for which information on existing environmental resources and project effects is readily available. In addition, developers can begin coordination and consultation with agencies and stakeholders early in the planning process to resolve issues and begin collecting any additional information prior to beginning the licensing process.

## 2.7.6 Costs and Financing of Pumped Storage Hydropower

Because of the site-specific nature of PSH project development, capital costs are difficult to broadly characterize and estimate. Costs of a PSH project are influenced by site-specific geotechnical and topological conditions; size of the reservoirs and dams or ring dikes; length of tunnels; use of surface vs. underground powerhouses; type of electromechanical technology; type of transmission system interconnection; environmental issues; the permitting process; the regulatory environment; the business plan; and the ownership structure (Text Box 2-11).

Text Box 2-11.

### Pumped Storage Hydropower in Hawaii

The islanded nature of Hawaii's markets as well as the state's high energy costs and ambitious renewable energy goals (100% renewable generation by 2045) make it an ideal location for PSH to supply grid flexibility. PSH can work in tandem with other energy resources in the state (solar, wind) to function as a battery for these systems. The Kauai Island Utility Cooperative has proposed a 25-MW PSH facility for the Puu Lua reservoir on the west side of Kauai and is awaiting preliminary approval. Preliminary estimates put the cost of this project at between $55 million and $65 million. The utility estimates that the ultimate cost of electricity with the facility in place would be 35% less than the utility's traditional oil-based generation [249].

A study of historical costs for 14 representative PSH facilities in the United States estimated the cost of a fixed-speed PSH project to be between $1,750/kW and $2,500/kW [235]. Other assessments estimate capital costs for a new fixed-speed PSH project to be between $1,850 and $2,500/kW [248], between 1,500/kW and $2,500/kW [250], and between $1,000/kW and $2,000/kW [251]. Estimates for the capital costs of a new adjustable-speed facility fall between $1,800/kW and 3,200/kW [250].[79]

The design and construction of a PSH project represents a significant investment and requires detailed economic and financial modeling. Economic and financial models provide different ways of assessing the merits of a project in monetary terms; while an economic model evaluates the project from the perspective of society as a whole, the financial model (also known as business model or pro forma) evaluates the project from the perspective of the owner. A developer will optimally conduct both economic and financial analyses.

The business model determines how project costs and benefits are allocated over time. Because PSH facilities can be developed by different types of owners, they will have different types of business models and distinct economic, competitive, and regulatory challenges. In the United States, utility-scale power plant ownership typically falls into two general categories: regulated utilities and IPPs.

**Financing of PSH Projects by Regulated Utilities.** The financing of PSH projects by regulated utilities is a unique case. Regulated utilities typically use cost-based business models and recover the costs of reasonable capital investments through rates that are approved by state regulators. Because of this, regulated utilities are not exposed to market risk in the way that IPPs are, and the cost of equity is usually lower for utility projects than for IPP projects. As a result of lower cost of equity, the financial structure of utility projects tends to be more heavily weighted with equity. Also, utilities are often more receptive than IPPs to investments with long return periods.

In the IOU market sector, project financing is typically based on rate recovery or investor at-risk funding. Most IOUs choose the rate-based recovery approach to minimize financing risk, even for strategic projects which may serve a future grid need. For these rate-based projects, the return on investment is specified in the agreements with the state utility regulators (e.g., public utility commissions), thus documenting both the need for the project and the reduced risk to the investor shareholders. Such projects typically require pre-approval from the respective utility commission and, for large projects, the IOU normally prepares an initial application to study the project. The study proposal details the tasks and budget to take the project from initial concept to feasibility.

At the conclusion of the initial study, if the project is attractive from the perspective of both the IOU and electricity customers, a second application normally leads to more detailed design and construction phases. The initial proposal usually takes the IOU up to a year

79. The costs are listed as given in each study; they are not converted to present day dollars. Given the scale of various activities and long development times of PSH projects, there is always some uncertainty about what is included or excluded in reported capital costs. For example, it is often unknown whether the engineering, administration, financing fees, interest, or other "soft costs" are reported as project capital costs or if they are reported in some other way. Since these costs can be significant, any conclusions about project costs and guidelines that are based on historic data need to be considered with care.

to develop, and the utility commission usually requires another year or more to approve the initial studies. Subsequent design and construction periods normally extend three to five years, depending on the complexity of the design and the need for environmental studies. Even this financing approach is not completely without risk. The IOUs are normally required to provide a balance of debt and equity throughout this process and may be responsible for any cost overruns outside the rate recovery basis. Alternatively, the utility commission may require that the IOU share in any cost savings on the project when determining the final rate recovery basis.

**Financing of PSH Projects by IPPs.** IPPs use market-based business models and are fully exposed to the volatility of competitive electricity markets. This often leads them to favor low-risk projects because the return on project investment is not guaranteed. IPPs also tend to favor projects that are not capital-intensive and that have short construction time and quick returns.

Most IPPs will seek to finance projects with non-recourse project financing. This means that, for both equity and debt investors, the revenues and assets of the PSH project are the only source of principal and interest payments on debt and of returns on capital to equity investors. Given the regulated nature of electricity markets in the United States, project lenders are more likely to require IPPs to have long-term PPAs with creditworthy entities to provide additional security for repayment of project debt.

Lenders also want to have confidence that the combination of project revenues and project equity is sufficient for construction. Historically, many IPP projects—including wind, solar, and gas-fired combined cycle projects—were constructed under a lump sum, fixed price contract for engineering, procurement, and construction services, known as an "EPC Agreement." Lenders have traditionally required the EPC Agreement Counterparty (usually at least one financially solvent construction company) to provide financial guarantees to support both the price and schedule provisions of the EPC Agreement. The use of such EPC Agreements is not typical for hydropower projects in the United States.

### 2.7.7 Treatment of Pumped Storage Hydropower in Electricity Markets

The value of PSH services and contributions to the grid depends on many factors, including their location in the system, the capacity mix of other generating technologies, the level of RE penetration within the system, the profile of electricity demand, the topology and available capacity of the transmission network, and other factors. Two PSH plants of similar size but in different locations may provide very different value to the power system. Hence, the valuation of PSH projects is site-specific and depends on the conditions within a particular utility system or electricity market.

While PSH plants provide numerous services and contributions to the power system (a total of 20 PSH services and contributions were identified by Koritarov et al. [83]), in existing U.S. electricity markets they typically can receive revenues only, from energy, certain ancillary services (typically for regulation, spinning, and non-spinning reserves), and capacity markets. The provision of black start capability is typically arranged through a long-term contract. Most existing markets have no established mechanisms to provide revenues for other services and contributions of PSH to the power grid. In contrast to competitive electricity markets, the traditional regulated utilities do not have established revenue streams for specific PSH services. The system operator typically optimizes the operation of PSH plants to minimize generation costs for the system as a whole. Therefore, in both traditional and restructured market environments, many PSH services and contributions are not explicitly monetized. Since PSH plants typically provide multiple services at the same time, it is difficult to distinguish the specific value of particular services and contributions, such as the inertial response, voltage support, transmission deferral, improved system reliability, and energy security.

#### *Pumped Storage Hydropower Scheduling in Energy and Grid Services Markets*

Existing market rules related to scheduling resources in U.S. electricity markets are not favorable for PSH or other energy storage technologies. Electricity markets in the United States use a bidding process to determine the market clearing levels of supply and demand offers for energy and ancillary grid services in the day-ahead and real-time markets. Most markets treat generation and demand functions of energy storage technologies separately and do not optimize their operation over the 24-hour period. While separate generation and demand bids work well for pure generation or demand market participants, this approach creates challenges for energy storage technologies such as pumped storage. These technologies both consume and produce electricity, and those two functions need to be coordinated.

In addition, the operation of PSH plants in sub-hourly markets is typically not fully optimized [252]. Ideally, the operation of a PSH plant should be optimized by a market operator (e.g., ISO/RTO). This would allow the ISO/RTO to make better use of the fast response characteristics of PSH plants, better balance the variability of load and variable generation resources, reduce overall power supply costs, and improve reliability of system operation. As shown in Table 2-7, PSH plants have extremely fast ramping capabilities and can quickly change their mode of operation, switching from pumping to generation, or vice versa, in minutes. Theoretically, if there is a need to provide fast ramping or balance the variability of load or of other renewables, a PSH facility could change mode of operation several times within the same hour.

PSH plants also participate in ancillary grid services markets, as they have technical capabilities to provide a number of ancillary service products in a cost-effective manner. Ideally, the energy and ancillary services provided by a PSH plant should be co-optimized to maximize the benefit for the entire power system.

The following topics related to market design issues could be studied to help system operators extract the full value of PSH [83].

- **Full optimization in day-ahead markets.** This optimization entails allowing the day-ahead market to schedule the mode of PSH based on minimizing costs over the full time horizon. As of 2015, PJM was the only market performing this type of optimization.
- **Full optimization in real-time markets.** This optimization entails allowing the real-time market to schedule the mode of PSH based on minimizing costs and information that has been updated since the day-ahead market. As of 2015, no market performed this action in the real-time unit commitment models.
- **Lost opportunity costs based on multiple hours for ancillary-service clearing prices.** Since the value of PSH depends greatly on its optimal operation over longer time periods (typically at least a day), the lost opportunity costs of its water resources are complex. Pricing mechanisms should account for situations where providing ancillary services in one hour results in a lost opportunity to provide energy in another.
- **Make-whole payments for PSH operation.** If PSH units are fully optimized in the market by the ISO, the owner/operators should be given guarantees by the ISO that following ISO schedules means operational losses will not be incurred [252].
- **Settlements based on sub-hourly time intervals.** If financial settlements are based on sub-hourly prices, the PSH plant will have opportunities to use its fast response to meet real-time pricing swings, since this would benefit both the plant and the power system. With settlements based on hourly prices, PSH and other resources have little incentive to respond to sub-hourly prices, and instead follow only the average hourly price. New York ISO, Southwest Power Pool, and CAISO settle sub-hourly, while all markets calculate sub-hourly prices as part of the real-time dispatch. FERC has proposed to require sub-hourly settlements in all markets.
- **Pay for performance for regulating reserves.** PSH can improve system reliability by providing regulating reserves that respond faster than those provided by many other technologies. PSH could therefore earn additional revenue if reserve payments were based on quality of performance (i.e., because PSH can provide similar services faster and with more reserve capacity compared to other technologies). All of the ISOs have modified rules in response to FERC Order 755 and are implementing design modifications related to a pay-for-performance market.

- **Market and pricing for primary frequency response.** Primary frequency response is a service that is not incentivized in most electricity markets. If the market for that service were established, it could provide an additional revenue stream for PSH, especially given that adjustable-speed PSH units are particularly well suited to provide primary frequency response. FERC has established a public docket to consider primary frequency response.
- **Market and pricing for flexibility reserves.** Different types of flexibility reserves are being proposed in the Mid-Continent and California ISOs, and are also discussed more broadly throughout the industry to address the operational challenges from variable renewable generation. Such new services can bring additional revenues to PSH plants, especially adjustable-speed PSH, which can provide reserves during both the generation and pumping modes of operation.
- **Market and pricing for voltage control.** As voltage support is a local service, there were no markets as of 2015 for voltage control in the United States, only cost recovery mechanisms. A pricing mechanism for voltage control could bring additional revenues to PSH.
- **Capital cost compensation.** Financing long-lived resources with high capital costs and low operating costs is difficult without a firm long-term commitment, regardless of how worthwhile a project is for rate payers. Capacity markets, where they exist, cover only a portion of capital costs for new units and only offer annual commitments at most. Treating PSH as a regulated, rate-based, transmission-like resource under system operator control might be beneficial by providing more certainty to PSH investors.

## 2.7.8 Trends and Opportunities

Trends and opportunities for PSH and for new energy storage in general include:

- Development of next-generation PSH technologies, and validation of the performance and reliability of these new technologies to contribute to hydropower growth.
- Enhancement of the environmental performance of new and existing PSH technologies. For example, environmental issues associated with PSH siting may be reduced with closed-loop PSH.
- Recognition of existing market rules and their impact on energy storage value, which could advance PSH. Energy storage acts as both generation and load, but in most markets those two functions are considered and procured separately. Storage value propositions include sub-hourly benefits that may not be captured with standard power system models and methods. In addition, storage value propositions span generation, transmission, and distribution systems and include a variety of benefits provided to the overall power system that are typically not part of revenue streams for energy storage projects.
- Improvement in understanding that, while many new energy storage technologies have had limited commercialization, this is not the case with PSH, a commercially proven and available technology.
- Standardization of the communications and control systems of new energy storage technologies, which could help PSH interoperate with existing utility systems.
- Advancements to streamlining the licensing process for PSH projects in order to expedite development.
- Sub-hourly settlements in energy markets and increased opportunities for energy arbitrage in sub-hourly markets.
- Treatment of PSH as a new storage asset class, which could help capture the full value of services and improve the economics in areas with resource constraints. In addition, crediting hydropower and PSH for its fast regulation response could improve system operations in situations where resource adequacy is a power system reliability issue.

Key recommendations from a recent DOE Report to Congress [66] for activities that can help accelerate pumped storage developments in the United States include the development of tools that would help evaluate the feasibility of conversion from fixed-speed to adjustable-speed technologies, and investigation of market mechanisms that would accurately compensate PSH for the full range of services provided to the power grid.

# 2.8 Economic Impact of Hydropower

Hydropower makes economic contributions in many regions of the United States. The construction and operation of hydropower facilities requires a qualified workforce and stimulates economic activity related to those jobs. To describe the role that hydropower plays in the U.S. economy through employment, this section categorizes and quantifies the number of workers employed; provides estimates of workforce demographics, which are key to planning for future hydropower; and discusses how most hydropower facilities also have non-hydropower uses (e.g., recreation and flood management) that have economic value in their own right.

### Highlights:

- In 2013, operations, construction, and upgrades at conventional hydropower plants supported approximately 143,000 jobs in the United States.
- Nearly 25,000 jobs are supported nationally by hydropower construction and upgrades, along with $1.4 billion in earnings ($2004), and nearly $3.3 billion in output.
- Multiple uses of existing hydropower facilities, such as recreation, transportation, drinking water, and flood management, can provide net economic benefits.

## 2.8.1 Hydropower Employment and Related Economic Activity

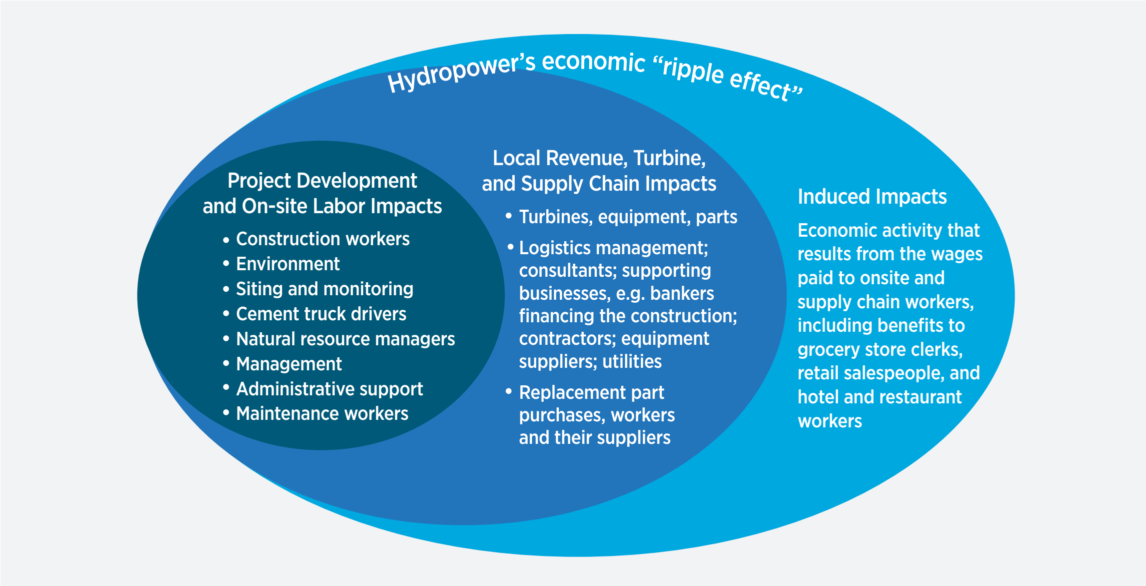
Hydropower owners need workers to operate and maintain facilities, install upgrades, and permit and construct new facilities. Construction and operation have an economic ripple effect—companies further down the supply chain need production workers, transportation workers, accountants, lawyers, managers, and other types of workers to supply inputs such as generation equipment, business-to-business services, or other materials. Workers supported by these expenditures—those who work at hydropower sites as well as throughout the supply chain—spend money on housing, transportation, recreation, food, health care, and other economic goods. These impacts, known as induced effects, are also quantified in this section. The total number of jobs and their ripple effect provide insight into how hydropower supports employment and economic activity in the United States.

This section contains impacts estimated using a combination of observed employment and economic modeling. Navigant Consulting, Inc., maintains GKS Hydro©, a database of observed employment at hydropower facilities in North America that serves as the source for data about onsite O&M jobs. DOE's Jobs and Economic Development Impacts (JEDI) [253] Conventional Hydro model is used to estimate all other O&M and construction phase jobs, as well as workers' earnings and overall output.[80] JEDI is an input-output (I-O) model that can be used to estimate gross economic impacts for energy projects. Appendix H contains more detail about the JEDI methodology, including general information about the model and how to interpret results.

As of year-end 2013, hydropower O&M supports approximately 118,000 total ongoing full-time equivalent (FTE) jobs nationwide (Table 2-8). Navigant Consulting, Inc. estimates that more than 23,000 of these jobs are at operating sites, with such jobs as plant operators, mechanics, electricians, and engineers [254].[81] These positions earn an average of $50,000–$56,000 annually (Table 2-8). The JEDI model presents results in three categories: Project Development and On-site Labor; Local Revenue, Turbine, and Supply Chain; and Induced. Figure 2-51 illustrates the economic ripple effect from one hydropower facility and includes sample jobs in each result category.

80. JEDI reports employment in full-time equivalent (FTE) jobs. One FTE is the equivalent of one person working 40 hours per week for one year. Earnings include wages and salaries, as well as employer provided supplements such as health insurance and retirement contributions. Output is a measure of overall economic activity. It includes all payments for inputs and the value of production.

81. Navigant also produced estimates of hydropower jobs in 2009. These estimates are not directly comparable to those presented here, however, because the *Hydropower Vision* solely includes construction and O&M activity associated with conventional hydropower, whereas Navigant included a more broad set of technologies in its previous study. Further differences between the Navigant studies can be explained by temporary spikes in hydropower activity around 2008 and 2009.




Source: National Renewable Energy Laboratory

**Figure 2-51.** Hydropower's economic ripple effect: sample occupations by category from the Jobs and Economic Development Impacts mode

**Table 2-8.** Estimate of Employment, Earnings, and Output from the Operation of Hydropower Facilities (2013)

| | Employment (FTE) | Earnings (Millions, $2004) | Average Annual FTE Earnings ($2004) | Output (Millions, $2004) |
|---|---|---|---|---|
| **Onsite** | 23,000 | $1,300 | $56,000 | $1,300 |
| **Supply Chain** | 54,000 | $2,800 | $52,000 | $10,400 |
| **Induced** | 41,000 | $1,800 | $50,000 | $5,400 |
| ***Total*** | 118,000 | $5,900 | $53,000 | $17,100 |

Sources: Navigant [254] (for onsite employment data only); remainder of data from JEDI

JEDI modeling calculates that, in 2013, supply chain and industry expenditures from hydropower O&M supported an estimated 54,000 jobs and nearly $10.4 billion in output (Table 2-9). Similar to onsite jobs, these positions earn an average over $50,000 annually, for a total of more than $2.8 billion in earnings. This category includes jobs in areas such as steel production, concrete factory workers, consultants, and accountants. Expenditures made by onsite and supply chain workers support an estimated 41,000 induced jobs, $5.4 billion in economic activity, and $1.8 billion in earnings. This translates to average annual compensation of $50,000.

Table 2-8 lists 2013 domestic jobs in each of the JEDI result categories, along with the associated earnings and overall economic activity. The on-site employment data are from consulting and research firm Navigant [255], while the other data are results from JEDI modeling.

Source: Daniel Rabon

**Figure 2-52.** Final adjustments of line boring equipment for installation of new turbine blade dowels

**Table 2-9.** Estimate of Economic Activity Supported by Construction and Upgrades at Hydropower Facilities

| | Employment (FTE) | Earnings (Millions, $2004) | Output (Millions, $2004) |
|---|---|---|---|
| **Onsite** | 8,000 | $600 | $900 |
| **Supply Chain** | 6,000 | $400 | $1,100 |
| **Induced** | 11,000 | $500 | $1,400 |
| ***Total*** | 25,000 | $1,400 | $3,300 |

Note: Totals may not sum due to rounding
Source: Navigant [254]

Construction and upgrades also support employment (Figure 2-52), although it is inherently temporary and lasts only as long as the upgrade or installation does. This is not to say that these jobs do not exist prior to and after projects, however; they could have been supported by hydropower or other construction activity in the past and could continue to be supported by other activities in the future, although this possibility is not estimated in the *Hydropower Vision.* Navigant [256] identified nearly 90 expansion and upgrade projects in the United States in 2013, along with several small (less than 1 MW) new construction projects.

Construction and upgrades to existing facilities are a smaller portion of economic activity than operation of existing facilities, but still a measurable part of the overall hydropower workforce.

Nearly 25,000 jobs are supported nationally by hydropower construction and upgrades, along with $1.4 billion in earnings ($2004), and nearly $3.3 billion in output (Table 2-9). The majority of these—approximately 10,500—are induced jobs that are supported by onsite and supply chain worker expenditures. Estimates show nearly 8,000 onsite workers and more than 6,000 through the supply chain.

### 2.8.2 Hydropower Workforce Demographics and Occupations

Hydropower has existed in the United States long enough to create a multi-generation workforce, i.e., one that has seen the retirements of workers who entered the industry as young professionals. Estimating the ages and occupations of hydropower workers provides insight and helps the industry understand potential future staffing needs. This is particularly important for occupations that require high levels of education or hydropower-specific training and that also have high concentrations of older workers who are nearing retirement age. Such positions may be difficult to fill due to education requirements and competition for workers from industries with similar workforce needs, and that difficulty would be compounded by the need to fill many of them within a short time span. The demographics of the hydropower workforce can be used to estimate future worker replacement needs and communicate these needs to institutions that provide education and training, as well as to individuals who might pursue careers in the hydropower industry.[82] Table 2-10 includes the distribution of onsite hydropower workers by occupation categories, with sample jobs listed for each.[83]

As illustrated in Figure 2-53, certain hydropower occupations may face high concentrations of workers retiring by 2030.[84] Managerial, supervisory, and highly skilled craft worker occupations are older than the U.S. average, with a concentration between the ages of 46 and 55. This is not always the case—there are more engineers and unskilled craft workers between age 26 and 35 than the U.S. average. Hydropower workers in other professional occupations most closely resemble the United States as a whole.[85]

High concentrations of older workers could indicate difficulty replacing the workforce, but it does not necessarily confirm this. For instance, the age distribution in managerial and supervisory occupations that is older than the distribution for all U.S. workers could represent movement from non-supervisory or management occupations after gaining experience in the hydropower industry [254]. Yet skilled craft workers

**Table 2-10.** Distribution of 2013 Onsite Hydropower Operations and Maintenance Workers by Occupation

| Occupation Category | Sample Jobs | Employment (2013) |
|---|---|---|
| Craft workers, unskilled | Construction laborers, helpers | 1,500 |
| Craft workers, skilled | Heavy equipment operators, mechanics | 6,200 |
| Supervisory craft workers | Managers of electricians, mechanics | 1,500 |
| Managers | Program managers, operations managers | 1,100 |
| Engineering | Civil engineers, environmental engineers | 2,800 |
| Administration | Accountants, clerical workers | 3,000 |
| Professional | Biologists, hydrologists, regulatory/compliance support workers | 7,100 |

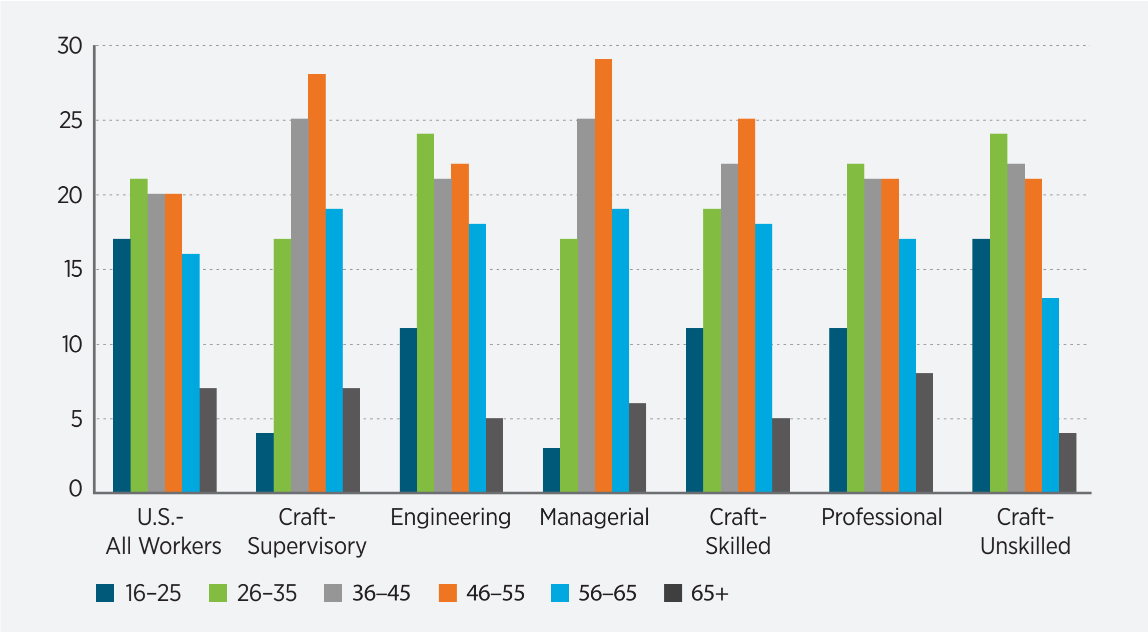
Source: Navigant [254]

82. Chapter 3 of the *Hydropower Vision* includes projections of replacement needs by occupational category through 2050.

83.. Appendix I contains further detail about specific occupations included in each category.

84. The *Hydropower Vision* roadmap contains further detail about workforce projections.

85. All distribution lines show a slight increase in the oldest age category. This is because the oldest category includes all workers of ages 65 and older, whereas all other age groups only include workers of one age.




Sources: U.S. Census Bureau American Community Survey [257], Navigant [256]

**Figure 2-53.** Age distributions of workers in hydropower occupations and distribution of all U.S. workers (2013)

are also older than average, so advancing skilled craft workers to supervisory positions as supervisors retire may prove problematic, as the pool of skilled craft workers who could fill these positions are themselves near retirement age. Filling managerial occupations may be somewhat less problematic, as these could draw from the pool of engineers and workers in professional occupations. Chapter 3 of the *Hydropower Vision* report provides a more detailed discussion of future workforce needs, including estimates of retirements by occupation.

### Regional Distribution of Onsite Workers by Occupation

Another key factor to consider when evaluating the hydropower workforce is location of the worker. The number of workers varies regionally, as do the number and size of hydropower facilities; hydropower facilities are concentrated in the Pacific and Southeast. The widest regional differences can be seen in skilled craft workers and professionals; the range of skilled craft workers as a percentage of total regional hydropower employment ranges from 39% in the Northeast to 18% in the Southeast (Table 2-11). Similarly, professionals account for 41% of the onsite O&M workforce in the Southeast and only 16% of the workforce in the Rockies [254].

Regional differences in workforce are due to a number of factors. Different regions have different geographies and resources, and hydropower is more common in some areas than others. Staffing requirements at large facilities differ from those at small facilities, so the mix of small and large hydropower plants also impacts the distribution of workers. Further variation can be explained by O&M practices that differ by company, technology, and region. For example, some companies have a central staffing pool that serves several dams, while other companies have staff onsite at most of their dams.

Potential workforce replacement needs, therefore, could vary regionally. For example, skilled craft workers are older on average than the U.S. average workforce, and generally older than most other occupations within the hydropower workforce. Replacement of these workers may be less complicated in the Southeast, which has a lower concentration of workers within these occupations than the Northeast. This is further explored in chapter 3 of the *Hydropower Vision* report, which contains projections of workforce replacement needs as well as estimates of new hydropower workers that could be needed to fulfill the *Hydropower Vision.*

Text Box 2-12.

### Economic Development Driven by Inexpensive Electricity

Hydropower can support economic development activity by providing a relatively inexpensive source of electricity, compared to other generation sources. Businesses—especially those that consume large amounts of electricity—can recognize advantages to locate in areas with hydropower to minimize their costs. The New York Power Authority requires businesses that receive hydropower to provide employment data so that the Authority can track the number of jobs created or retained due to lower-priced electricity. The New York Power Authority estimates that approximately 800 New York businesses and non-profits receive hydropower and support approximately 426,000 jobs [258].

Data show job creation due to hydropower in other regions as well. Microsoft, Yahoo, and Dell, for example, built large data centers in the Pacific Northwest because of inexpensive, clean hydropower [259]. Similarly, Apple purchased the DOE-funded 45-mile Hydroelectric Project from Earth By Design Hydro to power data centers in Central Oregon. Energy-intensive companies such as aluminum manufacturers have historically chosen to locate in areas with hydropower (and, in turn, inexpensive and reliable electricity), such as upstate New York and the Pacific Northwest [260].

**Table 2-11.** Percentage of Workers within Each Occupational Category by Region

| | Northeast | Southeast | Southwest | Midwest | Rockies | Pacific |
|---|---|---|---|---|---|---|
| **Craft—Unskilled** | 5% | 4% | 5% | 10% | 14% | 7% |
| **Craft—Skilled** | 39% | 18% | 28% | 34% | 35% | 28% |
| **Craft—Supervisory** | 6% | 7% | 8% | 5% | 9% | 5% |
| **Managerial** | 6% | 5% | 3% | 5% | 8% | 3% |
| **Engineering** | 14% | 11% | 11% | 12% | 6% | 14% |
| **Administrative Clerical** | 12% | 14% | 10% | 10% | 13% | 14% |
| **Professional** | 18% | 41% | 38% | 24% | 16% | 29% |

Source: Navigant [254]

## 2.8.3 Economic Impacts from Multiple Uses

Hydropower construction and O&M activity do not fully capture the economic impact of hydropower. It is unique among electricity generation sources in that many facilities in existence have multiple uses such as recreation, transportation, water supply, flood control, and others. A hydropower facility's economic value often exceeds that of electricity generation and has an impact on local economies and jobs. This necessitates a broad approach and the inclusion of such uses when assessing the economic effects of hydropower.

Despite the importance of estimating national impacts from multiple uses, the calculations are not always straightforward. Multi-purpose reservoirs, for example, often serve competing uses for a variety of stakeholders, such as water storage for irrigation and recreational activities like boating. Furthermore, hydropower uses can vary from site to site because of geography, regional needs, the size of facilities, and other factors. Government agencies, consultancies, academics, and professionals have sought to quantify both positive and negative impacts from hydropower facilities in cost-benefit studies, but these analyses typically focus on a specific site or region. Summaries of several of these studies are presented in Table 2-12 to provide insight into the range of national hydropower benefits beyond those from electricity generation.

Results from the studies cited in Table 2-12 vary from site to site depending on the scope of the facility and the method of assessment; however, all show positive net economic benefits from hydropower, even when considering impacts such as loss of potential revenue from fishing or boating. The methodologies also vary depending on scope, although within the United States most follow guidelines and evaluation techniques established by federal agencies such as the Corps, the U.S. Water Resources Council, FERC, Reclamation, and the Department of the Interior.

Studies conducted by these federal agencies suggest considerable overall economic impacts from the multiple uses of hydropower facilities, often in excess of benefits from electricity generation, construction, or O&M. This is compounded by the fact that many hydropower facilities, especially large reservoirs, have been in existence for many years and benefits have accrued over time.

**Table 2-12.** Summary of Study Results Quantifying Impacts from Multiple Uses of Hydropower

| Study | Project and Geography | Uses Analyzed | Estimated Impact |
|---|---|---|---|
| Reclamation [261] and Reclamation [262] | Hoover Dam Nevada, Arizona | Irrigation, flood control | $2.6 billion since 1950 |
| McMahon et al. [263] | Reallocated water use at Lake Lanier and the Apalachicola-Chattahoochee-Flint River Basin | Recreation, water supply, includes loss of benefits | $20 billion over 57 years |
| Corps [264] | Garrison Dam Lake Sakakaewa, North Dakota | Flood control, navigation, water supply, recreation, hydroelectricity | $1.8 billion lifetime benefits |
| Corps, cited in Oak Ridge National Laboratory [265] | Varies | Flood control | $20 billion annually |
| Department of the Interior [267] | Western United States | Irrigation, domestic water supply | $60 billion in economic activity; 378,000 annual jobs |

For example, Reclamation [261] estimates $1.26 billion in direct flood control benefits from the Hoover Dam since 1950 and Reclamation [262] estimates a total crop value of approximately $1.34 billion from the dam's irrigation water system in 1991 alone. The Hoover Dam provides water supply to more than 20 million people [261]. The Corps [264] reached similar conclusions when estimating economic impacts from the Garrison Dam/Lake Sakakaewa project in North Dakota, estimating total lifetime[86] benefits from the dam of approximately $1.8 billion, with $415 million from flood control, $7 million from navigation, $606 million from water supply, $86 million from recreation, and $639 million from hydropower use, respectively.

McMahon et al. [263] analyzed competing uses for Lake Lanier and the Apalachicola-Chattahoochee-Flint River Basin, the principal source of drinking and industrial water supply for the Atlanta metropolitan area, and found that the value of multiple uses exceeds the value of electricity from the hydropower. Lake Lanier serves a range of purposes, including hydropower, navigation, and recreation. Under the Apalachicola-Chattahoochee-Flint Basin Water Control Plan, priority has been given to hydropower and navigation objectives in reservoir management. McMahon et al. [263] compared alternative water allocations for municipal and industrial water supply, hydropower, and recreation. The present value of total benefits from reallocated water use has been estimated to increase from $19,100 million to $19,253 million during the 57 years of remaining lifetime of the basin [263]. Individual benefits for recreational purposes have been calculated to increase from $808 million to $982 million, and by $19,100 million for municipal and industrial water supply. Benefits from reducing hydropower generation to accommodate additional recreation and water supply have been estimated to decrease from $74 million to $53 million [263].[87]

The finding of significant positive net economic impacts from the multiple uses of dams and hydropower projects is repeated in other surveys of studies. A 2015 report by the Oak Ridge National Laboratory [265], for example, highlighted some of these findings. Oak Ridge cited a Corps estimate that flood control from multi-purpose hydropower facilities alone prevented more than $20 billion in flood damages annually, making flood control one of the most economically beneficial benefits from reservoirs [268]. An appraisal from the Department of the Interior suggested that irrigation water from Reclamation reservoirs generated $55.2 billion in economic output and supported 353,000 jobs nationwide [266]. Benefits of a smaller magnitude have been estimated for municipal and industrial water supply benefits, estimated to support 25,000 jobs annually and $4.7 billion in economic output in the West in 2013 alone [267]. Oak Ridge also referenced benefits of cooling water for the electricity sector to have a value of $14 ($2014) per acre-foot [269].

### *Analysis of Competing Uses*

Multiple uses of dams and hydropower facilities can also lead to competing uses. Population change, drought, changing regional preferences, or many other factors could lead to an evaluation of the economic impact of reducing different uses of hydropower facilities, including generation of electricity. Because many of these factors, such as population preferences and geography, can be variable, it is difficult to make a general statement about what use of reservoirs or hydropower facilities is optimal. Despite this variability and subsequent ambiguity, these competing (or potentially competing) uses are part of the economic value of hydropower. Researchers have attempted to quantify optimal uses of specific sites and come to different conclusions for different dams and facilities. Table 2-13 provides a summary of these studies.

Loomis [270] estimated potential recreation benefits from dam removal and subsequent restoration of the Lower Snake River in Washington. The analysis estimated 1.5 million visitor days five years after the removal of the four dams on Lower Snake River, and 2.5 million visitors annually during years 20–100, resulting in annualized benefits of $193 million to $310 million. The study concludes that these benefits exceeded the reservoir recreation loss of $31.6 million, but were about $60 million less than the total cost of the dam removal alternative. This study looked solely at recreation and tourism, not electricity from hydropower, but still provides insight into different types of recreation in a specific region.

86. Modeled for an 80-year period of analysis.

87. This example is anecdotal, not a quantitative estimate of losses.

**Table 2-13.** Studies that Quantify Impacts of Competing Dams and Hydropower Facility Uses

| Study | Project and Geography | Competing Uses | Results |
|---|---|---|---|
| Loomis [270] | Lower Snake River Washington | Reservoir and river recreation | River recreation benefits exceed reservoir benefits by $161 to $278 million |
| Debnath et al. [271] | Lake Tenkiller Oklahoma | Electricity and Recreation | Recreation benefits exceed electricity benefits |
| Ward and Lynch [272] | Rio Chama basin New Mexico | Electricity and Recreation | Electricity benefits exceed recreation losses from managing lake volumes |

Debnath et al. [271] conducted a study on hydropower in Oklahoma, evaluating hydropower generation and urban and rural water supply versus recreational uses at Lake Tenkiller. The findings suggested that the value of electricity that could be generated by releasing more water and lowering the lake level below its normal level in the summer months was more than offset by reduced recreational benefits. Similar results were obtained by Hanson et al. [273], who found that during summer, when recreational benefits were valued most, higher lake levels should be maintained.

In contrast, Ward and Lynch [272] also looked at tradeoffs between managing lake levels for recreation and hydropower in New Mexico. They found that benefits of hydropower electric production were higher than losses from managing lake volumes for recreation.[88]

## 2.8.4 Trends and Opportunities

The main trend and opportunity for Economic Value of Hydropower is that of replacing the existing hydropower workforce over time, as workers retire. These replacements will be needed in addition to new jobs supported by construction and operation of any new facilities. Therefore, development and promotion of professional and trade-level training and education programs are critical.

Hydropower is an economic driver in some regions of the country, supporting economic activity from construction and O&M as well as providing inexpensive electricity to help businesses compete globally. The multiple uses of hydropower facilities also have substantial economic impacts. Studies reviewed in this section focus on existing dams and larger hydropower installations, which aren't necessarily the same types of installations that will be built in the future. However, these new facilities will still have impacts beyond their construction and operation years. Hydropower can displace more carbon-intensive forms of generation, reducing GHG emissions and improving public health. These impacts are quantified and monetized in Chapter 3 of the *Hydropower Vision* report.

Chapter 3 explores these potential future impacts that could arise as a result of achieving the *Hydropower Vision.* It contains estimates of the economic value of GHG reductions, public health impacts from reduced pollution, reduced water consumption, and job needs supported by the *Hydropower Vision.* It also contains projections of when existing hydropower workers will retire or otherwise exit the hydropower workforce, providing estimates of the number of workers needed to maintain current employment levels.

88. Ward and Lynch [272] do not address specific aspects of recreation benefits such as boating or real estate values. These were estimated with the New Mexico Fish and Wildlife Department's RIOFISH model.

# Chapter 2 References

[1] U.S. Energy Information Administration (2015c). Table 7.2b Electricity Net Generation: Electric Power Sector. Monthly Energy Review. October 27, 2015. Accessed May 24, 2016. *http://www.eia.gov/totalenergy/data/monthly/*.

[2] Uria-Martinez, R.; P. O'Connor; and M. Johnson. 2015. 2014 Hydropower Market Report. DOE/EE 1195. U.S. Department of Energy, Washington, D.C. (US). Accessed May 2, 2016, *http://energy.gov/eere/water/downloads/2014-hydropower-market-report.*

[3] "The World's First Hydroelectric Power Plant Began Operation," America's Story from America's Library, Library of Congress. Accessed May 24, 2016. *http://www.americaslibrary.gov/jb/gilded/jb_gilded_hydro_1.html*.

[4] U.S. Energy Information Administration. Monthly Energy Review. U.S. Department of Energy. Accessed February 3, 2016. *http://www.eia.gov/totalenergy/data/monthly/*.

[5] U.S. Census. Series G171-182. Power Electric Energy, Production by Type of Prime Move: 1902 to 1945 (in MWh). Accessed May 24, 2016. *http://www2.census.gov/prod2/statcomp/documents/HistoricalStatisticsoftheUnitedStates1789-1945.pdf*

[6] U.S. Energy Information Administration. Form 860_US Capacity by Generator Unit_Y1891-Y2014. U.S. Department of Energy. October 21, 2015. Accessed February 3, 2016. *http://www.eia.gov/electricity/data/eia860/index.html*

[7] Bracmort, K., A. Vann, and C.V. Stern. July 7, 2015. Hydropower: Federal and Nonfederal Investment. CRS Report R42579. Congressional Research Service. Accessed May 3, 2016. *https://www.fas.org/sgp/crs/misc/R42579.pdf*

[8] U.S. Energy Information Administration, Form EIA-860 Annual Electric Generator Report, and Form EIA-860M. Hydropower has a long history in the United States. July 8, 2011. Accessed May 24, 2016. *http://www.eia.gov/todayinenergy/detail.cfm?id=2130*

[9] Federal Energy Regulatory Commission, Energy Infrastructure Updates (2011-2015). Accessed February 3, 2016. *http://www.ferc.gov/legal/staff-reports.asp*

[10] U.S. Energy Information Administration. Annual Energy Review (Table of generation, electric power Sector, 1949-2011). U.S. Department of Energy. Accessed May 3, 2016. *http://www.eia.gov/totalenergy/data/annual/xls/stb0802b.xls*

[11] U.S. Energy Information Administration. Electric Power Monthly, 2012-present. U.S. Department of Energy. Accessed May 3, 2016. *http://www.eia.gov/electricity/monthly/index.cfm*.

[12] "How Hydropower Works," U.S. Department of Energy. Accessed May 24, 2016, *http://energy.gov/eere/water/how-hydropower-works*.

[13] U.S. Energy Information Administration. Monthly Energy Review. U.S. Department of Energy. Accessed February 3, 2016. *http://www.eia.gov/totalenergy/data/monthly/*.

[14] U.S. Army Corps of Engineers. 2011. U.S. Army Corps of Engineers Civil Works Program: Five-Year Development Plan. Accessed May 24, 2016. *http://www.usace.army.mil/Missions/CivilWorks/Budget.aspx*.

[15] "Hydroelectric Powerplants Listed by Others," U.S. Bureau of Reclamation. Accessed May 24, 2016. *http://www.usbr.gov/power/data/faclothr.html*.

[16] Oldham, K., "Decommissioning dams—costs and trends," WaterPower and Dam Construction. 2009. Accessed on May 3, 2016. *http://www.waterpowermagazine.com/features/featuredecommissioning-dams-costs-and-trends/*

[17] National Hydropower Asset Assessment Program. "NHAAP FY15 Hydropower Plant Summary." Unpublished, 2015.

[18] Hawaiian Electric Company, Inc. 2015. 2014 Renewable Portfolio Standard Status Report. Hawaiian Electric Company Inc., Hawai'i Electric Light Company Inc., Maui Electric Company, Limited. Accessed May 23, 2016. *https://www.mauielectric.com/about-us/key-performance-metrics/renewable-energy*

[19] McManamay, R.A., C.O. Oigbokie, S.C. Kao, and M.S. Bevelhimer, "Classification of US hydropower dams by their modes of operation," River Research and Applications, 2016. DOI: *http://dx.doi.org/10.1002/rra.3004*.

[20] "National Inventory of Dams," Corps (U.S. Army Corps of Engineers). Accessed May 3, 2016. *http://geo.usace.army.mil/pgis/f?p=397:1:0*.

[21] Hadjerioua, Boualem, Yaxing Wei, and Shih-Chieh Kao. 2012. An Assessment of Energy Potential at Non-powered Dams in the United States. GPO DOE/EE-0711. U.S. Department of Energy Wind and Water Power Program, Washington, DC. Accessed May 3, 2016. *http://energy.gov/eere/water/downloads/assessment-energy-potential-non-powered-dams-united-states*

[22] Sale, M.J., S-C. Kao, M. Ashfaq, D.P. Kaiser, R. Martinez, C. Webb, and Y. Wei. October 2012. Assessment of the Effects of Climate Change on Federal Hydropower. ORNL/TM-2011/251. Oak Ridge National Laboratory, Oak Ridge, TN. Accessed April 29, 2016. *http://nhaap.ornl.gov/content/climate-change-impact-assessment*

[23] Held, I.M. and B.J. Soden, "Robust Responses of the Hydrological Cycle to Global Warming," Journal of Climate, Volume 19, 5686–5699, March 17, 2006. Accessed May 3, 2016. DOI: *http://dx.doi.org/10.1175/JCLI3990.1*.

[24] Canadian National Energy Board. 2013. Canada's Energy Future 2013: Energy Supply and Demand Projections to 2035. Nº de cat. NE2-12/2013F-PDF, ISSN 2292-1729. Accessed May 3, 2016. *https://www.neb-one.gc.ca/nrg/ntgrtd/ftr/2013/2013nrgftr-eng.pdf*.

[25] North American Electric Reliability Corporation, NERC Regions and Balancing Authorities (Maps), as of October 21, 2015. NNERC. Accessed May 24, 2016. *www.nerc.com/AboutNERC/keyplayers/Pages/default.aspx*

[26] "Western watches markets," Western Area Power Administration. Accessed May 24, 2016. *https://www.wapa.gov/newsroom/NewsFeatures/2013/Pages/watches-market.aspx*

[27] National Hydropower Asset Assessment Program, Oak Ridge National Laboratory. Accessed May 24, 2016. *http://nhaap.ornl.gov/*.

[28] Stori, V. 2013. Environmental Rules for Hydropower in State Renewable Portfolio Standards. Clean Energy States Alliance, Montpelier, VT (US). Accessed May 3, 2016. *http://www.cesa.org/resource-library/resource/environmental-rules-for-hydropower-in-state-renewable-portfolio-standards*.

[29] U.S. Energy Information Administration. April 2013. Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants. Independent Statistics & Analysis, U.S. Energy Information Administration, U.S. Department of Energy, Washington, DC. Accessed May 3, 2016. *http://www.eia.gov/forecasts/capitalcost/*.

[30] International Renewable Energy Agency. June 2012. Renewable Energy Technologies: costs analysis series. Volume 1: Power Sector, Issue 3/5. International Renewable Energy Agency, Abu Dhabi, United Arab Emirates. Accessed May 3, 2016. *http://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-hydropower.pdf*.

[31] U.S. Energy Information Administration. May 29, 2012. Seasonal hydroelectric output drives down wholesale electricity prices in the West. U.S. Energy Information Administration, U.S. Department of Energy, Washington, DC. Accessed May 3, 2016. *http://www.eia.gov/todayinenergy/detail.cfm?id=6450#*.

[32] U.S. Energy Information Administration. January 12, 2015. Wholesale power prices across the country in 2014. U.S. Energy Information Administration, U.S. Department of Energy, Washington, DC. Accessed May 3, 2016. *http://www.eia.gov/todayinenergy/detail.cfm?id=19531*.

[33] Maloney, P. "PURPA: still generating electricity, but with a few worms in the mix. The barrel: the essential perspective on global energy," October 29, 2012. S&P Global, Platts. Accessed May 24, 2016. *http://blogs.platts.com/2012/10/09/purpa_today/*.

[34] "Detailed Summary Maps, Renewable Portfolio Standards," Database of State Incentives for Renewables and Efficiency. Accessed May 3, 2016. *http://www.dsireusa.org/resources/detailed-summary-maps/*.

[35] Graf, W.L. 2006. Downstream Hydrologic and Geomorphic Effects of Large Dams on American Rivers. Geomorphology Volume 79, Issue 3-4, 2006, pages 336-360.

[36] Liermann, C.R., C. Nilsson, J. Robertson, and R.Y. Ng., "Implications of Dam Obstruction for Global Freshwater Fish Diversity, BioScience, Volume 62, Issue 6, pages 539-548. DOI: *http://dx.doi.org/10.1525/bio.2012.62.6.5*.

[37] Costanza, R., Pérez-Maqueo, O., Martinez, M. L., Sutton, P., Anderson, S. J., and Mulder, K. 2008. The value of coastal wetlands for hurricane protection. AMBIO: A Journal of the Human Environment, 37(4), 241-248.

[38] Jager, H.I. and B.T. Smith, "Sustainable Reservoir Operation: Can We Generate Hydropower and Preserve Ecosystem Values?" River Research and Applications, Volume 24, Issue 3, pages 340–352, March 2008, DOI: *http://dx.doi.org/10.1002/rra.1069*.

[39] Poff, N.L. and D.D. Hart, "How dams vary and why it matters for the emerging science of dam removal," BioScience, August 2002, Volume 52, Issue 8, pages 659-668.

[40] Powers, S.M., J.P. Julian, M.W. Doyle, and E.H. Stanley, "Retention and Transport of Nutrients in a Mature Agricultural Impoundment." Journal of Geophysical Research, Biogeosciences 2013, Volume 118, Issue 1, pages 91-103.

[41] Čada, G.F., "A Review of Studies Relating to the Effects of Propeller-Type Turbine Passage on Fish Early Life Stages." North American Journal of Fisheries Management 10: 418–426. Volume 10, Issue 4, 1990. Accessed May 3, 2016. *http://www.tandfonline.com/doi/abs/10.1577/1548-8675%281990%29010%3C0418%3AAROSRT%3E2.3.CO%3B2?journalCode=ujfm20*.

[42] Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B. Richter, R. Sparks, and J. Stromberg, "The natural flow regime: a new paradigm for riverine conservation and restoration," BioScience, 1997, Volume 47, pages 769-784.

[43] Opdam, P., J. Verboom, and R. Pouwels, "Landscape cohesion: an index for the conservation potential of landscapes for biodiversity," Landscape Ecology, March 2003, Volume 18, Issue 2, pp 113-126. DOI: *http://dx/doi.org/10.1023/A:1024429715253*.

[44] Hopping, P., P. March, T. Brice, and J. Cybularz. January 1997. Update on development of auto-venting turbine technology. Accessed May 3, 2016. *http://www.researchgate.net/publication/242113133_Update_on_Development_of_Auto-Venting_Turbine_Technology*.

[45] McManamay, R. A., D.J. Orth, C.A Dolloff, and M.A. Cantrell, "Gravel addition as a habitat restoration technique for tailwaters," North American Journal of Fisheries Management, Volume 30, Issue 5, 2010 pages 1238-1257. DOI: *http://dx.doi.org/10.1577/M10-007.1*.

[46] "Managing Reservoir Sediment," Western Water and Power Solution Bulletin, No. 8, 2008, U.S. Bureau of Reclamation. Accessed April 9, 2016. *https://www.usbr.gov/research/docs/updates/pre-2012/Managing-Reservoir-Sediment.pdf*.

[47] Ward, J.V. and J.A. Stanford, "Ecological Connectivity in Alluvial River Ecosystems and Its Disruption By Flow Regulation," Regulated Rivers: Research and Management, 1995, Volume 11, pages 105-119. DOI: *http://dx.doi.org/10.1002/rrr.3450110109*.

[48] Bessert, M. L., and G. Ortí. 2008. Genetic effects of habitat fragmentation on blue sucker populations in the upper Missouri River (Cycleptus elongatus Lesueur, 1918). *Conservation Genetics,* 9(4), 821-832.

[49] Larson, K.B., S.E. Niehus, J.D. Tagestad, K.D. Ham, S.H. Geerlofs, and M.C. Richmond. 2014. The Integrated Basin-Scale Opportunity Assessment Initiative: Pilot Assessment for the Deschutes River Basin. PNNL-23197. Prepared for the U.S. Department of Energy, Washington, D.C., by the Pacific Northwest National Laboratory, Richland, Washington. Accessed May 3, 2016. *http://basin.pnnl.gov/Content/reports/2014/BSOA_Deschutes_final_report_PublicDisclaimer.pdf*.

[50] McManamay, R.A., N. Samu, S.C. Kao, M.S. Bevelhimer, S.C. Hetrick, "A multi-scale spatial approach to address environmental impacts of small hydropower development," Environmental Management, Volume 55, 2015, pages 217-243. DOI: *http://dx.doi.org/10.1007/s00267-014-0371-2*.

[51] Coutant, C. C. and R. R. Whitney. 2000. Fish behavior in relation to passage through hydropower turbines: a review. Trans. Am. Fish. Soc., 129: 351–380.

[52] Pracheil, B.M., G.E. Mestl, and M.A. Pegg, "Movement Through Dams Facilitates Population Connectivity in a Large River," River Research and Applications, April 1, 2014. Accessed May 25, 2016. DOI: *http://dx.doi.org/10.1002/rra.2751*.

[53] Pracheil, B.M., C.R. DeRolph, M.P. Schramm, and M.S. Bevelhimer, "A fish-eye view of riverine hydropower systems: the current understanding of the biological response to fish passage," Reviews in Fish Biology and Fisheries, January 13, 2016. DOI *http://dx.doi.org/10.1007/s11160-015-9416-8*.

[54] Odeh, M.. 1999. A Summary of Environmentally Friendly Turbine Design Concepts. DOE/ID/13741. U.S. Department of Energy, Idaho Operations Office. Accessed May 24, 2016. *http://www1.eere.energy.gov/wind/pdfs/doewater-13741.pdf*.

[55] Hogan, T.W., G.F. Cada, and S.V. Amaral. 2014. The Status of Environmentally Enhanced Hydropower Turbines, Fisheries, 39:4, 164-172, Publisher: Taylor & Francis. Accessed May 3, 2016. *http://www.tandfonline.com/loi/ufsh20#.VyjAxpfG8Xg*.

[56] Johnson, G.E. and D.D. Dauble, "Surface Flow Outlets to Protect Juvenile Salmonids Passing through Hydropower Dams." Reviews in Fisheries Science, Volume 14, Issue 3, 2006, pages 213-244. DOI: *http://dx.doi.org/10.1080/10641260600864023*.

[57] Office of Technologies Assessment. 1995. Fish Passage Technologies: Protection at Hydropower Facilities. OTA-ENV-641. U.S. Congress, Office of Technologies Assessment. Accessed May 3, 2016. *http://www.scribd.com/doc/127919022/4101294-Fish-Passage-Technologies-Protection-at-Hydropower-Facilities#scribd*.

[58] Irwin, E.R. and M.C. Freeman. 2002. Proposal for adaptive management to conserve biotic integrity in a regulated segment of the Tallapoosa River, Alabama, U.S.A. Conservation Biology 16: 1212-1222.

[59] Walters, C. August 1986. Adaptive Management of Renewable Resources. MacMillan Publishing Company, New York, N.Y.

[60] Owen, D. and C. Apse, "Trading Dams," University of California Davis Law Review, 2015, Volume 48, pages 1043-1109.

[61] U.S. Bureau of Reclamation. March 2011. Hydropower Resource Assessment at Existing Reclamation Facilities. U.S. Department of Interior, Bureau of Reclamation, Power Resources Office. Denver, CO. Accessed May 24, 2016. *http://www.usbr.gov/power/AssessmentReport/*.

[62] Montgomery, Watson, Harza. 2009. Hydropower Modernization Initiative, Phase I, Needs and Opportunities Evaluation and Ranking. U.S. Army Corps of Engineers Northwest Division Hydroelectric Design Center, Contract No. W9127N-08-D-0003, Task Order 0013.

[63] U.S. Bureau of Reclamation. March 2012. Site Inventory and Hydropower Energy Assessment of Reclamation Owned Conduits: Supplement to the "Hydropower Resource Assessment at Existing Reclamation Facilities Report." Accessed May 24, 2016. *http://www.usbr.gov/power/CanalReport/*.

[64] Sale, M.J., N. Bishop, K. Johnson, A. Bailey, A. Frank, S. Reiser, and B.T. Smith. August 2014. Opportunities for New Energy Development in Water Conduits. ORNL/TM-2014/272, Oak Ridge National Laboratory, Oak Ridge, TN.

[65] Kao, S-C., R.A. McManamay, K.M. Stewart, N.M. Samu, B. Hadjerioua, S.T. DeNeale, D. Yeasmin, M. Fayzul, K. Pasha, A.A. Oubeidillah, and B.T. Smith. 2014. New Stream-Reach Development: A Comprehensive Assessment of Hydropower Energy Potential in the United States. GPO DOE/EE-1063. U.S. Department of Energy Wind and Water Power Program, Washington, DC. Accessed April 26, 2016. *http://nhaap.ornl.gov/nsd*

[66] U.S. Department of Energy. February 2015. Pumped Storage and Potential Hydropower from Conduits. Report to Congress. U.S. Department of Energy, Washington, DC. Accessed May 24, 2016. *http://energy.gov/eere/water/downloads/pumped-storage-and-potential-hydropower-conduits*.

[67] "Hydropower Sustainability Assessment Protocol, 2010," International Hydropower Association. Accessed May 3, 2016. *http://www.hydrosustainability.org/Protocol.aspx*.

[68] Sale, M.J., D. Hall, and J. Keil. 2016. Low Impact Hydropower Institute Certification Handbook, 2nd Edition. Low Impact Hydropower Institute, Harrington Park, NJ. Accessed May 3, 2016. *http://lowimpacthydro.org/*.

[69] Ela, E.; Gevorgian, V.; Tuohy, A.; Kirby, B.; Milligan, M.; O'Malley, M. "Market Designs for the Primary Frequency Response Ancillary Service -- Part I: Motivation and Design" Journal Name: IEEE Transactions on Power Systems; Journal Volume: 29; Journal Issue: 1, January 2014, Accessed May 3, 2016. DOI: 10.1109/TPWRS.2013.2264942. *http://www.osti.gov/scitech/biblio/1121511*.

[70] "Electricity Generating Capacity," last modified January 3, 2013. U.S. Energy Information Administration, U.S. Department of Energy. Accessed May 4, 2016. *https://www.EIA.gov/electricity/capacity/*.

[71] Lew, D.; G. Brinkman; E. Ibanez; A. Florita; M. Hummon; B-M. Hodge; G. Stark; J. King; S.A. Lefton; N. Kumar; D. Agan; S. Venkataraman and G.Jordan. September 2013. Western Wind and Solar Integration Study Phase 2. NREL/TP-5500-55588. National Renewable Energy Laboratory, Golden, CO (US); RePPAE, Wexford, PA (US); Intertek-APTECH, Houston, TX (US); GE Energy, Atlanta, GA (US). Accessed April 28, 2016. *http://primo-pmtna01.hosted.exlibrisgroup.com/Pubs:PUBS:NREL_HORIZON79670*.

[72] "Guide to Market Oversight—Glossary," Updated: March 15, 2016. Federal Energy Regulatory Commission. Accessed May 4, 2016. *http://www.ferc.gov/market-oversight/guide/glossary.asp*.

[73] Federal Energy Regulatory Commission, FERC (1996), "Promotion of wholesale competition through open access nondiscriminatory transmission services by public utilities and recovery of stranded costs by public utilities and transmitting utilities," Order No. 888, FERC Stats. & Regs. Issued April 1996. Accessed May 24, 2016. *http://www.ferc.gov/legal/maj-ord-reg/land-docs/order888.asp*.

[74] North American Electric Reliability Corporation. 2015. Glossary of Terms Used in NERC Reliability Standards. (updated May 17, 2016). North American Electric Reliability Corporation, Washington, D.C. (US). Accessed May 24, 2016. *http://www.nerc.com/files/glossary_of_terms.pdf*.

[75] Undrill, J. (2004) "Power plant operational issues relating to grid operation," presented at IEEE Xplore Conference: Power Engineering Society General Meeting, 2004. IEEE. Accessed May 4, 2016. DOI: *http://dx.doi.org/10.1109/PES.2004.1373182*.

[76] M. Piekutowski, A. Halley and S. Denholm, "The Future Role of Hydro Plant in Maximizing the Integration of Wind Generation," Wind Engineering (2012): Multi-Science Publishing Company; Vol. 36; No.1; pp 19-34. DOI: *http://dx.doi.org/10.1260/0309-524X.36.1.19*.

[77] Eto, J.H.; J. Undrill; P. Macken; R. Daschmans; B. Williams; B. Haney; R. Hunt; J. Ellis; H.F. Illian; C.A. Martinez; M. O'Malley; K. Coughlin; and K. Hamachi LaCommare. 2010. Use of Frequency Response Metrics to Assess the Planning and Operating Requirements for Reliable Integration of Variable Renewable Generation. LBNL-4142E. Lawrence Berkeley National Laboratory, Berkeley, CA (US). Accessed April 28, 2016. *http://eetd.lbl.gov/publications/use-of-frequency-response-metrics-to-*.

[78] E. Ela, V. Gevorgian, A. Tuohy, B. Kirby, M. Milligan, M. O'Malley, "Market Designs for the Primary Frequency Response Ancillary Service—Part I: Motivation and Design," IEEE Transactions on Power Systems. Vol. 29(1), January 2014: pp. 421-431. NREL Report No. JA-5D00-55356. Accessed May 24, 2016. DOI: *http://dx.doi.org/10.1109/TPWRS.2013.2264942*.

[79] North American Electric Reliability Corporation, "Essential Reliability Services Task Force Measures Framework Report," December 17, 2015. Accessed May 24, 2016. *http://www.nerc.com/Other/Pages/Essential-Reliability-Services-Task-Force-(ERSTF).aspx*.

[80] Key, T. 2013. Quantifying the Value of Hydropower in the Electric Grid: Final Report. Electric Power Research Institute report 1023144. Electric Power Research Institute, Palo Alto, CA (US). Accessed April 29, 2016. *http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001023144*.

[81] "U.S. Army Corps of Engineers Northwestern Division, dataquery," accessed May 23, 2016, *http://www.nwd-wc.usace.army.mil/cgi-bin/dataquery.pl*.

[82] Western Area Power Administration, released to Western Electricity Coordinating Council for Transmission Expansion Planning Policy Committee database. Accessed May 23, 2016, *https://www.wecc.biz/TransmissionExpansionPlanning/Pages/Datasets.aspx*.

[83] Koritarov, V.; H. Veselka; J. Gasper; B. Bethke; A. Botterud; J. Wang; M. Mahalik; Z. Zhou; C. Milostan; J. Feltes; Y. Kazachkov; T. Guo; G. Liu; B. Trouille; P. Donalek; K. King; E. Ela; B. Kirby; I. Krad and V. Gevorgian. 2014. Modeling and Analysis of Value of Advanced Pumped Storage Hydropower in the United States. Argonne National Laboratory Report ANL/DIS-14/7. Argonne National Laboratory, Argonne, IL (US). Accessed April 29, 2016. *https://anl.app.box.com/s/timqpu2moj7zw4t8t5ta9xpck14tta63*.

[84] R.K. Fisher, J. Koutnik, L. Meier, V. Loose, K. Engels, and T. Beyer. "A Comparison of Advanced Pumped Storage Equipment Drivers in the US and Europe," presented at HydroVision 2012, July 18, 2012, Louisville, KY. *http://dx.doi.org/10.13140/2.1.1082.4967*.

[85] J. Pfeifenberger. "Transmission Investment Trends and Planning Challenges," presented at EEI Transmission and Wholesale Markets School, Madison, WI, August 8, 2012. Accessed April 29, 2016. *http://www.brattle.com/system/publications/pdfs/000/004/432/original/Transmission_Investment_Trends_and_Planning_Challenges_Pfeifenberger_Aug_8_2012_EEI.pdf?1378772105*.

[86] Midcontinent Independent System Operator. 2014. MTEP14 MVP Triennial Review: A 2014 review of the public policy, economic, and qualitative benefits of the Multi-Value Project Portfolio. Midcontinent Independent System Operator, Inc. (MISO), Carmel, IN (US). Accessed April 29, 2016. *https://www.misoenergy.org/Library/Repository/Study/Candidate%20MVP%20Analysis/MTEP14%20MVP%20Triennial%20Review%20Report.pdf*.

[87] Milligan, M.; B. Kirby; T. Acker; M. Ahlstrom; B. Frew; M. Goggin; W. Lasher; M. Marquis and D. Osborn. 2015. Review and Status of Wind Integration and Transmission in the United States: Key Issues and Lessons Learned. NREL/TP-5D00-61911. National Renewable Energy Laboratory, Golden, CO (US). Accessed May 24, 2016. *http://primo-pmtna01.hosted.exlibrisgroup.com/Pubs:PUBS:NREL_HORIZON98071*.

[88] National Renewable Energy Laboratory. Data extracted from ABB Energy Velocity Suite (paid subscription only). *http://new.abb.com/enterprise-software/energy-portfolio-management/market-intelligence-services/velocity-suite*.

[89] J. Bakke, Z. Zhou, and S. Mudgal. 2013. Manitoba Hydro Wind Synergy Study. Midcontinent Independent System Operator, Inc. (MISO), Carmel, IN (US). Accessed April 28, 2016. *https://www.misoenergy.org/_layouts/MISO/ECM/Download.aspx?ID=160821*.

[90] State of Hawaii Department of Business, Economic Development, and Tourism. 2015. Hawaii Energy Facts and Figures. State of Hawaii Department of Business, Economic Development, and Tourism, Honolulu, HI, (US). Accessed April 29, 2016. *http://energy.hawaii.gov/resources/hawaii-state-energy-office-publications*.

[91] State of Hawaii Department of Business, Economic Development, and Tourism. *http://energy.hawaii.gov/*.

[92] Personal communications with Jeff Willliams, Power Cost Equalization Program Manager, Alaska Energy Authority.

[93] U.S. Energy Information Administration. 2013. Form EIA-860: Annual Electric Generator Report. U.S. Energy Information Administration. Washington, D.C. (US). Accessed May 2, 2016. *http://www.EIA.gov/electricity/capacity/xls/existing_gen_units_2011.xls*.

[94] GE Energy. 2010. Western Wind and Solar Integration Study. Subcontract Report NREL/SR-550-47434. GE Energy, Schenectady, NY (US). Accessed May 24, 2016. *http://primo-pmtna01.hosted.exlibrisgroup.com/Pubs:PUBS:NREL_HORIZON86161*.

[95] Acker, T.. 2011a. IEA Wind Task 24 Integration of Wind and Hydropower Systems; Volume 1: Issues, Impacts, and Economics of Wind and Hydropower Integration. NREL Report No. TP-5000-50181. Northern Arizona University on behalf of the National Renewable Energy Laboratory U.S. Department of Energy Wind and Hydropower Program, Flagstaff, AZ (US). Accessed April 28, 2016. *http://energy.gov/eere/wind/wind-program-newsletter-first-quarter-2012*.

[96] Ela, E.; M. Milligan; and B. Kirby. 2011. Operating Reserves and Variable Generation. A comprehensive review of current strategies, studies, and fundamental research on the impact that increased penetration of variable renewable generation has on power system operating reserves. NREL Report No. TP-5500-51978. National Renewable Energy Laboratory, Golden, CO (US). Accessed May 24, 2016. *http://primo-pmtna01.hosted.exlibrisgroup.com/Pubs:PUBS:NREL_HORIZON83046*.

[97] Exeter Associates, Inc., and GE Energy. 2012. PJM Renewable Integration Study Task Report: Review of Industry Practice and Experience in the Integration of Wind and Solar Generation. Prepared for PJM Interconnection, LLC by Exeter Associates, Inc., Columbia, MD (US) and GE Energy, Atlanta, GA (US). Accessed April 28, 2016. *http://www.pjm.com/committees-and-groups/subcommittees/irs/pris.aspx*.

[98] Palchak, D., and Denholm, P. 2014. Impact of Generator Flexibility on Electric System Costs and Integration of Renewable Energy. Tech. Report TP-6A20-62275. National Renewable Energy Laboratory, Golden, CO (US). Accessed April 29, 2016. *http://www.energy.gov/eere/analysis/downloads/impact-generator-flexibility-electric-system-costs-and-integration-renewable*.

[99] Acker, T. and C. Pete. 2012. Western Wind and Solar Integration Study: Hydropower Analysis. NREL Report No. SR-5500-53098. National Renewable Energy Laboratory, Golden, CO (US). Accessed May 24, 2016. *http://primo-pmtna01.hosted.exlibrisgroup.com/Pubs:PUBS:NREL_HORIZON83601*.

[100] J. Bakke, Z. Zhou, and S. Mudgal. 2013. Manitoba Hydro Wind Synergy Study. Midcontinent Independent System Operator, Inc. (MISO), Carmel, IN (US). Accessed April 28, 2016. *https://www.misoenergy.org/_layouts/MISO/ECM/Download.aspx?ID=160821*.

[101] Acker, T. 2011b. IEA Wind Task 24 Integration of Wind and Hydropower Systems; Volume 2: Participant Case Studies. NREL Report No. TP-5000-50182. Northern Arizona University on behalf of the National Renewable Energy Laboratory U.S. Department of Energy Wind and Hydropower Program, Flagstaff, AZ (US). Accessed April 28, 2016. *http://energy.gov/eere/wind/wind-program-newsletter-first-quarter-2012*.

[102] E. Ibanez, T. Magee, M. Clement, G. Brinkman, M. Milligan, and E. Zagona, "Enhancing hydropower modeling in variable generation studies," Energy, The International Journal 74 (2014): pgs. 518-528. Accessed May 24, 2016. DOI: *http://dx.doi.org/10.1016/j.energy.2014.07.017*.

[103] North American Electric Reliability Corporation, "Written Statement of Gerry Cauley, President and CEO, North American Electric Reliability Corporation, to the Quadrennial Energy Review Task Force, February 4, 2016". February 4, 2016. Accessed May 23, 2016. *http://www.nerc.com/news/testimony/Pages/Cauley-Participates-on-DOE-Quadrennial-Energy-Review-Panel-.aspx*.

[104] U.S. Energy Information Administration (EIA). 2015a. Annual Energy Outlook 2015, April, DOE/EIA-0383(2015). U.S. Energy Information Administration, Washington, D.C. (US). Accessed May 2, 2016. *http://www.eia.gov/forecasts/aeo/*.

[105] Bolinger, M. 2013. Revisiting the Long-Term Hedge Value of Wind Power in an Era of Low Natural Gas Prices. LBNL-6103E. Lawrence Berkeley National Laboratory, Berkeley, CA (US). Accessed May 24, 2016. *https://emp.lbl.gov/publications/revisiting-long-term-hedge-value-wind-power-era-low-natural-gas-prices*.

[106] Borenstein, Severin, and Bushnell, James. 2015. The U.S. Electricity Industry after 20 Years of Restructuring. Energy Institute at Haas School of Business, Berkeley, CA. Accessed May 24, 2016. *http://www.nber.org/papers/w21113*.

[107] Federal Energy Regulatory Commission (FERC). 2014e. Q3 2014 Brookfield White Pine Hydro LLC transactions. FERC Electronic Quarterly Reports. Federal Energy Regulatory Commission, Washington D.C. (US). Accessed May 5, 2016. *http://eqrreportviewer.ferc.gov*.

[108] "Wholesale Electricity and Natural Gas Market Data," last modified April 28, 2016. U.S. Energy Information Administration. U.S. Department of Energy. Accessed May 4, 2016. *http://www.EIA.gov/electricity/wholesale*.

[109] "Electric Power Markets: National Overview," Updated February 29, 2016. Federal Energy Regulatory Commission. Accessed May 4, 2016. *http://www.ferc.gov/market-oversight/mkt-electric/overview.asp*.

[110] Northwest PowerPool (NWPP). 2015. Northwest PowerPool Area Assessment of Reliability and Adequacy 2015 Summer Operating Conditions. Northwest PowerPool. March, 2015. Accessed May 3, 2016. *http://www.nwpp.org/documents/Seasonal-Assessments/Summer-Assessment-2015.pdf*.

[111] Patton, D.B., P. LeeVanSchaick, and J. Chen. 2014. 2013 State of the Market Report for the New York ISO Markets. Potomac Economics, Market Monitoring Unit for the New York ISO, Fairfax, VA (US). Accessed May 23, 2016. *https://www.potomaceconomics.com/index.php/markets_monitored/new_york_iso*.

[112] "Wholesale Electricity and Natural Gas Market Data," 2014 data. Last modified April 28, 2016. Accessed May 4, 2016. *http://www.EIA.gov/electricity/wholesale*.

[113] U.S.-Canada Power System Outage Task Force. 2004. U.S.-Canada Power System Outage Task Force, Final Report on the August 2003 Blackout in the United States and Canada: Causes and Recommendations. United States and Canada. Accessed May 3, 2016. *http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/BlackoutFinal-Web.pdf*.

[114] Federal Energy Regulatory Commission (FERC) (2003) "Docket No. ER03-291, Order Accepting Application". February, 2003. Accessed May 23, 2016. *https://www.gpo.gov/fdsys/pkg/FR-2003-01-08/html/03-376.htm*.

[115] Electric Reliability Council of Texas (ERCOT). 2012. ERCOT Nodal Protocols Section 6: Adjustment Period and Real-Time Operations. Electric Reliability Council of Texas, Austin, TX (US). Accessed May 2, 2016. *http://www.ercot.com/content/mktrules/protocols/current/06-100112_Nodal.doc*.

[116] Loose, V.W. 2011. Quantifying the Value of Hydropower in the Electric Grid: Role of Hydropower in Existing Markets. SAND2011-1009. Sandia National Laboratories, Albuquerque, NM (US). Accessed May 4, 2016. *http://prod.sandia.gov/techlib/access-control.cgi/2011/111009.pdf*.

[117] Federal Energy Regulatory Commission. WECC reporting regions. Western Electricity Coordinating Council, Salt Lake City, UT (US). Accessed May 3, 2016. *http://www.ferc.gov/market-oversight/mkt-electric/wecc-subregions.pdf*.

[118] Final Rule by the Federal Energy Regulatory Commission Issued October 20, 2011, Frequency Regulation Compensation in the Organized Wholesale Power Markets. Code of Federal Regulation 18 CFR Part 35 (2011): Docket Nos. RM11-7-000 and AD10-11-000; Order No. 755. Accessed May 5, 2016. *http://www.ferc.gov/whats-new/comm-meet/2011/102011/E-28.pdf*.

[119] "2016/2017 RPM Base Residual Auction Results," PJM Interconnection. PJM DOCS #753726. Accessed May 4, 2016. *http://www.pjm.com/~/media/markets-ops/rpm/rpm-auction-info/2016-2017-base-residual-auction-report.ashx*.

[120] "Installed Capacity: View Strip Auction Summary," New York Independent System Operator (NYISO). Accessed May 4, 2016. *http://icap.nyiso.com/ucap/public/auc_view_strip_detail.do*.

[121] Federal Energy Regulatory Commission (FERC) (2014a. OE Energy Market Snapshot, Central Version—September 2014 Data. Office of Enforcement, Federal Energy Regulatory Commission, Washington D.C. (US). Accessed May 24, 2016. *http://www.ferc.gov/market-oversight/mkt-snp-sht/mkt-snp-sht.asp*.

[122] Federal Energy Regulatory Commission (FERC) (2014b. OE Energy Market Snapshot, East Version—September 2014 Data. Office of Enforcement, Federal Energy Regulatory Commission, Washington D.C. (US). Accessed May 24, 2016. *http://www.ferc.gov/market-oversight/mkt-snp-sht/mkt-snp-sht.asp*.

[123] Order Confirming and Approving Rate On A Final Basis by the Federal Energy Regulatory Commission. Issued October 16, 2014, 149 FERC ¶ 61,043 (2014): Docket Nos. EF14-5-000, EF14-5-001. Accessed May 24, 2016. *https://www.ferc.gov/whats-new/comm-meet/2014/ca10-16-14.asp*.

[124] Electric Reliability Council of Texas. 2014. About the Operating Reserve Demand Curve and Wholesale Electric Prices. Electric Reliability Council of Texas, Austin, TX (US). Accessed May 4, 2016 *https://www.hks.harvard.edu/hepg/Papers/2014/ORDCUpdate-FINAL.pdf*..

[125] "Wholesale Electricity and Natural Gas Market Data," October 2015. Last modified April 28, 2016. Accessed May 4, 2016. *http://www.EIA.gov/electricity/wholesale*.

[126] Shie-Jie, D., Y. Shen, and H. Sun. "Optimal Scheduling of Hydro-Electric Power Generation with simultaneous Participation in Multiple Markets," presented at 2006 IEEE PES Power Systems Conference and Exposition, Oct. 29 2006 - Nov. 1 2006. DOI: 10.1109/PSCE.2006.296160. Accessed May 25, 2016. *http://dx.doi.org/10.1109/PSCE.2006.296160*.

[127] S. Niu and M. Insley, "On the Economics of Ramping Rate Restrictions at Hydro Power Plants: Balancing Profitability and Environmental Costs," Energy Economics (2013): 39, 39-52, September 2013. Accessed May 25, 2016. DOI: *http://dx.doi.org/10.1016/j.eneco.2013.04.002*.

[128] Notice of proposed rulemaking by the Federal Energy Regulatory Commission on Issued September 17, 2015, Settlement Intervals and Shortage Pricing in Markets Operated by Regional Transmission Organizations and Independent System Operators. Code of Federal Regulation 18 CFR Part 35 (2015) Docket No. RM15-24-000. Accessed May 4, 2016. *https://www.ferc.gov/whats-new/comm-meet/2015/091715/E-1.pdf*.

[129] North American Electric Corporation (NERC). 2013. Special Protection Systems (SPS) and Remedial Action Schemes (RAS): Assessment of Definition, Regional Practices, and Application of Related Standards. Revision 0.1, April 2013.

[130] D. Aswani, R. Clarke-Johnson, and G. Runyan. 2011. The Impact of Hydroelectric Power and Other Forms of Generation on Grid Frequency Stability for the WECC Region. American Governor Company, Warminster, PA (US). Accessed May 4, 2016. *https://www.americangovernor.com/wp-content/uploads/2013/04/Impact-of-Hydropower-on-Grid-Stability-HV2011.pdf*.

[131] Notice of Inquiry by the Federal Energy Regulatory Commission on Issued February 18, 2016, Essential Reliability Services and the Evolving Bulk-Power System - Primary Frequency Response. Docket No. RM16-6-000 (2016). Accessed May 4, 2016. *http://www.ferc.gov/whats-new/comm-meet/2016/021816/E-2.pdf*.

[132] Ashton, L. "Dam Management Plan Makes the Most of Columbia River's Water." Los Angeles Times. March 18, 2001. Accessed May 4, 2016. *http://articles.latimes.com/2001/mar/18/local/me-39196*.

[133] Ela, E., M. Milligan, A. Bloom, A. Botterud, A. Townsend, and T. Levin. 2014. Evolution of Wholesale Electricity Market Design with Increasing Levels of Renewable Generation. National Renewable Energy Laboratory, Golden, CO (US). NREL/TP-5D00-61765. Accessed May 2, 2016. *http://www.nrel.gov/docs/fy14osti/61765.pdf*.

[134] "Negative wholesale electricity prices occur in RTOs." Accessed May 4, 2016. *http://www.EIA.gov/todayinenergy/detail.cfm?id=6730*. ***Note** The original chart and associated discussion of the frequency of negative prices in RTOs originally published on June 18, 2012 has been removed because of incomplete data from an external source.*

[135] Loutan, C. "ERSTF, Loads and Resources Balance". Presented at NERC Conference, Vancouver, B.C., September 17, 2014—September 18, 2014.

[136] California Independent System Operator (CAISO). 2015. Q1 2015 Report on Market Issues and Performance. California Independent System Operator (CAISO), Folsom, CA. Accessed May 24, 2016. *http://caiso.com/market/Pages/MarketMonitoring/MarketIssuesPerfomanceReports/Default.aspx*.

[137] Bird, L.; J. Cochran, and X. Wang. 2014. Wind and Solar Energy Curtailment: Experience and Practices in the United Sates. NREL/TP-6A20-60983. Accessed May 24, 2016. *http://primo-pmtna01.hosted.exlibrisgroup.com/Pubs:PUBS:NREL_HORIZON97383*.

[138] Midcontinent Independent System Operator, Inc. 2015. Bi Directional EAR. Seams Management Working Group. January, 2015. Midcontinent Independent System Operator, Inc., Carmel, IN (US). Accessed May 3, 2016. *https://www.misoenergy.org/_layouts/MISO/ECM/Redirect.aspx?ID=191104*.

[139] Order On Tariff Revisions by the Federal Energy Regulatory Commission on Issued October 16, 2014, 149 FERC ¶ 61,042 (2014): docket No. ER14-2574-000. Accessed May 4, 2016. *http://elibrary.ferc.gov/idmws/docket_sheet.asp?DOCKET=ER14-2574*.

[140] Xu, L. and D. Tretheway. 2014. Flexible Ramping Products, Incorporating FMM and EIM: Draft Final Proposal. California Independent System Operator, Infrastructure Development Group, Folsom, CA (US). Accessed May 3, 2016.*https://www.caiso.com/Documents/DraftFinalProposal_FlexibleRampingProduct_includingFMM-EIM.pdf*.

[141] Sale, M.J. 2011. Outlook for the U.S. Army Corps of Engineers Hydropower Program. M.J. Sale & Associates. 2011-WRO-P-02. Accessed May 3, 2016. *http://www.iwr.usace.army.mil/Portals/70/docs/iwrreports/2011-WRO-P-02.pdf*.

[142] U.S. Library of Congress, Congressional Research Service. Hydropower: Federal and Non-Federal Investment by Bracmort, K. C. V. Stern, and A. Vann. 7-5700. 2013.

[143] National Research Council, "Corps of Engineers Water Resources Infrastructure: Deterioration, Investment, or Divestment?" The National Academies Press (2012), DOI: *http://dx.doi.org/10.17226/13508*.

[144] Energy Information Administration. "Preside1nt's proposed budget calls for strategic review of government's role in TVA." Today in Energy. May 7, 2013. Accessed May 4, 2016. *http://www.EIA.gov/todayinenergy/detail.cfm?id=11151*.

[145] Lazard (2014). "TVA Strategic Assessment" Lazard Freres & Co. January 2014. Accessed May 24, 2016. *http://www.sec.gov/Archives/edgar/data/1376986/000137698614000019/a8-klazardreportxxjune2014.htm*.

[146] Southwestern Power Administration (2009). Integrated System 2009 Power Repayment Studies and Rate Proposal.

[147] "Current rates." Alaska Electric Light and Power. 2015. Accessed January 21, 2016. *http://www.aelp.com/Rates/ourrates.htm*.

[148] Fay, G.; Melendez, A.V. and C. West. 2013. Alaska Energy Statistics 1960-2011 Final Report. Institute of Social and Economic Research, University of Alaska Anchorage, Anchorage, AK (US). Accessed May 2, 2016. *http://iser.uaa.alaska.edu/Publications/2013_12-AlaskaEnergyStatistics2011Report_Final_2014-04-30.pdf*.

[149] The Alaska Center for Energy and Power, University of Alaska Fairbanks. 2014. An Alaska-British Columbia Transmission Intertie. The Alaska Center for Energy and Power, Fairbanks AK (US). Accessed May 2, 2016. *http://www.akenergyauthority.org/Content/Policy/RegionalPlanning/Documents/AK-BCTransIntertieReport033114.pdf*.

[150] Electric Power Systems, Inc. (2013). "Alaska Energy Authority Alaska Railbelt Transmission Plan Draft Review." Electric Power Systems, Inc. November, 2013.

[151] Global Energy Concepts, LLC. 2006. A Catalog of Potential Sites for Renewable Energy in Hawaii. Global Energy Concepts, LLC. Kirkland, WA (US). Accessed May 3, 2016. *http://energy.hawaii.gov/resources/hawaii-state-energy-office-publications*.

[152] "Renewable Portfolio Standard (Hawaii)," Database of State Incentives for Renewables and Efficiency. Updated June 10, 2015. Accessed May 25, 2016. *http://programs.dsireusa.org/system/program/detail/606*

[153] "Columbia River Treaty 2014/2024," U.S. Army Corps of Engineers and Bonneville Power Administration (U.S. Entity). Accessed May 24, 2016. *http://www.crt2014-2024review.gov/*.

[154] U.S. Entity (2013b). "U.S. Entity Regional Recommendation for the Future of the Columbia River Treaty after 2024". December, 2013. Accessed May 24, 2016. *http://www.crt2014-2024review.gov/RegionalDraft.aspx*.

[155] Kirkpatrick, K. (2013). "The Columbia River Treaty's Canadian Entitlement: The Role of Liberalized and Integrated North American Electricity Markets in a New Calculation". Washington Journal of Environmental Law & Policy. Vol 3:2013. December, 2013. Accessed May 24, 2016. *http://www.crt2014-w024review.gov/Files/Columbia%20River%20Treaty%20Review%20-%20Fact%20Sheet%20-%20Canadian%20Entitlement—FOR%20PRINT.pdf*.

[156] "Territory Served," PJM Interconnection. Accessed May 4, 2016. *http://www.pjm.com/about-pjm/who-we-are/territory-served.aspx*.

[157] "Electric Power Markets: New England (ISO-NE)," Federal Energy Regulatory Commission. Updated March 10, 2016. Accessed May 4, 2016. *http://www.ferc.gov/market-oversight/mkt-electric/new-england.asp*.

[158] Energy Information Administration. "Age of electric power generators varies widely." Today in Energy. June, 2011. Accessed May 4, 2016. *http://www.EIA.gov/todayinenergy/detail.cfm?id=1830*.

[159] Heeter, J., Belyeu, K., Kuskova-Burns., K. (2014). Status and Trends in the U.S. Voluntary Green Power Market (2013 Data). NREL/TP-6A20-63052. Accessed May 24, 2016. *http://primo-pmtna01.hosted.exlibrisgroup.com/Pubs:PUBS:NREL_HORIZON98848*.

[160] Green-e. 2013. Clarification on Treatment of Repowered Hydropower Facilities under Version 2.3 of the Green-e Energy National Standard. Green-e Energy, San Francisco, CA (US). Accessed May 4, 2016. *http://www.green-e.org/docs/energy/Energy_Repowered_Hydro_Clarification_2013.pdf*.

[161] "Monroe Hydro Project," Natel Energy. 2016. Accessed May 4, 2016. *http://www.natelenergy.com/monroe-hydro-project/*.

[162] U.S. Environmental Protection Agency. 2010. Guide to Purchasing Green Power Renewable Electricity, Renewable Energy Certificates, and On-Site Renewable Generation. DOE/EE-0307. Environmental Protection Agency, Washington D.C. (US). Accessed May 24, 2016. *https://www.epa.gov/greenpower/guide-purchasing-green-power*.

[163] "Cross-State Air Pollution Rule (CSAPR)." U.S. Environmental Protection Agency. Accessed May 4, 2016. *http://www.epa.gov/crossstaterule/*.

[164] A Rule by the Environmental Protection Agency on October 23, 2015, Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units. Vol. 80 Friday, No. 205 October 23, 2015, Book 2 of 2 Books, Pages 64661–65120. Accessed May 4, 2016. *https://www.federalregister.gov/articles/2015/10/23/2015-22842/carbon-pollution-emission-guidelines-for-existing-stationary-sources-electric-utility-generating*.

[165] Pacific Northwest Utilities Conference Committee (PNUCC). 2014. The Northwest and 111(d). Pacific Northwest Utilities Conference Committee, Portland, OR (US). Accessed May 3, 2016.*http://pnucc.org/sites/default/files/The%20Northwest%20and%20111d%202014%201009%20final.pdf*.

[166] Chupka, M.; M. Celebi, and K. Spees. 2014. Hydropower and the EPA Section 111(d) Proposal. The Brattle Group, Washington, D.C. (US). Accessed May 4, 2016. *http://www.brattle.com/system/publications/pdfs/000/005/112/original/Hydropower_and_the_EPA_Section_111(d)_Proposal.pdf?1422314120*.

[167] American Public Power Association. 2014. Power Plants are not Built on Spec: 2014 Update. American Public Power Association, Arlington, VA (US). Accessed May 4, 2016. *http://www.publicpower.org/files/PDFs/Power_Plants_Not_Built_on_Spec_2014.pdf*.

[168] Wiser, R., M. Bolinger, G. Barbose, N. Darghouth, B. Hoen, A. Mills, S. Weaver, K. Porter, M. Buckley, F. Oteri, and S. Tegen. August 2014. 2013 Wind Technologies Market Report. DOE/GO-102014-4459, LBNL-6809E. Lawrence Berkeley National Laboratory, Berkeley, CA (US). Accessed May 3, 2016. *https://emp.lbl.gov/publications/2013-wind-technologies-market-report*.

[169] Harper, J.P., M.D. Karcher, and M. Bolinger. September 20, 2007. Wind Project Financing Structures: A Review & Comparative Analysis. LBNL-63434. Lawrence Berkeley National Laboratory, Berkeley, CA (US). Accessed May 25, 2016. *https://publications.lbl.gov/islandora/object/ir%3A152156*.

[170] Wiser, R.H., and E.P. Kahn. 1996. Alternative Windpower Ownership Structures: Financing Terms and Project Costs. LBNL-38921. Lawrence Berkeley National Laboratory, Berkeley, CA (US). Accessed May 3, 2016. *https://emp.lbl.gov/publications/alternative-windpower-ownership*.

[171] Sawyer, M. (2014). "Red Rock Hydroelectric Project," presented at National Hydropower Association Hydropower Finance Summit. October 2, 2014.

[172] USACE (2014). "Federal Interest Rates for Corps of Engineers Projects for Fiscal Year 2015". United States Army Corps of Engineers. October, 2015. Accessed May 25, 2016. *http://planning.usace.army.mil/toolbox/guidance.cfm?Option=Type&BL=None&Type=EGM&Sort=YearDesc*.

[173] Bonneville Power Administration (BPA). 2014. BPA Financial Reserves. Bonneville Power Administration, Portland, OR (US). Accessed May 4, 2016. *https://www.bpa.gov/Finance/FinancialPublicProcesses/AccesstoCapital/July_16_2014_Financial_Reserves_Workshop.pdf*.

[174] Collins, J. "Project Development and Financing Mahoning Creek - A Case Study," presented at National Hydropower Association Hydropower Finance Summit. October 2, 2014.

[175] Ocwieja, M. "Financing a Small Hydro Portfolio," presented at National Hydropower Association Hydropower Finance Summit. October 2, 2014.

[176] Bolinger, M.. May 2014. An Analysis of the Costs, Benefits, and Implications of Different Approaches to Capturing the Value of Renewable Energy Tax Incentives. LBNL-6610E. Lawrence Berkeley National Laboratory, Berkeley, CA (US). Accessed May 23, 2016. *https://emp.lbl.gov/publications/analysis-costs-benefits-and-0*.

[177] Schwabe, P., K. Cory, and J. Newcomb. 2009. Renewable Energy Project Financing: Impacts of the Financial Crisis and Federal Legislation. Technical Report NREL/TP-6A2-44930. National Renewable Energy Laboratory, Golden, CO (US). Accessed May 24, 2016. *http://primo-pmtna01.hosted.exlibrisgroup.com/Pubs:PUBS:NREL_HORIZON90557*.

[178] Mendelsohn, M., and C. Kreycik. 2012. Federal and State Structures to Support Financing Utility-Scale Solar Projects and the Business Models Designed to Utilize Them. NREL/TP-6A20-48685. National Renewable Energy Laboratory, Golden, CO (US). Accessed May 3, 2016. *http://www.energy.gov/eere/slsc/downloads/federal-and-state-structures-support-financing-utility-scale-solar-projects-and*.

[179] Bolinger, M.; R.H. Wiser and N.R. Darghouth. Preliminary Evaluation of the Impact of the Section 1603 Treasury Grant Program on Renewable Energy Deployment in 2009. Lawrence Berkeley National Laboratory, Berkeley, CA (US). Accessed May 2, 2016. *http://eetd.lbl.gov/publications/preliminary-evaluation-of-the-impact-*.

[180] Kreycik, C. 2010. Financing Renewable Energy at Government Facilities. National Renewable Energy Laboratory, Golden, CO (US). Accessed May 3, 2016. *https://financere.NREL.gov/finance/content/financing-renewable-energy-government-facilities*.

[181] U.S. Department of Energy. 2014b. Draft Guidance for EPAct 2005 Section 242 Program. Accessed January 21, 2016. *http://energy.gov/eere/water/articles/energy-department-seeks-feedback-draft-guidance-hydroelectric-production*.

[182] Myers, E. "Tax-Advantaged Financing for Hydroelectric Facilities: American Municipal Power, Inc. Case Study," presented at National Hydropower Association Hydropower Finance Summit. June, 2013.

[183] A. Ang, V. Bhansali, and Y. Xing, "Build America Bonds," The Journal of Fixed Income (2010): Vol. 20, No. 1. Summer, 2010. Accessed May 25, 2016. *http://www.nber.org/papers/w16008*.

[184] Ordinance No. 8607 by the City of Lawrence Kansas on December 21, 2010, An Ordinance Authorizing the issuance for the City of Lawrence, Kansas of industrial revenue bonds, and repealing Ordinance No. 8599 and Ordinance No. 8604. Accessed May 5, 2016. *http://lawrenceks.org/assets/ecodev/2012_Abatement_Report/Appendix/IRBs/Bowersock_Dam_IRBs*.

[185] Friedman, J. and S. Fazell. 2012. US-China Market Review Summer 2012. American Council on Renewable Energy, Washington, D.C. (US). Accessed May 3, 2016. *http://www.naseo.org/Data/Sites/1/documents/committees/financing/resources/qecb/QECBs_and_the_Potential_to_Finance_Clean_Energy.pdf*.

[186] Allen, J.W., and Britt, J.J. "Department of Energy Announces New Loan Guarantee Program for Renewable Energy and Energy Efficiency Projects." Renewable Energy Outlook, March 7, 2014. Accessed May 2, 2016. *http://www.renewableenergyoutlook.com/2014/05/07/department-of-energy-announces-new-loan-guarantee-program-for-renewable-energy-and-energy-efficiency-projects/*.

[187] Hitchcock, S.M. "BETC: Oregon's Tax Incentive to Reduce Energy Costs." Saalfeld Griggs PC (2012). Accessed May 3, 2016. *http://www.sglaw.com/betc-oregons-tax-incentive-to-reduce-energy-costs/*.

[188] Templeton, A. (2011). "Oregon Irrigators Embrace Hydropower." Published August 5, 2011. Accessed January 21, 2016. *http://www.opb.org/news/article oregon-irrigators-move-into-the-hydro-business/*.

[189] Federal Energy Regulatory Commission and State of Colorado (2010). "Memorandum of Understanding between the Federal Energy Regulatory Commission and the State of Colorado through the Governor's Energy Office to Streamline and Simplify the Authorization of Small Scale Hydropower Projects." August 2010. Accessed May 4, 2016. *https://www.ferc.gov/legal/mou/mou-co.pdf*.

[190] Colorado Energy Office. Revised October 2015. "Colorado Small Hydropower Handbook." Colorado Energy Office. Accessed May 24, 2016. *https://www.colorado.gov/pacific/energyoffice/atom/32666*.

[191] Donaldson, D. "House Approves Five More Years of Renewable Energy." Renewable Energy Alaska Project. 2012. Accessed May 4, 2016. *http://alaska renewableenergy.org/tag/renewable-energy-grant-fund/*.

[192] Energy Information Administration (EIA). 2014. Annual Energy Review. Electricity net generation: electric power sector, back to 1949. Energy Information Administration, Washington D.C. (US). US DOE. September 27, 2012; and Electric Power Monthly. Net generation by energy source: total (all sectors). Accessed May 24, 2016. *http://www.eia.gov/total energy/data/annual/*.

[193] Sale, M.J., N.A. Bishop, Jr., S.L. Reiser, K. Johnson, A.C. Bailey, A. Frank, and B.T. Smith. 2014. Opportunities for Energy Development in Water Conduits: A Report Prepared in Response to Section 7 of the Hydropower Regulatory Efficiency Act of 2013. ORNL/TM-2014/272. Prepared for the U.S. Department of Energy by the ORNL Water Power Technologies Team.

[194] International Finance Corporation. February 2015. Hydroelectric Power : A Guide for Developers and Investors. International Finance Corporation, World Bank Group. Accessed May 25, 2016. *http://www.ifc.org/wps/wcm/connect/topics_ext_content/ifc_external_corporate_site/ifc+sustainability/learning+and+adapting/knowledge+products/publications/hydroelectric_power_a_guide_for_developers_and_investors*

[195] American Rivers, et al. 2013a. A New Paradigm for Collaborative Development of Small Hydropower Projects, A Step-by-Step Process. American Rivers, Community Hydropower Consulting, and Bradley Floretin. Accessed May 3, 2016. *http://www.smallhydro.co/#!resources/c3nu*.

[196] "Integrated Licensing Process (ILP)." Federal Energy Regulatory Commission. Updated March 3, 2015. Accessed May 25, 2016. *https://www.ferc.gov/industries/hydropower/gen-info/licensing/ilp.asp*.

[197] Meier, P., P. Blaszczyk, C. Harris, and K. Gilbert. 2010. "Project Development: From Concept to Construction: Steps to Developing a Hydro Project." Hydro Review, volume 29, Issue 3. Accessed May 4, 2016. *http://www.hydroworld.com/articles/hr/print/volume-29/issue-3/articles/project-development.html*.

[198] Federal Energy Regulatory Commission (FERC). 2001. Report on Hydroelectric Licensing Policies, Procedures, and Regulations—Comprehensive Review and Recommendations Pursuant to Section 603 of the Energy Act of 2000. Federal Energy Regulatory Commission, Washington D.C. (US). Accessed May 3, 2016. *http://www.ferc.gov/legal/maj-ord-reg/land-docs/ortc_final.pdf*.

[199] Opperman, J.J., J. Royte, J. Banks, L.R. Day and C. Apse, "The Penobscot River, Maine, USA: a Basin-Scale Approach to Balancing Power Generation and Ecosystem Restoration," Ecology and Society (2011): Volume 16, Issue 3, Article 7. *http://dx.doi.org/10.5751/ES-04117-160307*. Accessed May 4, 2016. *http://www.ecologyandsociety.org/vol16/iss3/art7/*.

[200] Penobscot River Restoration Trust. (n.d.) Penobscot River Restoration Trust, fact sheet. Augusta, ME (US). Accessed May 25, 2016. *http://www.penobscotriver.org/content/4011/fact-sheet-and-faq-s*.

[201] Larson K.B., G.E. Johnson, J.D. Tagestad, C.A. Duberstein, M.S. Bevelhimer, R.A. McManamay, C.R. DeRolph, and S.H. Geerlofs. 2014. The Integrated Basin-Scale Opportunity Assessment Initiative: Scoping Assessment for the Connecticut River Basin, Final Report. PNNL-23778. Pacific Northwest National Laboratory, Richland, WA (US). Accessed May 3, 2016. *http://basin.pnnl.gov/Content/reports/Connecticut/BSOA_Ph1_ScopingAssessment_CT_final_PNNL-23778_23Oct2014.pdf*.

[202] Stredwick, T. May 19, 2015. "Balancing Unit Efficiency and Fish Passage." Hydro Review, volume 34, Issue 4. Accessed May 25, 2016. *http://www.hydroworld.com/articles/hr/print/volume-34/issue-4/articles/balancing-unit-efficiency-and-fish-passage.html*.

[203] Oregon Water Resources Department, 2013. Accessed May 25, 2016. *http://www.oregon.gov/owrd/pages/index.aspx*.

[204] Hartmann, J., D. Harrison, J. Opperman, and R. Gill. 2013. The Next Frontier of Hydropower Sustainability: Planning at the System Scale. The Nature Conservancy, Arlington, VA (US). Accessed May 4, 2016. *http://www.conservationgateway.org/ConservationPractices/Freshwater/WaterInfrastructure/Pages/hydroatscale.aspx*.

[205] J. Opperman, G. Grill, and J. Hartmann, "The Power of Rivers: Finding balance between energy and conservation in hydropower development," The Nature Conservancy (2015): Washington, D.C. (US). Accessed May 25, 2016. DOI: *http://dx.doi.org/10.13140/RG.2.1.5054.5765*.

[206] Interstate Renewable Energy Council (IREC). 2013. Model Interconnection Procedures, 2013 Edition. Interstate Renewable Energy Council, Latham, NY (US). Accessed May 4, 2016. *http://www.irecusa.org/model-interconnection-procedures/*.

[207] U.S. Department of Energy, U.S. Department of the Interior, Army Corps, 2010. Memorandum of Understanding for Hydropower Among The Department Of Energy, The Department of the Interior and The Department of the Army. Accessed May 25, 2016. *http://energy.gov/eere/water/downloads/hydropower-memorandum-understanding*.

[208] Federal Energy Regulatory Commission (FERC). 2011. Ideas for Implementing and Participating in the Integrated Licensing Process (ILP), Tools for Industry, Agencies, Tribes, Non-Governmental Organizations, Citizens, and FERC Staff, Version 2.0. Federal Energy Regulatory Commission, Washington D.C. (US). Accessed May 3, 2016. *http://www.ferc.gov/industries/hydropower/gen-info/licensing/ilp/eff-eva.asp*.

[209] "What is an Electric Generator?" Artinaid, 2013. Accessed April 29, 2015. *http://www.artinaid.com/2013/04/what-is-an-electric-generator/*.

[210] "Overview of Small Hydro Construction Operation," French Development Enterprises, LLC. 2014.

[211] "Innovative Technologies," International Energy Agency Small Scale Hydropower Task Force. Accessed April 28, 2016. *http://www.small-hydro.com/Programs/innovative-technologies.aspx*.

[212] American Society of Mechanical Engineers Hydropower Technical Committee. The Guide to Hydropower Mechanical Design. Kansas City: PennWell Hydro Group, 1996.

[213] Feng, J.; R. Li; R. Liang; and X. Shen, "Eco-environmentally friendly operational regulation: an effective strategy to diminish the TDG supersaturation of reservoirs," Hydrology and Earth System Sciences, 18(3), 1213-1223 (2014). Accessed April 28, 2016. DOI: *http://dx.doi.org/ 10.5194/hessd-10-14355-2013*.

[214] "Fish-Friendly Turbine Making a Splash in Water Power," U.S. Department of Energy, last modified October 21, 2011. Accessed May 25, 2016. *http://energy.gov/articles/fish-friendly-turbine-making-splash-water-power*.

[215] "Sunset Passage and Energy Project Fact Sheet," Snohomish County Public Utilities District. April 2014. Accessed May 25, 2016. *http://www.snopud.com/?p=1956*.

[216] Bishop, N.; D. Linke; C. Vansant; C. Alsbert; J. Anders; A. Grovue; S. Hill-Nelson; K. Johnson; B. Smith; D. Youlen; and K. Young. 2015. New Pathways for Hydropower: Getting Hydropower Built–What Does it Take? ORNL/TM-2015/48. Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (US). Accessed May 25, 2016. *http://hydropower.ornl.gov/media/publications/*.

[217] Infrastructure Fact Sheet, 2009. American Society of Civil Engineers. Accessed April 28, 2016. *http://www.infrastructurereportcard.org/2009/sites/default/files/RC2009_dams.pdf*.

[218] Fisher, R.K.; J.R. Degnan; and G.F. Wachter. "Rehabilitation & Upgrading of Existing Hydroelectric Plans Employing New Design Techniques." Presented at American Power Conference, Chicago, Illinois, April 18–20, 1983.

[219] Richmond, M.C. and P. Romero-Gomez, "Fish Passage through Hydropower Turbines: Simulating Blade Strike using the Discrete Element Method," 27th IAHR Symposium on Hydraulic Machinery and Systems, Montreal, Canada, September 22–26, 2014. IOP Conf. Series: Earth and Environmental Science 22 (2014): 062010. Accessed May 25, 2016. DOI: *http://dx.doi.org//10.1088/1755-1315/22/6/062010*.

[220] "Dam Safety 101: Top Issues Facing the Dam Community." 2016. Association of State Dam Safety Officials. Accessed May 25, 2016. *http://www.damsafety.org/news/?p=c0fdade4-ab98-4679-be22-e3d7f14e124f*

[221] Technical Manual for Dam Owners: Impacts of Plants on Earthen Dams. 2005. FEMA 534. Federal Emergency Management Agency, Washington, D.C. (US). Accessed April 28, 2016, *https://www.fema.gov/media-library/assets/documents/1027*.

[222] "About NERC>Key Players>Regional Entities." North American Electric Reliability Corporation. As of July 25, 2012. Accessed May 25, 2016. *www.nerc.com/AboutNERC/keyplayers/Pages/Regional-Entities.aspx*.

[223] North American Electric Reliability Corporation. "2003 Blackout Final Report." April 1, 2004. Accessed May 25, 2016. *http://www.nerc.com/pa/rrm/ea/Pages/Blackout-August-2003.aspx*.

[224] Frantzis, L. and Graham, S. "Utility Business Models in Solar: Opportunities and Trends." Presentation at Intersolar North America. ©2011. Accessed June 21, 2016. *http://www.navigant.com/~/media/WWW/Site/Insights/Energy/Utility_Business_Models.pdf*.

[225] "Reservoir Operations Study." Tennessee Valley Authority ©2004. Accessed June 21, 2016. *http://152.87.4.80/environment/reports/ros_eis/index.htm*.

[226] Wunderlich, W. O. 1991. Heat exchange between a water surface and the atmosphere.

[227] Welt, F., Hachem, S., and Kahawita, R. Edited by Broch, E., Lysne, D.K., Flatabo, N., and HellandHansen, E. "Integration of river water temperature constraints within real time operation of hydroplants." Paper presented at HYDROPOWER '97, Trondheim, Norway, June 30-July 2, 1997.

[228] Labadie, J.W., "Optimal operation of multi-reservoir systems: State-of-the-art review," Journal of Water Resources Planning and Management 130 (2004): 93-111. Accessed June 21, 2016. *http://dx.doi.org/10.1061/(ASCE)0733-9496(2004)130:2(93)*.

[229] Sullivan, G.P.; R. Pugh; A. P. Melendez; and W.D. Hunt. 2010. Operations and Maintenance Best Practices: A Guide to Achieving Operational Efficiency. Federal Energy Management Program, U.S. Department of Energy, Washington, D.C. (US). Accessed May 25, 2016. *http://energy.gov/eere/femp/downloads/operations-and-maintenance-best-practices-guide*.

[230] Oak Ridge National Laboratory, MESA Associates, Inc., and Hydro Performance Processes, Inc. August 2, 2012. Hydropower Advancement Project, Best Practice Catalog, Machine Condition Monitoring, Revision 2.0. Accessed May 25, 2016. *http://hydropower.ornl.gov/research/hydropower/best-practices/*.

[231] U.S. Department of Energy, "Global Energy Storage Database." c2016. Accessed June 22, 2016. *http://www.energystorageexchange.org*.

[232] Botterud, A.; T. Levin; and V. Koritarov. 2014. Pumped Storage Hydropower: Benefits for Grid Reliability and Integration of Variable Renewable Energy. ANL/DIS-14/10. Argonne National Laboratory (ANL), Argonne, IL (US). Accessed April 28, 2016, *http://www.ipd.anl.gov/anlpubs/2014/12/106380.pdf.*

[233] "International Energy Statistics," U.S. Energy Information Administration. U.S. Department of Energy. Accessed May 2, 2016. *http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=2&pid=82&aid=7&cid=regions&syid=2004&eyid=2012&unit=MK*.

[234] Koritarov, V.; L. Guzowski; J. Feltes; Y. Kazachkov; B. Gong; B. Trouille; and P. Donalek. 2013a. Modeling Adjustable Speed Pumped Storage Hydro Units Employing Doubly-Fed Induction Machines. ANL/DIS-13/06. Argonne National Laboratory (ANL), Argonne, IL (US). Accessed May 25, 2016. *https://anl.box.com/s/8qs5ieljm6q1op97pg367s117p91dorh*.

[235] Technical Analysis of Pumped Storage and Integration with Wind Power in the Pacific Northwest. 2009. U.S. Army Corps of Engineers, Northwest Division, Hydroelectric Design Center. Accessed May 25, 2016. *http://www.hydro.org/wp-content/uploads/2011/07/PS-Wind-Integration-Final-Report-without-Exhibits-MWH-3.pdf*.

[236] Aubert, S.; P. Steimer; S. Linder; and C. Hillberg. "Variable Speed Pumped Storage with Converter-Fed Synchronous Machines (CFSM)—A High Value in Grids with Large Penetration of Wind and Solar Generation." HYDRO 2014, Lake Como, Italy, October 13–15, 2014.

[237] Koritarov, V.; L. Guzowski; J. Feltes; Y. Kazachkov; B. Gong; B. Trouille; P. Donalek; and V. Gevorgian. 2013b. Modeling Ternary Pumped Storage Units. ANL/DIS-13/07. Argonne National Laboratory (ANL), Argonne, IL (US). Accessed May 25, 2016. *https://anl.box.com/s/52hqlvletrpc087y4ds2wutgn2ds13xt*.

[238] Koritarov, V.; T. Guo; E. Ela; B. Trouille; J. Feltes; I. Krad; C. and Clark. "Operational Capabilities and Valuation of Benefits Provided by Advanced Pumped Storage Hydropower Technologies." Presentation at HydroVision, Portland, OR, July 2015.

[239] Hadjerioua**,** B.; R. Martinez; H A. Shanafield III; Y. Wei; J. D. McCulla; Norm Bishop; A. M. Alsharif, and B. T. Smith. 2012. National Resource Assessment of Pumped Storage Hydropower. Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (US).

[240] Hadjerioua, B.; N. Bishop; R. Uria-Martinez; and E. Hopping. 2014. "Evaluation of the Feasibility and Viability of m-PSH in the U.S. - Preliminary first case study, Coal Mine." Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (US).

[241] "Riverbank Minnesota, LLC; Notice of Preliminary Permit Application Accepted for Filing and Soliciting Comments, Motions To Intervene, and Competing Applications." Federal Energy Regulatory Commission. April 9, 2010. Accessed May 25, 2016. *https://www.federalregister.gov/articles/2010/04/09/2010-8065/riverbank-minnesota-llc-notice-of-preliminary-permit-application-accepted-for-filing-and-soliciting*.

[242] Tedrick, S. "Two billion dollar underground hydroelectric facility a possibility just outside of Granite Falls." Advocate Tribune. April 15, 2010. Accessed May 25, 2016. *http://www.granitefallsnews.com/article/20100415/NEWS/304159936*.

[243] "Gravity Power Grid-Scale Electricity Storage System," Gravity Power, LLC (n.d.), accessed May 2, 2016, *http://www.launchpnt.com/portfolio/energy/grid-scale-electricity-storage/*.

[244] Grid Energy Storage. 2013. U.S. Department of Energy. Accessed May 25, 2016. *http://energy.gov/oe/downloads/grid-energy-storage-december-2013*

[245] Patel, S. "The Big Picture: Storage Snapshot," Power: Business and Technology for the Global Generation Industry since 1882. April 30, 2014. Accessed May 2, 2016, *http://www.powermag.com/the-big-picture-storage-snapshot*.

[246] Issued Preliminary Permits for Pumped Storage Projects Map. Federal Energy Regulatory Commission. April 1, 2016. Pumped Storage Projects: Existing and Proposed Projects. Accessed May 25, 2016. *http://www.ferc.gov/industries/hydropower/gen-info/licensing/pump-storage.asp*.

[247] Kauai Island Utility Cooperative. Accessed June 22, 2016. *http://website.kiuc.coop/*.

[248] Akhil, A.A.; G. Huff; A.B. Currier; B.C. Kaun; D.M. Rastler; S.B. Chen; A.L. Cotter; D.T. Bradshaw; and W.D. Gauntlett. 2013. DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA. SAND2013-5131. Sandia National Laboratories (SNL), Albuquerque, NM (US). Accessed April 28, 2016, *http://energy.gov/sites/prod/files/2013/08/f2/ElecStorageHndbk2013.pdf*.

[249] "State Land Board Approves KIUC Energy Storage Plan." Kauai Island Utility Cooperative. November 14, 2014. Accessed May 25, 2016. *http://kauai.coopwebbuilder.com/content/state-land-board-approves-kiuc-energy-storage-plan*.

[250] Vishwanathan, V.; M. Kintner-Meyer; P. Balducci; and C. Jin. 2013. National Assessment of Energy Storage for Grid Balancing and Arbitrage, Phase II, Volume 2: Cost and Performance Characterization. PNNL-21388. Pacific Northwest National Laboratory (PNNL), Richland, WA (US). Accessed May 25, 2016. *http://www.pnl.gov/publications/abstracts.asp?report=415454*.

[251] 2011. Quantifying the Value of Hydropower in the Electric Grid: Plant Cost Elements. Electric Power Research Institute. Technical Report 1023140. Palo Alto, CA (US). Accessed April 28, 2016, *http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001023140*.

[252] Ela, E.; B. Kirby; A. Botterud; C. Milostan; I. Krad; and V. Koritarov. 2013. The Role of Pumped Storage Hydro Resources in Electricity Markets and System Operation. NREL/CP-5500-58655. National Renewable Energy Laboratory (NREL), Denver, CO (US). Accessed May 25, 2016, *http://primo-pmtna01.hosted.exlibrisgroup.com/Pubs:PUBS:NREL_HORIZON81213*.

[253] Jobs and Economic Development Impact (JEDI) Models. National Renewable Energy Laboratory. Accessed May 25, 2016. *http://www.nrel.gov/analysis/jedi/*.

[254] U.S. Department of Energy. Prepared by Navigant Consulting, Inc., and the National Renewable Energy Laboratory. DOE/EE-1400. Forthcoming (2016). "United States Hydropower Workforce Assessment and Future Scenarios".

[255] U.S. Department of Energy. Prepared by Navigant Consulting, Inc., and the National Renewable Energy Laboratory. DOE/EE-1400. Forthcoming (2016). "United States Hydropower Workforce Assessment and Future Scenarios".

[257] U.S. Census Bureau. 2014. American Community Survey. Accessed May 25, 2016. *https://www.census.gov/programs-surveys/acs/*.

[258] "Economic Development Programs," New York Power Authority, accessed May 2, 2016, *http://www.nypa.gov/services/economicdev/economic.htm*.

[259] Glanz, J. 2012. "Data Barns in a Farm Town, Gobbling Power and Flexing Muscle." *New York Times,* September 23. Accessed May 2, 2016, *http://www.nytimes.com/2012/09/24/technology/data-centers-in-rural-washington-state-gobble-power.html?pagewanted=all&_r=0*.

[260] "Energy needed to produce aluminum," August 16, 2012. Energy Information Administration, Today in Energy. Accessed May 25, 2016. *http://www.eia.gov/todayinenergy/detail.cfm?id=7570*.

[261] "Boulder Canyon Project - Hoover Dam." Bureau of Reclamation. Last modified February 1, 2012. Accessed May 25, 2016, *http://www.usbr.gov/projects/Project.jsp?proj_Name=Boulder+Canyon+Project+-+Hoover+Dam*.

[262] Simonds, Wm. J. 2009. Hoover Dam: The Boulder Canyon Project. U.S. Bureau of Reclamation. Project History; originally completed in 1995. Reformatted, reedited, and reprinted by Brit Storey in 2009. Accessed May 25, 2016. *http://www.usbr.gov/projects/Project.jsp?proj_Name=Boulder+Canyon+Project+-+Hoover+Dam*.

[263] McMahon, G.; W. Wade; B. Roach; M. Farmer; and A. Fredrich. 2004. Lake Lanier National Economic Development Update: Evaluation of Water Supply, Hydropower and Recreation Benefits. Atlanta Regional Commission, Cobb County-Marietta Water Authority. Accessed May 2, 2016. *http://www.1071coalition.org/downloads/LL%20Econ%20Dev%20Study%202004.pdf*.

[264] Garrison Dam/Lake Sakakawea Project North Dakota Surplus Water Report. 2010. U.S. Army Corps of Engineers. Accessed May 25, 2016. *http://denr.sd.gov/mr/PublicDraftSakakaweaSurplusWaterReport.pdf*.

[265] The Economic Benefits of Multipurpose Reservoirs in the United States. 2015. Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (US). Accessed May 2, 2016. *http://www.ieahydro.org/media/65043df2/HYDRO2015MultipurposeReservoirs_Paper_14August2015.pdf.*

[266] U.S. Department of the Interior Economic Report FY 2013 Draft. 2014. U.S. Department of the Interior. Accessed May 25, 2016. *http://www.iwr.usace.army.mil/Media/NewsStories/tabid/11418/Article/481131/report-measures-value-to-the-nation-of-us-army-corps-of-engineers-civil-works-p.aspx*.

[267] U.S. Department of the Interior Economic Report FY 2013 Draft. 2014. U.S. Department of the Interior. Accessed May 25, 2016. *https://www.doi.gov/ppa/economic_analysis/fy-2013-economic-report*.

[268] Value to the Nation of the U.S. Army Corps of Engineers Civil Works Program. 2013. Institute for Water Resources, accessed May 2, 2016, *http://www.iwr.usace.army.mil/Portals/70/docs/iwrreports/2013-R-09_vtn.pdf*.

[269] Russell, C. 1970. Industrial Water Use. National Water Commission.

[270] Loomis, J., "Quantifying recreation use values from removing dams and restoring free-flowing rivers: A contingent behavior travel cost demand model for the Lower Snake River," Water Resources Research, 38 (2002): 1-8. Accessed May 25, 2016. DOI: *http://dx.doi.org/ 10.1029/2000WR000136*.

[271] Debnath, D.; T. Boyer; A. Stoecker; and L. Sanders, "Nonlinear reservoir optimization model with stochastic inflows: Case study of Lake Tenkiller," Journal of Water Resources Planning and Management 141 (2014), accessed May 25, 2016. DOI: *http://dx.doi.org/10.1061/(ASCE)WR.1943-5452.0000409*.

[272] Ward, F. and T. Lynch, "Integrated River Basin Optimization: Modeling Economic and Hydrologic Interdependence," Water Resources Bulletin, 32 (1996): 1127–1138. Accessed May 25, 2016. *https://www.sciencebase.gov/catalog/item/505397e0e4b097cd4fce63bf*.

[273] Hanson, T.; L. Hatch; and H. Clonts, "Reservoir water level impacts on recreation, property, and nonuser values," Journal of the American Water Resources Association, 38 (2002): 1007–1018. DOI: *http://dx.doi.org/10.1111/j.1752-1688.2002.tb05541.x*.

[274] B. Hadjerioua, K. D. Patrick, S. Kao, Y. Wei, S. K. SanthanaVannan, G. Palanisamy, H A. Shanafield III, M.J. Sale, R. Devarakonda, and B. T. Smith, "National Hydropower Asset Assessment Project" Oak Ridge National Laboratory (ORNL), World Environmental & Water Resources Congress, Palm Springs, California, May 2011.

# 3 Assessment of National HYDROPOWER POTENTIAL

U.S. DEPARTMENT OF ENERGY

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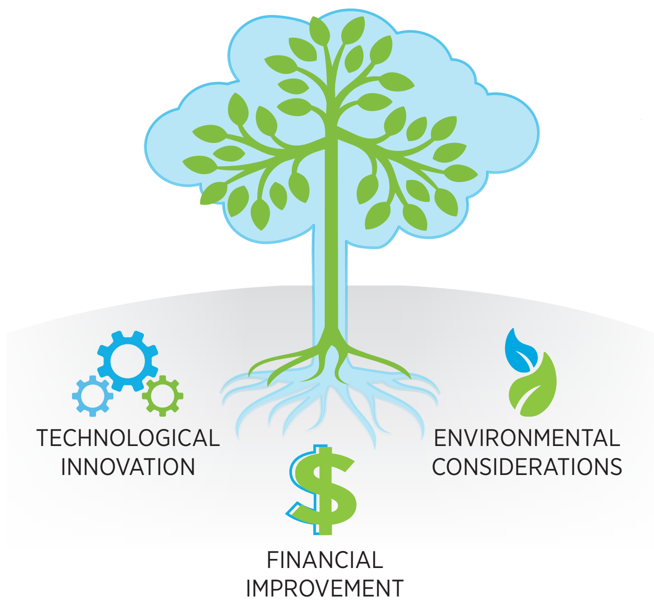
# Overview

The *Hydropower Vision* report utilized economic modeling of the electric sector to explore an array of possible futures for the hydropower industry. This summary provides an overview of the methods applied and highlights key conclusions that may be drawn from the extensive body of analysis presented in full in Chapter 3. These results are intended to provide new insights into the opportunities and challenges for hydropower and to quantify certain costs and benefits of the industry.

The analysis contained here considers potential contributions over time to the electric sector of both the existing hydropower fleet and new hydropower deployment resulting from: upgrades at existing plants, powering of non-powered dams (NPD), pumped storage hydropower (PSH), and new stream-reach development (NSD).

## KEY ELEMENTS FOR GROWTH




**The analysis indicates that three key variables in combination have the greatest influence on potential growth scenarios.**

Scenarios and modeling results presented here are not intended as DOE forecasts or projections. Growth potential is tied to a complex set of variables, and changes in these variables over long periods of time are difficult to predict. Modeling results serve primarily as a basis for identifying key factors and drivers that are likely to influence the role and scale of hydropower within the nation's energy mix in the coming decades. This analysis enabled improved understanding of the U.S. hydropower industry, which, in turn, informs the *Hydropower Vision.*

### *Modeling Tools*

The primary computational tool used to assess potential growth trajectories and evaluate resulting cost and benefit impacts was the National Renewable Energy Laboratory's (NREL's) Regional Energy Deployment System (ReEDS) model. ReEDS is an electric sector capacity expansion model that simulates the cost of constructing and operating generation and transmission capacity to meet electricity demand and other power system requirements on a competitive economic basis over discrete study periods. For this report, the focus study periods were from 2017 through 2030 and 2050. Results from ReEDS include estimated electricity generation, geographic distribution of new electricity infrastructure additions, transmission requirements, and capacity additions of power generation technologies built and operated during the study period. These outputs enable calculation of some key impacts including the first quantification of greenhouse gas (GHG) emissions reductions from U.S. hydropower.

The development of the *Hydropower Vision* entailed a number of modeling enhancements that allow the work presented here to be among the most sophisticated and comprehensive multi-decadal national-scale assessments of U.S. hydropower to date. However, it is important to acknowledge certain limitations of the modeling when considering the outcomes. Geographic information system screening of resource potential is used to evaluate environmental considerations rather than site-specific assessment of environment sustainability, and climate change uncertainties are evaluated only through variations in the potential magnitude and timing of water availability. In addition, the ReEDs model is limited to the continental United States; consequently, the resource potential of Alaska and Hawaii is not evaluated quantitatively in the report (they are, however, discussed qualitatively). Similarly, insufficient data exist to effectively model the potential of existing water conveyances, such as canals and conduits. Though some impacts do extend beyond the electric sector, ReEDS models only the electric sector and does not directly include interactions with other sectors, including those associated with non-power-related land and water use. Analysis evaluating the effects of alternate government policy options for hydropower is also outside the scope of the *Hydropower Vision*.

### *Modeling Approach*

The full *Hydropower Vision* analysis involved more than 50 modeled scenarios (Figure O3-1). Each scenario examined the effects of a key variable or combination of variables that influence the deployment of hydropower facilities in electricity market competition with other generation sources. This exploratory analysis established the relative influences of a wide range of variables on the hydropower industry. From this full suite of scenarios, nine were selected as providing insights particularly relevant within the context of the *Hydropower Vision* pillars of optimization, growth, and sustainability. These nine scenarios are described in detail throughout Chapter 3. From among these nine scenarios, four scenarios became the ultimate focus of the hydropower industry development and impacts analysis presented in this chapter summary. Reference cases for comparing alternative hydropower deployment scenarios are provided by (1) a *Business-as-Usual* scenario, which assumes a continuation of existing market and technology development trends, and (2) a baseline scenario under which no new unannounced hydropower is built (after 2016).

### *Assessing Growth Potential*

The nine selected scenarios and their primary differentiating elements are summarized in Table O3-1, and the four focus scenarios are highlighted within the table. Table O3-2 summarizes assumptions that are constant across all scenarios, including *Business-as-Usual*. Table O3-3 summarizes the resource estimates and modeled resource potential used in the analysis. Notably, modeled resource potential represents a conservative interpretation of the total hydropower technical potential, as it is intended to focus modeling efforts on the most competitive resource sites. Specific differences among resource estimates are described in detail in Section 3.2.2.

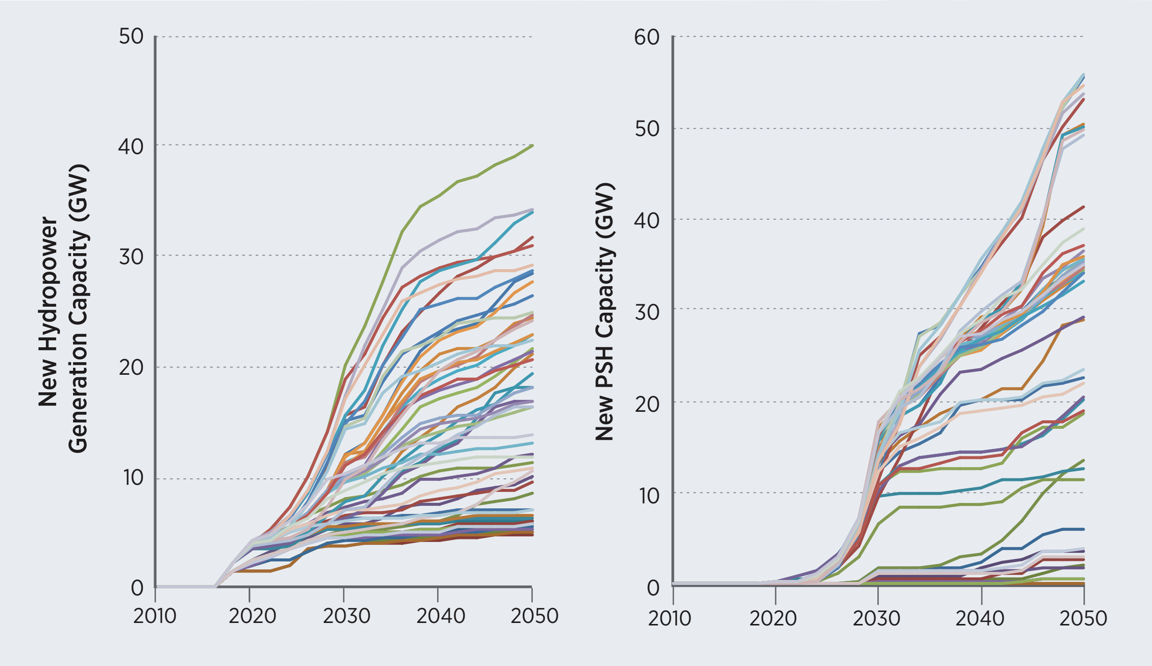



**Figure O3-1.** More than 50 potential scenarios of new hydropower capacity (GW) growth between 2017 and 2050 were analyzed using the Regional Energy Deployment System model to assess the influence of a wide range of variables on growth curves

**Table O3-1.** Nine Selected *Hydropower Vision* Analysis Scenarios

| | Scenario | Key Variables Assessed |
|---|---|---|
| 1 | *Business-as-Usual* | Reference model conditions and cost reduction trajectories; legally protected lands are excluded |
| 2 | *Advanced Technology* | Reduced hydropower costs resulting from innovation |
| 3 | *Low Cost Finance* | Reduced hydropower costs due to improved financial terms reflecting lower risks and long asset life |
| 4 | *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* | Combination of variables in scenarios #2 and #3, plus seven environmental considerations |
| 5 | *Advanced Technology, Low Cost Finance* | Combination of variables in scenarios #2 and #3, with no environmental considerations |
| 6 | *Advanced Technology, Low Cost Finance, Critical Habitat* | Combination of variables in scenarios #2 and #3, plus one environmental consideration |
| 7 | *Advanced Technology, Low Cost Finance, Critical Habitat, Low VG Cost* | Scenario #6, plus low costs of variable generation technologies (i.e., wind and solar) |
| 8 | *Advanced Technology, Low Cost Finance, Critical Habitat, High Fossil Fuel Cost* | Scenario #6, plus high cost of fossil fuels |
| 9 | *Advanced Technology, Low Cost Finance, High Fossil Fuel Cost* | Scenario #8, with no environmental considerations |

Within the model, environmental considerations directly impact only NSD resource sites. The incremental effect on species and habitats at existing facilities, NPDs, and for PSH facilities is expected to be relatively limited.

**Table O3-2.** Constants across Modeled Scenarios

| Input Type | Input Description |
| --- | --- |
| Electricity demand | AEO[a] 2015 Reference Case (average annual electricity demand growth rate of 0.7%) |
| Fossil technology and nuclear power | AEO 2015 Reference Case |
| Non-hydro/wind/solar photovoltaics renewable power costs | NREL Annual Technology Baseline 2015 Mid-Case Projections |
| Policy | As legislated and effective on December 31, 2015. |
| Transmission expansion | Pre-2020 expansion limited to planned lines; post-2020, economic expansion, based on transmission line costs from Eastern Interconnection Planning Collaborative |

Note: Despite the Supreme Court stay of the Clean Power Plan (CPP), the CPP is treated as law in all scenarios and is thus assumed active. The CPP is modeled using mass-based goals for all states with national trading of allowances available. Though states can ultimately choose rate- or mass-based compliance and will not necessarily trade with all other states, a nationally traded mass-based compliance mechanism is viewed as a reasonable reference case for the purpose of exploring hydropower deployment under a range of electricity system scenarios.

a. "AEO" refers to the U.S. Energy Information Administration's Annual Energy Outlook (e.g., EIA [18])

**Table O3-3.** Resource Estimates and Modeled Resource Potential

| Resource Category | Technical Resource Potential (gigawatts [GW]) | Modeled Resource Potential (GW)[d] |
| --- | --- | --- |
| Upgrades and Optimization of Existing Hydropower Plants | 8–10% increase in generation | 6.9 |
| Powering of Non-Powered Dams[a] | 12 | 5 |
| Powering Existing Canals and Conduits[b] | 2 | n/a |
| New Stream-Reach Development[c] | 65.5 | 30.7 |
| New Pumped Storage Hydropower | >1,000 | 109 |

Note: Potential in Alaska and Hawaii is not included due to lack of contemporary high-resolution resource assessments.

a. In the development of the modeled potential for NPD, existing technical potential estimates were modified to include the removal of some existing dams (slated for removal) and the addition of some projects omitted from the 2012 resource assessment. Technical potential estimates of generation and capacity were also revised to be consistent with improved methodologies from the 2014 NSD assessment that better replicate the sizing and economics of real-world projects.

b. Canals and conduits are discussed qualitatively in the report as there have been no nationwide resource assessments for them.

c. Existing technical potential estimates for NSD were modified for reaches in a handful of Western basins that were discovered to have relied on an earlier version of the site sizing methodology.

d. The modeled resource potential is the portion of the technical resource potential made available to the model. Economic assumptions and corrections have been applied to reduce the technical resource potential to the modeled resource potential.

The analysis scenarios that demonstrated the most influence on the market potential of hydropower relative to *Business-as-Usual* generally focused on three key factors or variables: 1) technology innovation to reduce cost; 2) improved financing and lending conditions grounded in hydropower's relatively low-risk hardware and long-lived facility life; and 3) the individual or combined influence of an array of relevant environmental considerations, beyond the exclusion of legally protected lands.[1] Other scenarios explored impacts from broader electric sector trends such as low and high variable generation (VG) cost, and low and high fossil fuel costs, with particular interest in conditions with high fossil fuel costs or low VG costs. Potential impacts to hydropower from climate change were partially captured by modeling changes in the magnitude and timing of hydropower water availability, which directly influences energy availability in the model.

### *Deployment of New Hydropower Generation*

Across the nine selected scenarios, post-2016 deployment of hydropower generation (upgrades, NPD, and NSD) is 5–31 gigawatts (GW) in 2050 (Figure O3-2, left panel). This full range demonstrates how *Advanced Technology* and *Low Cost Finance* assumptions promote additional hydropower generation growth, but their combined effect is greater than their individual effect. The right panel of Figure O3-2 more clearly highlights the individual influences of technology and finance cost reduction. *Advanced Technology* assumptions alone have little effect—an additional 0.8 GW by 2050 as compared to 5.2 GW under *Business-as-Usual*—while *Low Cost Finance* assumptions alone provide only a modest increase—an additional 1.8 GW by 2050 as compared to *Business-as-Usual* deployment. Combining these factors, along with several alternative electricity market conditions and hydropower environmental considerations, produces the full range of results shown in the left panel of Figure O3-2.

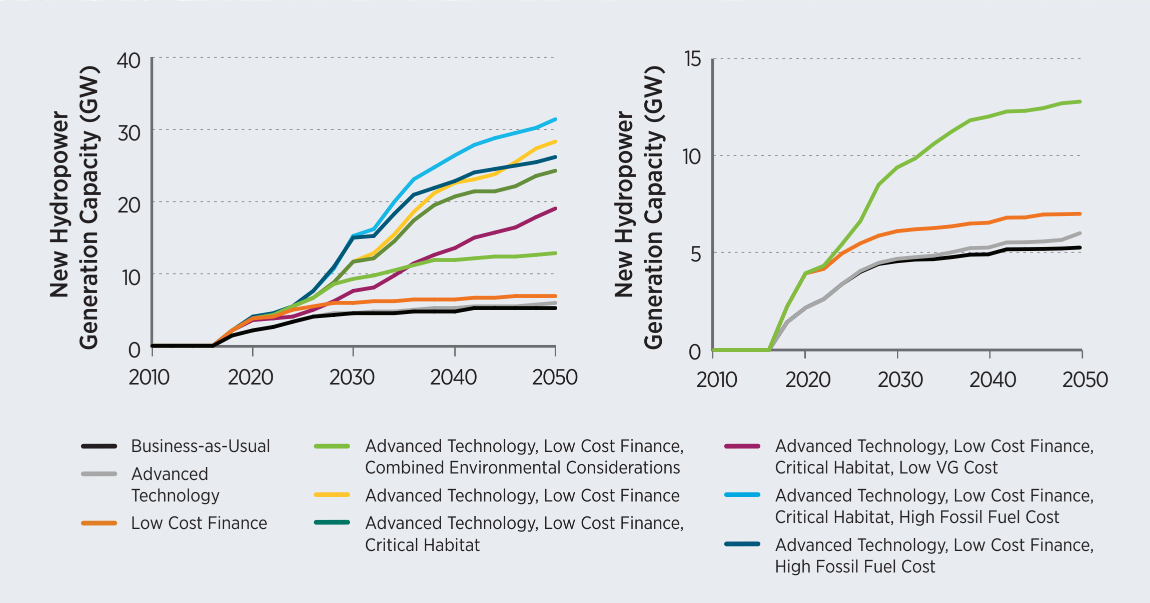



**Figure O3-2.** ReEDS modeled deployment of new hydropower generation capacity (GW) in 2017–2050 for the nine selected scenarios (left panel) and the four scenarios highlighted in this overview (right panel) [each panel uses a unique y-axis]

1. Within the model, environmental considerations directly impact only NSD resource sites. The incremental effect on species and habitats at existing facilities, NPDs, and for PSH facilities is expected to be relatively limited.

The *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* scenario is highlighted in the right panel of Figure O3-2 to emphasize the importance of incorporating environmental considerations into sustainable hydropower development, particularly NSD. This scenario is the subject of additional emphasis within this chapter overview. In the *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* scenario, an additional 7.6 GW is deployed relative to *Business-as-Usual,* for a total of 12.8 GW of new hydropower generation capacity by 2050. Nearly 75% of this amount is deployed by 2030 (see Table O3-4).

Figure O3-3 and Table O3-4 offer long-term snapshots of differences between the *Business-as-Usual* and *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* scenarios. The *Business-as-Usual* scenario achieves the majority of its 2050 growth (99%) from upgrading and optimizing existing hydropower plant capacity. This 5.2 GW of upgrades deployed under *Business-as-Usual* conditions is 76% of the total 6.9 GW of modeled upgrade capacity potential. The *Advanced Technology, Low Cost Finance and Combined Environmental Considerations* scenario deploys an additional 1.1 GW of upgrades, 4.8 GW powering of NPDs, and 1.7 GW of NSD.

The largest remaining potential for additional hydropower generation capacity beyond the *Advanced Technology, Low Cost Finance* and *Combined Environmental Considerations* scenario is through consideration of further development of new projects on undeveloped stream-reaches. Text Box O3-1 discusses how innovation and transformative technologies might help make this resource available.

## Pumped Storage Hydropower Deployment

The left panel of Figure O3-4 illustrates PSH deployment across the nine selected scenarios, with a range of 500 megawatts (MW) to 55 GW in 2050, while the right panel of Figure O3-4 shows PSH deployment for the four focus scenarios of the

**Table O3-4.** Summary of Modeling Results for the *Business-as-Usual* and *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* Scenarios in 2030 and 2050

| Resource Category | *Business-as-Usual* Scenario (GW) | | *Advanced Technology, Low Cost Finance, Combined Environmental Consideration* Scenario *(GW)* | |
|---|---|---|---|---|
| | 2030 | 2050 | 2030 | 2050 |
| **Total New Hydropower Generation Capacity** | 4.57 | 5.28 | 9.40 | 12.79 |
| Upgrades and Optimization of Existing Hydropower Plants | 4.53 | 5.23 | 5.62 | 6.27 |
| Powering of Non-Powered Dams (NPD) | 0.04 | 0.04 | 3.56 | 4.83 |
| Low-impact New Stream-Reach Development (NSD) | 0.00 | 0.00 | 0.22 | 1.69 |
| **New Pumped Storage Hydropower (PSH) Capacity** | 0.17 | 0.48 | 16.25 | 35.52 |
| *Total New Hydropower Capacity* | 4.74 | 5.76 | 25.64 | 48.31 |

Note: The *Business-as-Usual* scenario reflects economic outcomes under reference conditions and assumes no changes in policy or underlying electric sector fundamentals. Moreover, modeling on a national scale requires non-trivial generalizations and averaging of project level details that may limit the ability of the model to perceive niche megawatt-scale opportunities where they exist. For example, NPDs that might be powered under conditions similar to the *Hydropower Vision* low cost finance terms, which are available to some projects today, or under alternative project specific financing or policy terms (e.g., a corporate power procurement designed to meet specific third-party needs that may not be limited to lowest cost).

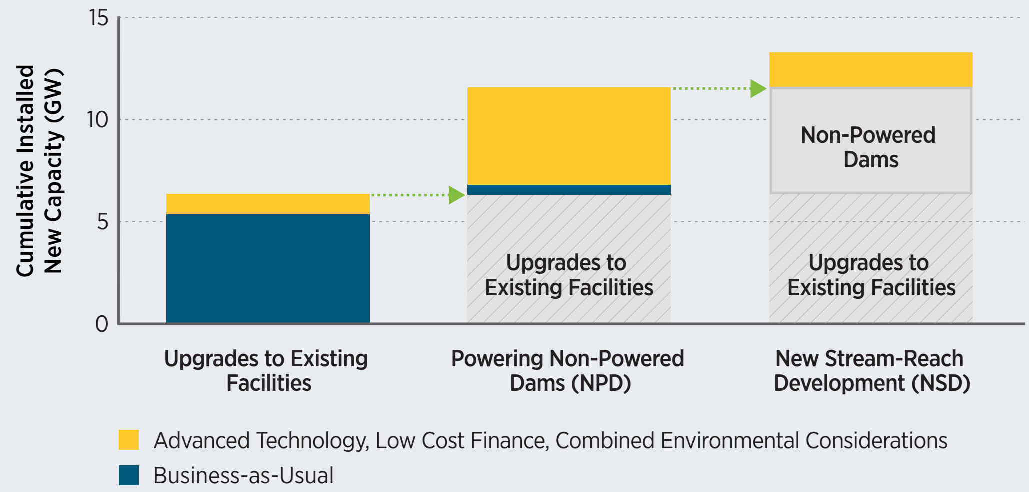
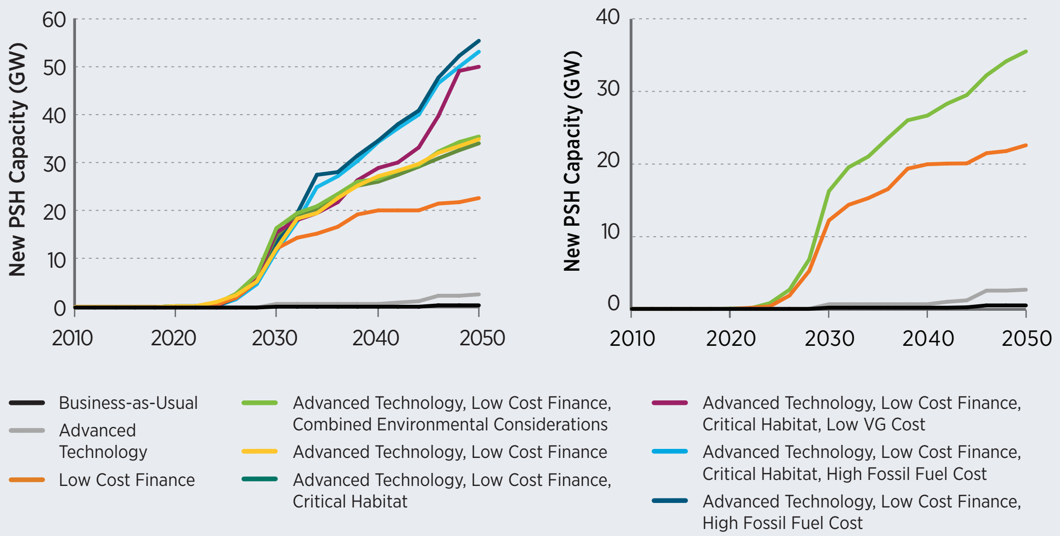



**Figure O3-3.** ReEDS modeled cumulative 2050 deployment of both existing and new hydropower generation capacity by resource category (GW)




Note: Although PSH is deployed regionally, modeling does not evaluate or designate specific PSH locations within a balancing area and environmental considerations by scenario are not applied to the PSH resource supply (environmental considerations are only applied to NSD resource). Notwithstanding these modeling nuances, PSH development will require location-specific compliance with applicable regulations, including environmental considerations.

**Figure O3-4.** ReEDS modeled deployment of new pumped storage hydropower capacity, selected scenarios, 2010–2050 (GW)

*Hydropower Vision*. For new PSH capacity, *Advanced Technology* assumptions alone have a modest effect on deployment (2.6 GW by 2050) as compared to *Business-as-Usual* (0.5 GW in 2050), while *Low Cost Finance* assumptions alone provide a comparably significant increase in deployment (22.6 GW by 2050). Under the focus scenario combining *Advanced Technology* and *Low Cost Finance* assumptions, 35.5 GW of new PSH capacity deployment occurs by 2050, with approximately half of this (53%) occurring by 2030 (see Table O3-4). In this scenario, PSH provides more operating reserves (52%) than any other technology by 2050, when high VG penetration could result in acute grid integration challenges (during the Spring night when electricity load is lowest) (see Figure O3-4).

As shown in the left panel of Figure O3-4, PSH deployment is strongly influenced by fossil fuel and VG costs, as *High Fossil Fuel Costs* and *Low VG Costs* create an electricity system that more highly values the use of energy storage to provide grid flexibility. This result stems largely from higher penetration of VG in the grid. Figure O3-5 plots new PSH capacity in 2030 and 2050 versus the percent of demand met by VG in those years under the *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* scenario assumptions. Though the exact relationship between PSH and VG depends on many electricity system characteristics, there is a clear positive correlation between VG energy and PSH capacity in the modeled scenarios.

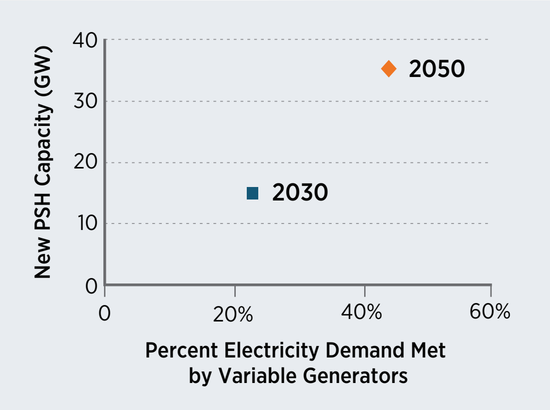


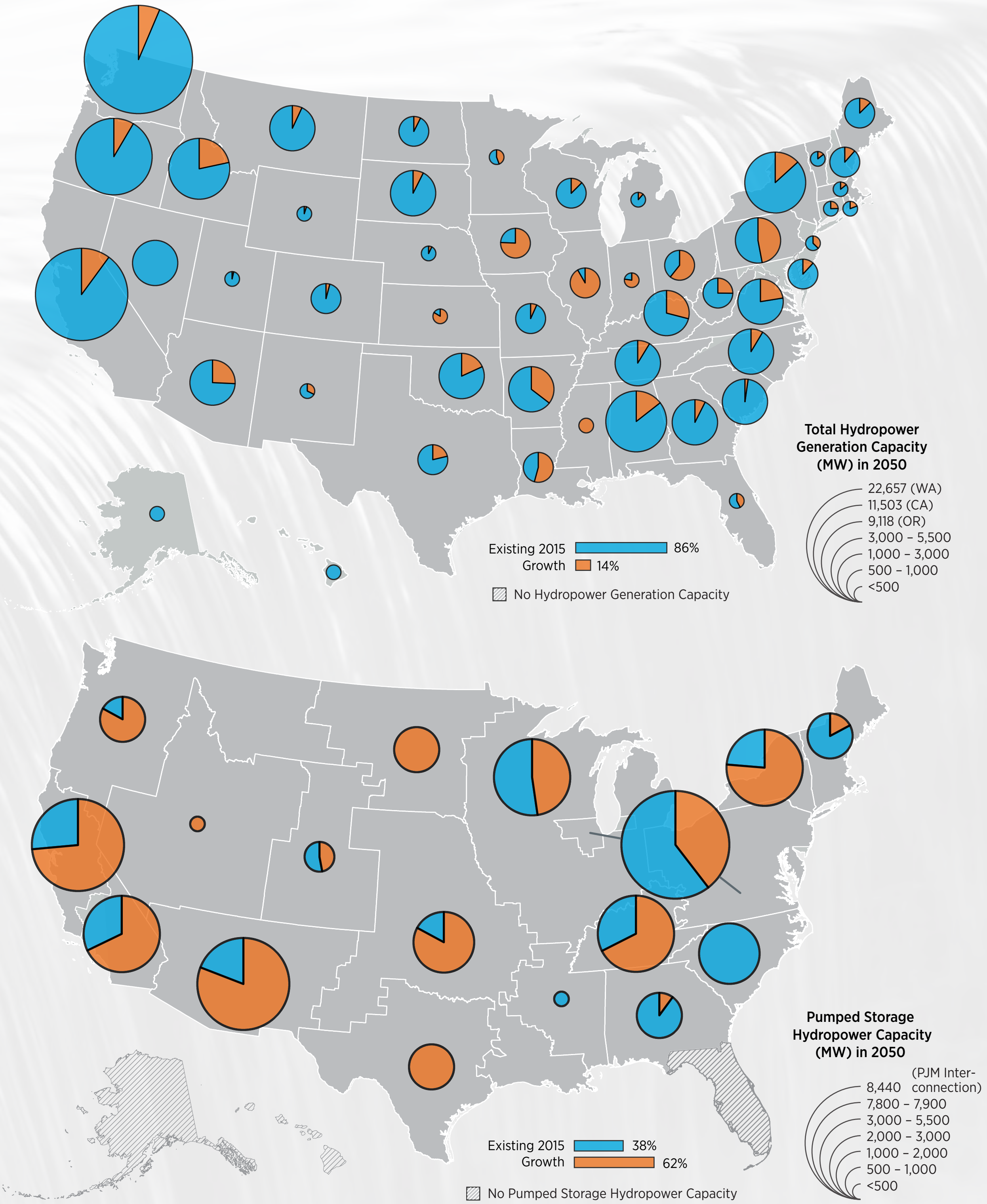

**Figure O3-5.** The relationship between new pumped storage hydropower growth and generation from variable generators under *Advanced Technology, Low Cost Finance, and Combined Environmental Considerations* assumptions

## Combined Hydropower Capacity Results

Notable observations from the analysis of growth potential include:

- U.S. hydropower could grow from 101 GW of combined generating and storage capacity at the end of 2015 to nearly 150 GW by 2050, with growth distributed broadly throughout the nation.
- Technology research, development, and deployment to reduce levelized cost of energy, plus improved lending terms, are essential to achieve growth beyond *Business-as-Usual*.
- In the near term (before 2030), hydropower generation growth is likely to be driven primarily through optimizing and upgrading the existing fleet, and powering NPDs.
- In the mid- to long term (from 2030–2050), additional growth may come through sustainable deployment of NPDs and NSD.
- PSH growth can increase in both the 2030 and 2050 periods, while complementing renewable energy (VG) growth by providing flexibility and other important grid services.

Geographically, hydropower generation and pumped storage capacity growth as observed is distributed across the nation. Figure O3-6 highlights the specific geographical growth characteristics of the *Advanced Technology, Low Cost Finance, Combined Environmental Consideration* scenario.




Note: ReEDS modeling applies to the continental United States only, so potential growth in Alaska and Hawaii is not captured.

**Figure O3-6.** Hydropower generation capacity (MW, top) and pumped storage hydropower capacity (MW, bottom) in 2050, illustrating growth from 2017 under the modeled scenario *Advanced Technology, Low Cost Finance, Combined Environmental Exclusions*

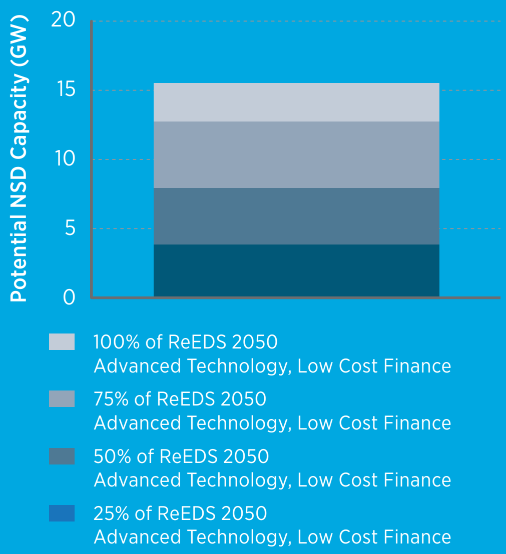
Text Box O3-1.

## Evaluating New Stream-Reach Development Potential

Beyond the hydropower generation deployed in the four focus scenarios, and specifically in the *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* scenario, the largest remaining potential for additional hydropower generation capacity is in NSD. However, cost and environmental considerations create challenges for development of this resource. New—even transformative—hydropower technologies and project designs capable of avoiding or minimizing adverse environmental and social impacts are generally understood to be essential for calculable growth of NSD.

Alternative scenarios presented in Chapter 3 demonstrate NSD growth opportunities if innovative approaches to the challenges presented by NSD deployment were to become widely available. A 2014 DOE resource assessment [14] found more than 60 GW of NSD technical potential across the United States. After applying additional economic assumptions, a modeled resource potential of 30.7 GW is made available to ReEDS. If innovation were to successfully address the cost and environmental considerations to make all 30.7 GW available for deployment (e.g., the *Advanced Technology, Low Cost Finance* scenario), the resulting economic opportunity estimated under reference electricity market assumptions is 15.5 GW of additional economic NSD growth above the 1.7 GW achieved under similar economic conditions with *Combined Environmental Considerations*. Using this opportunity as an upper bound, the figure below conveys conceptually that the greater the effectiveness of innovation, the more NSD that is potentially accessible to the nation. The table then details estimates of the deployment and economic impacts at various NSD deployment levels, with the gross jobs values being an average between job estimates corresponding to low and high domestic content.

**Range of potential future NSD deployment beyond modeled results**




**New Stream-Reach Development Deployment Outcomes with *Advanced Technology* and *Low Cost Finance* Assumptions**

| Fraction of Additional New Stream-Reach Development Deployment | Cumulative New Stream-Reach Development Deployment (GW) | 2017–2050 Present Value of Hydropower Economic Investment[a] ($ billion) | Gross Jobs[b] |
|---|---|---|---|
| 25% | 2.8 | 4 | 15,000 |
| 50% | 7.6 | 11 | 41,000 |
| 75% | 11.7 | 19 | 63,000 |
| 100% | 15.5 | 32 | 83,000 |

a. Capital investment and annual operating expenses

b. Gross jobs are calculated from the average of a range from job estimates related to low to high domestic content for the total 15.5 GW deployment.

## *Selected Costs, Benefits, and Impacts of Hydropower*

In addition to examining the key factors influencing a broad range of potential futures for U.S. hydropower, Chapter 3 quantifies a subset of the costs and benefits associated with future hydropower deployment and operations through 2050. To estimate the impacts of new hydropower capacity (hydropower generation and PSH), many metrics are compared between a given scenario and its corresponding baseline scenario in which hydropower electricity market conditions remain the same and no new unannounced (as of 2016) hydropower is built through 2050. Impacts for the existing fleet were estimated by comparing the quantified costs and benefits of existing hydropower capacity to those that would result if this capacity were to be replaced by the regional composite mix of other cost-competitive generation sources in future (model) years under a baseline scenario with reference electricity market assumptions.

Focusing on the existing hydropower fleet and new deployment as modeled under the *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* scenario, identified *Hydropower Vision* economic and social benefits. These benefits include $209 billion savings from avoided global damages from GHG emissions; $58 billion savings in avoided mortality, morbidity, and economic damages from cumulative reduction in emissions of sulfur dioxide ($SO_2$), nitrogen oxide ($NO_X$), and fine particulate matter ($PM_{2.5}$); and 30 trillion gallons of avoided water withdrawals from 2017 to 2050. Additionally, more than 195,000 jobs are supported in 2050 (see Figure O3-7).

This scenario reflects the impact of key variables affecting deployment—technology, markets, and sustainability. It also presents a credible outcome of combined actions by government, industry, and public stakeholders to successfully reduce technology cost through research and development and more efficient regulatory process; monetize the long asset life of hydropower in project financing; and address the co-objective of environmental preservation. These objectives, among others, are discussed in the *Hydropower Vision* roadmap.

Impacts specific to the existing fleet and new deployment under the *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* scenario are provided in more detail below. Additional impact metrics and results associated with the balance of the nine selected scenarios are described within Chapter 3 and demonstrate a broader range of possible hydropower industry impacts.

**Benefits—Existing and New Capacity, 2017–2050[a,b,c]**

| | Economic Investment | Greenhouse Gases | Air Pollution | Water | Jobs |
|---|---|---|---|---|---|
| **Existing Fleet and New Capacity Additions Combined (149.5 GW)** | $148 billion in cumulative economic investment[d]<br>$110 billion for hydropower generation and $38 billion for PSH | Cumulative GHG emissions reduced by 5,600,000,000 metric tons $CO_2$-equivalent, saving $209 billion in avoided global damages | $58 billion savings in avoided mortality, morbidity, and economic damages from cumulative reduction in emissions of $SO_2$, $NO_X$, and $PM_{2.5}$<br>6,700–16,200 premature deaths avoided | Cumulative 30 trillion gallons of water withdrawals avoided for the electric power sector | Over 195,000 hydropower-related gross jobs spread across the nation in 2050 |

**Figure O3-7.** Selected benefits and impacts from the existing hydropower fleet and from new deployment, 2017–2050

a. Cumulative benefits are reported on a Net Present Value basis ($2015) for the period of 2017 through 2050.

b. Estimates reported reflect central values within a range of estimates as compared to the *baseline scenario* with no new hydropower.

c. Existing fleet includes new projects and plant retirements announced as of the end of 2015; new development reflects the modeled scenario titled *Advanced Technology, Low Cost Finance, and Combined Environmental Considerations.*

d. Capital investment and annual operating expenses, 2017–2050.

### Impacts: Existing Fleet

Cumulative impacts from avoided power-sector GHG and air pollutions emissions from 2017 to 2050 from the existing hydropower fleet total $184.5 billion in savings from avoided global damages from GHG emissions, and $58 billion in savings from avoided mortality, morbidity, and economic damages from cumulative reduction in emissions of $SO_2$, $NO_X$, and $PM_{2.5}$ (Figure O3-8). The existing hydropower fleet also avoids approximately 1,450 billion gallons of water withdrawals per year compared to the energy sources that would otherwise be deployed; and 100 billion gallons of water consumption savings per year as of 2016. These savings represent a 4.1% and 7.3% reduction in national water withdrawal and consumption, respectively. Long-term jobs supported by the existing fleet exceed 120,000 in 2050.

### Impacts: New Capacity Additions

Relying on the mid-range *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* scenario, the cumulative impacts from avoided power-sector GHG emissions from new hydropower capacity additions from 2017 to 2050 total nearly $25 billion in savings from avoided global damages (Figure O3-9 and Table 03-5). In addition, cumulative capital investment is estimated at more than $71 billion. These new investments are estimated to support approximately 76,000 new full-time equivalent jobs.

### Impacts: Combined Existing Fleet and New Capacity Deployment

The overall impacts to human health from reduced air pollution were estimated through 2050 and comprise 294,000 metric tons of fine particulate matter (PM), 2,760,000 metric tons of nitrogen oxides ($NO_X$), and 1,418,000 metric tons of sulfur dioxide ($SO_2$). These reductions could result in avoidance of 6,700–16,200 premature deaths (see Note "d" in Table 03-5 for additional detail regarding interactions between air pollution impacts of the existing fleet and new hydropower capacity). Cumulative capital and operating expenditures from 2017–2050 are approximately $110 billion for hydropower generation and $38 billion for PSH. Cumulative avoided GHG emissions from the combined capacity of existing and new hydropower were calculated to be 5.6 billion metric tons of carbon dioxide from 2017–2050, corresponding to $209 billion in avoided global damage (Table O3-5, Figure O3-7).

**Benefits—Existing Capacity, 2017–2050[a,b,c]**

| | Economic Investment | Greenhouse Gases | Air Pollution | Water | Jobs |
|---|---|---|---|---|---|
| **Existing Fleet (101.2 GW)** | $77 billion in cumulative economic investment[d] | Cumulative GHG emissions reduced by 4,900,000,000 metric tons $CO_2$-equivalent, $184.5 billion savings | $58 Billion savings in avoided mortality, morbidity, and economic damages from cumulative reduction in emissions of $SO_2$, $NO_X$, and $PM_{2.5}$ | Cumulative 30 trillion gallons of water withdrawals avoided for the electric power sector | 120,500 hydropower-related gross jobs spread across the nation in 2050 |

**Figure O3-8.** Selected benefits and impacts from the existing hydropower fleet and from new deployment, 2017–2050

a. Cumulative benefits are reported on a Net Present Value basis ($2015) for the period of 2017 through 2050.

b. Estimates reported central values within a range of estimates as compared to the *baseline scenario* with no new hydropower.

c. Existing fleet includes new projects and plant retirements announced as of the end of 2015.

d. Capital investment and annual operating expenses, 2017–2050.

**Benefits—New Capacity, 2017–2050[a,b,c]**

| | Economic Investment | Greenhouse Gases | Air Pollution | Water | Jobs |
|---|---|---|---|---|---|
| **New Capacity Additions (48.3 GW)** | $71 billion in cumulative economic investment[d] | Cumulative GHG emissions reduced by 700,000,000 metric tons $CO_2$- equivalent, $24.5 Billion savings | n/a[e] | n/a[f] | 76,000 hydropower-related gross jobs spread across the nation in 2050 |

**Figure O3-9.** Selected benefits and impacts from new hydropower capacity additions under the *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* scenario, 2017–2050

a. Cumulative benefits are reported on a Net Present Value basis ($2015) for the period of 2017 through 2050.

b. Estimates reported reflect central values within a range of estimates as compared to the *baseline scenario* with no new hydropower.

c. Existing fleet includes new projects and plant retirements announced as of the end of 2015; new development reflects the modeled scenario titled *Advanced Technology, Low Cost Finance, and Combined Environmental Considerations*.

d. Capital investment and annual operating expenses, 2017-2050.

e. In the model, once the Clean Power Plan carbon cap is realized, the addition of new hydropower can displace marginal natural gas generation, thereby allowing for additional coal generation—and associated criteria pollutant emissions which reduced the calculated value of avoided air pollution emissions for new hydropower deployment by $6.2 billion over the 2017-2050 time period. However, this result reflects the model's use of AEO 2015 Reference Case natural gas prices, which are higher than those in the more recent AEO 2016 Reference Case. AEO 2016 data were unavailable for inclusion in the *Hydropower Vision* analysis, but lower natural gas prices could allow new hydropower to displace more coal relative to natural gas. Due to the sensitivity of this result to recently updated natural gas price projections, the $6.2 billion reduction in value is not reflected in the total value of avoided $SO_2$, $NO_X$, and $PM_{2.5}$ in the *Advanced Technology, Low Cost Finance, and Combined Environmental Considerations* scenario.

f. Cumulative 2017-2050 water use impacts from new hydropower capacity in the *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* scenario include a 0.1% increase in water withdrawals (0.8 trillion gallons). Given the magnitude of these impacts relative to those from the existing fleet and model precision limitations generally, these results are not reflected in the avoided water use impacts reported here.

**Table O3-5.** Cumulative Impacts of Hydropower under the *Advanced Technology, Low Cost Finance,* and *Combined Environmental Considerations* Scenario, 2017–2050[1]

| Resource Category | Capacity, 2050 (GW) | Avoided GHG Emissions ($B) | Avoided Emissions of $SO_2$, $NO_X$, and $PM_{2.5}$ ($B)[b] | Avoided Water Use (trillion gallons)[c] | Annual Jobs Supported, 2050 |
|---|---|---|---|---|---|
| Existing Hydropower | 101.2 | 184.6 | 57.8 | 30.1 withdrawals, 2.2 consumption | 120,500 |
| New Hydropower | 48.3 | 24.5 | n/a[d] | n/a[e] | 76,000 |
| *Total* | 149.5 | 209 | 57.8 | 30.1 withdrawals, 2.2 consumption | 196,500 |

a. As compared to the baseline scenario, under which no new unannounced (as of 2016) hydropower is built.

b. Savings in avoided mortality, morbidity, and economic damages.

c. Water withdrawal is water that is removed from the ground or diverted from a water source for use, but then returned to that source, Water consumption is water that is removed from the immediate water environment altogether, e.g., through evaporation or use for production and crops.

d. The Clean Power Plan (CPP)—which is estimated to provide substantial air quality benefits [65]—limits total carbon emissions but does not directly limit $SO_2$, $NO_X$, and $PM_{2.5}$ emissions. In the model, once the CPP carbon cap is realized, the addition of new hydropower can displace marginal natural gas generation, thereby allowing for additional coal generation—and associated criteria pollutant emissions, which reduced the calculated value of avoided air pollution emissions for new hydropower deployment by $6.2 billion and avoided water withdrawals by 0.8 trillion gallons over the 2017–2050 time period. However, this result reflects the model's use of AEO 2015 Reference Case natural gas prices, which are higher than those in the more recent AEO 2016 Reference Case. AEO 2016 data were unavailable for inclusion in the *Hydropower Vision* analysis, but lower natural gas prices could allow new hydropower to displace more coal relative to natural gas. Due to the sensitivity of this result to recently updated natural gas price projections, the $6.2 billion reduction in value is not reflected in the total value of avoided $SO_2$, $NO_X$, and $PM_{2.5v}$.

e. Cumulative 2017–2050 water use impacts from new hydropower capacity in the *Advanced Technology, Low-Cost Finance,* and *Combined Environmental Considerations* scenario include a 0.1% increase in water withdrawals (0.8 trillion gallons) and a 0.0% change in water consumption (0.00 trillion gallons). Given the magnitude of these impacts relative to those from the existing fleet and model precision limitations generally, these results are also not reflected in the avoided water use impacts reported here; they are, however, summarized in the main body of Chapter 3.

### *Key Modeling Findings*

Along with the highlights already noted, several general conclusions may be drawn from the full analysis presented in Chapter 3:

- Across the breadth of potential scenarios, growth of hydropower capacity could also add billions of dollars in societal value in the form of avoided GHG and air pollution emissions, avoided water consumption, and avoided water withdrawals.
- Although opportunities for new hydropower capacity and generation are less than implied by gross resource assessments, they do imply continuation and incremental growth of a robust multi-billion dollar industry under all scenarios, including *Business-as-Usual.*
- Continued investment in the hydropower industry is expected to be significant, as indicated by the $4.2 billion per year investment estimate under *Business-as-Usual*; and $9.9 billion per year under the *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* scenario.
- Comprehensive sustainability and cost reduction advances through innovation will play a major role in determining what levels of NSD are ultimately realized.
- Modeled ranges yield dramatically different results based on assumptions, indicating that actions defined in the *Hydropower Vision* roadmap (chapter 4) as well as external factors such as climate change (Text Box O3-2) can influence outcomes.
- Due to its large installed capacity and long capital lifetime, the existing fleet will continue to contribute a substantial majority of the societal benefits of hydropower as a whole.

Text Box O3-2.

#### Hydropower in an Uncertain Climate Future

Climate change creates uncertainty for hydropower generation, with potential impacts that include increasing temperatures and evaporative losses that result in reductions in available water resources and changes in operations; changes in precipitation and decreasing snowpack that result in changes in seasonal availability of resources and changes in operations; and increased intensity and frequency of flooding that results in greater risk of physical damage and changes in operations.

The impact of water availability on future hydropower deployment was explored by modeling low (*Dry*) and high (*Wet*) hydropower water availability futures for each of the nine selected scenarios. Most upgrades are economically attractive even with reduced water availability, which leads to less than a 5% change in deployment under *Business-as-Usual* conditions. NPDs are also similarly unaffected by changing water availability under *Advanced Technology, Low Cost Finance* assumptions, which support construction of a large fraction of the NPD resource even when water availability is reduced. In contrast, the range of NSD deployment variation across *Wet* and *Dry* conditions is 42–74% of the reference NSD deployment for scenarios in which NSD is economically feasible.

Hydropower energy production varies across alternate water availability scenarios, both for existing and new resources. From the reference long-term average output of 270 terawatt-hours (TWh), variation in existing fleet generation in climate scenario spans 260–290 TWh in 2030, and 250–310 TWh in 2050. For new hydropower generation, energy production across the full range of *Wet* and *Dry* variants for the nine selected scenarios spans 13–120 TWh in 2030 and 6–260 TWh in 2050.*

* The low end of the range declines because *Business-as-Usual* in *Dry* conditions does not build enough new capacity to replace reduced generation due to declining water availability for previously built hydropower.

# 3.0 Introduction

Hydropower has played a pivotal role in the U.S. electricity generation sector for more than a century, and the technology has the potential to remain an important source of energy in the nation's electricity future. Chapter 3 of the *Hydropower Vision* applies detailed electric sector modeling and impacts assessment to explore an array of possible futures for the hydropower industry and to better understand a subset of the quantifiable impacts associated with multiple scenarios. Within the analysis conducted, no scenario or set of scenarios is intended as a hydropower industry forecast. Rather, the work detailed in this chapter is intended to provide new quantitative insights and understanding regarding future opportunities, costs, and benefits associated with the existing hydropower fleet and potential new hydropower deployment. The results detailed in this chapter are meant to inform a variety of stakeholders and decision makers of the future potential and value of hydropower technology in the nation's electricity future.

This chapter details analysis considering an array of future scenarios for hydropower development, including those that maintain existing levels of industry activity (*Business-as-Usual*), as well as several more ambitious scenarios, described in Section 3.3. It then examines a subset of potential impacts, opportunities, and benefits that might be realized from the existing fleet and new hydropower facilities under these scenarios. Based on these data, new insights on the growth potential of hydropower technologies and a detailed understanding of potential drivers and influences on future growth are identified. In addition, this chapter examines the development potential within specific hydropower market segments, and the drivers and effects relevant to future growth within those market segments. The chapter also explores critical uncertainties in hydropower development—specifically, how future growth may intersect with a changing climate and environmental and social considerations that are important to all power generation technologies but sometimes have unique implications for hydropower.

Analysis work presented in this chapter relies primarily on the National Renewable Energy Laboratory's (NREL's) Regional Energy Deployment System (ReEDS) capacity expansion model ([1], [2]) with supplemental analysis methods applied to model outputs when analyzing impacts. In addition, Chapter 3 and its related appendices serve as documentation for a synthesis of recent cost and resource assessments conducted by Oak Ridge National Laboratory, characterizing the nation's hydropower resource potential and applying it for the first time in the *Hydropower Vision*.

Section 3.1 describes the electric sector expansion model and the approach used for this analysis, which includes acknowledging the general challenges and limitations in modeling hydropower at a national level. This section includes particular focus on hydropower modeling assumptions.

Section 3.2 provides an overview of the hydropower resources modeled in ReEDS and describes how the modeled resource differs from other forms of resource estimates, such as physical or technical resource potential.

Section 3.3 provides a high-level overview of the economic assumptions that characterize hydropower opportunities, and briefly documents the input assumptions used to describe the existing and future electric sector, including generation technology resource, cost, and performance; electricity demand; fuel prices; and retirements. Additional details are included in Appendices B, C, and D. Section 3.4 also lays out the full range of scenarios and model input parameters that are varied in order to create the range of outcomes. This section also defines the selected scenarios for which the impact metrics are calculated.

Section 3.4 presents and explores the range of future hydropower deployment captured by nine selected scenarios, identified for their ability to reflect both priorities in the hydropower stakeholder community (e.g., technology cost reduction, environmental considerations) as well as the potential for uncertainty in the broader electric sector (e.g., high fossil fuel prices). This section explores how the specific market and resource conditions embodied in these scenarios inform the possibilities for future hydropower growth by varying technology cost reduction, long-term asset valuation, among other assumptions. One focus specific to new stream-reach development (NSD) is the extent to which development potential intersects with selected environmental and social considerations.

The results from these scenarios can inform the need for innovative technology and planning solutions to improve sustainability outcomes. Section 3.4 also explores the manner in which changes in water availability resulting from climate change could impact future contributions of hydropower to the grid.

Section 3.5 details a subset of quantifiable impacts for future hydropower deployment as well as benefits associated with continued operation of the existing fleet capabilities through 2050. Impacts discussed include electric sector economics, greenhouse gas (GHG) emissions, air quality, water usage, and workforce. In summary, the analytic framework presented in Chapter 3 is intended to provide insight into a range of possible outcomes for U.S. hydropower and to demonstrate potential impacts associated with scenarios that result in continued operation of the existing hydropower fleet as well as new growth in the hydropower industry. These data and insights are intended to provide information for a variety of stakeholders and decision makers with respect to the potential future for hydropower as a source of clean and renewable energy for the nation.

# 3.1 Analytical Approach: Overview

Evaluating potential drivers of growth and quantifying a range of future costs and benefits associated with the hydropower industry requires multiple methods and datasets. Within the quantitative analysis detailed in this chapter, existing resource data and characterizations are used in a detailed electric sector modeling framework, with other methods derived from the literature to quantify potential benefits (e.g., avoided GHG damages) and impacts (e.g., hydropower-derived employment). Analytical methods are applied to both the existing hydropower fleet and varying levels of new hydropower deployment in the form of upgrades, NSD, powering of non-powered dams (NPD), and pumped storage hydropower (PSH). The basic modeling and analysis approaches applied to the existing fleet and to new hydropower potential are described in this section.

## 3.1.1 Existing Fleet

With nearly 100 gigawatts (GW) of combined hydropower generation and PSH capacity—10% of all U.S. generating capacity—the existing fleet has a tremendous national impact on the power system. The methodology and assumptions used to characterize the impacts of the existing fleet were a core consideration throughout the *Hydropower Vision* effort. The focus included whether to calculate the historical versus "as-of" or future value of the existing fleet, as well as methodological concerns focused on if and how a particular impact might be assessed. In order to analyze the existing fleet, this analysis ultimately considers the benefits of the existing fleet as of 2015 and through the future study period. Estimates of historical benefits, costs, and environmental impacts were deemed to be outside the scope of the *Hydropower Vision*.

Existing fleet benefits (e.g., GHG emissions) through 2050 are calculated as a function of the other electricity generators in the grid, on a regional basis. Analysis of the existing fleet uses the average characteristics of the rest of the regional electric system in a given year to characterize the value of existing hydropower in that same region and year. In effect, the assumption is that, if the existing hydropower fleet were not available, it would be replaced by the average characteristics of the rest of the electric sector in that region. Estimates for the present are based on the average electric sector characteristics of 2015, while average electric characteristics of the future are estimated in ReEDS.

## 3.1.2 Potential New Deployment

For new hydropower potential—including that from upgrading the existing fleet, NPD, NSD, and PSH—the NREL ReEDS model is used to capture the complex dynamics of the power grid and simulate how those might evolve under different scenarios. In this modeled context, the future scenarios of hydropower industry growth can be explored, with modeled representations of hydropower resources competing against other generation technologies (and other hydropower technologies) to see how the grid may evolve most economically. The specific costs and benefits of hydropower can be isolated by comparing scenarios of growth (such as what might happen if technology costs can be decreased) to control scenarios ("baselines") with no hydropower growth. The differences between these two sets of scenarios then highlight how new hydropower affects the selected cost and benefit metrics analyzed.

Although the *Hydropower Vision* analyzed more than 50 total scenarios, impact metrics detailed within the main report body are calculated for a subset of nine selected modeling scenarios chosen to capture key hydropower industry priorities (e.g., aggressive cost reduction, financial valuation of the long-term asset life of hydropower, environmental considerations) as well as key electric sector uncertainties (e.g., high fossil fuel prices and low variable generation [wind and solar] technology costs). Metrics of interest include: primarily costs measured in terms of changes in electricity rates and cumulative system expenditures; benefits derived from changes in power sector GHG emissions, air pollution, water consumption, and water withdrawals; and other impacts measured in terms of contribution to electricity capacity and generation, workforce and economic development, changes in electric sector sensitivity to fossil fuel price volatility, and reductions in consumer expenditures on natural gas.

Ecological, environmental, and other positive and negative externalities associated with hydropower were not quantified; in this sense, the impacts analysis is not comprehensive of all potential costs and benefits of new hydropower deployment. However, environmental considerations for hydropower growth, particularly NSD, are examined for several modeled scenarios.

## 3.1.3 Regional Energy Deployment System (ReEDS)

As noted in Section 3.0, the NREL's ReEDS[2] electric sector capacity expansion model is the primary analytic tool used to quantify the impacts studied in the *Hydropower Vision* analysis. ReEDS simulates the construction and operation of electricity generation and transmission capacity while meeting electricity demand and other system requirements through 2050 for each of 134 supply-demand balancing area (BA) regions. The model uses a system-wide[3] least-cost optimization to estimate the type, location, and timing of fossil, nuclear, renewable, and storage resource deployment; the necessary transmission infrastructure expansion; and the generator dispatch and fuel needed to satisfy regional demand requirements and maintain grid reliability. It includes a sophisticated representation of variable generation renewable resources and the flexible systems necessary for their integration, including natural gas and energy storage systems such as PSH. ReEDS also incorporates technology, resource, and policy constraints, including state renewable portfolio standard policies, enacted tax credits, and the the U.S. Environmental Protection Agency's Clean Power Plan (CPP).[4] The model considers only the continental United States and performs the least-cost optimization sequentially in 2-year solve periods.[5] Additional details of the ReEDS model formulation are contained in the ReEDS documentation [1] and more recent publications containing ReEDS analysis, particularly the *NREL 2015 Standard Scenarios Annual Report* [2] and the U.S. Department of Energy's (DOE's) *Wind Vision* report [3].

2. *http://www.nrel.gov/analysis/reeds/description.html*
3. The ReEDS model optimizes the electric sector of the continental United States as a system, in contrast to optimizing around impacts to individual market actors or specific regions.
4. Model results do reflect the December 2015 renewable energy tax credit extension.
5. Alaska, Hawaii, and Puerto Rico are not currently included in ReEDS due to model limitations. Potential hydropower capacity from canals and conduits are also not currently included in ReEDS. ReEDS assumes exogenous estimates of net energy transfers from Canada to the United States [4] but ignores the limited interactions with Mexico.

For the *Hydropower Vision*, ReEDS is used to generate a set of future U.S. electric sector scenarios from which the impacts of a growing hydropower of a future hydropower industry can be assessed. As noted above, ReEDS scenarios are not forecasts or projections; rather, they aim to provide a consistent framework for understanding the effects of potential future conditions.

The primary outputs of the ReEDS model include the location, capacity, and generation of all power generation technologies built and operated during the study period along with the transmission infrastructure expansion necessary to support this new generation. Capital costs, fixed operating costs, variable operating costs, fuel usage and costs, and other associated costs are reported, along with transmission capital and operating costs. Cost metrics—such as present value system cost and an approximation of electricity prices (neither of which incorporate environmental externalities) can be derived from this raw cost information. Capacity expansion and generation results are then used to inform impacts assessments (e.g., GHG emissions, other environmental and health benefits, thermal cooling water use, energy diversity and risk, and workforce and economic development). The hydropower deployment results are further analyzed to more thoroughly assess their physical attributes, regional distribution, and potential intersection with environmental considerations.

### 3.1.4 Challenges and Limitations

The development of the *Hydropower Vision* entailed a number of improvements to how hydropower is modeled in ReEDS, making the representation of U.S. hydropower for this study among the most sophisticated and complete to date for models of its class. Some modeling limitations and challenges, however, persist. These are briefly discussed in this section to provide context and acknowledge the many important issues about which continued work may provide enhanced resolution and better intelligence in future analyses.

**Hydropower Technology Representation.** A core difficulty in modeling hydropower is attempting to capture the unique, site-specific dynamics that drive technology choice and project economics in the real world. In modeling hydropower potential, attributes are often approximated from resource and cost assessment efforts that necessarily rely on limited data and assumptions based on averages across site-specific features. The *Hydropower Vision* analysis uses the most current U.S. resource assessment and cost data available as of 2015, but these data can still only provide generalized, uncertain estimates that are more accurate at an aggregate scale than for individual projects. The results presented in this chapter should be interpreted as capturing large-scale trends and identifying regions and areas with economically competitive hydropower potential, not necessarily implying that a specific dam will be powered at a specific cost, or that an individual stream-reach is ideal for development.

Future improvements are believed to be most valuable for characterizing the full potential of upgrading and expanding the existing fleet, as well as predicting and estimating the cost of environmental mitigation measures for all types of hydropower.

**Modeling Sustainability.** Issues of sustainability are of paramount importance to the development and operation of hydropower projects, but are difficult to translate into robust modeling assumptions. In practice, decisions related to hydropower are ultimately made through processes that rely on input from a variety of stakeholders with an equally diverse set of economic, social, and environmental objectives. Modeling realities limit the investigation of these multiple objectives to the economic optimization performed by the ReEDS model, and the *Hydropower Vision* analysis can only begin to explore these issues through scenario analyses that observe how economics intersect with other considerations. Because of this, the *Hydropower Vision* analysis does not claim that sustainability has been approximated in the modeling process, only that the bounds of some considerations have been explored.

A key conclusion from this effort is that better data and new modeling techniques would be particularly valuable to incorporate sustainability concerns into models themselves. Some data advances were made during the *Hydropower Vision*, including the creation of national data layers of stream connectivity and the predicted habitat of migratory fish species. However, further improvement is necessary in the development of science-based environmental metrics and approaches that can consider hydropower development in the context of multiple objectives beyond economics.

**Modeling Climate Change.** Climate change has the potential to significantly alter many aspects of the power system and its relationships with other systems such as water supply. Modeling these complex interdependencies is difficult, but previous work with ReEDS has examined climate impacts such as temperature effects on load and the thermal fleet operation and expansion [5]. The analysis presented here also explores isolated potential impacts of climate change on hydropower through the modeling of changes in runoff and the resulting magnitude and timing of water availability for hydropower generation. However, fully resolving climate change in a modeled context must link together the joint impacts on energy and water systems, such as operational impacts to thermal generators, changes to electricity demand, and the availability and timing of water for hydropower generation. Such a comprehensive climate scenario is outside the scope of the *Hydropower Vision*, so climate change is discussed in this report with respect to its direct and isolated effects on the hydropower industry only.

The issue of a changing climate also highlights the modeling challenges in sustainability and the technology representation for hydropower discussed previously, as changes to water quality and temperature could influence project design and operations to minimize or mitigate environmental and economic impacts. Beyond these considerations, adaptation to climate may also intersect with hydropower development in ways the *Hydropower Vision* analysis does not model, such as adding power generating capabilities to new water resource infrastructure constructed to accommodate future changes in the timing and availability of water.

**Costs and Benefits.** The cost and benefit metrics included in the *Hydropower Vision* analysis are only a subset of those that are typically of interest to hydropower's many stakeholders. In addition, the direct cost metrics in the ReEDS model do not include environmental or health externalities that are not directly incorporated into existing electricity cost structures. Some of these externalities (such as electric sector GHG emissions) are evaluated separately using the outputs of the ReEDS scenarios as described in Section 3.5. Many additional hydropower-specific considerations, such as impacts on water quality or species populations require complex site-specific modeling techniques and strategies to resolve and therefore cannot be addressed at the national-scale of the modeling analysis considered here. As described in Section 3.4, this analysis includes some sensitivity scenarios that attempt to explore the intersection of hydropower deployment and other, non-economic considerations. The assumptions embedded in these scenarios are not intended to serve as proxies for sustainability concerns. Rather, they are simply a first step towards identifying and understanding the effects of other water uses that new hydropower deployment must complement.

It is also not feasible to quantify in an electric sector model many of the potential benefits associated with hydropower development, including recreation opportunities and water supply capabilities. Instead, the analysis calculates those metrics where data and methods are adequate for scientifically credible evaluations. For a more thorough accounting of the cost and benefits of hydropower development, future research must address these additional quantification challenges.

**Additional Potential Outside of the Modeling Scope.** The modeling scenarios described in this chapter of the *Hydropower Vision* are not intended to be interpreted as representative of the full range of outcomes possible for the hydropower industry. Instead, they constitute a useful—albeit imperfect—modeling tool to explore the major opportunities, challenges, and drivers of a 21st century hydropower industry. To that end, there are certain segments of the power sector that cannot be modeled in the existing ReEDS model. As such, these topics are discussed qualitatively throughout the report.

The largest model constraint is that the scope of the ReEDS model prevents the explicit modeling of Alaska and Hawaii. Hydropower is a potentially important resource in these states; their unique hydropower resources and power markets are discussed in Chapter 2 of the *Hydropower Vision*.

Also absent from ReEDS is the generation potential from conduits and canals, for which consistent site-specific data are not available on a basis that allows for integration into a national electric sector model. Distributed owner and state-level assessments do exist; for example, the resource potential for canals owned by the U.S. Bureau of Reclamation (Reclamation) is about 104 megawatts (MW) [6]. Beyond this quantity, states such as California, Massachusetts, Oregon, and Colorado have all done partial assessments of canal and conduit potential, but there have been no nationwide resource assessments that could be modeled consistently in ReEDS [7] (Sale et al. 2014).

An additional market segment that is only partially modeled is Canadian hydropower and the extent to which it interacts with U.S. markets. As of 2015, the ReEDS model uses a static forecast from Canada's National Energy Board of new hydropower development and anticipated exports of energy to the United States [8]. Changing policy and market conditions in the United States could result in subsequent changes to how Canadian hydropower competes in cross-border markets.

**Broader Power System Considerations in the ReEDS Model**. ReEDS is a system-wide least-cost optimization model. As such, it does not consider revenue impacts for individual project developers, utilities, or other industry participants, and does not resolve some other factors that may influence power system economics. These factors include:

- Constraints associated with the supply chain and manufacturing sector, which are not included. All technologies are assumed to be available up to their technical resource potential.[6]
- Technology cost reductions from manufacturing economies of scale and "learning by doing" are not calculated in the model internally; these market behaviors are defined as inputs that do not depend on the capacity deployed by the model.
- With the exception of future natural gas fuel costs, foresight is not considered explicitly in ReEDS (i.e., the model makes investment decisions based on the conditions it observes at a given point in time, without considering how those conditions may change further into the future).
- ReEDS is deterministic and has limited considerations for risk and uncertainty, so it cannot study inter-annual variability in hydropower energy availability. As such, the model is restricted to projections of average system behavior.
- As an electric-sector-only model, ReEDS does not directly include fuel infrastructure, land competition challenges associated with fossil fuel extraction and delivery, or water competition challenges with agricultural or other use.[7] As is the case for all models, these challenges in combination mean that ReEDS represents a simpler power system than exists in reality. The advances made in the *Hydropower Vision* ensure a thorough examination of many key issues surrounding the hydropower industry. These include competition with other technologies; regional distribution of new deployment; influence of economic drivers, such as cost reductions and fuel prices; and initial explorations of the potential influence of climate change, as well as the intersection of possible hydropower development with other priority water uses.

6. ReEDS does, however, include a growth penalty on capital costs for rapid technology deployment. For hydropower, capital costs will be greater than their base defined amounts if annual capacity additions are to exceed 1.44 times the additions in the previous year.
7. The model does include a static resource supply of water availability for new thermal cooling water requirements by new capacity, and this resource supply implies relative water availability between the electric sector and other sectors.

# 3.2 Hydropower Resource Potential

Understanding and characterizing the potential opportunity for hydropower in the future begins with a base level of knowledge of the existing fleet and the types and quantities of new resource development potential. Details and data presented in this section are intended to provide this initial foundation and to assist in understanding new power generation and storage opportunities presented by hydropower technologies. This section will also define the hydropower resource representation in ReEDS and help to inform interpretations of ReEDS scenario results in Section 3.4.

## 3.2.1 Defining Resource Potential

The opportunities for developing new hydropower resources are varied and have been studied at multiple levels of detail. To understand how differences in these studies ultimately influence hydropower modeling in ReEDS, it is useful to understand a few basic distinctions between different types of energy potential estimates:

- **Physical Potential** is the amount of power or energy recoverable for a given resource. For solar, this quantity might be regional or global insulation; for hydropower, it consists of the average physical energy moving through a river system (i.e., flow multiplied by elevation change).
- **Technical Potential** is the "achievable energy generation of a particular technology given system performance, topographic limitations, environmental, and land-use constraints" [9]. In practice, this quantity reflects energy generation and power output based on the limits of current commercial technologies.
- **Modeled Potential** in the context of the *Hydropower Vision* analysis is the subset of technical potential made available to the ReEDS model. Practical and economic reasons discussed later in this section motivate removal of some hydropower technical potential for ReEDS modeling to better characterize hydropower deployment opportunities within the modeling framework.
- **Market Potential** is the amount of a technology competitively deployed under specific market conditions. The use of the ReEDS model to simulate deployment outcomes produces a range of estimates for market potential.

Most existing hydropower resource estimates assess technical potential, although variations in the assumptions underlying these estimates can produce large differences in the results.

## 3.2.2 Challenges in Modeling of New Hydropower Resources

Analysis presented in Chapter 3 draws from the best available technical resource potential assessments and assumptions in order to construct a modeled representation of hydropower resources that are useful for exploring market potential in ReEDS. This modeled resource builds upon the methodologies and data from these technical resource estimates with some minor updates and revised assumptions. In its existing construction, the modeled resource is intended to be a conservative interpretation of hydropower's technical potential, meaning that the modeled potential in ReEDS is lower for all hydropower resource categories than the technical potential described subsequently and in Chapter 2 of the *Hydropower Vision*. The differences between technical and modeled potential are described here.

**Increased Modeling Resolution to Identify Economically Competitive Hydropower.** Existing technical potential estimates of NPD and NSD are built from site-specific resource estimates at more than 53,000 existing dams [13] and nearly 230,000 stream-reaches [14], respectively. However, the ReEDS model requires hydropower resources to be aggregated to its 134 BAs. To facilitate this aggregation, the modeled NPD resource only includes projects greater than 500 kilowatts (kW), and the modeled NSD resource only includes projects greater than 1 megawatts (MW). This simplification allows a more accurate identification of economic resources for application within the competitive framework in ReEDS. This is because smaller facilities are by construction the most expensive resources in the hydropower supply curve and, as such, are uneconomical to deploy in the model under most conditions.

These project size thresholds effectively remove 0.5 GW of NPD and many of the 53,000 existing dams, as well as over 20 GW of NSD and approximately 220,000 reaches, from the technical potential estimates to arrive at the modeled resource. The final NPD modeled resource contains 5 GW from 671 dams, while the final modeled NSD resource contains 30.7 GW from nearly 8,000 reaches. So while hundreds of thousands of potential projects have been removed, thousands of the most economic projects remain. The intent is not to dismiss the potential from responsible hydropower projects below these size thresholds, but instead to allow the ReEDS model to more easily identify economically competitive hydropower capacity. While these reductions can be significant, no *Hydropower Vision* modeling scenario deploys 100% of either NPD or NSD resource, so removing this resource improves modeled resolution for lower-cost hydropower without eliminating opportunities that would otherwise deploy in ReEDS.

**Lack of Site-Specific Data.** Estimates of NPD and NSD resource have benefited from rigorous DOE-sponsored resource assessments [13, 14]. Other resources though, including PSH, canals and conduits, and the potential for upgrading and expanding the existing fleet lack similarly comprehensive and site-specific resource estimates that could be used in ReEDS. The *Hydropower Vision* analysis includes approaches for estimating PSH and upgrade potential in order to illustrate the impacts of key levers. More technical potential (than is modeled) may exist in both cases, but any additional potential has not been sufficiently quantified to date. The limited data available on canal and conduit resource potential prohibits an explicit modeling representation. These projects are still considered to be an important component of future growth in the hydropower industry, however, and many of the modeling conclusions drawn from NPD and NSD can be instructive for maximizing the use of the nation's existing water supply infrastructure.

## 3.2.3 Model Representation: Existing Hydropower Fleet

The ReEDS model uses net summer capacity (versus full rated capacity) in order to better characterize electric sector resource adequacy requirements, so the modeled hydropower generation capacity of 76 GW and PSH capacity of 22 GW is slightly lower than referenced in Chapter 2 of the *Hydropower Vision*. Notwithstanding this technicality, the total amount of generation from existing hydropower is consistent with that described in Section 2.1. With the exception of announced upgrades, expansion opportunities, and 200 MW of announced plant retirements (through 2018), there are no changes to the existing fleet represented in ReEDS into the future.

While ReEDS maintains a largely static representation of the existing fleet, in practice many future uncertainties may alter the contributions it makes to nation's power grid. In particular, as projects undergo relicensing, they may be subject to new operating conditions that could affect future generation and capacity levels. In addition, some existing facilities may face conditions including minimum flow requirements and ramp rate restrictions that might further impact the future contributions of the existing hydropower fleet. While these possibilities are not reflected in the model, they are important to the discussion of the *Hydropower Vision* for the existing fleet.

## 3.2.4 Model Resource: Existing Fleet Upgrade Potential

The potential to upgrade or expand the existing hydropower fleet is the most difficult of the hydropower resources to quantify, as there are many different types of opportunities at existing facility sites. Individual units can be upgraded via the refurbishment or replacement of turbines and generators, while modifications to the water conveyance system could increase generation efficiency, and modified impoundment structures could be raised to increase plant hydraulic head. The capacity at existing plants could also be expanded through the addition of new generators in existing or new powerhouses. Optimized dispatch of units at a plant, and the coordination of plants within a system, can also increase

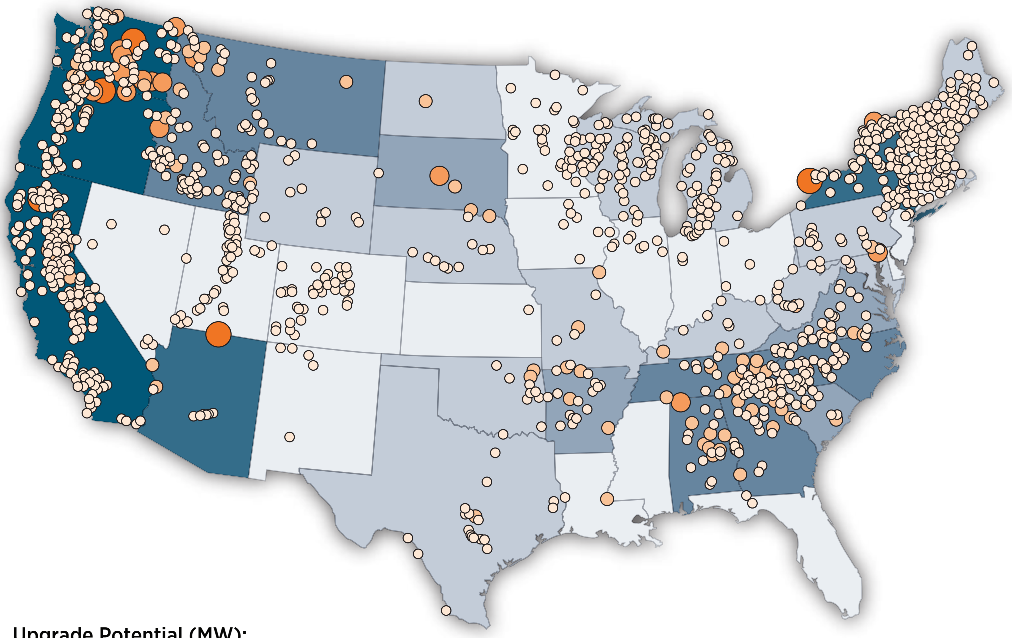



**Figure 3-1.** Modeled upgrade potential at the state- and plant-level

generation from the same amount of water without any physical modification to a plant. No efforts have fully documented the potential to optimize the existing 100 GW of hydropower assets in the United States. Limited case studies have shown that in-plant upgrade opportunities may increase generation on average by 8–10% [10, 11]. The National Academy of Sciences believes that untapped generation increases from upgrades and rehabilitation at U.S. Army Corps of Engineers (Corps) facilities could be at least 20% [12]. This latter estimate suggests that upgrade potential may be much higher than suggested by case studies completed as of 2015.

Given ReEDS model limitations, upgrade and expansion potential is modeled generically as a capacity increase with the equivalent capacity factor of the existing facility. In total, upgrade resource potential at 1,799 plants comprises 6,856 MW of potential (Figure 3-1), resulting in the potential opportunity to grow the existing fleet by about 9%. Additional details about the upgrade resource assessment employed in this analysis can be found in Appendix B.

### 3.2.5 Model Resource: Powering Non-Powered Dams

The powering of existing dams that previously lacked generation capabilities, or NPD, represents another way to expand hydropower production while making use of existing waterway infrastructure. Contemporary high-resolution resource assessments covering the continental United States have found technical potential for 12 GW of new capacity on NPDs [13]). Limited NPD potential exists in Alaska and Hawaii; however, no studies have been done to systematically quantify the opportunity.

The NPD resource included in the ReEDS analysis is a refinement of the 12 GW of technical potential described by Hadjerioua et. al [13]. In addition to minor corrections that were made to adjust resource potential for dams slated for removal or with powerhouses under construction, the modeled resource

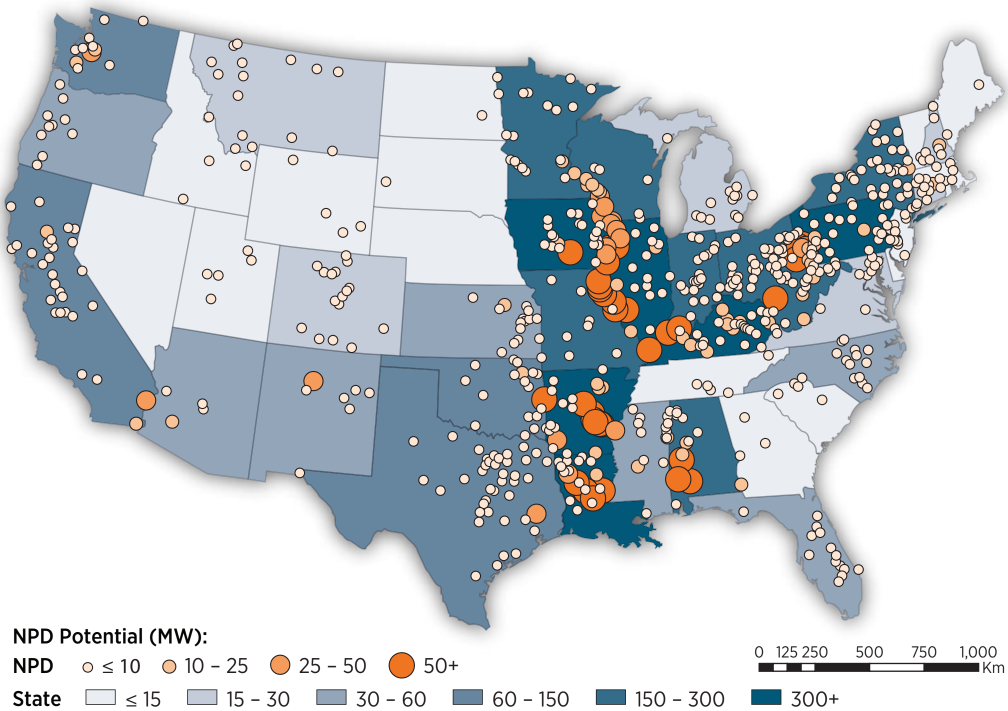



**Figure 3-2.** State- and project-level distribution of modeled non-powered dams potential

entails a significant change in the assumptions used to estimate individual NPD potential. Specifically, the power and generation potential of the NPD resource has been revised to be consistent with the methodological advances made between the publication of the original resource assessment in 2012 [13], and an NSD resource assessment completed in 2014 [14]. Applying the economic sizing methodology developed for NSD by Kao et. al [14] more accurately reflects the size of modern real-world NPD projects, improves the modeled economics[8] of the NPD projects to make them more competitive in ReEDS, and allows for full comparability between the NSD and NPD resource estimates. This change, however, reduces resource potential by more than 50%, down to 5.6 GW.

Additionally, a minimum facility size of 500 kW reduces the total modeled NPD potential to 5 GW at 671 facilities (down from more than 50,000), with an energy potential of 29 terrawatt-hours (TWh) per year. These filters on NPD resource do not reflect a belief in absolute limitations in NPD deployment; rather, they are targeted towards identifying the most economic resources for application within the competitive framework in ReEDS. Even in scenarios with the largest growth in NPDs, dozens of small projects with challenging economics remain unutilized within the modeled 5 GW.

The resulting resource is mapped in Figure 3-2.[9] NPD resource is located primarily along major rivers across the Midwest and South, at sites that are often lock-and-dam infrastructure. Appendix B includes additional discussion of NPD resource estimates.

8. In the revised NPD resource, project capacities decline. These lower capacities, however, improve overall economics through increases in capacity factor that more accurately reflect common run-of-river-style developments.

9. NPD resource includes 393 MW across 20 NPD projects are either already under construction as of 2015, or that have been approved and are in the near-term pipeline for development. These projects are assumed to be deployed in every *Hydropower Vision* scenario. These include: B. Everett Jordan Hydro Project (NC), Bowersock Mills (KS), Cannelton, Dorena Lake (IN), Lower St. Anthony Falls Hydroelectric Project (MN), Meldahl (OH), Red Rock (IA), Robert V Trout Hydropower Plant (CO), Smithland (KY), Turnbull Drop (MT), and Willow Island (WV).

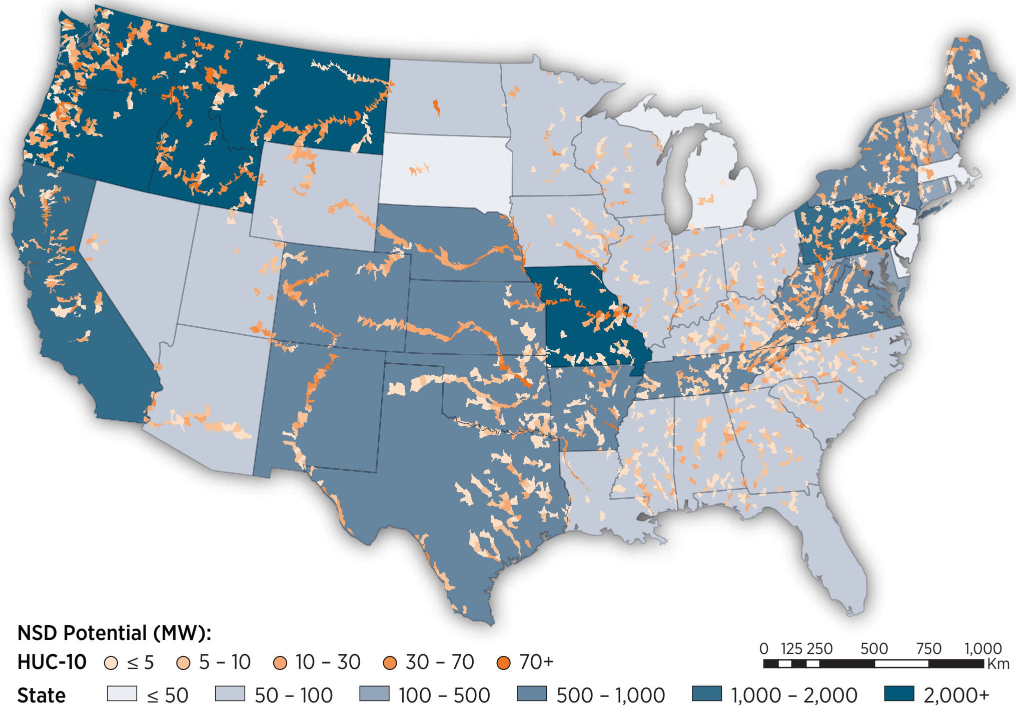


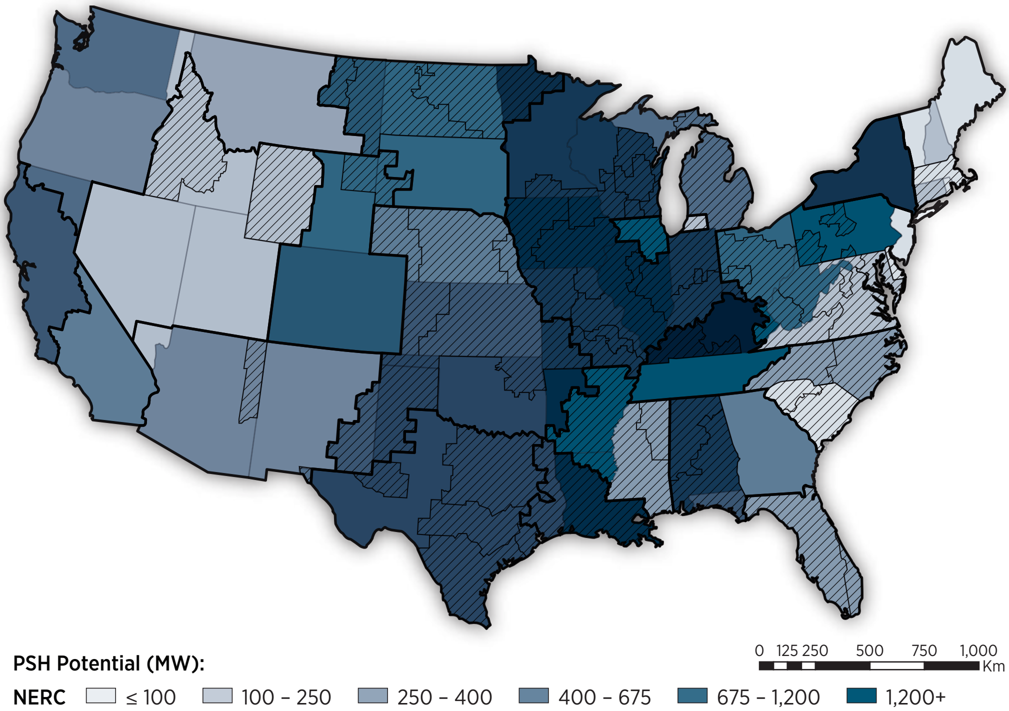

**Figure 3-3.** Distribution of new stream-reach development resource potential at the state and watershed level

## 3.2.6 Model Resource: New Stream-Reach Development

The largest source of potential new hydropower capacity comes from the development of new projects on undeveloped stream-reaches; however, NSD is also the most costly and potentially environmentally challenging class of hydropower potential due to the need for new impoundment structure construction. A 2014 DOE resource assessment [13] identified 66 GW of NSD potential and forms the basis of the resource estimates used in the modeling work detailed here. NSD resource estimates are framed by the need to minimize disruption to ecosystems. As such, the assumption is that impoundment area is minimized and NSD would generally operate as "run-of-river" with limited water storage capacity so they do not disrupt natural flows. As a result, NSD is presumed less flexible than much of the existing hydropower fleet. Data limitations prevented the extension of these systematic assessment efforts beyond the continental United States to Alaska and Hawaii. However, Kao et al. [14] consolidated existing NSD project inventories to generate a lower bound technical potential estimate of 4.7 GW in Alaska and 145 MW in Hawaii.

For modeling in ReEDS, base resource estimates are adjusted to reflect corrections to the original resource assessment (noted previously) and to limit the modeling of NSD to those projects with a power potential of 1 MW or more. The latter helps the ReEDS model more accurately identify economically competitive NSD potential by reducing the number of reaches under model consideration to those with the lowest development costs and representing high resolution for those resources. The resulting modeled NSD resource has 30.7 GW capacity and 176 TWh of energy production potential at less than 8,000 sites. While this number is lower than the original estimate of 66 GW at more than 200,000 reaches, it is important to note that there are no *Hydropower Vision* scenarios that approach the full deployment of all 30.7 GW of modeled NSD resource. Many of the projects that are not deployed—and those that are not modeled—are small projects with high costs that are not competitive under the scenarios explored in this analysis.

The NSD potential is mapped in Figure 3-3 at the watershed level, due to the uncertainties inherent in estimating NSD resource. See Appendix B for more detail on NSD resource assumptions.




Note: ReEDS balancing areas shaded with slashes indicate no publicly available permits.

**Figure 3-4.** North American Electric Reliability Corporation regional-level pumped storage hydropower resource potential

## 3.2.7 Model Resource: Pumped Storage Hydropower

No national resource assessment exists for PSH, and the variety of possible plant configurations and designs makes it difficult to characterize PSH resources. "Open-loop" systems can be installed at existing dams or new reservoirs along existing waterways, while "closed-loop" configurations disconnect both reservoirs from natural waterbodies. Closed-loop configurations are possible in any location with sufficient elevation change, making PSH construction theoretically possible in most geographic regions. In this context, historical studies of PSH have found potential in excess of 1,000 GW based on physical geography [15]. The potential for new closed-loop concepts using existing "brownfield" sites, such as abandoned mines, has not been quantified.

This modeling analysis uses historical proposed development as a lower bound for resource availability by examining all PSH projects proposed to the Federal Energy Regulatory Commission (FERC) since 1980.

This exercise produces 108.7 GW of PSH potential across 166 sites. This approach reflects only a subset of potential PSH projects, however, as some hydropower owners and developers either do not need FERC authorization to pursue projects (Corps, Reclamation, Tennessee Valley Authority), or have potential PSH projects defined but have not yet sought to secure development rights via the regulatory process.

To avoid overly constraining PSH potential in regions without previously proposed projects, every ReEDS balancing area is also allowed to deploy one "artificial" 750 MW closed-loop PSH project, adding another 100 GW to the total resource base. This example size was selected because 750 MW is an approximate average of the capacity of PSH projects proposed in the decade leading up to the *Hydropower Vision*. Figure 3-4 illustrates the distribution of the resource derived from FERC permit applications. Given the uncertainty in the PSH resource, the available supply and deployment results are shown in aggregate, based on

**Table 3-1.** Hydropower Resource Potential Capacity and Energy Statistics

| | Upgrade | NPD | NSD | PSH[a] |
|---|---|---|---|---|
| Total Capacity (MW) | 6,856 | 5,047 | 30,669 | 108,742 |
| Potential Project Sites | 1,799 | 671 | 7,977 | 166 |
| Average Capacity (MW) | 3.9 | 7.6 | 3.8 | 655 |
| Median Capacity (MW) | 0.4 | 1.6 | 1.9 | 600 |
| Minimum Capacity (MW) | 0.00006 | 0.5 | 1.0 | 5.0 |
| Maximum Capacity (MW) | 394 | 192 | 357 | 2,000 |
| Energy Production Potential (TWh) | 27 | 28 | 176 | n/a |

Note: Announced projects scheduled to come online by 2018 are not included in these statistics.
a. PSH data detailed here are derived from resource potential reflected in FERC preliminary permit applications.

sub-regions defined by the North American Electric Reliability Corporation. Balancing areas with only artificial resource available are shaded with diagonal lines. Appendix B contains additional information on PSH resources.

### 3.2.8 Model Resource Potential Summary

Table 3-1 summarizes key characteristics of hydropower resources modeled in ReEDS.

## 3.3 Hydropower Modeling Economics and Scenarios

The hydropower resource data described in the previous section are crucial to quantifying the range of hydropower market potential in the *Hydropower Vision* analysis. In addition to the resource data, however, market potential analysis requires characterization of existing and future hydropower costs. Potential climate change impacts on water availability and environmental siting considerations must also be considered. The subsequent sections describe how each of these facets is addressed in this modeling analysis.

### 3.3.1 Hydropower Costs and Cost Projections

Each of the hydropower resources identified in the *Hydropower Vision* has individualized cost dynamics that influence economic competitiveness. In general, the cost of developing and operating a hydropower project is highly site-specific, but the *Hydropower Vision* analysis uses a generalized cost estimation methodology for greater consistency and clarity. Appendix B includes a full accounting of the methods used to derive and assign cost to hydropower resource potential, and Table 3-2 summarizes the results of current cost estimates. All costs are reported in 2015 currency (2015$).

Upgrades are often the lowest-cost hydropower resource, but some small projects such as those with installed capacities of only a few hundred kilowatts are estimated to be costly. NPD typically has intermediate costs, while NSD is the most expensive hydropower generation resource on average. PSH capacity costs span a narrower range due to strong economies of scale with capacity. Artificial PSH resource is

**Table 3-2.** Summary of Modeled Hydropower Initial Capital Cost

| Resource | Minimum Cost ($/kW) | Average Cost ($/kW) | Maximum Cost ($/kW) |
|---|---|---|---|
| **Upgrades** | 800 | 1,500 | 20,000 |
| **Non-Powered Dams** | 2,750 | 5,800 (low head)<br>4,200 (high head) | 9,000 |
| **New Stream-reach Development** | 5,200 | 7,000 (low head)<br>6,000 (high head) | 15,600 |
| **Pumped Storage Hydropower** | 1,750 | 2,700 | 4,500 |

Note: the threshold for low- vs. high-head NPD and NSD is 30 feet.

costed conservatively at $3,500/kW. Figure 3-5 illustrates the full range of existing capital costs across hydropower resources modeled in Chapter 3. Fixed operations and maintenance (O&M) costs also exhibit economies of scale. The smallest NPD resource costs $180/kW per year, while larger plants, including the nation's largest hydropower plant, Grand Coulee, costs $4.2/kW per year.

The *Hydropower Vision* employed literature review and expert stakeholder input to develop three potential future cost trajectories to understand how these initial cost assumptions might evolve across the study period for NSD, high- and low-head NPD, and PSH. The costs of operating, maintaining, and upgrading the existing fleet are constant in all three scenarios. Table 3-3 summarizes the characteristics of each cost trajectory.

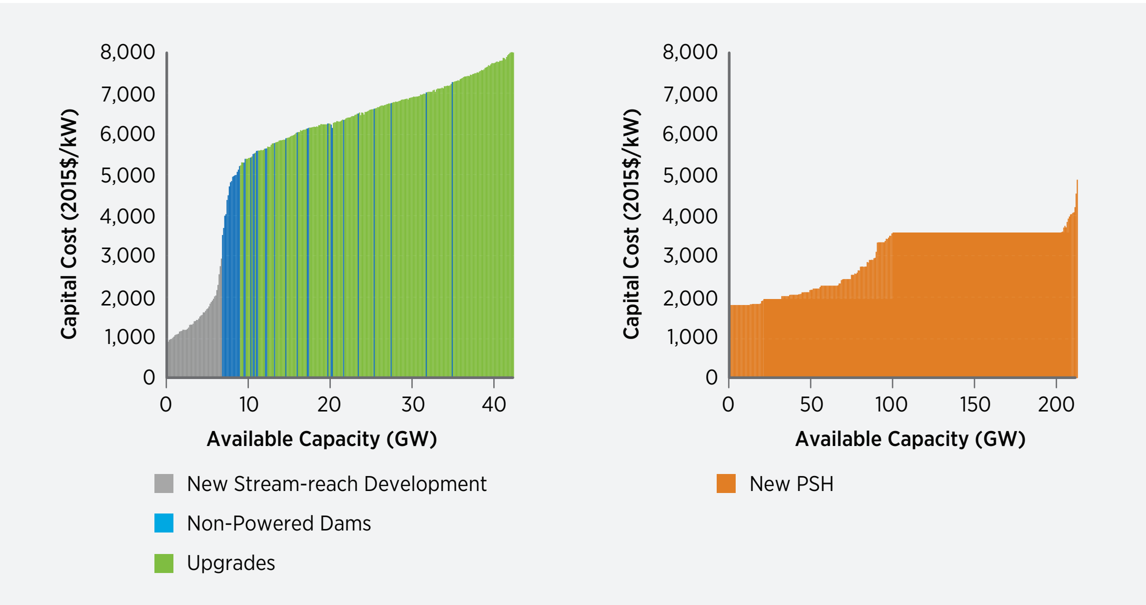



**Figure 3-5.** Capital cost of hydropower resources (y-axis truncated above $8,000/kW)

**Table 3-3.** *Hydropower Vision* Analysis Cost Reduction Scenarios (Change From Initial Costs)

| Capital Cost | *Business-as-Usual* (relative to 2015) | | *Evolutionary Technology* (relative to 2015) | | *Advanced Technology* (relative to 2015) | |
|---|---|---|---|---|---|---|
| | 2035 | 2050 | 2035 | 2050 | 2035 | 2050 |
| NSD | 5% | 9% | 15% | 18% | 30% | 35% |
| Low-Head NPD | | | 15% | 18% | 30% | 35% |
| High-Head NPD | | | 10% | 13% | 25% | 33% |
| PSH | | | 7% | 11% | 12% | 15% |
| Upgrades | None | | None | | None | |
| **Fixed O&M Cost** | | | | | | |
| NPD and NSD | None | | 25% | 28% | 50% | 54% |
| Other Types | | | None | | None | |

- The *Business-as-Usual* cost conditions assume a low, learning-based capital cost reduction consistent with the EIA Annual Energy Outlook for NPD, NSD, and PSH. All O&M costs and capital costs for all other hydropower types remain constant under central assumptions.
- The *Evolutionary Technology* assumptions envision a world in which NSD and NPD development is increasingly standardized, while automation and dissemination of best practices reduce the O&M costs for these new projects. PSH capital costs also experience modest cost reductions based on continued process, contracting, design, and technological improvements within the conventional hydropower and dam construction industries.
- The *Advanced Technology* assumptions are based on major technology advances in NPD and NSD from modularity and advanced manufacturing. These advances further drive down capital costs for these hydropower resources. NPD and NSD O&M costs are significantly reduced through modularity and design for reduced O&M, in conjunction with smart, data-driven monitoring and maintenance planning. PSH achieves slightly greater cost reductions with *Advanced Technology* assumptions than under *Evolutionary Technology* by using new technologies (e.g., penstock materials) and leveraging advancements in other, non-hydropower construction industries including oil and gas.

### 3.3.2 Financing Treatment

ReEDS standard financing assumptions include an 8% nominal discount rate and 20-year valuation, implying a 20-year economic life. Typically, these assumptions are applied to all technologies. It is common for hydropower projects, however, to have a feasible lifetime of 30, 50, or even 100 years. To accommodate the difference in hydropower asset life relative to wind, solar, or natural gas plants, an alternative asset valuation treatment is defined for hydropower and denoted as *Low Cost Finance*.

*Low Cost Finance* represents an investment environment where the long physical life and stable revenue stream of hydropower is more highly valued during project financing and decision making than is historically typical in the industry. Thorough examination of alternative financing conditions resulted in these input conditions being defined as an effective 40% reduction in the cost of capital. This reduction reflects real-world financing conditions seen when developers and investors, both in the private and public sectors (e.g., municipal or utility districts), value the long life of hydropower assets. Whereas alternate cost trajectories phase in through time and vary across hydropower types, the *Low Cost Finance* assumption is applied immediately to all ReEDS solve years and hydropower technologies. Appendix B details the conditions surrounding the improved asset valuation assumptions.

### 3.3.3 Scenarios of Water Availability in a Changing Climate

Future water availability trends driven by climate change have the potential to alter the economic attractiveness of hydropower projects by changing the nature of the "fuel" needed by hydropower plants. Total annual water availability could change due to overall changes to hydro-meteorological variables, and the temporal distribution of water availability within a year could change. A prime example of this is earlier snowmelt from higher temperatures leading to earlier reservoir filling [16, 17].

The *Hydropower Vision* analysis examines two alternative water availability futures—one in which the United States on average becomes dryer (that is, less runoff) through 2050, and one in which it becomes wetter. Figure 3-6 illustrates, in terms of runoff, the magnitude and regional nature of changes in annual and summer water availability under *Wet* and *Dry* conditions scenarios. Other seasonal changes are detailed in Appendix B along with further description of scenario development. At a national scale, *Wet* conditions exhibit an 11% increase in runoff in 2030 and a 22% increase in 2050. The *Dry* conditions scenario envisions an average reduction in water availability of 4% in 2030 and 8% in 2050. However, regional and seasonal variations are apparent and can influence the characteristics of hydropower deployment examined within the *Hydropower Vision* analysis.

These scenarios do not resolve the complex relationship within the existing storage fleet between water storage capabilities, competing uses, and generation capability. Addressing these important interdependencies to model the seasonal and annual impacts of climate change on the existing fleet would require additional research.

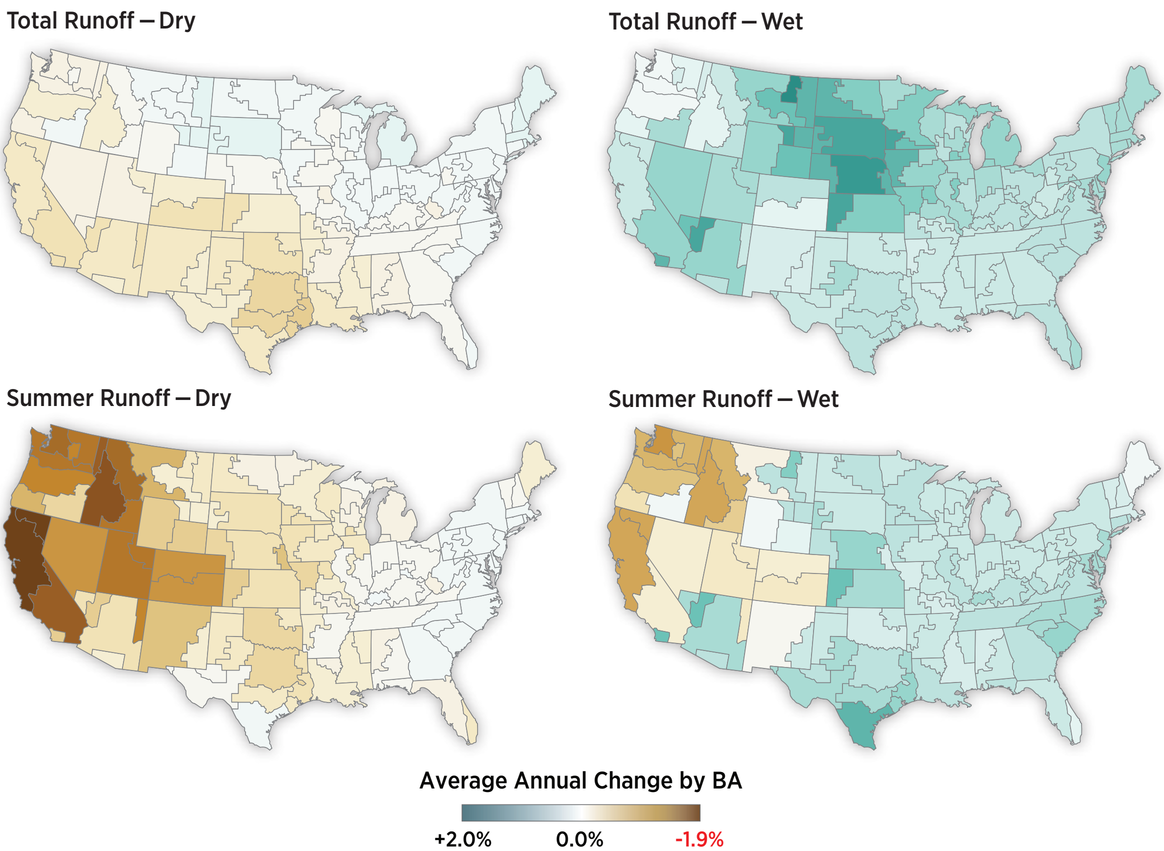



**Figure 3-6.** Average annual and summer seasonal change in total runoff

## 3.3.4 Hydropower Environmental Considerations

The ReEDS model identifies economically favorable hydropower development under multiple constraints and assumptions; however, the framework does not directly include hydropower environmental considerations, which can be particularly influential for NSD resources. To examine the influence of environmental attributes on NSD development and provide better context for the future of the hydropower industry, the modeling analysis in the *Hydropower Vision* employs a series of sensitivity scenarios. These scenarios explore how NSD deployment intersects with other existing priority uses of the nation's water resources, such as providing habitat for valued species.

In these scenarios, hydropower technologies must compete against all other electric sector technologies but deployment of NSD that overlaps a specific consideration or combination of considerations is avoided. The intent of these scenarios is not to assert that hydropower development in these areas is not possible. Instead, these scenarios help illustrate that achieving NSD growth must include accommodating and complementing the many other values of rivers. They also demonstrate the opportunity for addressing environmental considerations through innovation, when deployment results are compared to scenarios that do not explicitly avoid regions overlapping environmental considerations.

The following environmental considerations are implemented as sensitivity scenarios in the *Hydropower Vision* analysis. Datasets used in the environmental considerations analysis and the details of their geospatial implementation are described more thoroughly in Appendix B. Two example maps of environmental attributes are shown in Figure 3-7.

1. **Critical Habitat**: NSD is avoided in ecologically sensitive areas, as defined by their designation as critical habitat. The data for this consideration were provided by the U.S. Fish and Wildlife Service and are also inclusive of species managed by other U.S. agencies.
2. **Ocean Connectivity**: NSD is avoided at locations that would disturb existing river connectivity to the ocean. Connectivity in this context is extended to reaches on which data for artificial downstream passage exist, either through explicit passage technology or implicitly through navigation locks. This layer was developed uniquely for the *Hydropower Vision* analysis.
3. **Migratory Fish Habitat**: NSD is avoided on reaches in which potamodromous and diadromous fish species are likely to be present, based on ocean connectivity and/or reach characteristics such as length and average annual flow rates. This layer was developed uniquely for the Hydropower Vision analysis.
4. **Species of Concern**: NSD is avoided on reaches where aquatic species (fish, mussels, and crayfish) of concern are known to exist. This includes those listed under the Endangered Species Act (endangered, threatened, a candidate for listing, proposed for listing, or of concern), or as "near threatened," "vulnerable," "endangered," or "critically endangered" according to the International Union for Conservation of Nature. This layer was developed uniquely for the *Hydropower Vision* analysis.
5. **Protected Lands**: Areas with formal protections designated as Status 1 or 2 under the U.S. Geological Survey's Gap Analysis Program[10] are avoided for development. Gap Analysis Program 1 and 2 designations cover a variety of areas, ranging from state or local parks to formal conservation areas managed explicitly for species preservation.
6. **National Rivers Inventory**: Development is avoided on potentially high-value river systems, as approximated by placement on the National Rivers Inventory. Note that hydropower potential located along designated Wild and Scenic Rivers is already excluded in the base *Hydropower Vision* supply curves because of statutory limitations.

10. The Gap Analysis Program is an effort to catalogue and spatially document lands afforded formal protection designations by federal, state, local, and private owners.

7. **Low Disturbance Rivers**: NSD is avoided on stream-reaches that are minimally altered from their natural state as approximated by categorization of low or very low levels of disturbance, as measured by the National Fish Habitat Action Plan.
8. **Combined Considerations**: Three scenarios explore the combined influence of multiple environmental considerations (as detailed in 1–7). *Combined Species Concerns* includes items 1–4, *Combined Sensitive Lands* includes items 5–7, and *Combined Environmental Considerations* includes all seven considerations. *Combined Environmental Considerations* particularly illustrates that accommodating the wide variety of use values of reaches with NSD potential is essential for realizing growth.

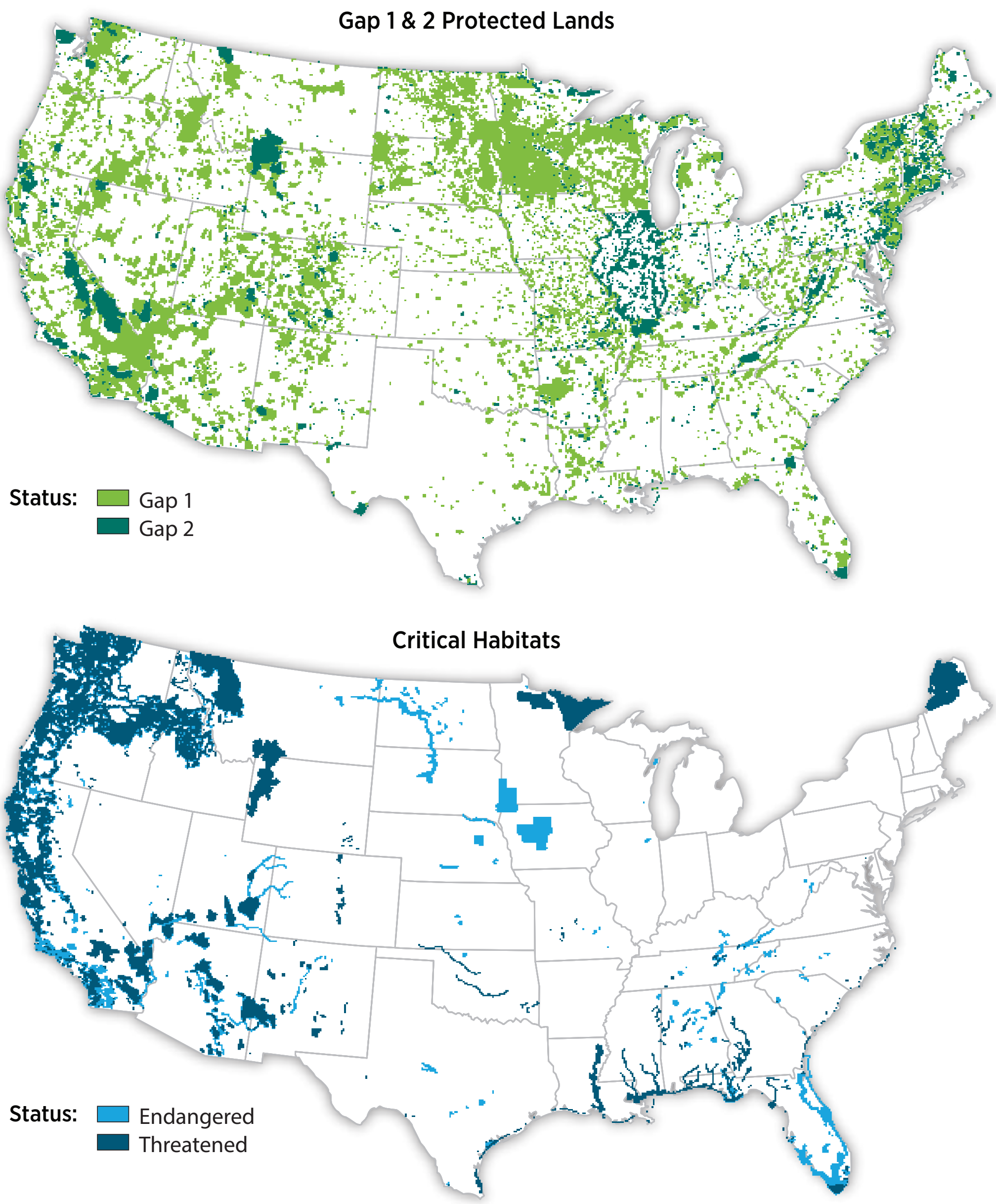



**Figure 3-7.** Spatial distribution of two selected environmental considerations

### 3.3.5 *Hydropower Vision* Analysis Scenario Framework

The assumptions described previously and in Appendix D are used in varying combinations within the *Hydropower Vision* analysis to develop a suite of modeling scenarios that documents the range of market opportunities for hydropower deployment and the resulting impacts. As a reference for subsequent sections, Tables 3-4 and 3-5 summarize assumptions that are constant across all scenarios and those that are varied across scenarios. The *Hydropower Vision* analysis is intended to demonstrate a wide range of hydropower futures and how these futures could be affected by key factors of relevance to the hydropower industry. Alternative policy options for hydropower or other technologies are not included in the scenario analysis. While energy policy is important to the future of hydropower and the electric sector as a whole, policy analysis is outside the scope of the *Hydropower Vision*.

**Table 3-4.** Constants across Modeled Scenarios

| Input Type | Input Description |
|---|---|
| Electricity demand | AEO 2015 Reference Case (average annual electricity demand growth rate of 0.7%) |
| Fossil technology and nuclear power | AEO 2015 Reference Case |
| Non-hydro/wind/solar photovoltaics renewable power costs | NREL Annual Technology Baseline 2015 Mid-Case Projections |
| Policy | As legislated and effective on December 31, 2015.[a] |
| Transmission expansion | Pre-2020 expansion limited to planned lines; post-2020, economic expansion, based on transmission line costs from Eastern Interconnection Planning Collaborative |

Note: Appendix D describes the non-hydropower technology and other assumptions noted here in additional detail. “AEO” refers to the U.S. Energy Information Administration’s Annual Energy Outlook (i.e., EIA [18])

a. Despite the Supreme Court stay of the Clean Power Plan (CPP), the CPP is treated as law in all scenarios and is thus assumed active. The CPP is modeled using mass-based goals for all states with national trading of allowances available. Though states can ultimately choose rate- or mass-based compliance and will not necessarily trade with all other states, a nationally traded mass-based compliance mechanism is viewed as a reasonable reference case for the purpose of exploring hydropower deployment under a range of electricity system scenarios. Scenarios and implications resulting from excluding the CPP are discussed in Appendix F.

**Table 3-5.** Summary of Sensitivity Scenario Data Variations

| Sensitivity Scenario Variation | Description | Input Data Changes |
|---|---|---|
| **High and Low Fossil Fuel Cost** | These scenarios examine the sensitivity of results to changes in fossil fuel costs. | Fossil fuel costs: High Cost uses AEO 2015 High Coal Cost Case and AEO 2014 Low Oil and Gas Resource Case; Low Cost uses AEO 2015 Low Coal Cost Case and AEO 2015 High Oil and Gas Resource Case (see Appendix D, for further detail) |
| **High and Low Variable Generator Cost** | These scenarios examine the sensitivity of results to changes in variable generator (wind and solar photovoltaics (PV)) costs. | Wind/Solar costs: NREL ATB[a] High/Low-Case Projections for wind. Utility PV reaching the DOE 62.5% reduction scenario in 2020 and remaining constant thereafter (high cost) or reaching the DOE 75% reduction scenario by 2020 and remaining constant thereafter (low cost). Distributed rooftop PV following the DOE 50% reduction scenario (high cost) or following the 62.5% reduction scenario to 2020 then the 75% reduction scenario by 2030 (see Appendix D, for further detail) |
| **Evolutionary and Advanced Technology** | These scenarios examine the sensitivity of results to changes in hydropower costs. | Hydropower costs/financing: Reference financing, with AEO Mid/Low Cost Reduction Pathways |
| **Low Cost Finance** | These scenarios examine the sensitivity of results to changes in hydropower asset valuation. | Hydropower costs/financing: Reference costs, with long-term asset valuation providing an approximate 40% reduction in the cost of capital |
| **Dry and Wet scenarios of Water Availability** | These scenarios examine the sensitivity of results to changes in water availability for hydropower.[b] | Hydropower resource: Hydropower water availability adjusted over time, based on prevailing wet/dry conditions |
| **Environmental Attribute Scenarios:**<br>1. Critical Habitat<br>2. Ocean Connectivity<br>3. Migratory Fish Habitat<br>4. Species of Concern<br>5. Protected Lands<br>6. National Rivers Inventory<br>7. Low Disturbance Rivers<br>8. Combined Sensitive Lands (5–7)<br>9. Combined Species Concerns (1–4)<br>10. Combined Environmental Consideration (all) (1-7) | These scenarios examine the sensitivity of results to hydropower NSD resource avoidance in areas with certain environmental attributes. Resource avoidance highlights opportunities for environmental mitigation activities. | Hydropower resource: Portions of resource excluded based on the indicated environmental attributes |

Note: For the purposes of electric sector modeling described in this chapter, variable generators are defined as wind and solar photovoltaic generators, based on their variable resource characteristics. While solar thermal technology without thermal storage is also included in the ReEDS model as variable generation, economically built CSP in ReEDS uses thermal storage that allows dispatchability. The primary purpose of the High and Low Variable Generator Cost scenarios is examining the relationship between hydropower and variable generation, so costs of CSP systems with storage are not varied in these scenarios.

a. National Renewable Energy Laboratory's Annual Technology Baseline

b. Water quality is another possible concern. The ReEDS model is not designed to incorporate water quality metrics, which are better analyzed using tools with more spatial and temporal resolution and the ability to model individual power plants and waterways. Though water quality is not explicitly included in the ReEDS model analysis, the range of deployment scenarios is expected to encompass most of the influence water quality concerns might have on long-term hydropower deployment.

# 3.4 Hydropower Market Potential

More than 50 scenarios were simulated for the *Hydropower Vision* by varying the parameters in Table 3-5 (see Appendix F for results from all scenarios). A full list of those parameters is available in Appendix E. This large suite of scenarios is used to identify the key drivers of future hydropower market potential that are the focus of this chapter. Examining this broad suite of scenarios revealed the following themes.

- Maintaining the existing fleet allows it to provide continued electricity system benefits under a wide range of electric sector futures. All scenarios reflect the optimization pillar of the *Hydropower Vision* with continued operation of all hydropower facilities that are not scheduled to retire, allowing the existing fleet to continue providing energy and maintaining system reliability under a range of fossil fuel or variable generation (VG) cost assumptions.
- Improving hydropower economics is central to the growth pillar of the *Hydropower Vision*. A set of scenarios examines the deployment response to changes in hydropower costs and value. The *Advanced Technology* and *Low Cost Finance* settings are applied individually and in combination to demonstrate the effect of improved economics on the potential for hydropower growth.
- An important factor in the future of the U.S. hydropower industry is environmental sustainability, and any future with hydropower growth must consider the environmental impacts of that growth. Twelve scenarios embed an avoidance of NSD resource potential that overlaps with certain environmental considerations, while incentivizing hydropower deployment with *Advanced Technology* and *Low Cost Finance* assumptions to demonstrate the opportunities from mitigating environmental impacts of new hydropower (environmental attributes are described in Section 3.3 and Table 3-5). Any difference in hydropower deployment between these environmental considerations scenarios and the *Advanced Technology, Low Cost Finance* scenario represents an opportunity to address the relevant environmental considerations through investment in innovation. Upgrades to the existing hydropower generation fleet and new NPD growth are negligibly affected by these scenarios, but PSH deployment can be indirectly affected by reduced NSD growth that corresponds to additional fossil or renewable technology deployment.
- Non-hydropower technology costs are important to the *Hydropower Vision* because they influence the relative competitiveness between hydropower and other technologies in the electricity market. To better understand the relationship between hydropower, fossil fuel, and renewable generation technologies, the *High* and *Low* variants on *Fossil Fuel* and *VG Cost* are applied to several hydropower cost and value combinations. This set of scenarios allows a thorough discussion of potential impacts under a wide range of deployment and electricity market scenarios. Collectively, these scenarios demonstrate a more comprehensive range of hydropower market opportunities than can be described with hydropower-only scenario parameters.

Climate uncertainty and the inter-annual variability of hydropower generation create the need to include sensitivity analysis on hydropower water availability. Defining and studying a comprehensive climate scenario is outside the scope of the *Hydropower Vision*, and ReEDS is unable to provide a stochastic treatment of inter-annual variability. As such, these sensitivity scenarios are limited to representing an average increase or decrease in regional and seasonal hydropower water availability over time. Climate-influenced water availability is examined by combining the *Wet* and *Dry* water availability scenarios with several other combinations of scenario parameters. These scenarios demonstrate the importance of long-term water availability on hydropower industry growth and operation.

From the full suite of scenarios, nine are chosen that collectively support the *Hydropower Vision* pillars of optimization, growth, and sustainability. These nine selected scenarios, listed below, demonstrate the importance to the U.S. hydropower industry of maintaining the existing fleet, reducing technology cost, valuing the long asset life of hydropower facilities, and considering local environmental attributes. Scenarios that avoid NSD resource with certain environmental attributes reveal the opportunities provided by investment in environmental impact mitigation. Scenarios incorporating high fossil fuel costs or low VG costs show the effect of non-hydropower technology costs on hydropower competitiveness in the U.S. electric sector. *Wet* and *Dry* water availability scenario variants are modeled for all nine selected scenarios to show how expected future water availability can influence hydropower deployment. While not inclusive of all possible hydropower industry outcomes, these scenarios provide a wide range of possible pathways for the hydropower industry across many alternative notions of the future U.S. hydropower industry and the electricity market as a whole.

1. **Business-as-Usual:** This scenario uses all reference input parameters to the ReEDS model.
2. **Advanced Technology:** This scenario shows the effect of technology cost reduction on hydropower deployment.
3. **Low Cost Finance:** This scenario shows the effect of long-term asset valuation on hydropower deployment.
4. **Advanced Technology, Low Cost Finance:** This scenario explores the combined impact of technology cost reduction and long-term valuation on hydropower deployment when environmental impacts are assumed to be fully mitigated throughout the NSD resource base and thus are not avoided.
5. **Advanced Technology, Low Cost Finance, Combined Environmental Considerations:** This scenario explores a future with improved hydropower economics where difficulty mitigating environmental impacts leads to avoiding NSD resource overlapping with any of the environmental attributes discussed in Section 3.4.[11]
6. **Advanced Technology, Low Cost Finance, Critical Habitat:** This scenario represents a future with improved hydropower economics and intermediate avoidance of NSD resource with environmental considerations. The *Critical Habitat* attribute is part of this and other scenarios because when combined with *Advanced Technology* and *Low Cost Finance* assumptions, it achieves intermediate NSD deployment levels across the full range of scenarios examined, not because of a perceived importance of critical habitats over other environmental attributes.
7. **Advanced Technology, Low Cost Finance, Critical Habitat, Low VG Cost:** This scenario explores the influence of a power system that has access to low cost variable renewable power with improved hydropower economics and intermediate avoidance of NSD with environmental considerations. Low-cost VG can compete with hydropower generation (upgrades, NPD, and NSD) while complementing PSH growth.
8. **Advanced Technology, Low Cost Finance, Critical Habitat, High Fossil Fuel Cost:** This scenario explores the influence of high fossil fuel costs with improved hydropower economics and intermediate avoidance of NSD with environmental considerations. High fossil fuel costs improve competitiveness of hydropower generation (upgrades, NPD, and NSD) and VG, the latter of which can promote PSH growth.
9. **Advanced Technology, Low Cost Finance, High Fossil Fuel Cost:** This scenario explores an upper bound of hydropower deployment with improved hydropower economics while not avoiding NSD with environmental attributes when high future fossil fuel costs make fossil energy increasingly uncompetitive relative to hydropower and other non-fossil resources.

For some result metrics, four scenarios are chosen from the set of nine as representative low, intermediate, and high hydropower deployment scenarios. This selection primarily serves to improve the conciseness of results presentation while preserving the range of deployment outcomes. *Business-as-Usual* is used as the **low deployment scenario**, *Advanced Technology, Low Cost Finance, High Fossil Fuel Cost* is the **high deployment scenario**, and the **two intermediate scenarios** are *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* and *Advanced Technology, Low Cost Finance, Critical Habitat*.

11. As a reminder, the *Combined Environmental Considerations* scenarios avoids NSD resource overlapping with the following: *Critical Habitat, Ocean Connectivity, Migratory Fish Habitat, Species of Concern, Protected Lands, National Rivers Inventory*, and *Low Disturbance Rivers*.

Ultimately, the opportunity for new hydropower as embodied in this suite of scenarios depends on the characteristics of both the hydropower industry and the electricity sector as a whole, at the time of this report and into the future. The remainder of Section 3.4 details the nine selected pathways for hydropower deployment and the national-scale implications of hydropower's role in the U.S. electric sector, before exploring these scenarios more deeply for each hydropower market segment and investigating climate uncertainty. Section 3.5 describes the implications of these scenarios on the rest of the electric sector and examines a subset of the costs and benefits associated with selected scenarios, including electricity system costs, greenhouse gas emissions reductions, air pollution and human health benefits, thermal cooling water usage reduction, and impacts on workforce and economic development.

## 3.4.1 Potential for Growth: National Capacity and Energy in Selected Analysis Scenarios

This section explores the range of national hydropower capacity and energy deployment over the study period[12] for the nine selected scenarios. Across these scenarios, combined new post-2016 deployment[13] of upgrades, NPD, and NSD falls within ranges of 5–15 GW in 2030 and 5–31 GW in 2050, while new PSH ranges from 0–16 GW in 2030 and 0–55 GW in 2050. Hydropower generation energy production from this new post-2016 capacity (excluding net energy use by PSH) ranges from 17–76 TWh in 2030 and 21–170 TWh in 2050; when added to existing hydropower generation, total generation is 290–350 TWh in 2030 and 290–440 TWh in 2050. The rest of this section describes where each of the nine scenarios fits within those ranges and explores national expansion trends for each hydropower category.

### *National Capacity Additions*

As mentioned in the introduction to this section, capacity growth by 2050 across the nine selected scenarios ranges from 5–31 GW in total for upgrades, NPD, and NSD and from 0–55 GW for PSH. This spectrum of future growth is illustrated in two figures:

- Figure 3-8 plots the cumulative new deployment of hydropower capacity from the combined deployment of upgrades, NPD, and NSD, and that from PSH.
- Figure 3-9 plots the cumulative new deployment of hydropower capacity from upgrades, NPD, and NSD individually.

Many *Hydropower Vision* analysis scenario results are illustrated in this section for the full modeled period of 2017–2050; however, discussion is often focused on the magnitude of hydropower deployment in 2030 and 2050 as representative mid- and long-term milestone years.

***Business-as-Usual* Scenario:** The *Business-as-Usual* scenario provides a valuable reference point for discussing the nine selected scenarios. The *Business-as-Usual* scenario reflects conditions representative of the existing electricity market (e.g. future electricity demand and fossil fuel cost), along with reference or central cost and performance projections for all electricity technologies as modeled in ReEDS. *Business-as-Usual* assumptions motivate the deployment of 5.3 GW new hydropower generation; however, all economically deployed hydropower generation comes from using 76% of modeled upgrade resource potential. Just 500 MW PSH is built in this scenario. Throughout this section and the remainder of Chapter 3, the *Business-As-Usual* scenario is contrasted with numerous scenarios where the *Business-as-Usual* conditions are altered individually or in combination, and their implications for growth in the hydropower industry and the broader evolution of the electric power sector are explored.

12. While the *Hydropower Vision* study period is 2017–2050, the ReEDS model solves from 2010–2050, so many results are presented that include the historical years 2010–2017. Scenario variables only influence the solution in the 2017–2050 time period.

13. Unless otherwise stated, all cumulative quantities are reported in text as post-2016 numbers, though figures might show deployment beginning in 2010. Deployment from 2010–2016 consists of known projects rather than modeled economic growth.

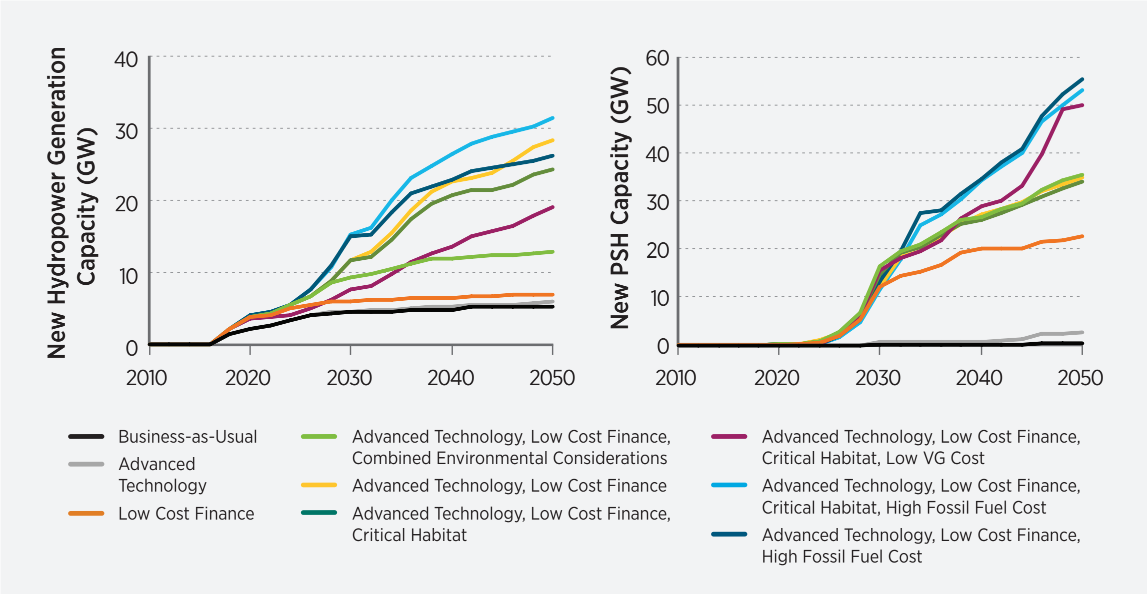



**Figure 3-8.** Capacity growth of hydropower generation and pumped storage hydropower in select deployment scenarios (each panel uses a unique y-axis)

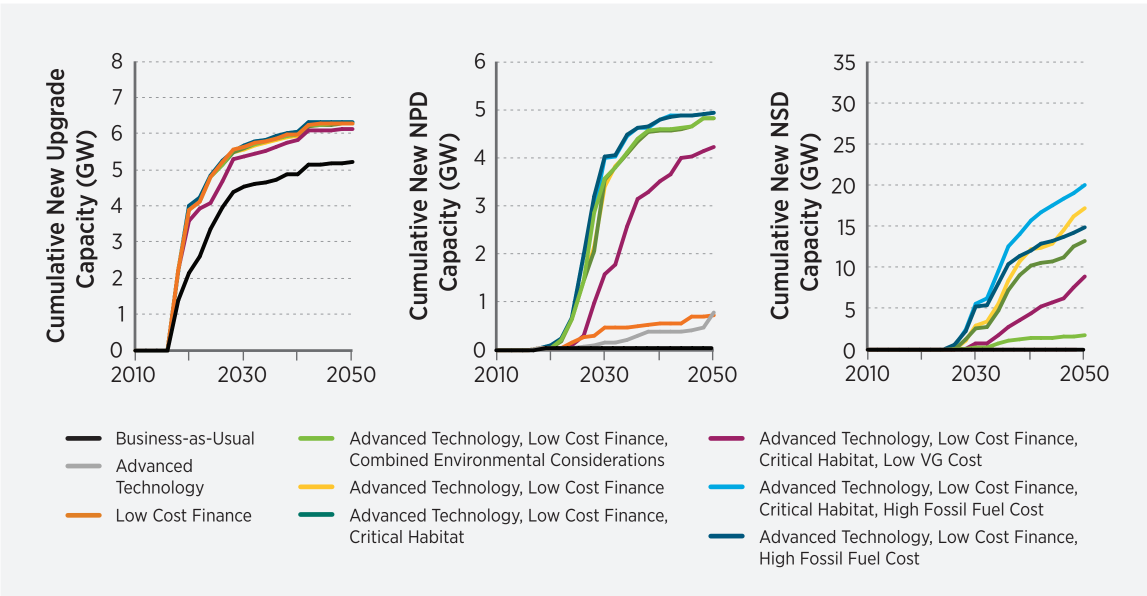



**Figure 3-9.** Capacity growth of upgrades, NPD, and NSD in select deployment scenarios (each panel uses a unique y-axis)

**Hydropower Cost and Financing**: Limited growth in the *Business-as-Usual* scenario suggests that existing economic conditions result in relatively little hydropower growth outside of upgrades to the existing fleet, but lower technology costs and long-term asset valuation could create an economic climate suitable for growth in NPD and NSD. The cost reduction pathways for NPD, NSD, and PSH assumed in the *Advanced Technology* scenario do not stimulate substantial hydropower generation growth beyond these upgrades, with only 800 MW of NPD and no NSD deployed through 2050. New PSH deployment, however, increases to 2.6 GW. Long-term asset valuation, which is assumed applicable to all hydropower types, could provide stronger motivation to deploy additional hydropower resources, as financing terms reflecting the long-lived, stable revenue streams of hydropower projects allow a considerable near-term and persistent reduction in the cost of capital. The 40% reduction in capital costs assumed in the *Low Cost Finance* scenario incentivizes an additional 1.1 GW of upgrades such that 82% of available upgrades are completed by 2030 and 91% by 2050. Long-term asset valuation has an even larger impact on PSH deployment, with 12 GW installed through 2030 and 23 GW through 2050. For PSH, intermediate deployment levels could be possible even with long-term asset valuation terms and conditions that have relatively lower impact on the cost of capital than is represented by the *Low Cost Finance* scenario.

Coupling *Advanced Technology* with *Low Cost Finance* conditions allows for a large incremental change in growth relative to *Business-as-Usual*. Most available NPD resource becomes economical under these conditions, with 63% utilization in 2030 (3.4 GW) and 89% utilization in 2050 (4.8 GW). A large portion of the NSD resource base is also deployed, reaching 17.2 GW and 56% utilization in 2050. New PSH capacity nears 35 GW in this scenario.

**Environmental Considerations**: *Advanced Technology* and *Low Cost Finance* are the major growth drivers in the scenarios considered here. Equally important for the future of hydropower growth, however, are sustainable development and environmental impact mitigation, particularly for NSD.[14] The *Advanced Technology, Low Cost Finance* scenario does not explicitly avoid any hydropower resource with identified environmental considerations. Thus, that scenario represents a deployment future that assumes successful environmental impact mitigation across the modeled NSD resource. To test model sensitivity to varying degrees of success in environmental impact mitigation, *Advanced Technology* and *Low Cost Finance* assumptions are combined with NSD resource avoidance for environmental considerations; the *Critical Habitat* attribute is used as an intermediate scenario; and *Combined Environmental Considerations* attributes represents a bounding case in which a substantial fraction of NSD resource is avoided due to environmental considerations.[15]

Relative to the case with all NSD resource available (*Advanced Technology, Low Cost Finance*), avoiding environmentally sensitive NSD resource necessarily lowers overall hydropower deployment with a direct reduction in NSD growth. Upgrades and NPD are largely unaffected by changes to NSD resource. Avoiding critical habitat areas reduces NSD deployment by only 200 MW through 2030, but deployment is 4 GW lower through 2050, as most NSD deployment occurs later in the study period after less expensive upgrades and NPDs are built. Avoiding resource overlapping with all environmental attributes, however, nearly eliminates NSD growth, with only 200 MW through 2030 and 1.7 GW through 2050. Under a given set of economic conditions, environmental considerations are a strong determinant of what NSD resource ultimately can be deployed. Additional discussion of how environmental considerations influence the regional distribution of hydropower resources and the characteristics of deployed facilities is included in Section 3.4.2.

PSH growth is not directly affected by environmental considerations, as little overlap in resource potential is assumed and changes are minor across environmental consideration scenarios. There are slight increases in PSH deployment with all environmentally-based NSD resource avoidance restrictions, because NSD capacity is displaced partly by VG resources that in turn support additional PSH installation. However, this effect is small, with only 700 MW more PSH in 2050 relative to the unconstrained case with all NSD resource available. This effect is not observed when only critical habitats are avoided.

14. Upgrades and NPDs would be deployed at sites with previously existing structures. NSD requires new infrastructure development and hence has the potential for greater environmental impact.

15. See Section 3.3 for a full list and description of all environmental attributes considered.

**Fossil and VG Costs**: The competitiveness of hydropower resources also depends on non-hydropower technology costs, with fossil fuel and VG costs expected to play a major role in the future evolution of the electric grid. From the large suite of fossil fuel and VG cost sensitivity scenarios, three are chosen to demonstrate a broader range of hydropower deployment pathways with *Advanced Technology, Low Cost Finance* assumptions. Two of these scenarios include *Critical Habitat* avoidance to reflect intermediate success addressing environmental impacts, with *High Fossil Fuel Cost* representing a scenario that improves competitiveness of both hydropower generation and PSH, and *Low VG Cost* representing a scenario that supports PSH growth but reduces hydropower generation competitiveness with VG. A scenario with no NSD avoidance for environmental attributes and *High Fossil Fuel Costs* pairs improved hydropower economics with assumed successful mitigation of environmental impacts across all NSD resource. This scenario thus embodies a modeled upper bound of hydropower deployment.

Hydropower resources compete differently in the electric sector for providing electricity services and thus respond differently to changes in fossil fuel or VG costs. While the flexible portion of the existing fleet and its potential upgrades can provide grid flexibility through reserve provision and load following, new NPD and NSD is assumed to be relatively inflexible owing to run-of-river operations. These resources are built primarily to supply low-cost energy to the grid. PSH, on the other hand, is built largely to supply grid flexibility through reserves, curtailment reduction, and shifting energy production from inflexible baseload and VG resource from times of low to high demand. Therefore, NPD and NSD (and, to a lesser extent, upgrades) compete most directly with energy-focused resources, such as combined cycle gas turbines, wind, and solar photovoltaics (PV). PSH competes most directly with flexible combined cycle gas and gas combustion turbine resources, while complementing wind and PV growth.

Relative to the *Advanced Technology, Low Cost Finance, Critical Habitat* scenario, including *Low VG Costs* reduces hydropower generation capacity 5 GW in 2050 by making VG more attractive, but additional VG supports 16 GW more PSH. More expensive hydropower generation resources are disproportionally affected; 2050 upgrades fall by only 150 MW while NPD is 600 MW lower and NSD is 4.3 GW lower. Exchanging *Low VG Costs* for *High Fossil Fuel Costs* promotes primarily NSD and PSH, with 1.7 GW more NSD in 2050 and 21 GW more PSH. *High Fossil Fuel Costs* do not encourage much additional upgrade or NPD deployment because all but extremely high-cost resources are utilized without the additional incentives provided by *High Fossil Fuel Costs*. The upper bound scenario combining *Advanced Technology, Low Cost Finance*, and *High Fossil Fuel Costs* with all NSD resource available achieves 15 GW new hydropower generation in 2030 and 31 GW in 2050; the 2050 quantity consists of 6.3 GW upgrades, 4.9 GW NPD, and 20 GW NSD. New PSH is 11 GW in 2030 and 53 GW in 2050 for the same scenario. This slightly lower quantity versus the equivalent scenario including the *Critical Habitat* consideration is because additional hydropower generation displaces VG, indirectly suppressing PSH growth. Alternate market conditions for upgrades, NPD, and NSD have unique effects for each resource class. These are explored in more depth, including impacts on regional distribution and technical characteristics, in Section 3.3.

While the lower bound on PSH growth is 500 MW under *Business-as-Usual* conditions, the upper-bound of new PSH is 16 GW in 2030 and 55 GW in 2050. PSH plays a different role in the power system. Its ability to provide reserves and dependable capacity either does not compete as directly with alternative technologies in the same way NPD and NSD do (such as with gas technologies), or it instead is potentially complementary (such as for VG). This role changes the relative economics of PSH and makes its deployment more sensitive to hydropower cost and value drivers than other hydropower technologies, resulting in a wider range of potential deployment pathways than the other hydropower resources. Deployment is also strongly influenced by fossil fuel and VG costs, with *High Fossil Fuel Costs* and *Low VG Costs* creating an electricity system that more highly values the use of energy storage to provide grid flexibility.

To add context to these total growth levels, Figures 3-10 through 3-13 plot historical and modeled new annual growth of the hydropower resources for representative low, intermediate, and high hydropower deployment scenarios that sufficiently characterize the range of hydropower deployment across the nine

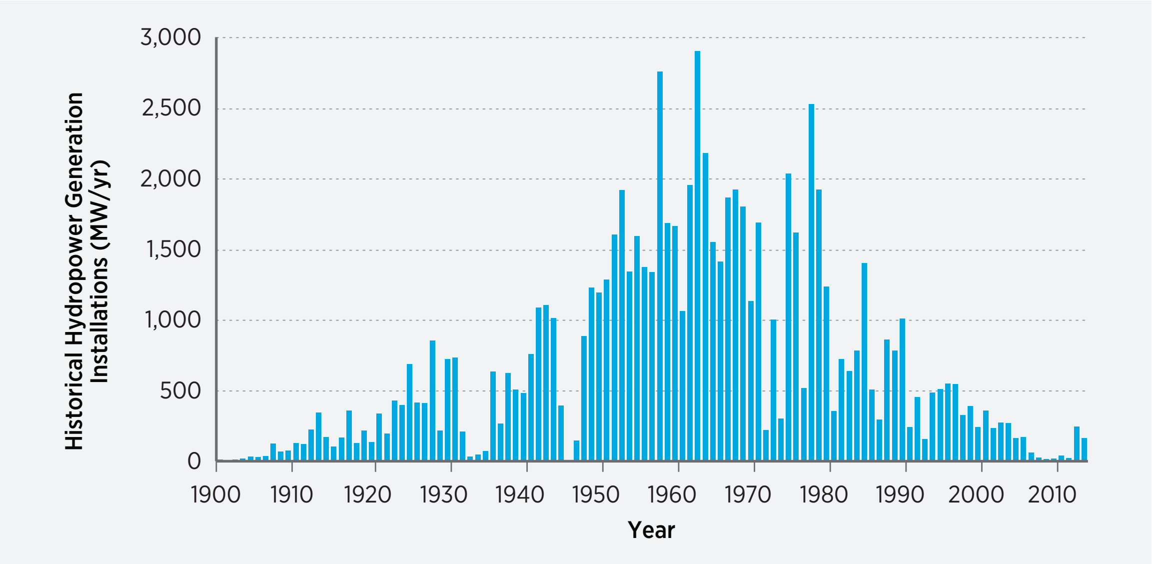



**Figure 3-10.** Historical hydropower generation capacity installations through 2010

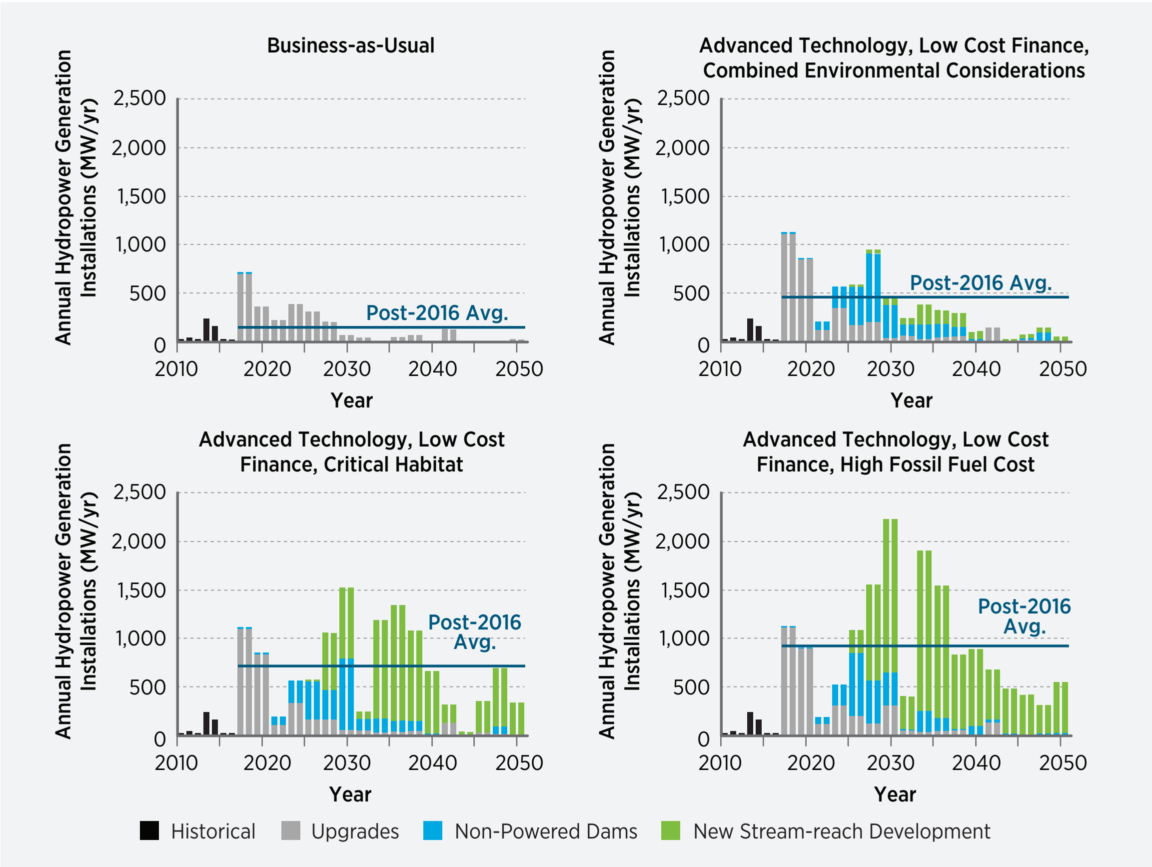



**Figure 3-11.** Post-2010 capacity growth from upgrades, non-powered dams, and new stream-reach development in representative low, intermediate, and high deployment scenarios

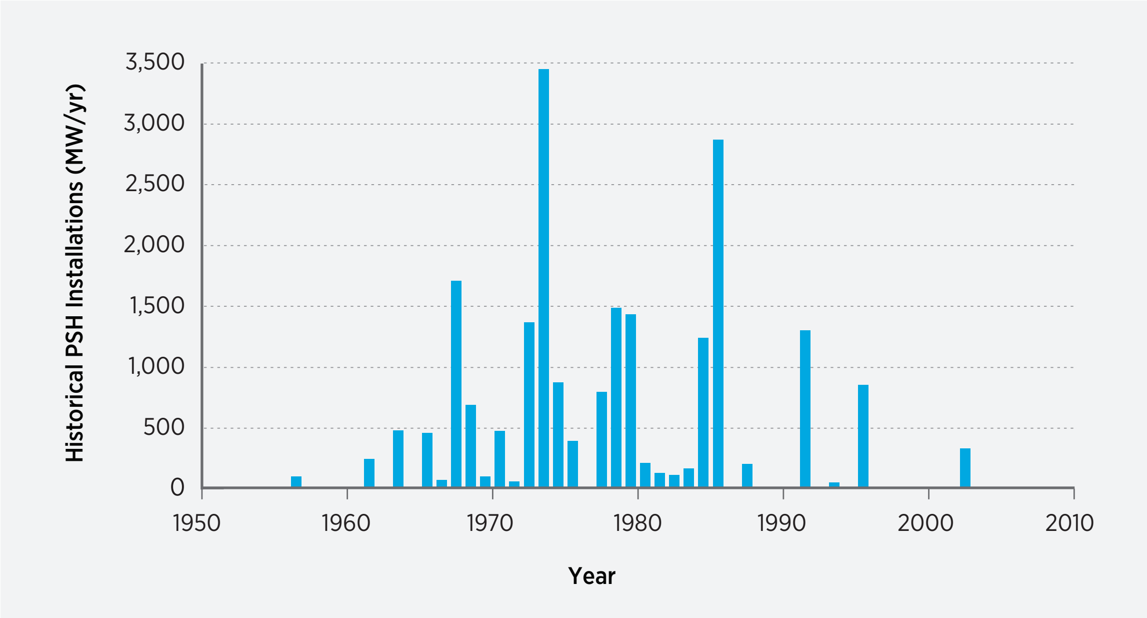



**Figure 3-12.** Historical pumped storage hydropower capacity installations through 2010

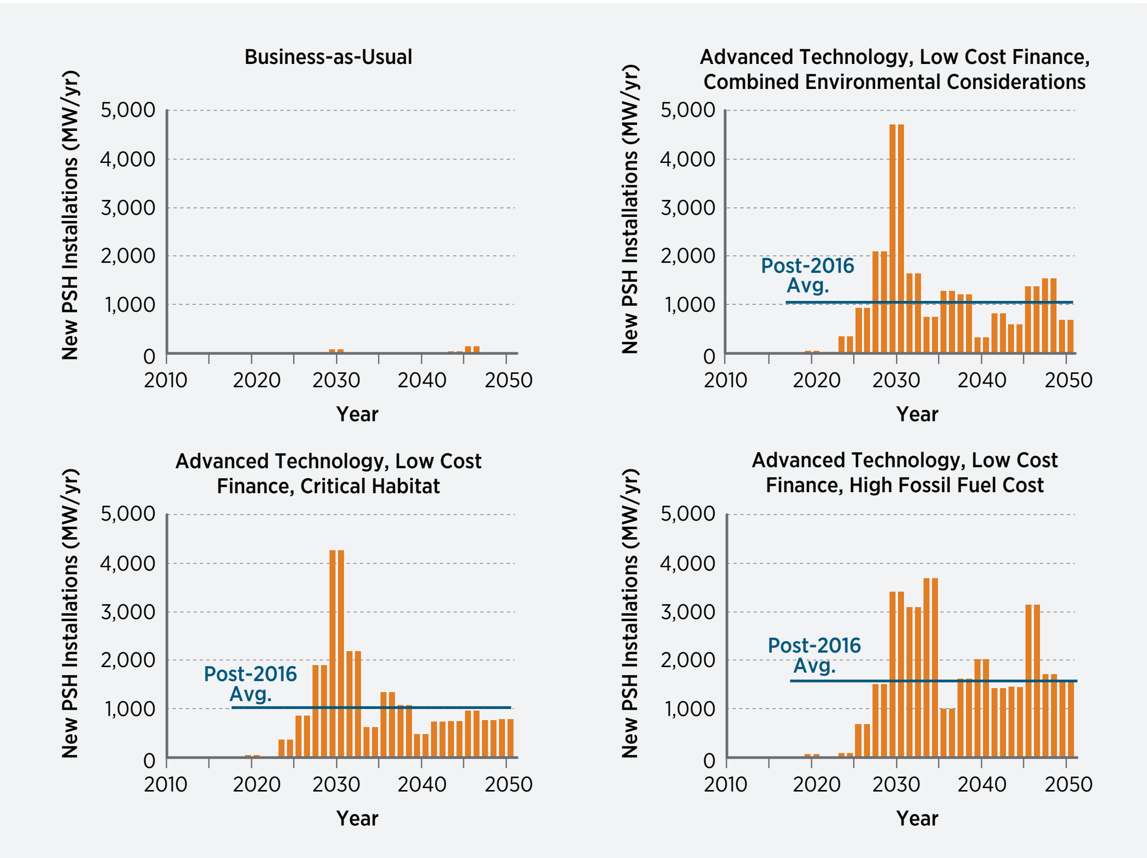



**Figure 3-13.** Post-2010 pumped storage hydropower capacity growth in representative low, intermediate, and high deployment scenarios

selected scenarios. Results for these four scenarios are often shown exclusively within the chapter to improve clarity and conciseness, and results for other scenarios appear in Appendix F. Figures 3-10 and 3-11 of hydropower generation installations demonstrate the near-term focus on existing fleet upgrades along with mid-term growth of NPD and long-term growth of NSD in scenarios supporting investment in these hydropower types.

Historical installations help put the new deployment results in perspective. In these scenarios, an initial focus on upgrades and NPD supports the optimization pillar of the *Hydropower Vision*, while the growth pillar is potentially reflected in long-term NSD installations. While annual growth is sometimes sporadic and approaches the historical maximum in the highest deployment scenarios, practical realities of the industry that are not modeled in ReEDS could buffer annual variability in hydropower construction.

The post-2016 average annual hydropower growth for each scenario is plotted for reference, and real-world construction would likely fall somewhere between a uniform average growth and the variable growth produced by the model.

The equivalent figures for PSH demonstrate rapid growth through 2030 when *Advanced Technology* and *Low Cost Finance* are assumed. While growth rates sometimes exceed historically observed annual PSH construction in high deployment scenarios, average installation rates are on par with historical values.

### Contributions to National Energy Supply

The range of combined upgrade, NPD, and NSD deployment across sensitivity scenarios produces a corresponding range in energy production,[16] and differences between scenarios in Figure 3-14 (left panel) reflect the capacity differences in Figure 3-8 (left panel). As a lower bound, the *Business-as-Usual* scenario yields only an 8% generation increase from 2016 levels to 2050, but the full range of selected scenarios

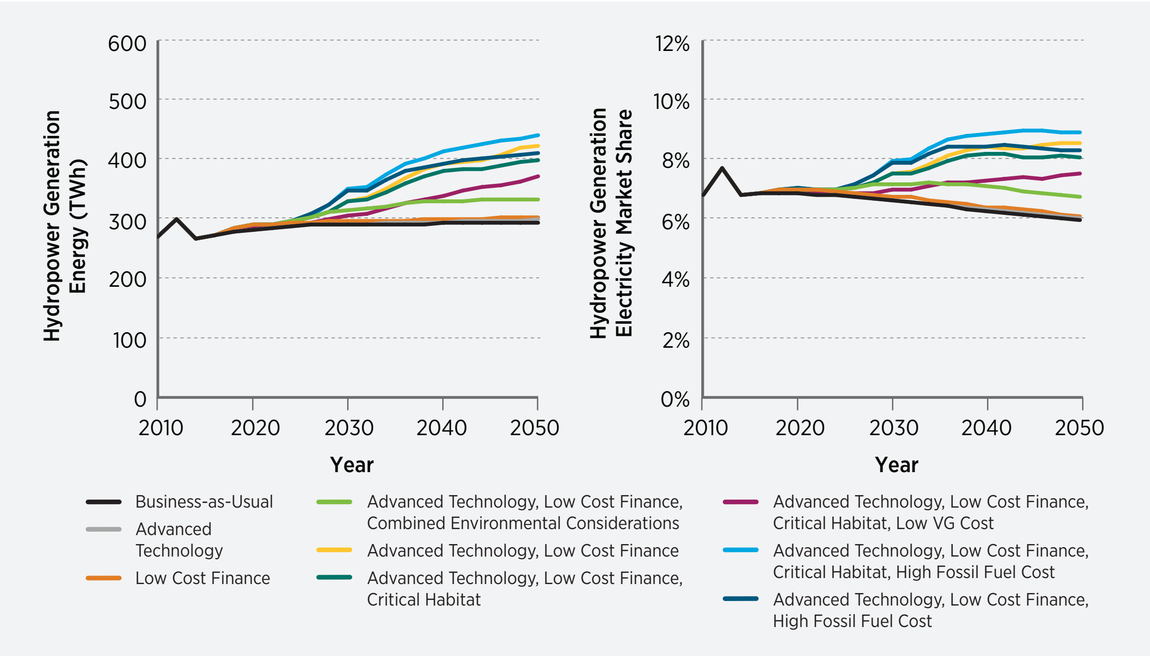



**Figure 3-14.** Electricity generation and share of national electricity consumption from the existing hydropower fleet and growth in upgrades, non-powered dams, and new stream-reach development (excludes net generation from pumped storage hydropower)

16. PSH is technically a net consumer of electricity, with round-trip efficiencies of up to 85% (modeled round-trip efficiency is 80%). As it serves a fundamentally different role in the power system, its consumption and production of energy are ***not*** included in the generation totals described throughout the *Hydropower Vision* document.

results in 290–350 TWh in 2030 and 290–440 TWh in 2050, which constitutes 6–28% and 8–61% increases, respectively. Higher generation scenarios align with high-capacity hydropower generation scenarios. Energy production is strongly influenced by expected future water availability, which is a strong function of climate change expectations. These interactions are discussed in Section 3.4.3.

In terms of market share (Figure 3-14), outcomes vary widely across scenarios. In scenarios with limited new hydropower capacity, the share of generation provided by hydropower declines, falling as low as 5.9% in 2050 in *Business-as-Usual* as generation remains flat while load growth continues. High-deployment scenarios, however, reach up to 7.9% share in 2030 and 8.9% share in 2050, with the best-case being the upper bound *Advanced Technology*, *Low Cost Finance*, *High Fossil Fuel Cost* scenario. Maintaining the existing fleet is essential to retaining hydropower's energy contribution to the electricity system, but new growth is necessary to grow its relative share of generation.

All scenarios with significant NPD or NSD deployment experience a greater relative increase in energy than capacity because NPD and NSD resources are expected to have higher capacity factors than much of the existing fleet. These projects are modeled as being developed and operated on a run-of-river basis, resulting in relatively higher capacity factors (but less flexibility) than the existing hydropower fleet, which operates with considerable water storage.

Figures 3-15 and 3-16 illustrate category-specific hydropower generation growth for representative low, intermediate, and high deployment scenarios. Figure 3-15 includes existing fleet generation for the *Advanced Technology, Low Cost Finance, Critical Habitat* scenario, and known new hydropower built between 2010 and 2016. Figure 3-16 shows new hydropower generation for post-2016 deployment only. Maintaining the existing fleet is important to the overall hydropower contribution to electricity generation, as it contributes the large majority of total hydropower energy through 2050 in all scenarios. Trends in energy growth by hydropower category follow those of capacity growth, with energy growth accelerating slightly in the mid- to long-term because NPD and NSD resource has higher capacity factors than the existing units where upgrades are applied. Across selected scenarios, new upgrades provide 17–21 TWh in 2030 and 20–24 TWh in 2050, new NPD provides 0–22 TWh in 2030 and 0–27 TWh in 2050, and new NSD provides 0–32 TWh in 2030 and 0–116 TWh in 2050.

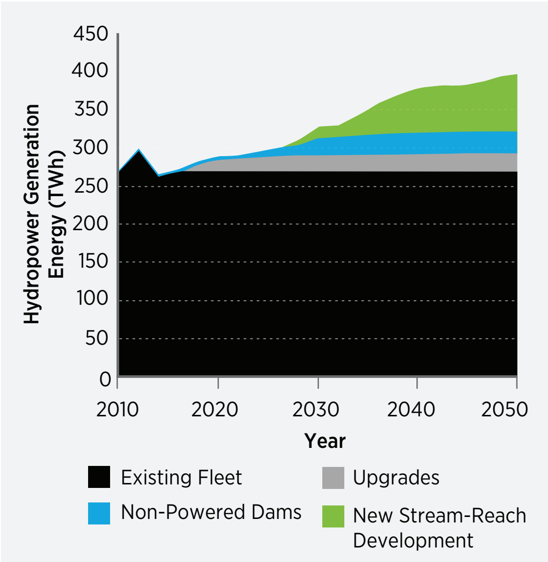



**Figure 3-15.** Total electricity generation from hydropower (excluding pumped storage hydropower) in the *Advanced Technology, Low Cost Finance, Critical Habitat* scenario (existing fleet generation in 2010–2014 adjusted to match historical data)

## *Pumped Storage Hydropower and Variable Generation*

The relationship between PSH and VG is explored further in Figure 3-17, which plots new PSH capacity in 2030 and 2050 versus the percent of demand met by VG in those years for the subset of the nine selected scenarios that includes *Advanced Technology, Low Cost Finance* assumptions. These results show a positive correlation between VG generation and PSH capacity, with higher-VG scenarios (*High Fossil Fuel Costs* and *Low VG Costs*) reaching 50% or more demand met by VG in 2050 and 50 GW or more PSH. PSH deployment is much lower when VG generation is lower in earlier years, or under reference VG and fossil cost conditions.

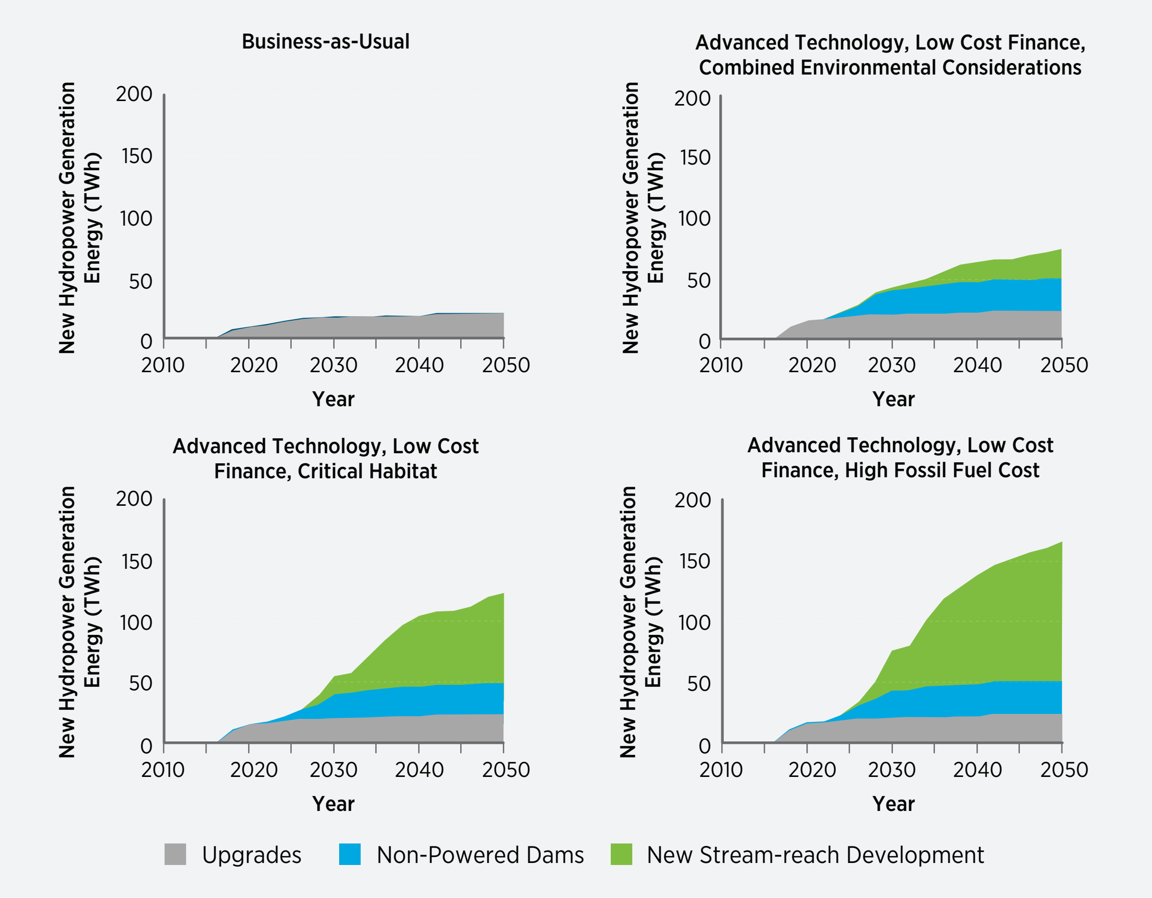
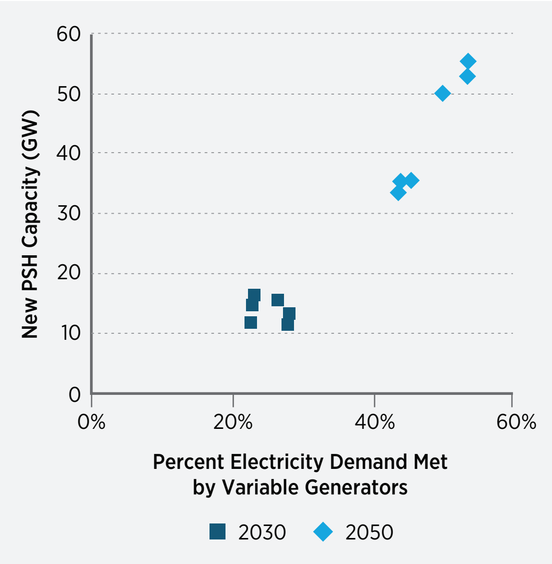



**Figure 3-16.** Electricity generation from new hydropower in representative low, intermediate, and high deployment scenarios (generation from the existing fleet and net energy use by pumped storage hydropower is not shown)




The exact relationship between PSH and VG, however, is dependent on the state of the electricity system, and the data shown here do not necessarily imply a specific functional relationship between the two quantities. For instance, higher assumed PSH costs could reduce PSH growth for a given VG generation, or other storage technologies (e.g. batteries, compressed air energy storage) could displace PSH if lower costs were assumed for those technologies. The complementary relationship between PSH and VG is supported by model results, but the details of this relationship must be borne out by the future realities of the electricity system.

**Figure 3-17.** The relationship between new pumped storage hydropower growth and generation from variable generators for fuel and cost sensitivities under *Advanced Technology* and *Low Cost Finance* conditions

## 3.4.2 Growth Considerations within Market Segments

Each of the nine scenarios presented in the *Hydropower Vision* analysis produces a different modeled outcome for each of the resource classes represented in ReEDS—Upgrades, NPD, NSD, and PSH. As mentioned previously, the intention of these scenarios is not to *predict* future outcomes for the hydropower industry. Instead, they serve a useful analytical purpose in demonstrating the relative sensitivity of each resource to key scenario levers such as technology cost, financing, the cost of variable generation technologies and fossil fuels, and the importance of environmental considerations. This investigative approach supports the development of the *Hydropower Vision's* roadmap by highlighting and quantifying the importance of specific key issues. To that end, this section documents key observations from the nine scenarios for each of the hydropower resource classes, addressing key components of site attributes and regionality. Discussion on the impact of climate change is in Section 3.4.3.

### *Market Potential for Upgrades*

As modeled, the capability to upgrade and expand the existing fleet is generally the most cost-effective and economically attractive of the hydropower resource options. Because of this cost effectiveness, upgrades are the first generation resource to deploy and are used extensively in most scenarios, forming the foundation of growth in the modeled scenarios. Of the 6.9 GW of potential, deployment in 2050 ranges from 5.2 GW under *Business-as-Usual* to approximately 6.3 GW in most scenarios incorporating *Low Cost Finance* assumptions and favorable market conditions. Unfavorable market conditions for hydropower generation resources, such as increasing competition from renewables under *Low VG Cost* assumptions, only slightly reduces deployment levels to 6.1 GW. Figure 3-18 illustrates the levels of use of upgrades in 2030 and 2050 across the selected modeled scenarios.

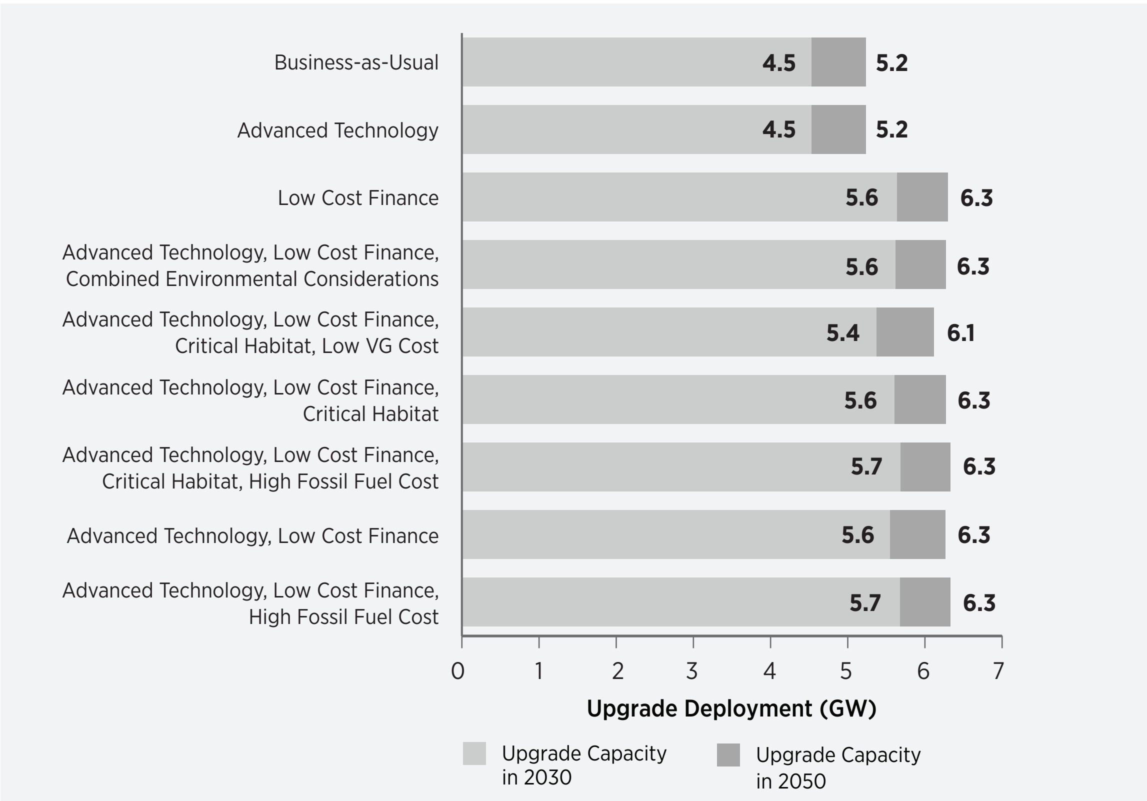



**Figure 3-18.** Deployment of upgrades in 2030 and 2050 in selected modeling scenarios

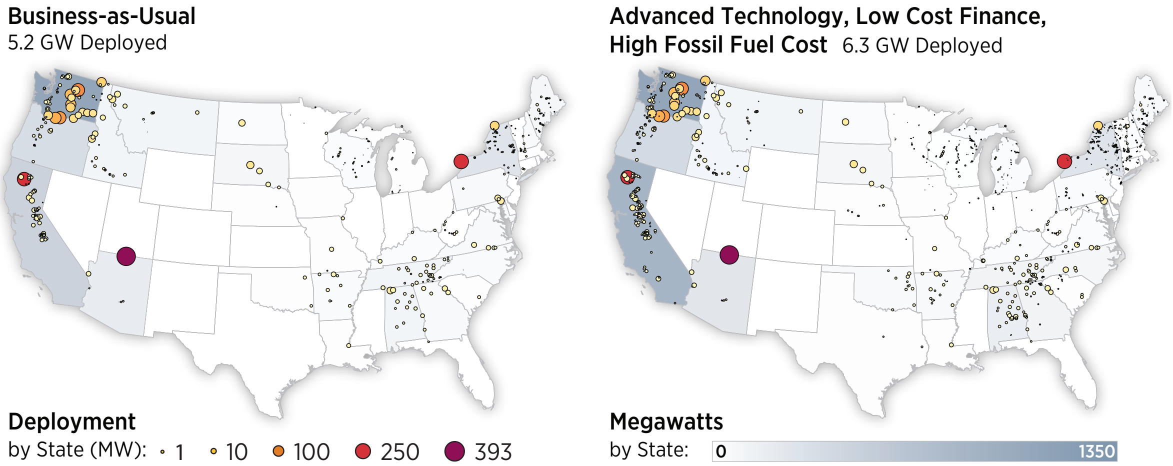



**Figure 3-19.** Regional deployment of upgrades for representative low and high deployment

The difference between the relatively low 5.2 GW scenarios and the higher 6.3 GW upgrades scenarios are overwhelmingly a function of the *Low Cost Finance* assumption, which improves the economics of otherwise marginal upgrade opportunities. Only the largest projects that benefit from the economies of scale inherent in hydropower development deploy in the 5.2 GW scenarios, with that level of deployment coming from upgrading 426 projects. The additional 1.1 GW seen in the higher deployment scenarios requires upgrading over 500 additional projects. Figure 3-19 illustrates the regional differences in these deployment levels using *Business-as-Usual* and *Advanced Technology*, *Low Cost Finance*, *High Fossil Fuel Cost* as representative high and low outcomes. An additional 500 small upgrade projects are spread across the United States, but produce noticeable increases in upgrade capacity in California and the Northeast.

The near-full utilization of potential upgrade capacity in *Low Cost Finance* scenarios does not mean all plants are considered economic to upgrade or expand. Generally, between 900 and 1,100 facilities are upgraded in these scenarios; however, an additional 600 to 800 projects with upgrade potential totaling approximately 500 MW are not. Owing to the economies of scale in the cost of constructing, operating, and maintaining hydropower projects, these small remaining projects are considered too expensive to be upgraded cost effectively. The challenging economics facing these facilities are apparent in the fact that no scenario achieves any meaningfully higher upgrade deployment. The highest—*Advanced Technology, Low Cost Finance, High Fossil Fuel Cost*—only deploys an additional 30 MW relative to the *Low Cost Finance* scenario.

### *Market Potential for NPDs*

After upgrades, NPDs are generally the next most economically competitive hydropower generation resource. Where a significant portion of the upgrade resource is competitive under *Business-as-Usual* conditions, the broad powering of non-powered dams requires meaningful cost reduction—either through access to financing mechanisms that value hydropower's long lifetime (*Low Cost Finance*) or through technology, development processes, and O&M cost reductions (*Advanced Technology*). Figure 3-20 illustrates the levels of NPD deployment across different market and hydropower economics assumptions.

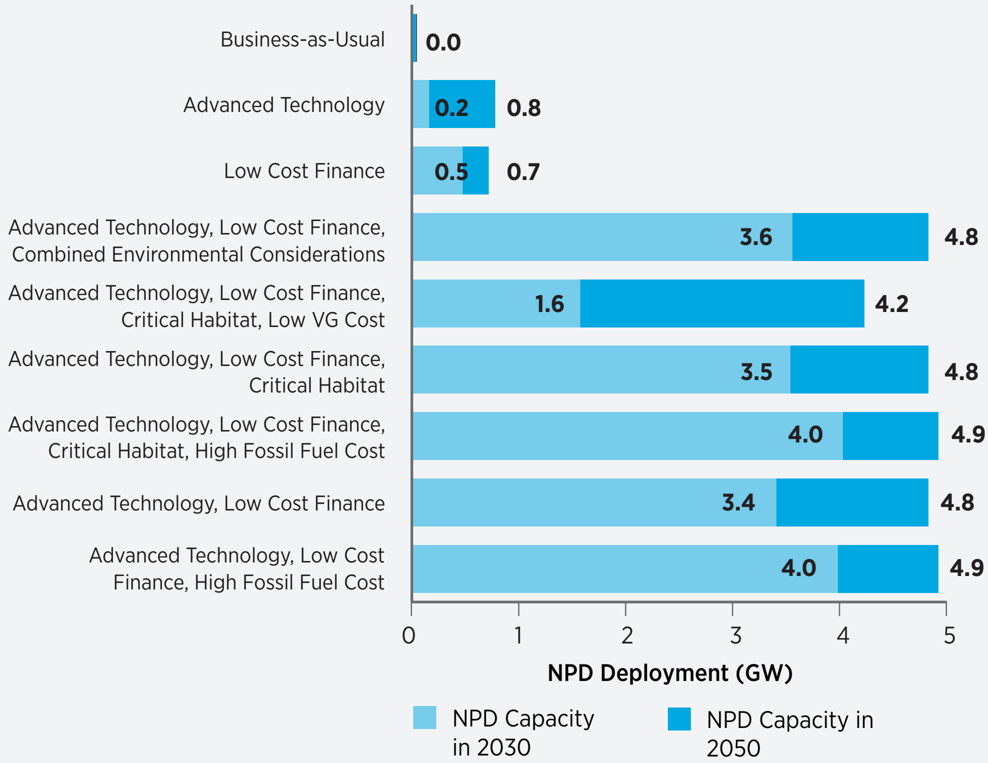



**Figure 3-20.** 2030 and 2050 deployment of NPD in selected modeling scenarios

No new previously unannounced NPD capacity is deployed economically under *Business-as-Usual* market and economic conditions. With individual advances in technology cost reduction or long-term valuation, 2050 deployment is between 700-800 MW with some minor variation in timing between scenarios.[17] When both *Low Cost Finance* and *Advanced Technology* advances are realized, deployment of NPD is more significant, ranging between 4.2 and 4.9 GW and resulting in the powering of between 450 and 600 existing dams of the 671 modeled. Both R&D and valuation solutions are essential to realizing the broad utilization of the nation's low-head NPD resources. In the scenarios with high deployment of NPD in excess of 4 GW, the median NPD project has a design head of only 40 ft. Without more favorable economic parameters such as in the scenarios where *Advanced Technology* or *Low Cost Finance* are used individually, only higher-head, lower-cost projects are deployed, and the median project head increases to above 90 ft. While canal and conduit projects are not modeled in ReEDS, the results from NPD suggest that similar approaches to cost reduction and valuations could be beneficial to these resource types.

The economically competitive NPDs are generally distributed consistent with the location of the remaining NPD resource potential; deployment is concentrated largely in the Midwest and the South at large existing dams along the Mississippi and its major tributaries. Figure 3-21 shows the regional distribution of these dams.

17. There are also minor changes in the geography of deployment. Where the *Low Cost Finance* scenarios reduce the cost of all NPD projects, the *Advanced Technology* scenario differentially reduces the cost of low-head versus high-head development (30% versus 25%, respectively, by 2050) and also reduces O&M cost, further changing the relative economics of different NPD projects.

Across all scenarios, a majority of the deployed capacity from NPDs is at Corps facilities that lack power infrastructure; these facilities are typically flood control or navigation structures such as locks and dams. In the scenarios combining *Advanced Technology* and *Low Cost Finance,* 75% of the deployed NPD capacity is on Corps infrastructure; at lower levels of deployment, this share rises to between 80–90%.

### Market Potential for NSD

Of the hydropower generation options, NSD shows the highest growth potential—but it also carries the greatest uncertainty. Many modeling scenarios show no growth for NSD, including the *Business-as-Usual* scenario. Scenarios that do see growth have a wide variation in outcomes between 1.7 GW and 20.1 GW of cumulative deployment in 2050, with variations in growth driven by the evolution of market factors and the potential intersection or incompatibility of NSD development with environmental considerations. Figure 3-22 documents the range of NSD deployment in the selected scenarios.

On the basis of economics alone, realizing NSD deployment requires effort by industry and stakeholders to drive down costs and better value the long life of hydropower assets—and these steps must be done in combination for NSD to deploy at all. Neither *Low Cost Finance* nor *Low-Hydropower Cost* conditions can independently motivate deployment of NSD, but in combination they provide an economic competitiveness threshold that could support GW of deployment. As is this case for NPD, cost reductions must come in part from innovation targeted at low-head development—the median NSD project deployed in the selected modeled scenarios has a design head of between 30 and 40 feet.

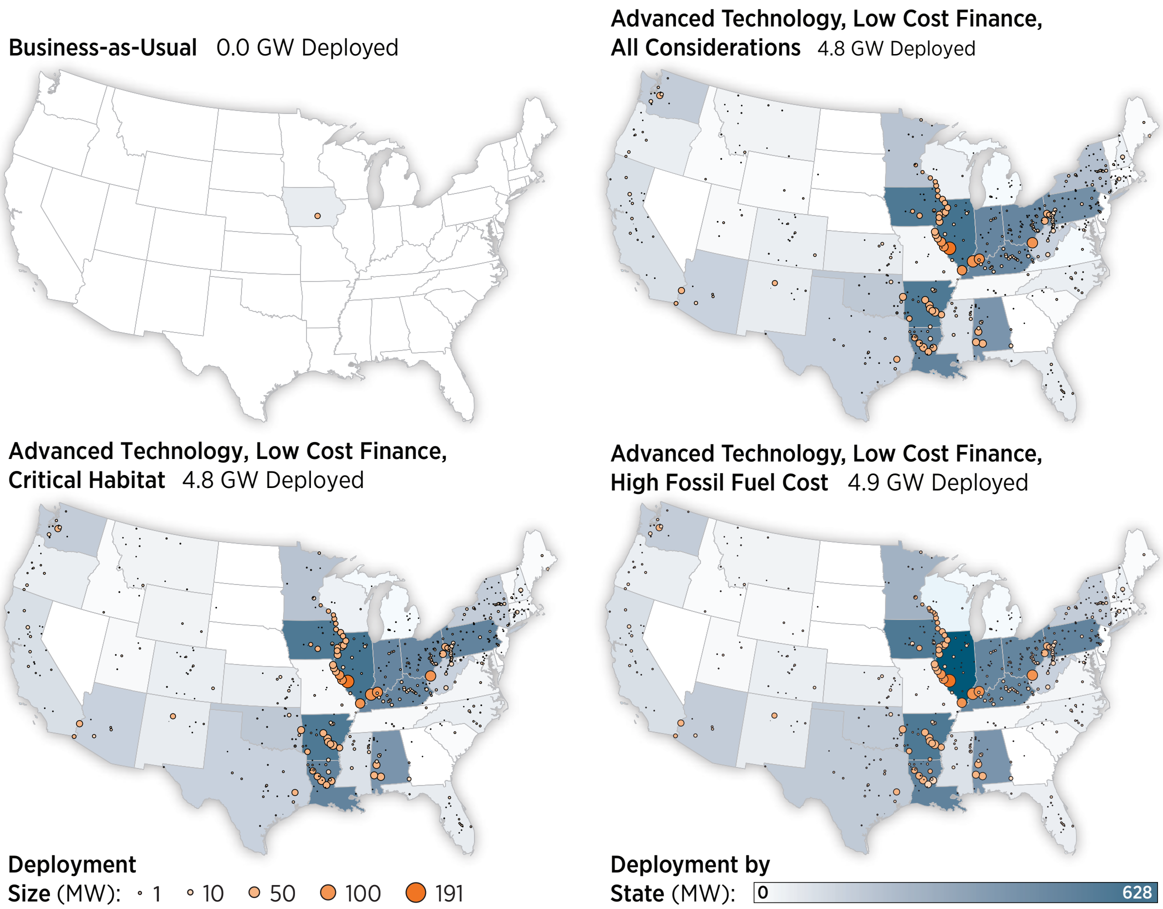



**Figure 3-21.** Regional deployment of NPD across a range of selected modeling scenarios

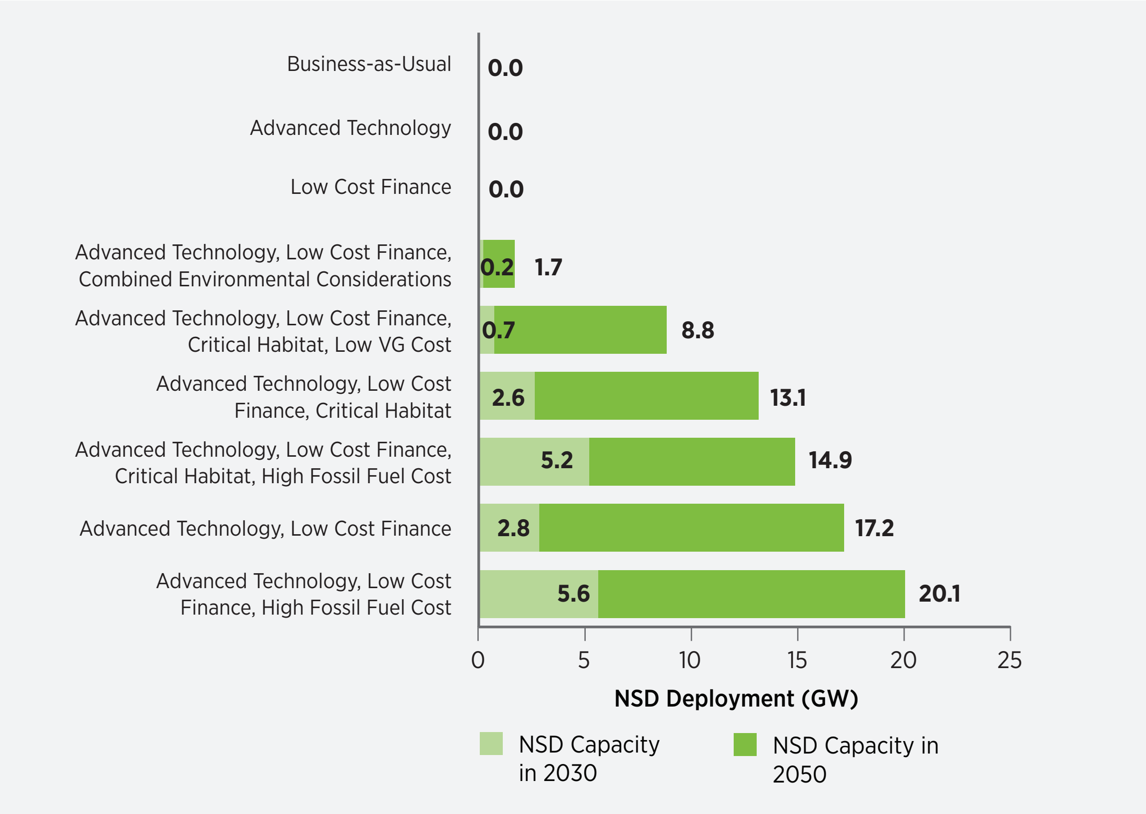



**Figure 3-22.** 2030 and 2050 deployment of NSD in selected modeling scenarios

The environmental considerations described in Section 3.3 are not proxies for sustainability singularly or in combination. They do, however, demonstrate the fundamental need for NSD development to accommodate, if not support and improve, the other values and uses of the nation's rivers. When NSD development is avoided in areas overlapping only one consideration—*Critical Habitat*—economic deployment is reduced by 2.3 GW relative to outcomes from the combination of *Advanced Technology* and *Low Cost Finance* (14.9 GW versus 17.2 GW). When development is avoided in areas intersecting any of the eight considerations modeled in the scenario with *Combined Environmental Exclusions*, only 1.7 GW of growth in NSD occurs.

Figure 3-23 provides two examples illustrating how environmental considerations scenarios can alter the regional deployment of NSD by mapping 2050 NSD deployment for representative low, mid, and high deployment scenarios.

In the scenario most favorable on economic merits alone—*Advanced Technology, Low Cost Finance*, *and High Fossil Fuel Cost*—NSD is competitively deployed in all but two states (Nevada and Delaware) in the continental United States, with particularly concentrated development in Oregon, Washington, Idaho, Montana, Missouri, and Pennsylvania. However, the uncertainties introduced by the example *Critical Habitat* consideration are readily visible, showing that development may not be possible in the Pacific Northwest if NSD cannot satisfy environmental and social objectives alongside the economic objectives optimized by the

ReEDS model. This result is even more apparent in the bounding case of the *Combined Environmental Considerations* scenario, which shows that meaningful deployment of NSD at the national scale may prove to be prohibitively challenging. The need for a sustainable development paradigm is evident, and steps towards this goal, both in terms of technology innovation and sustainability perspective, are documented in the *Hydropower Vision* roadmap (Chapter 4).

The range of NSD's potential contribution to the future power system also highlights the variation in potential logistical and infrastructure needs to support these scales of development. At the low end of deployment (1.7 GW under *Combined Environmental Considerations*), 375 new NSD projects would be required by 2050—along with the associated regulatory, construction, and manufacturing needs. At the high end of the NSD deployment spectrum (20.1 GW for the *Advanced Technology, Low Cost Finance, High Fossil Fuel Cost* scenario), these needs rise to a total of 3,608 projects. This range of project counts indicates that for significant NSD deployment, major advances are necessary to sustainably—from both environmental and logistical perspectives—deploy numerous small projects, as the average size of NSD across scenarios ranges from 4–8 MW.

## *Market Potential for PSH*

Unlike hydropower generation resources, the advent of closed-loop development opportunities ensures that the potential supply of pumped storage projects does not face the same resource availability constraints as upgrades, NPD, and NSD. Instead, the deployment of PSH is contingent on its ability to cost-effectively meet the needs of the evolving power system represented in ReEDS. Subsequently, dependent on market and value drivers, the range of overall

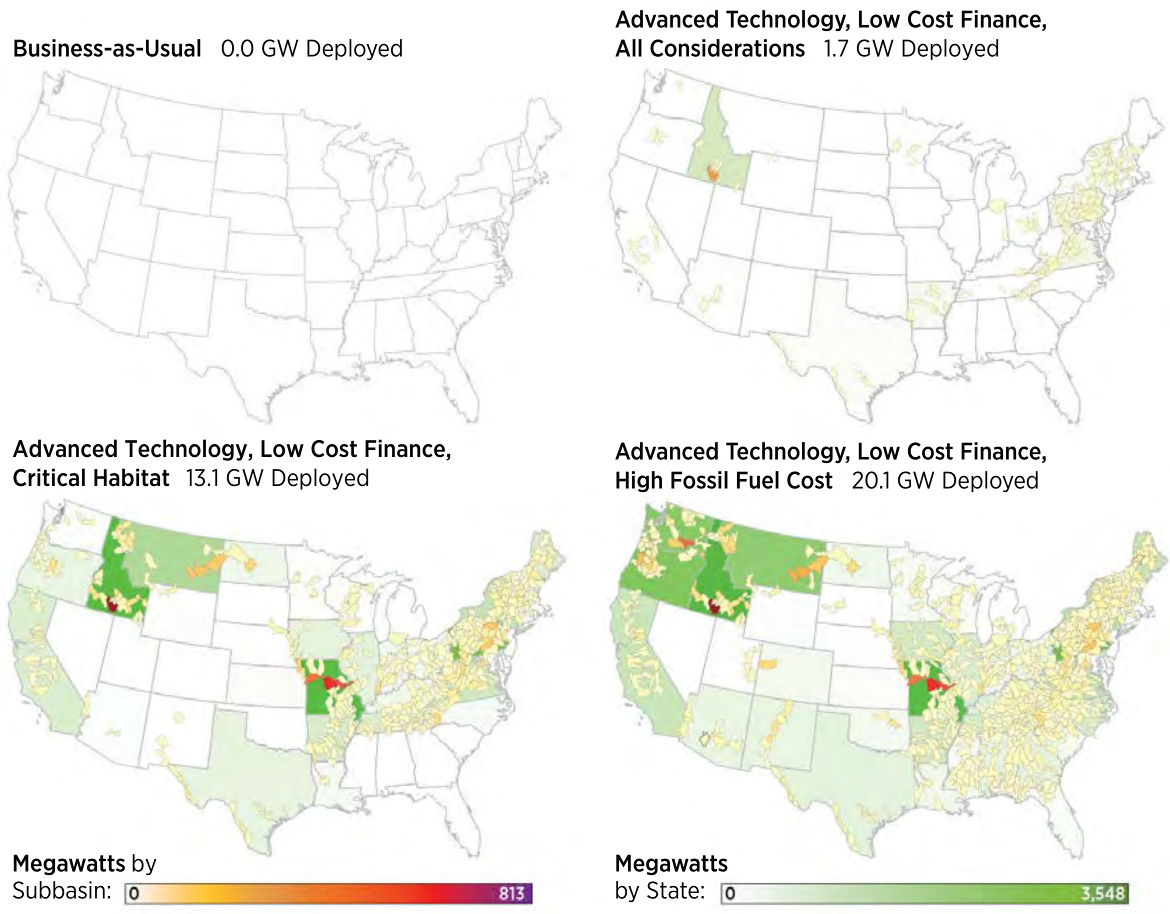



**Figure 3-23.** Regional deployment of NSD for representative low, mid, and high deployment scenarios

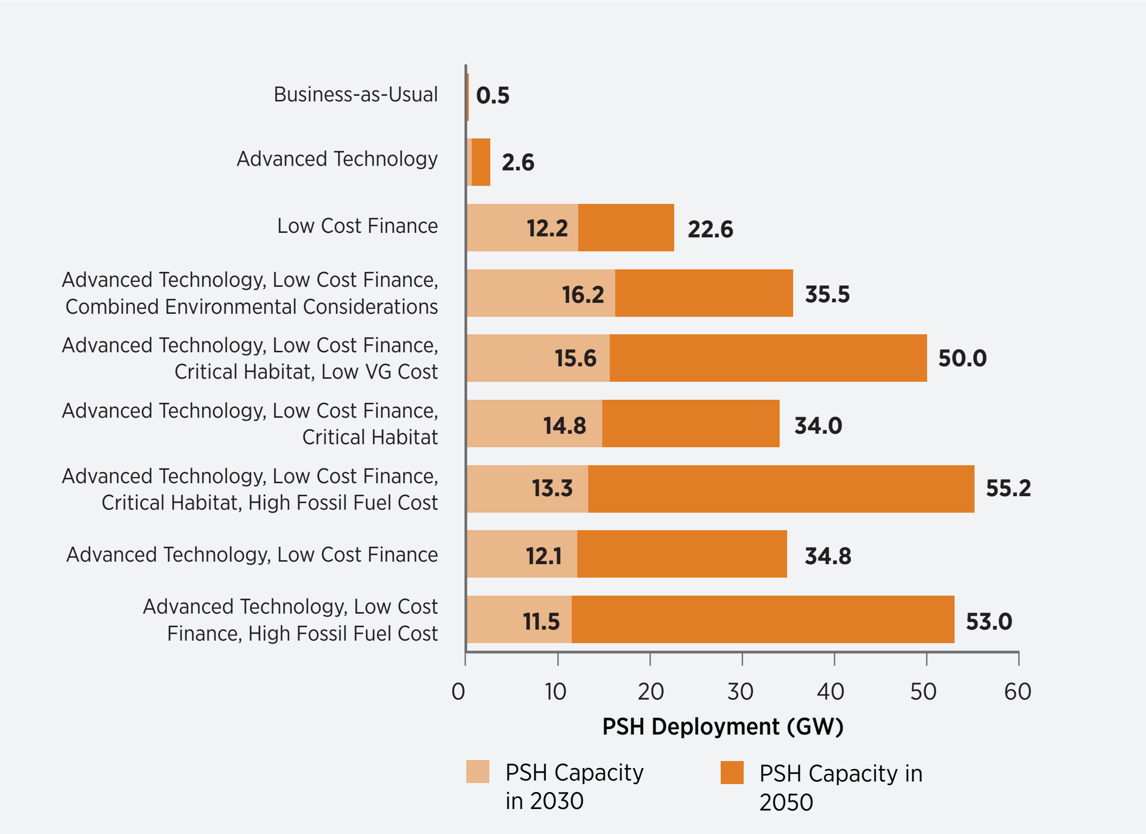



**Figure 3-24.** 2030 and 2050 deployment of PSH in selected modeling scenarios

2050 PSH deployment spans from a few hundred MW under *Business-as-Usual* conditions to more than 50 GW when cost, value, and market conditions align favorably. Levels of PSH deployment in 2030 and 2050 across scenarios are illustrated in Figure 3-24.

While the modest cost reductions for PSH in the *Advanced Technology* scenario support incrementally higher levels of deployment (2.5 GW), the real catalyst for use of PSH is application of the *Low Cost Finance* perspective that independently motivates the deployment of 22.6 GW of new PSH capacity. These conditions together produce somewhat higher deployment outcomes, between 34 and 36 GW. The highest levels of PSH deployment—50 GW and higher—are seen when combining improvements in cost and valuation with market conditions more favorable to storage technologies, namely *Low VG Costs* and *High Fossil Fuel Costs*. The increase in VG deployment in these scenarios relative to *Business-as-Usual* motivates the development of economically competitive PSH. Higher fossil fuel prices, however, favorably influence the economics of PSH in an additional way, as the natural gas-based combined cycle (CC) and combustion turbine (CT) capacities that would have otherwise balanced VG become relatively more expensive. Figure 3-25 shows the regional implications of the range of PSH deployment possible in the *Hydropower Vision* analysis.

When applying the *Low Cost Finance* perspective to PSH, significant deployment is seen throughout the country, with particularly high demand in California, the Southwest, Midwest, and Mid-Atlantic regions. When adding the modest cost reductions from the *Advanced Technology* conditions, additional deployment is seen in most regions, but PSH gains a particular economic edge in backing solar generators in the Southwest. Adding *High Fossil Fuel Cost* further increases deployment, most notably in the Mid-Atlantic/New York and Pacific Northwest regions.

As the utility-scale PSH projects available to the ReEDS model have large capacities relative to modeled hydropower generation projects, the number of new PSH projects necessary to reach the levels of modeled levels of deployment is much lower than that for upgrades, NPD, and NSD. The average capacity of a PSH plant varies by scenario from 700–1,000 MW, with the exception of the *Business-as-Usual* scenario that deploys a just one 300-MW plant. Thus, there is an approximately linear relationship between total capacity deployment and the number of required projects, with three projects in *Advanced Technology*, 22 in *Low Cost Finance,* and more than 70 when *High Fossil Fuel Cost* is introduced.

### 3.4.3 Hydropower in an Uncertain Climate Future

As discussed previously, climate change potentially creates significant uncertainty about water availability for hydropower generation, and this uncertainty can affect the long-term outlook of the hydropower industry. Water availability affects the energy production potential of hydropower resources, which in turn influences their economic attractiveness in the electric sector. To understand how this uncertainty in water availability could influence levels of growth, the bounding *Wet* and *Dry* conditions documented in Section 3.3 were applied to all nine selected scenarios. It is important to reiterate that these scenarios change only the availability of water for hydropower generation; they do not combine these adjustments with other potential impacts from a changing climate, such as the availability of water for thermal power

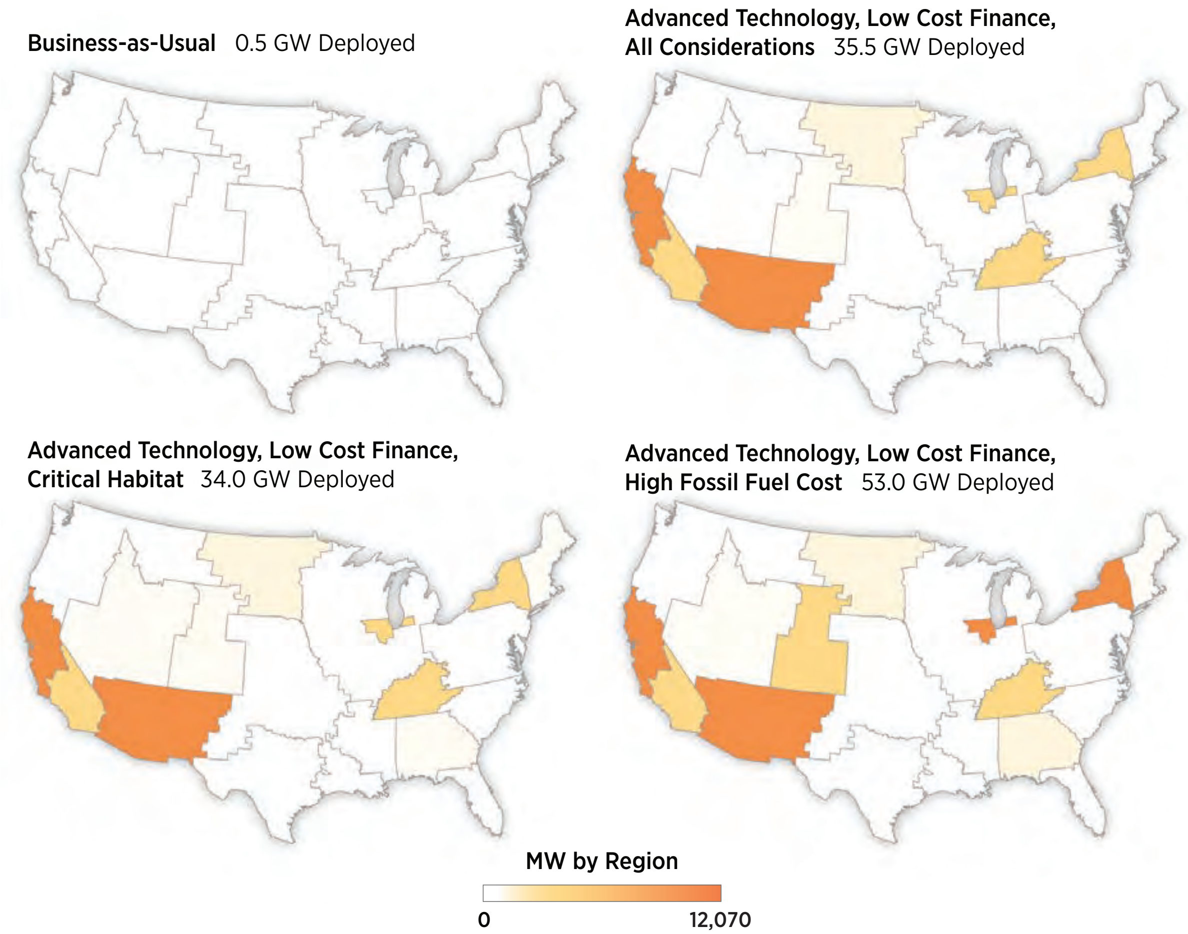



**Figure 3-25.** Regional deployment of PSH across a range of selected modeling scenarios

plant cooling or the influence of temperature on electricity demand. These scenarios also do not represent the influence of climate change on water quality (e.g. temperature), as doing so requires a detailed hydrology representation not included in the ReEDS electric sector modeling framework.

Even with this limited focus, the modeled scenarios can demonstrate a range of national impacts of water availability on hydropower deployment potential. Figure 3-26 plots the range of 2030 and 2050 new hydropower generation capacity deployed across the *Wet* and *Dry* variants of each of the nine selected scenarios, while also plotting the reference deployment value when water availability is unchanged throughout the study period. Most upgrades are economically attractive even with reduced water availability, so deployment under *Business-as-Usual* conditions changes no more than 5% with changing water availability (4.4–4.7 GW vs. 4.6 GW reference). Non-powered dams are also similarly unaffected by changing water availability when combined *Advanced Technology* and *Low Cost Finance* assumptions are sufficient to support construction of a large fraction of NPD resource even under reduced water availability.

In the scenarios implementing *Advanced Technology* and *Low Cost Finance* assumptions individually, the range of 2050 NPD deployment between *Wet* and *Dry* variants is up to 1.6 GW because water availability is

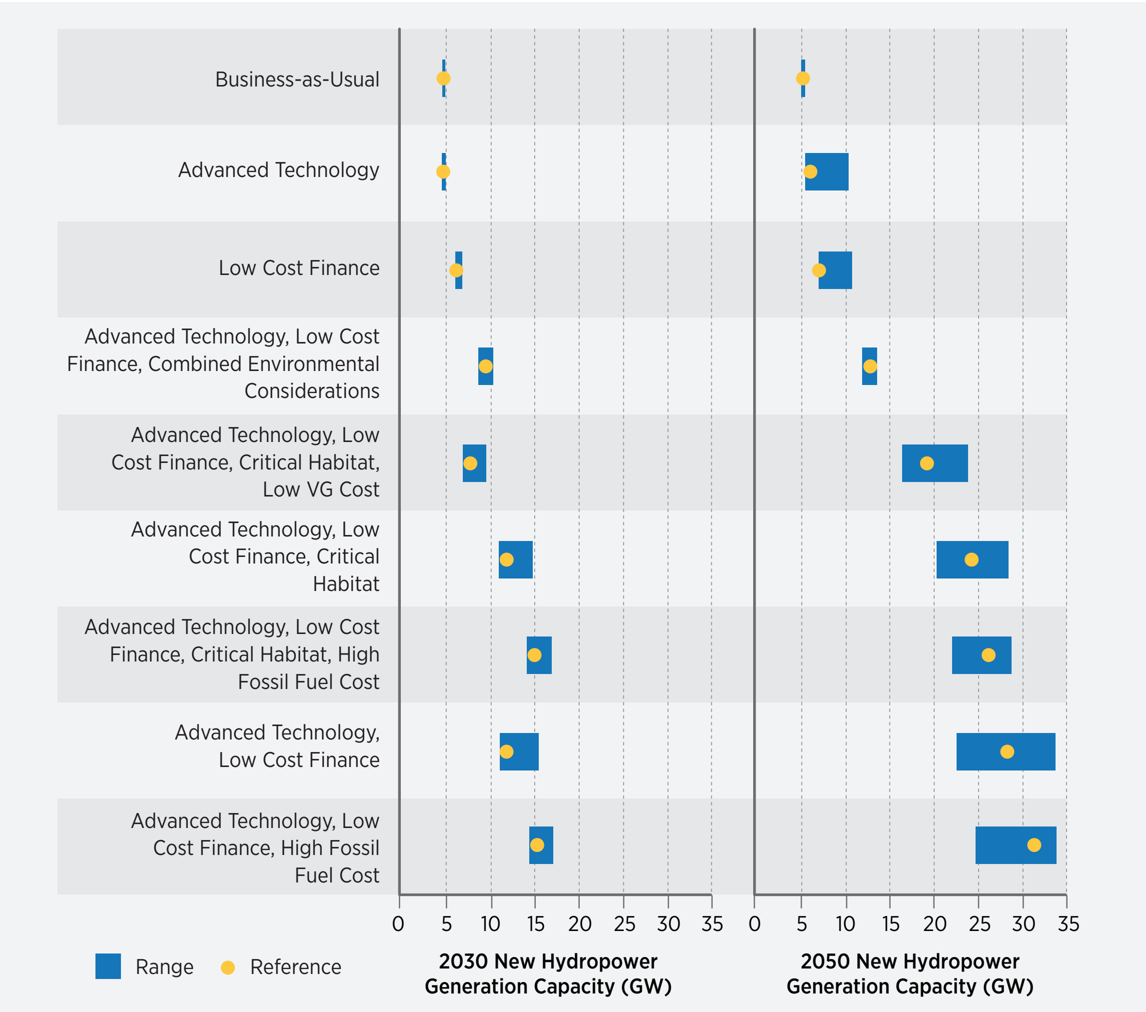



**Figure 3-26.** Range of new hydropower generation capacity in 2030 and 2050 across the *Wet* and *Dry* water availability scenario variants of the selected scenarios

important to NPD when these resources are marginal. That is, small changes in expected energy production can be enough to determine whether or not the capacity is economical in comparison with other available technologies. Most of the deployment spread across water availability variants, however, is attributed to changes in NSD deployment. For the top five deployment scenarios, the range of 2050 NSD growth varies from 6.3–10.5 GW, which accounts for most of the 6.7–11.2 GW deployment ranges shown in Figure 3-26. There is less variation with *Combined Environmental Considerations* because so little NSD resource is available. The range of NSD deployment variation across *Wet* and *Dry* conditions is 42–74% of the reference NSD deployment for scenarios when NSD is built.

Figure 3-27 plots the range of energy production from new hydropower generation built through 2030 and 2050 when water availability is varied. Energy from the existing hydropower generation fleet is not shown in the figure but is also influenced by assumed water availability. From the reference long-term average output of 270 TWh, existing fleet generation in climate scenario variants spans 260–290 TWh in 2030 and 250–310 TWh in 2050. Note that the modeled long-term trends do not assume any interannual variability, so actual generation could exceed these bounds. For new hydropower generation, energy production across the full range of *Wet* and *Dry* variants for the nine selected scenarios

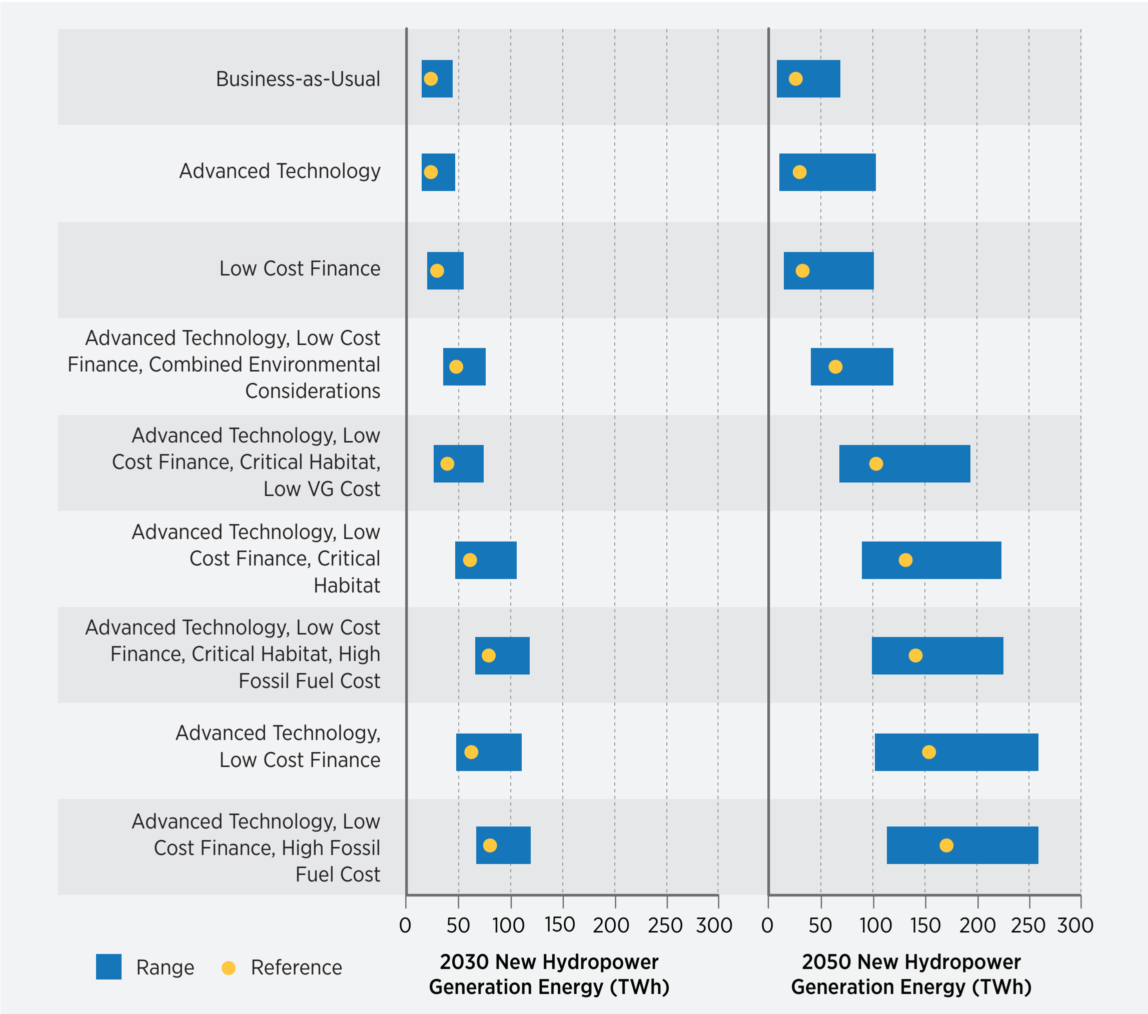



**Figure 3-27.** Range of new hydropower generation energy in 2030 and 2050 across the *Wet* and *Dry* water availability scenario variants of the selected scenarios

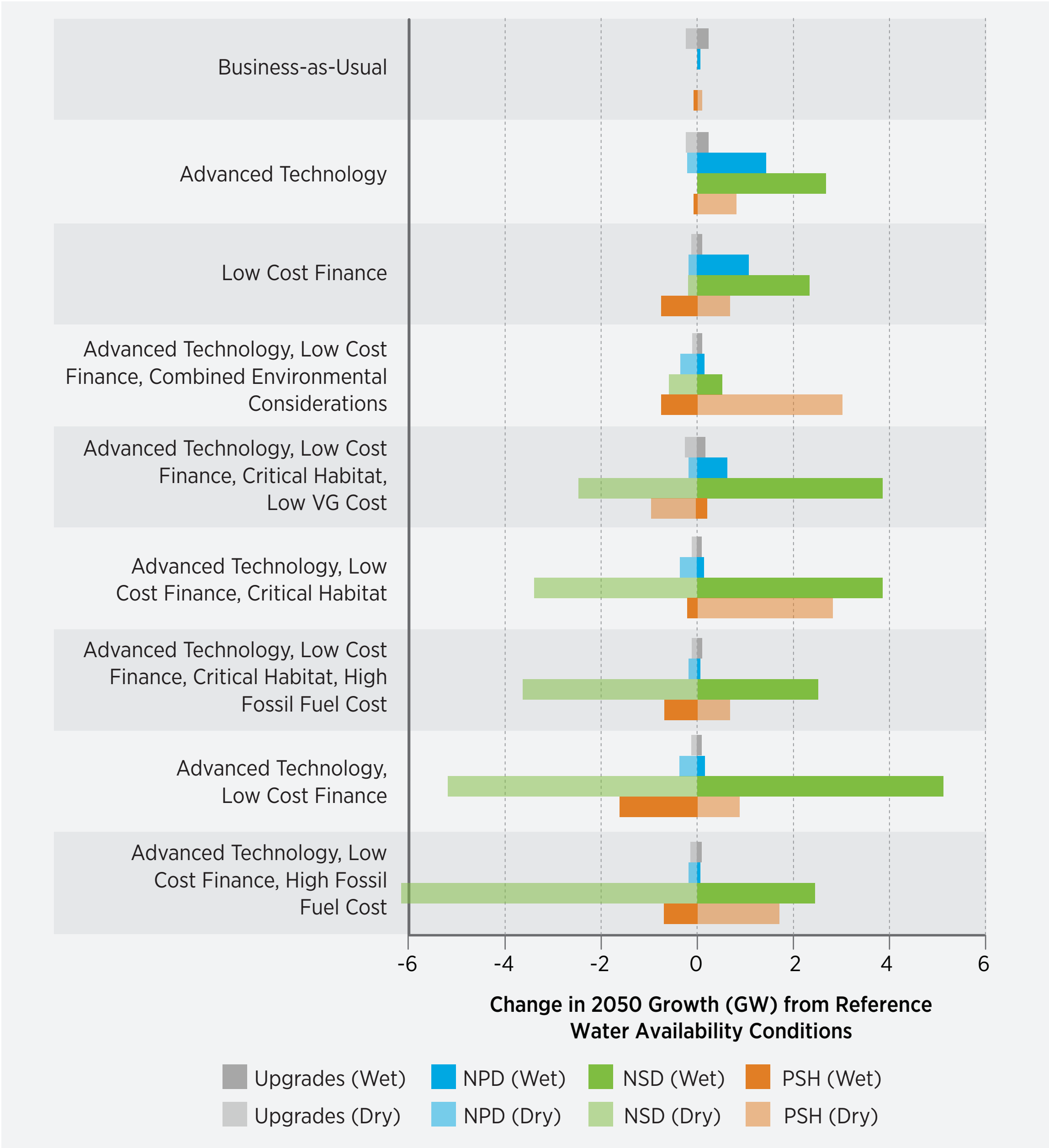



**Figure 3-28.** Influence of *Wet* and *Dry* water availability conditions on 2050 hydropower deployment in selected scenarios

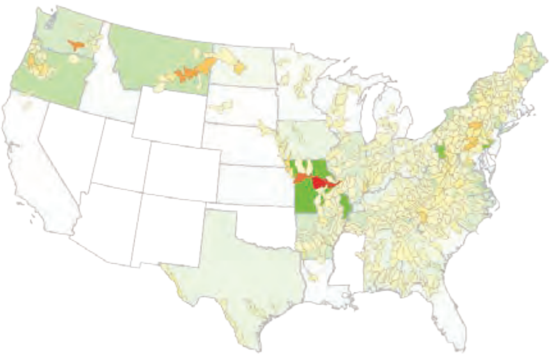
spans 13–120 TWh in 2030 and 6–260 TWh in 2050. The low end of the range declines because *Business-as-Usual* in *Dry* conditions does not result in building of enough new capacity to replace reduced generation from previously built hydropower due to declining water availability.

Water availability plays a key role in determining the economic attractiveness of hydropower resources, particularly higher-cost NSD resources that are more economical if greater energy production is expected. Low water availability scenarios also highlight the importance of maintaining and upgrading existing infrastructure so that hydropower can maintain its contribution to the U.S. electric sector.

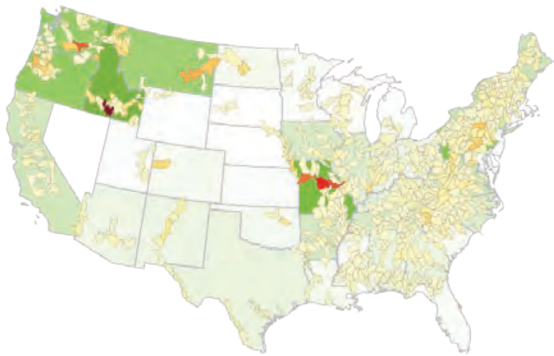
Figure 3-28 examines the impacts of water availability on each scenario by illustrating the impacts of *Wet* and *Dry* conditions on the 2050 growth of each hydropower resource category. Most of the differences in growth between scenarios are the product of changes to NSD deployment. Both NPD and upgrades experience higher deployment when more water is available and lower deployment when less water is available. These changes are within 1 GW except for the *Advanced Technology Scenario* and the *Low Cost Finance Scenario*, where a large fraction of the NPD resource is highly competitive with other technologies. The directional change in PSH deployment is typically opposite of those seen in the hydropower generation resources. This outcome is largely the result of regional market outcomes, particularly in the West.

Seasonal as well as annual changes to hydropower generation resources, particularly when reducing energy availability, can allow VG technologies to outcompete NSD (and some NPD) due to reduced capacity factors annually and across key seasons such as summer. Increased VG capacity can improve the value of PSH, resulting in greater deployment. Additionally, lower water availability results in a reduced capability for the existing fleet to meet reserve and balancing needs, again potentially improving the value of PSH.[18] While PSH variation is on the order of variation in other hydropower types, the relative change in PSH deployment is less than 10% for all water availability scenarios except *Business-as-Usual* and *Advanced Technology*, which deploy less than 3 GW of PSH under reference

**Advanced Technology, Low Cost Finance, High Fossil Fuel Cost, Dry** 13.8 GW Deployed



**Advanced Technology, Low Cost Finance, High Fossil Fuel Cost** 20.1 GW Deployed



**Advanced Technology, Low Cost Finance, High Fossil Fuel Cost, Wet** 22.5 GW Deployed

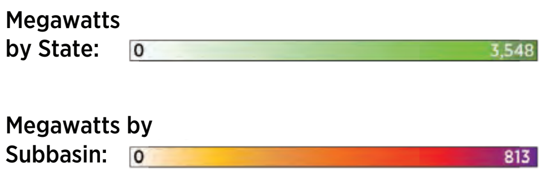



**Figure 3-29.** Influence of *Wet* and *Dry* water availability conditions on 2050 NSD deployment in the *Advanced Technology, Low Cost Finance, High Fossil Fuel Cost* scenario

18. It should be noted that the simplified water availability scenarios used here may not account for key economic and social impacts associated with climate change that may influence hydropower growth. In particular, water rights for hydropower resources are not explicitly modeled. This may suggest that PSH could face practical difficulties in securing water rights for development, as even closed-loop systems must perform an initial fill and then replenish water lost to evaporation and seepage.

water availability. On a relative basis, NSD opportunities are more affected by changing water availability than other hydropower types.

To examine the importance of regional differences in water availability, Figure 3-29 shows the change in NSD deployment across the *Advanced Technology, Low Cost Finance, High Fossil Fuel Cost* scenario and its *Wet* and *Dry* sensitivities. As the upper bound of NSD deployment, this scenario demonstrates the full possible range of effects from changes in water availability.

The impact of reduced water availability is illustrated in the lower deployment of NSD in western states in the *Dry* scenario. Deployment in the Eastern United States remains largely unchanged, but significantly less capacity is added in Idaho, Oregon, Washington, eastern Montana, and California. While the reductions in average annual water availability in California are modest, the modeled loss of runoff for Northern and Central California can exceed 70% during the summer months. Losing this much generation capability during what are often the most valuable times to produce power fundamentally harms the economic competitiveness of NSD in these and other areas, despite the cost (*Advanced Technology*) and value (*Low Cost Finance*) advances.

Results from the *Wet* scenario show a general increase in NSD deployment nationwide. However, some areas, such as Idaho and Western Montana, see a decrease in deployment despite increasing average annual water availability. The change in summer runoff alters the value proposition for the run-of-river NSD resource. By 2050, change in summer runoff for this area falls within a range of reductions of 25–40% despite an increase in the annual average.

# 3.5 Selected Costs, Benefits and Impacts of Hydropower Growth Scenarios

This section quantifies the costs and benefits associated with future hydropower deployment, as well as benefits associated with continued operation of the existing fleet through 2050. Future electricity rates and system costs; GHG and other pollution; and impacts on health, water for thermal cooling, and workforce are estimated for the nine selected scenarios. To estimate the impacts of new hydropower capacity (hydropower generation and PSH), a number of result metrics are compared between a given scenario and a corresponding baseline scenario in which hydropower electricity market conditions remain the same, and no new unannounced (as of the end of 2015) hydropower is built through 2050.[19]

The baseline scenario construct allows for quantification of impacts from all future hydropower deployment by quantifying the capacity and generation from other technologies that is offset by new hydropower, along with the corresponding implications within and outside the electric sector. It is important for a baseline to have consistent non-hydropower electricity market conditions with the scenario being compared, which means there are three baseline scenarios: a *High Fossil Fuel Cost Baseline* for the two scenarios with *High Fossil Fuel Costs*, a *Low VG Cost Baseline* for the scenario with *Low VG Costs*, and a *Central Baseline* for all other scenarios in which only hydropower parameters are varied. Impacts for the existing fleet are estimated by comparing the quantified costs and benefits of existing hydropower capacity to those that would result if this capacity were to be replaced by the composite mix of other generation sources in future (model) years under a baseline scenario with reference electricity market assumptions (e.g., the *Central Baseline*).

Results are often presented as a range from low to high, each corresponding to different methodological assumptions. These assumptions may include discount rates, different models used to calculate impacts, and assumptions about the growth of industries in the United States that support hydropower. Results ranges are also presented as a function of the nine modeled scenarios, which vary in future hydro

19. Announced post-2016 hydropower totals 40 MW of planned powering of non-powered dams, which has a negligible effect on the impacts assessed for the *Hydropower Vision* analysis.

power deployment (see Section 3.4). In many cases, the former methodological ranges are larger than the latter ranges of impacts across the four hydropower deployment scenarios analyzed.

The impacts discussion begins by examining the electric sector capacity and generation mix over time, which includes consideration of which technologies are displaced by incremental hydropower growth and a focused discussion of the role of PSH in providing operating reserves. Economic impacts within the electric sector are discussed next, with the key metrics being changes in national average electricity price, the present value of post-2016 electric system costs, and expenditures within the hydropower industry. Fossil fuel displacement then allows a discussion of energy diversity and risk. Changes in GHG and air pollution emissions are discussed, and these impacts are translated into an economic benefit using a range of social cost metrics in the literature. The thermal cooling water use reduction with displaced generation is then quantified. Finally, economic development impacts of hydropower deployment scenarios are discussed in the context of jobs and workforce needs.

Section 3.5 is organized as follows to characterize the listed impacts:

**3.5.1** Impacts on the electric sector

**3.5.2** National average electricity prices

**3.5.3** Present value of electricity system costs

**3.5.4** Hydropower industry expenditures

**3.5.5** Energy diversity and risk reduction

**3.5.6** Greenhouse gas emissions

**3.5.7** Air pollution and human health

**3.5.8** Thermal cooling water use

**3.5.9** Workforce and economic development

While the array of impacts detailed this section is extensive, it is by no means exhaustive. In particular, detailed site- and basin-specific environmental impacts of new hydropower deployment are not discussed, as such an assessment requires a level of detail that is outside the scope of the *Hydropower Vision*. Instead, this report uses scenarios with different environmental considerations to examine the high-level implications of local environmental characteristics and opportunities to address them. Lack of a broadly accepted methodology also prevents inclusion of biogenic emissions in the GHG discussion or water losses due to reservoir evaporation and leakage in the water use discussion. In addition, methodological limitations prevent quantification of indirect economic impacts from changes in water use or non-hydropower industry workforce changes.

## 3.5.1 Impacts on the Electric Sector

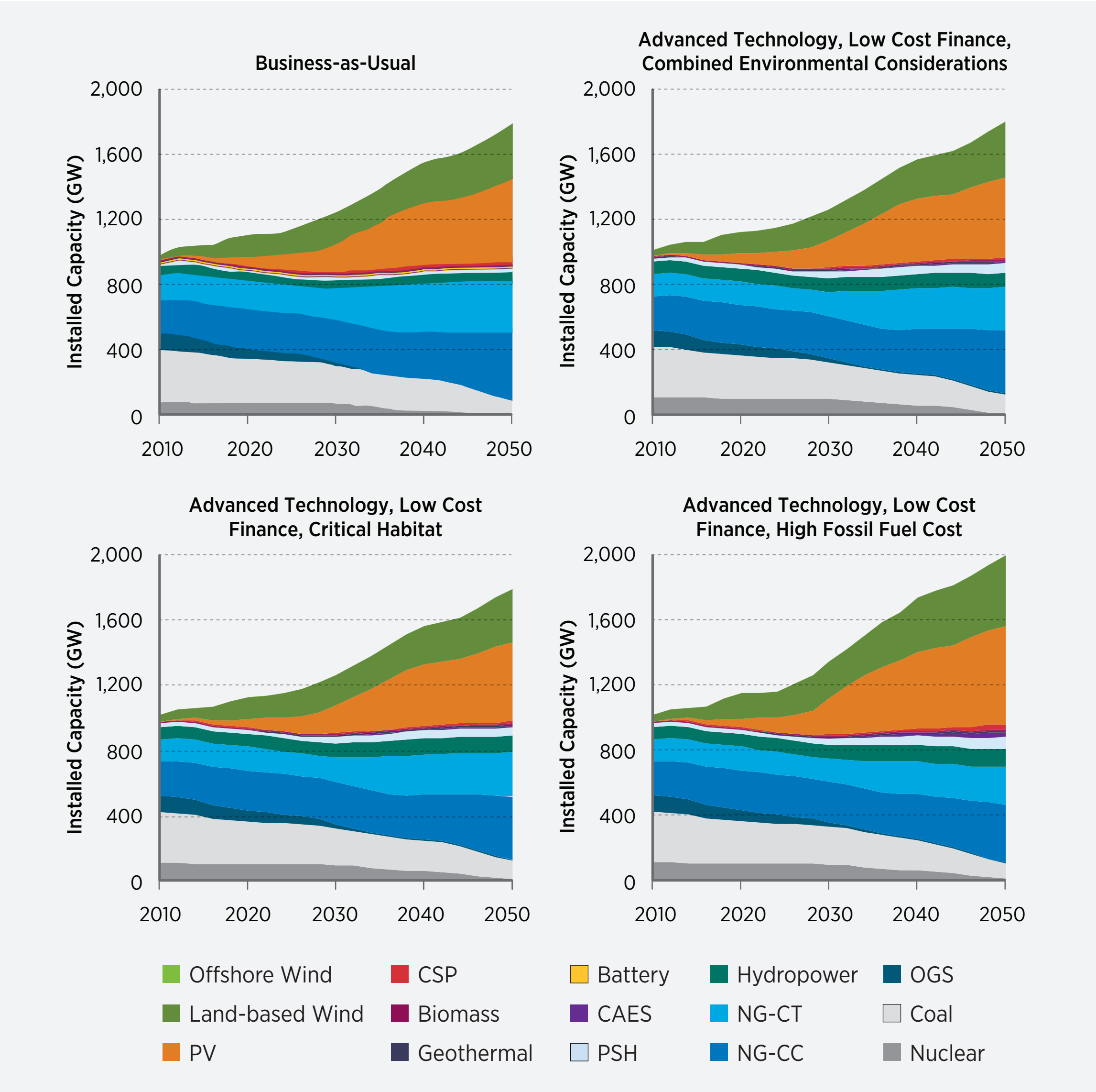
The U.S. electricity sector generated 4,093 TWh in 2014. This electricity comprised 39% coal, 27% natural gas, and 19% nuclear generation. Hydropower generation provided the most electricity of any renewable generation type at 6.3% in a lower-than-typical hydropower year, followed by 4.4% from wind, and 2.4% from other renewable generation including solar, geothermal, and biomass. The 6.3% of U.S. electricity produced by hydropower generation equated to about 260 TWh from the existing fleet [62]. Existing PSH consumed roughly 6 TWh of electricity in 2014 due to pumping efficiency losses, but PSH generation provided necessary flexibility services and reserves in the regions where it is available. The 102 GW of total existing hydropower constitutes 9.4% of the approximately 1,060 GW of total installed U.S. capacity at year-end 2014 [63].

Using these generation statistics as a reference point, this section describes the evolution of the U.S. electricity generation and capacity mix in the selected scenarios, focusing in some cases on the representative low, intermediate, and high scenarios for hydropower deployment. The scenarios examine several possible electric sector futures driven by fuel and technology costs, hydropower economics, and success with mitigating hydropower environmental impacts. These scenarios facilitate discussion of many variables important to the *Hydropower Vision,* but do not constitute a full range of possible outcomes. In addition, uncertainty exists in all electric sector results and increases as results extend further into the future. Factors that can influence electric sector outcomes include electricity load growth and distribution, plant retirement decisions, and future policy developments. While important, full consideration of all these issues is outside the scope of the *Hydropower Vision*.

## *Evolution of the Electric Sector*

It is important to understand the *Hydropower Vision* in the context of broader U.S. electricity system development, because many factors outside the hydropower industry can shape the future of U.S. hydropower. Fossil fuel and VG costs are two such variables discussed within this report; while other factors influence the electric sector, these two help examine a broader range of possible impacts.

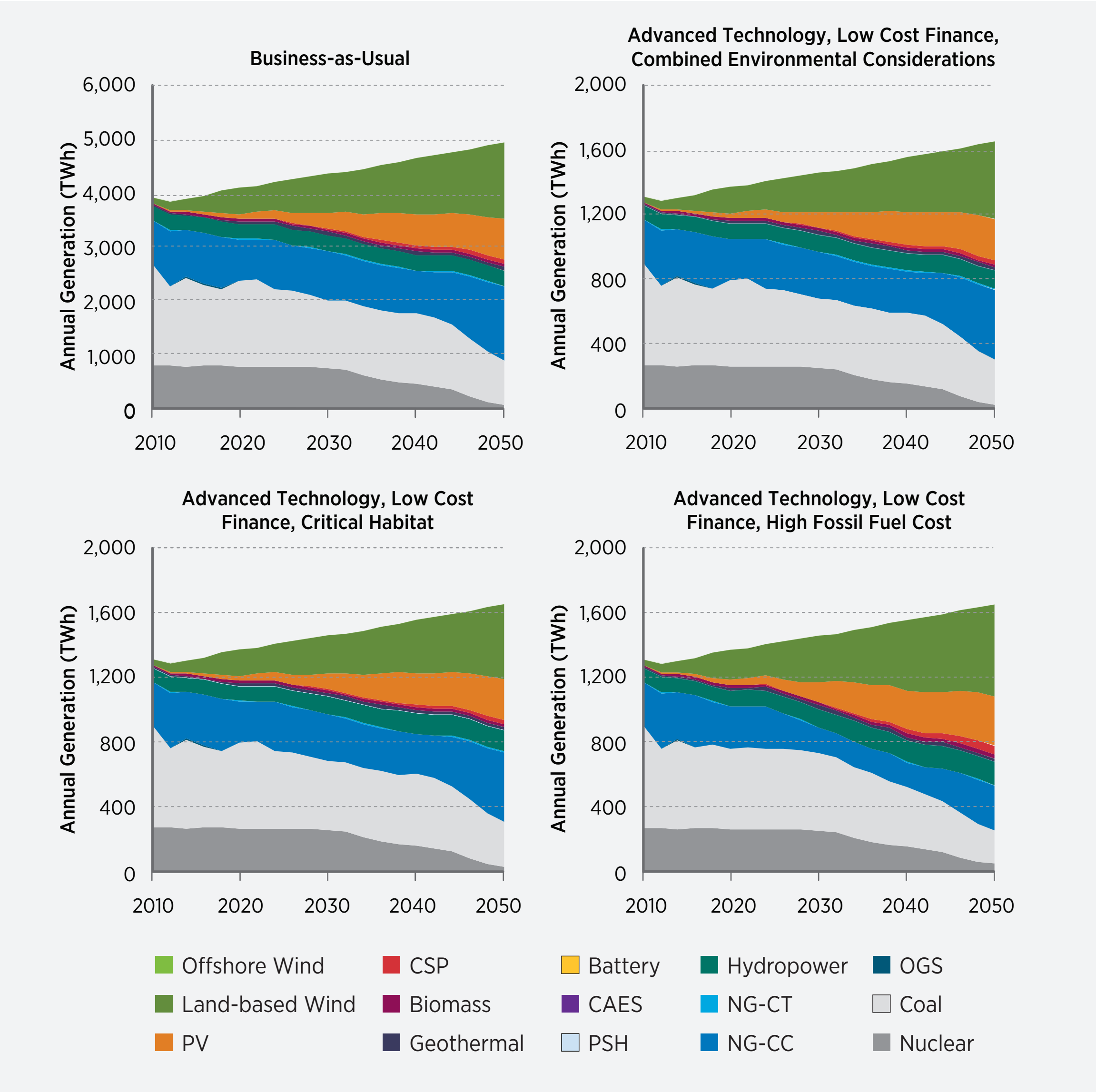
The national capacity and energy mix over time demonstrates overarching long-term trends in electric sector scenarios; these results are shown for the representative low, intermediate, and high deployment scenarios in Figures 3-30 and 3-31. Through 2030, total electricity sector capacity growth is modest, with most changes resulting from replacement of retiring fossil-fueled capacity with new renewable capacity. In the *Business-as-Usual* scenario, total hydropower generation capacity grows by 5 GW




Note: Solar Photovoltaics (PV), Concentrating Solar Power (CSP), Compressed Air Energy Storage (CAES), Pumped Storage Hydropower (PSH), Combustion Turbine Natural Gas (NG-CT), Combined Cycle Natural Gas (NG-CC), Oil-Based Generators and Gas-Steam Boilers (OGS).

**Figure 3-30.** Installed capacity by technology type and year in representative low, intermediate, and high deployment scenarios through 2030, while new PSH grows by 200 MW. At the same time, wind capacity grows by 110 GW and PV by 140 GW, and natural gas-based capacity grows by 45 GW to meet both reserve and electricity load requirements. Coal-based capacity declines by 50 GW and nuclear capacity is relatively stagnant (declining by 9 GW), as these technologies are not chosen over renewables or natural gas-based facilities after existing units retire. Near-term policy drivers such as renewable energy tax credits and the CPP help motivate success of renewables over fossil fuels and nuclear in this time period.

From 2030 to 2050, ReEDS predicts a rapid increase in capacity needs as fossil fuel and nuclear plants retire, electricity load increases, and economics favor VG with lower capacity value than the conventional resources being retired. For *Business-as-Usual* in 2050, wind capacity reaches 330 GW, while PV capacity reaches




Note: Solar Photovoltaics (PV), Concentrating Solar Power (CSP), Compressed Air Energy Storage (CAES), Pumped Storage Hydropower (PSH), Combustion Turbine Natural Gas (NG-CT), Combined Cycle Natural Gas (NG-CC), Oil-Based Generators and Gas-Steam Boilers (OGS).

**Figure 3-31.** Annual generation by technology type and year in representative low, intermediate, and high deployment scenarios

490 GW; combined, these resources supply 44% of electricity load. The grid flexibility needs required by new VG are provided by natural gas-based resources, primarily combustion turbines in the 2030s and combined-cycle units in the 2040s. Natural gas combustion turbines comprise a large portion of capacity but never supply more than 0.5% of electricity consumption in a year, as this capacity is used almost exclusively for peaking generation and reserves.

Scenarios that exclusively vary hydropower assumptions have a qualitatively similar national electricity mix as *Business-as-Usual* despite up to 31 GW of new hydropower generation and 55 GW new PSH. Differences are described in greater detail in subsequent sections of this chapter. Though the hydropower industry is substantially changed in many of these scenarios, particularly those including *Advanced Technology* and *Low Cost Finance* assumptions, the incremental change in hydropower remains small relative to the total electricity system size. As such, the national electric sector evolution remains largely the same.

In contrast, *High Fossil Fuel Costs* in the high hydropower deployment scenario example (*Advanced Technology, Low Cost Finance, High Fossil Fuel Cost*) drive the system towards greater use of renewable electricity and reduced use of natural gas. In 2050, wind capacity nears 440 GW, and PV capacity exceeds 600 GW. Together, those two generation sources supply 53% of electricity load, while the share of natural gas-based electricity falls to 17% from 28% in *Business-as-Usual.* Because variable generation has lower capacity value than the fully dispatchable resources it replaces, this scenario requires 210 GW more total capacity to meet planning and operating reserve requirements. Energy storage capacity also increases with VG penetration, reaching 105 GW of storage capacity in 2050.

The only other of the nine selected scenarios having a capacity expansion noticeably different from *Business-as-Usual* is the *Advanced Technology, Low Cost Finance, Critical Habitat, Low VG Cost* scenario. This scenario deploys less VG than when fossil fuel costs are high—but still more than *Business-as-Usual*—with 430 GW wind and 420 GW PV in 2050, which collectively supply 50% of 2050 electricity load. Assumed cost reduction trajectories are proportionally more favorable towards wind than PV, resulting in less PV capacity than *Business-as-Usual*. Natural gas-based generation supplies 22% of load, while storage capacity grows to 88 GW to provide grid flexibility.

### Technology Displacement Due to Hydropower Construction

Electric sector evolution is overall similar between *Business-as-Usual* and scenarios adjusting hydropower-specific parameters. Still, constant electricity load across all scenarios means that any additional electricity produced by hydropower resources must displace other technologies, and this generation displacement drives many of the impacts discussed in subsequent sections. Notably, such displacement is not unique to, or caused by hydropower and is germane to any technology that experiences growth in the context of total load remaining relatively constant. Regional differences in incremental hydropower deployment can also shift the regional distribution of VG and fossil fuel electricity, potentially resulting in high interannual variability in national displacement trends.

Figure 3-32 shows the difference in non-hydropower generation types between the representative low, mid, and high hydropower deployment scenarios and a baseline with no new hydropower. Positive numbers represent higher generation in the baseline scenario relative to the scenario allowing hydropower deployment.

Through the mid-2030s, hydropower displaces a mix of non-hydropower renewable energy (VG), as well as coal and natural gas. Past 2030, as VG growth accelerates and natural gas-based capacity and coal-fired units retire, hydropower displaces more natural gas and non-hydropower VG. *Business-as-Usual* builds 5 GW of new hydropower generation. These are primarily near-term upgrades, which tend to displace some natural gas and shift some electricity supply toward non-hydropower RE in early years and toward coal in later years, when remaining coal-based resources are used for flexible generation. When *Advanced Technology* and *Low Cost Finance* improve hydropower economic competitiveness, incremental hydropower resources displace a mix of natural gas and non-hydropower renewable energy. Relative displacement of natural gas is higher in scenarios with lower overall hydropower deployment (e.g., *Advanced Technology, Low Cost*

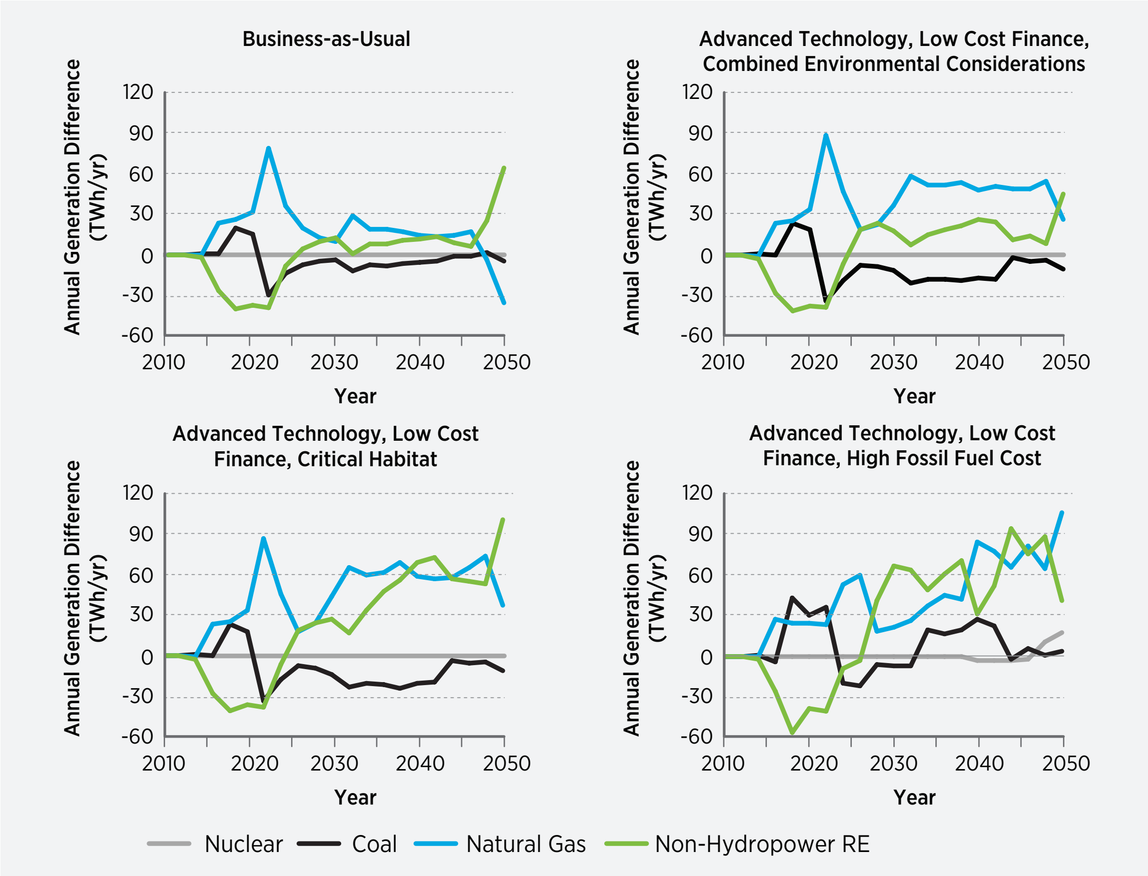
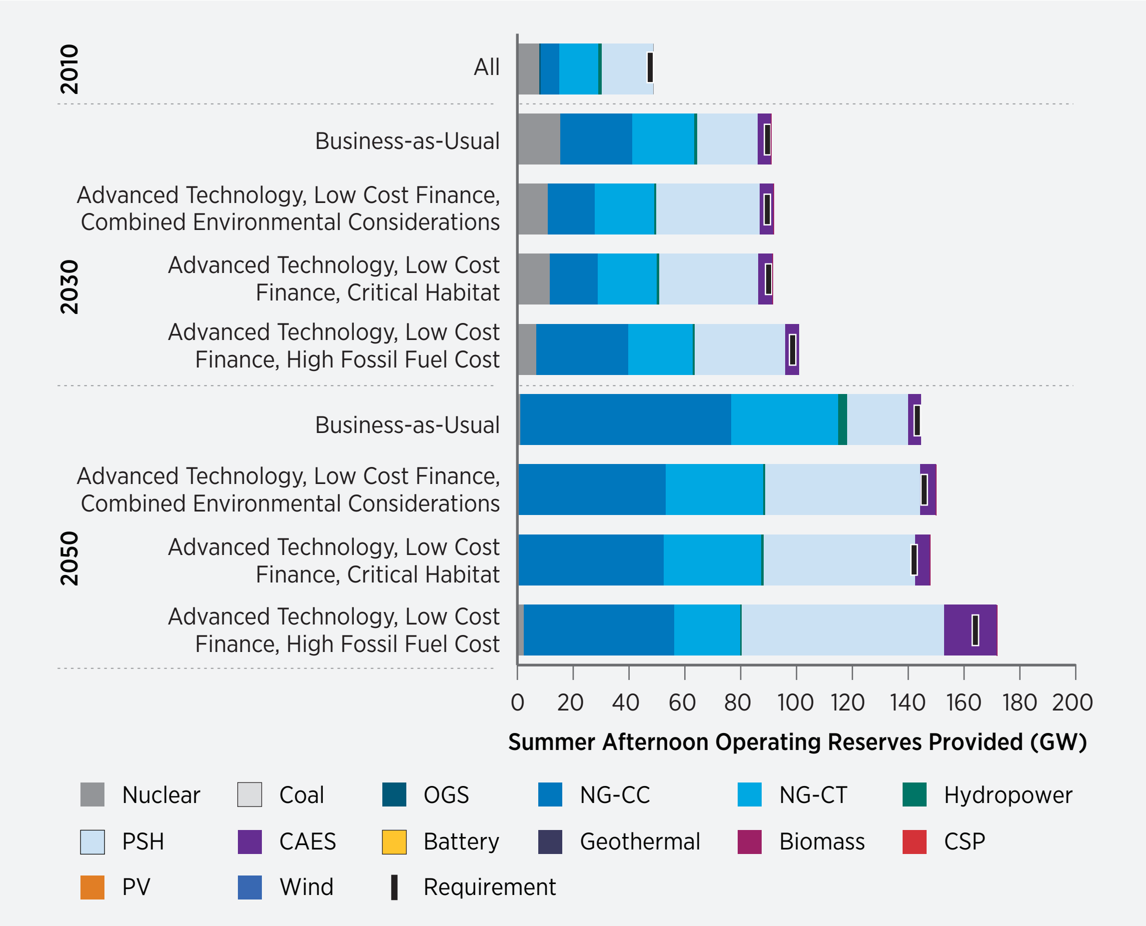



**Figure 3-32.** Difference in technology-specific generation between the baseline scenario and representative low, intermediate, and high deployment scenarios

*Finance, Combined Environmental Considerations*), with scenarios achieving higher levels of hydropower growth demonstrating non-hydropower RE displacement of a similar order as natural gas displacement.

Changes in coal-based generation vary, but many years have higher coal generation because new hydropower does not provide as much system flexibility as does the combination of natural gas and VG it replaces, particularly when new hydropower comprises inflexible NPD and NSD resource. These results demonstrate that under more favorable hydropower conditions, the technology could compete effectively with wind, PV, and natural gas-based resources. Nonetheless, the scale of this displaced generation—on the order of 0–100 TWh—represents a relatively small fraction of the electric sector as a whole (i.e., 2050 load is projected at more than 4,900 TWh).

Capacity displacement follows similar trends. For mid and high hydropower deployment scenarios, a greater share of natural gas-based ***capacity*** is displaced as compared to natural gas-based ***generation,*** because PSH displaces gas-based combustion turbines for reserve provision (and neither PSH nor combustion turbines contribute significantly to energy production). This effect is not observed with *Business-as-Usual,* because little new PSH is built. Across the representative low, mid, and high hydropower deployment scenarios, differences in 2050 capacity are in the range of 0–3 GW for coal, 1–54 GW for natural gas, and 5–42 GW for non-hydropower renewable energy.



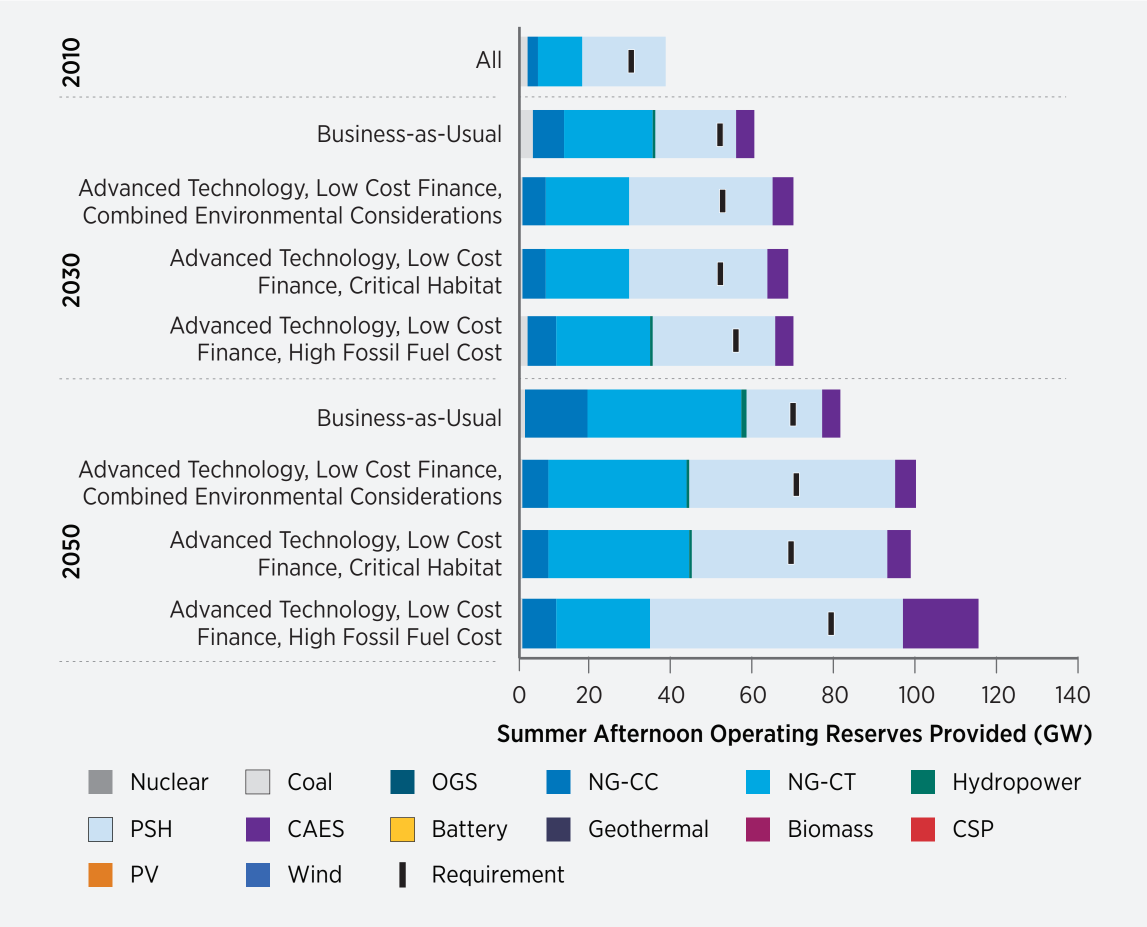

Note: Solar Photovoltaics (PV), Concentrating Solar Power (CSP), Compressed Air Energy Storage (CAES), Pumped Storage Hydropower (PSH), Combustion Turbine Natural Gas (NG-CT), Combined Cycle Natural Gas (NG-CC), Oil-Based Generators and Gas-Steam Boilers (OGS).

**Figure 3-33.** Comparison of summer afternoon operating reserves provision between representative low, intermediate, and high deployment scenarios

### *Pumped Storage Hydropower Role in Providing Electricity Reserves*

Section 3.4.1 discussed the relationship between PSH and VG generation, demonstrating that scenarios with higher VG generation support greater PSH deployment. One reason PSH can complement VG is its ability to provide reserve capacity. Load growth and VG growth increase operating reserve needs in the ReEDS model, as VG installation induces additional operating reserve requirements in the model. VG also has limited ability to provide planning reserves.

Figures 3-33 and 3-34 compare operating reserve provision by technology in 2010, 2030, and 2050 for the representative low, mid, and high deployment selected scenarios in the summer afternoon (Figure 3-33) and spring night (Figure 3-34). Summer afternoon is when national electricity load is the highest, so most generating capacity provides energy and little is left available for reserves. Spring night is when national electricity load is the lowest, so this time period reveals the preferred resources for reserves when there is a large amount of available capacity. In both time periods, operating reserves are provided primarily by NG-CC (natural gas combined cycle), NG-CT (natural gas-fired combustion turbines), and PSH, with some coal contribution in the short- to mid-term and some CAES in the mid- to long-term. Oversupply of reserves can occur if capacity can be made available for reserves at negligible cost. In




Note: Solar Photovoltaics (PV), Concentrating Solar Power (CSP), Compressed Air Energy Storage (CAES), Pumped Storage Hydropower (PSH), Combustion Turbine Natural Gas (NG-CT), Combined Cycle Natural Gas (NG-CC), Oil-Based Generators and Gas-Steam Boilers (OGS).

**Figure 3-34.** Comparison of spring night operating reserves provision between representative low, intermediate, and high deployment scenarios

*Business-as-Usual*, nearly all PSH capacity is committed to providing operating reserves in all years, and very little PSH is supplying energy. The cost of being available for reserves is negligible, so PSH is an attractive technology for operating reserves. When substantial new PSH capacity is constructed in scenarios with *Advanced Technology* and *Low Cost Finance* assumptions, its contribution to operating reserves grows in kind, displacing natural gas-based capacity. In these scenarios, PSH provides more operating reserves[20] than any other technology by 2050.

## 3.5.2 National Average Retail Electricity Price

Electricity prices are the most tangible and visible metric by which consumers experience the changing economics of the power system. As described in Section 3.1, the ReEDS model estimates a cost-of-service electricity price over time in each scenario. While ReEDS does not have sufficient resolution for this price to directly represent individual or regional consumer electricity prices, comparing national aggregate electricity prices provides an understanding of the incremental impact of a given scenario on electricity prices.

20. In addition to operating reserves, ReEDS also requires a certain level of planning reserves in the power system. Given its inherent flexibility, PSH can provide its full capacity towards planning reserves, supporting the deployment of variable wind and solar energy technologies that provide only a fraction of total capacity towards planning reserves.

Figure 3-35 plots the incremental change in ReEDS electricity price of the selected scenarios compared to a baseline scenario with no new hydropower. Allowing economic hydropower construction allows for slightly lower electricity prices in most years across all scenarios. Scenarios with *Advanced Technology* and *Low Cost Finance* assumptions tend to see greater improvements in the long-term due to increased deployment of economic hydropower. All changes to electricity price, however, are relatively small and of a similar order of magnitude because incremental new hydropower is a relatively small portion of the system. Electricity price reductions are typically on the order of 0.1¢/kilowatt-hour (kWh) or less, which corresponds to a 1% change or less. Across a wide range of future possible hydropower deployment scenarios, electricity prices are not likely to be strongly affected.

## 3.5.3 Present Value of Total System Cost

The total present value of expenditures within the modeled power system is a single-value economic metric for all capital and operating costs across the entire ReEDS study period. Total system costs are calculated for all scenarios. Changes in total system costs, as a function of changes in scenario inputs, are subsequently used to demonstrate the economic impact of changing the power system conditions.

*Business-as-Usual* has a total system cost of $3,960 billion (which represents a savings relative to the baseline). More than half of this cost comes from natural gas, coal, and nuclear fuel. The biggest drivers of system cost across the scenario sensitivities are fossil fuel and VG costs, as these variables alter the costs of the predominant technology types. Selected scenarios with *High Fossil Fuel Costs* have total system costs of $4,030 billion, while the *Advanced Technology, Low Cost Finance, Low VG Cost* scenario reduces costs to

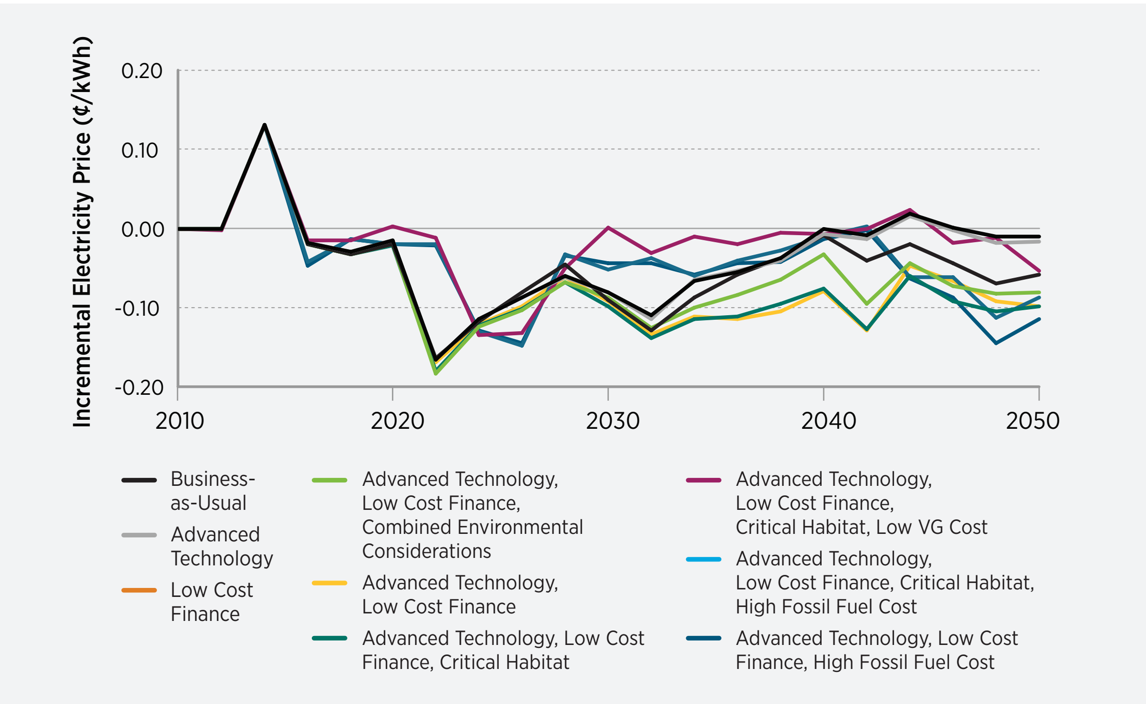



**Figure 3-35.** Incremental average electricity prices in selected scenarios relative to their corresponding baseline scenarios

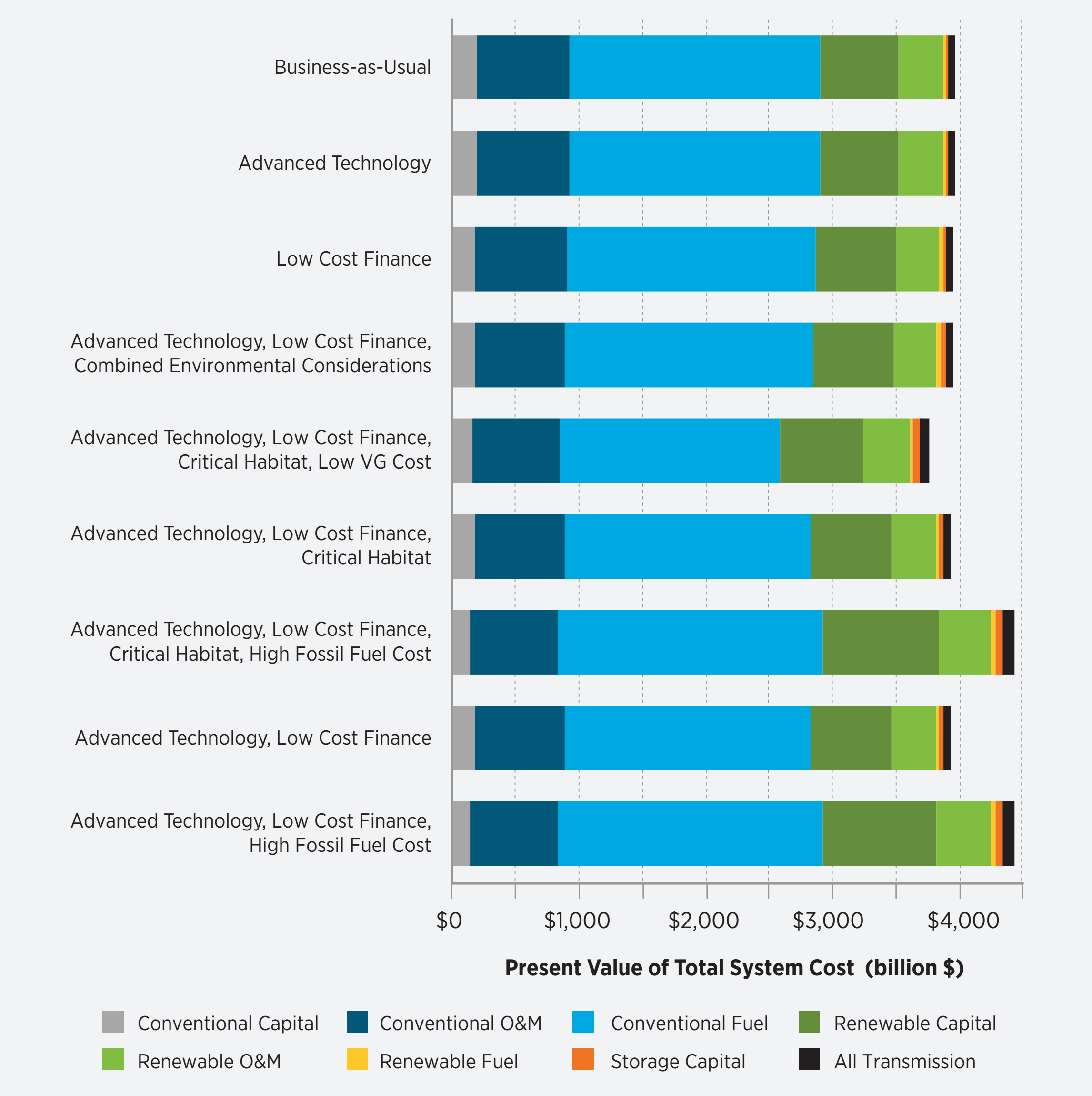



**Figure 3-36.** Present value of total system cost for the selected scenarios

$3,760 billion. Scenarios varying these cost assumptions in the opposite direction (not shown) change system costs by a similar magnitude in the opposite direction.

Relative to these major power system cost drivers, hydropower economics and resource variables have a less noticeable impact on system costs as a whole (Figure 3-36). System costs for scenarios varying hydropower economics and resource are $0–$26 billion less than *Business-as-Usual*, which corresponds to less than a 1% change for the scenario assuming *Advanced Technology, Low Cost Finance*, and no NSD resource avoidance.

While the effects of hydropower-specific variables are less than the changes caused by fossil fuel and wind/solar costs, the relative power system cost and savings of the selected scenarios can still be evaluated. To illustrate this comparison, Figure 3-37 plots the incremental present value of system savings for the selected scenarios relative to the baseline.

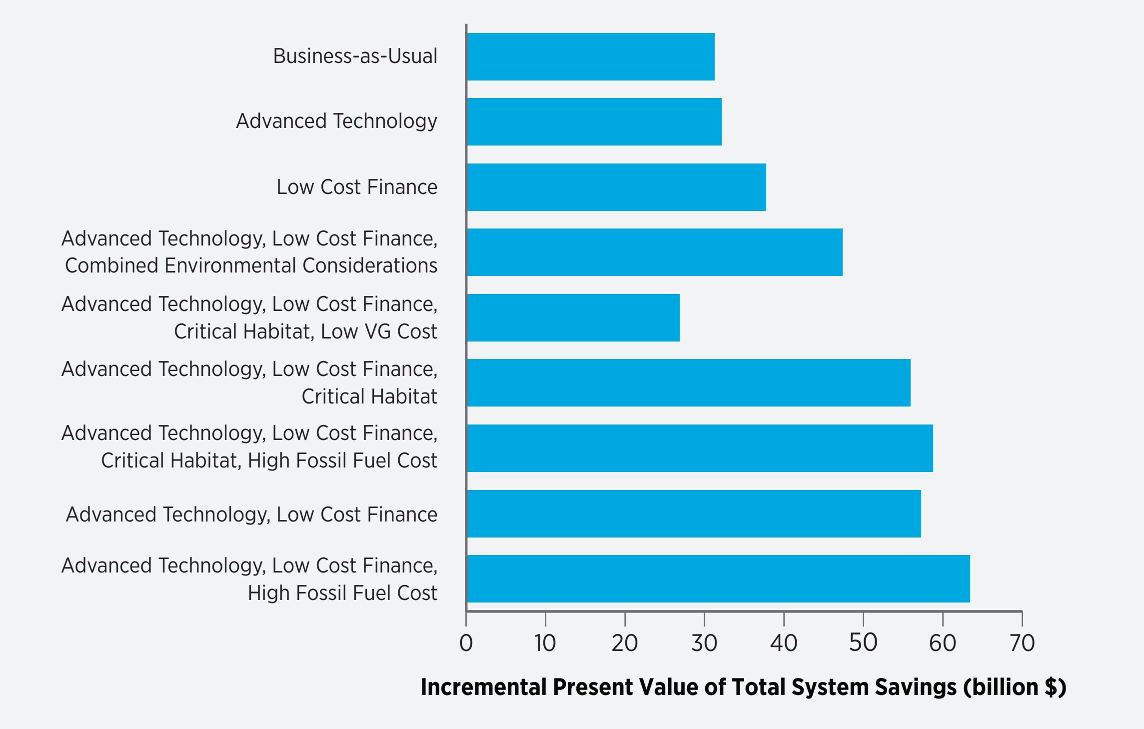



**Figure 3-37.** Incremental system costs of selected scenarios, relative to their corresponding baseline scenarios

The range of savings across selected scenarios is $27 billion to $63 billion, corresponding to 0.7–1.4% of total system costs. Absent any improvements to hydropower technology costs or financing, *Business-as-Usual* produces $31 billion in savings, primarily by allowing economic hydropower generation upgrades that produce low-cost electricity. While an additional $6 billion is spent on renewables due to direct and indirect expenditures from hydropower growth, $36 billion is saved in fossil and nuclear fuel and capital costs. The bulk of the latter is in fossil fuel savings.[21]

For other scenarios, savings are largely proportional to hydropower deployment, which follows from the hydropower economics and resource assumptions in these scenarios. The scenario with highest deployment, *Advanced Technology, Low Cost Finance, High Fossil Fuel Cost,* achieves $63 billion in savings. Renewable and storage costs increase by $75 billion, but these added costs are more than offset by fossil and nuclear cost savings of $134 billion. Though the relative costs and savings from each cost category vary across scenarios, savings are consistently achieved primarily through reduced fossil and nuclear costs, with the largest contributor being fossil fuel costs.

The notable exception to the relationship between savings and hydropower deployment is the *Advanced Technology, Low Cost Finance, Critical Habitat, Low VG Cost* scenario. With *Low VG Costs*, lower baseline natural gas usage and prices lead to a smaller incremental benefit from displacing natural gas-based generation with hydropower. Though *Low VG Costs* lead to an overall lower-cost system than *Business-as-Usual*, this system with high renewable generation and low fossil fuel generation reduces the opportunity for hydropower to displace fossil fuel generation and cost.

Though substantial in magnitude for the hydropower industry, incremental cost savings on the order of 1% remain relatively small in the context of total system costs. While the *Hydropower Vision* analysis scenarios reduce electric sector costs under a wide range of system conditions, the absolute change is much smaller than the stronger market drivers such as fossil fuel or VG costs.

21. The remaining balance is storage capital, storage operations and maintenance, and transmission costs.

## 3.5.4 Hydropower Capital and Operating Expenditures

Capital and operating costs for hydropower are shown for representative low, mid, and high deployment scenarios in Figure 3-38. Capital costs follow largely from trends in capacity deployment, while operating costs grow over time as new capacity comes online. Before 2018, expenses in all scenarios are primarily operating costs of the existing fleet and capital costs attributed to announced hydropower projects that come online through 2018. After 2018, costs in the *Business-as-Usual* scenario are primarily attributed to continued operation of the existing fleet, with the only notable difference being pre-2030 capital costs for upgrades. Other scenarios deploy NPD and NSD resource, so capital costs for hydropower generation are much higher than *Business-as-Usual* in many years. The temporary reduction in new capacity in the early 2030s can be attributed to the stagnating stringency of the CPP, which temporarily reduces incentives for low-carbon electricity before demand growth motivates additional low-carbon capacity growth. The highest-cost time periods are those when

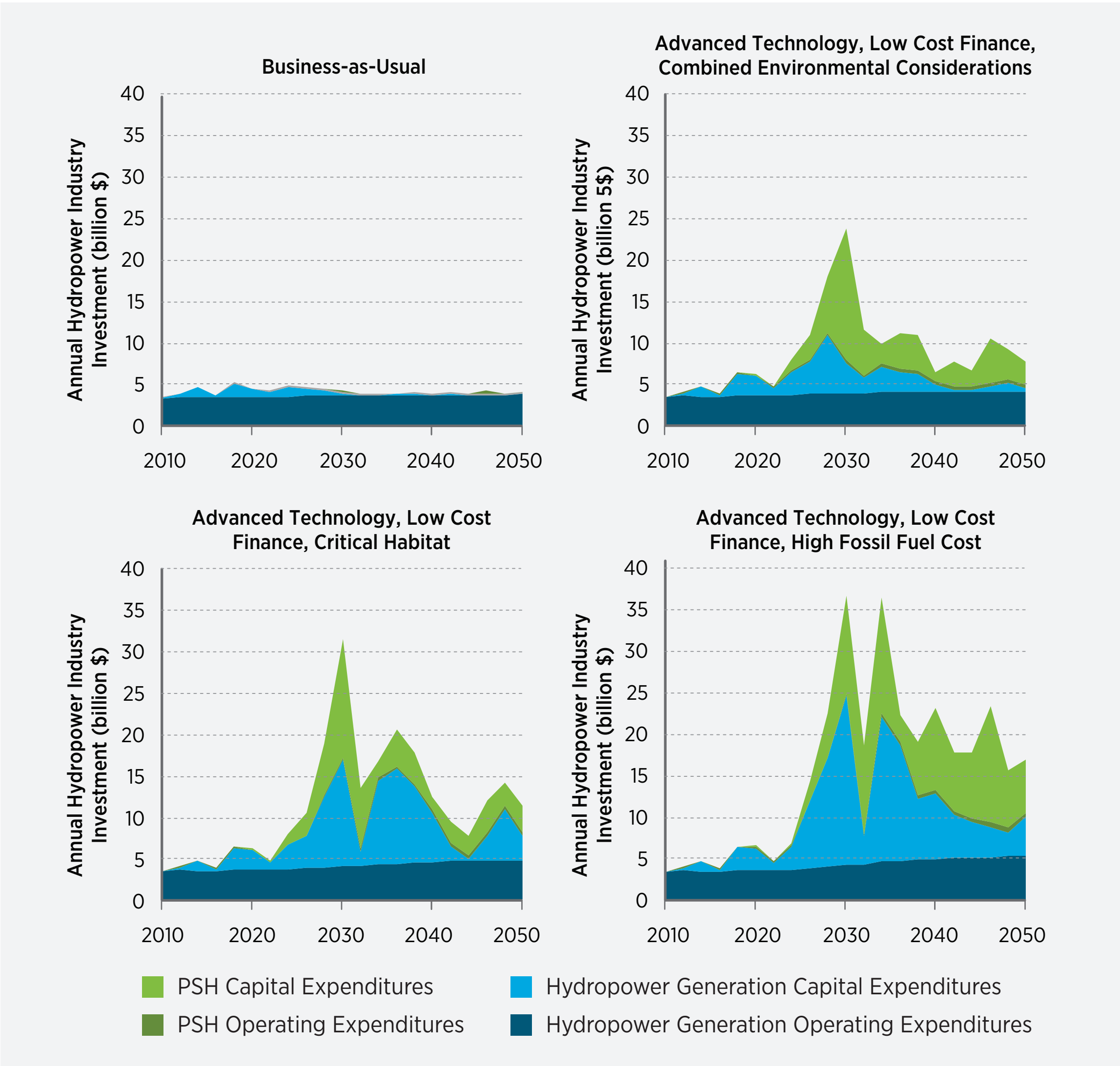



**Figure 3-38.** Hydropower industry investments by market segment in *Advanced Technology, Low Cost Finance, Critical Habitat* scenario and representative low, mid, and high deployment scenarios

large quantities of both NSD and PSH are deployed. While NSD deployment tends to fall in the later years, PSH deployment remains strong in scenarios supporting high deployment.

Annual variance in industry costs is likely higher than what would be observed in practice due to supply chain constraints, financing behavior, and construction schedules. The average post-2016 expenditures are $4.2 billion/year in *Business-as-Usual*; $9.9 billion/year in *Advanced Technology, Low Cost Finance, Combined Environmental Considerations*; $13.0 billion/year in *Advanced Technology, Low Cost Finance, Critical Habitat*; and $18.2 billion/year in *Advanced Technology, Low Cost Finance, High Fossil Fuel Cost*. For a given scenario, annual industry costs would likely be somewhere between this average and the range of values observed in model years.

### 3.5.5 Energy Diversity and Risk Reduction

Electric sector resource planning must account for unique risk profiles for different sources of electricity. For instance, capital-intensive technologies are subject to construction material prices, while fossil fuel-based technologies are subject to risks in fuel supply and price. Additional risks result from environmental impacts and the potential for social or political barriers to cost-effective construction and operation of electricity systems. Hydropower is exposed to risk in capital prices (and interest rates), environmental impacts, and variability in long-term and year-to-year water availability. Once built, however, hydropower becomes a low-cost electricity source with high predictability on the daily to weekly time scales that are important for balancing electricity supply and demand.

The impact of the selected scenarios on system cost uncertainty and risk can be examined in the context of the ReEDS model by comparing how hydropower growth reduces the range of potential system costs when other market variables are uncertain. With reference hydropower assumptions, the present value of system costs can range widely depending on the trajectory of fossil fuel and VG prices; high fossil fuel costs ***increase*** power system costs 14%, while low costs ***reduce*** this cost by 15%. Variation in VG costs with reference hydropower assumptions ***increases*** power system cost by up to 10%, or ***reduces*** it by 5%. Hydropower deployment under *Advanced Technology, Low Cost Finance* scenario conditions reduces these uncertain ranges by less than 1% in each case, as new hydropower deployment makes up a small fraction of the system as a whole.

New hydropower also reduces fossil fuel use, which can affect the supply-demand equilibrium for fossil fuels and, as such, potentially reduce fossil fuel prices. Figure 3-39 plots the difference in coal and natural gas usage between the nine selected scenarios and a no new hydropower baseline. Positive values indicate higher fuel use or cost than the baseline, while negative values indicate lower fuel use or cost than the baseline. Modeled coal use throughout the study period varies from 15–16 quadrillion British thermal units (Btu) in 2016 to 6–9 quadrillion Btu in 2050, while natural gas use is 7 quadrillion Btu in 2016 and 6–10 quadrillion Btu in 2050. As such, the differences shown in these figures are on the order of 10% or less of the total. For scenarios varying only hydropower assumptions, coal usage is slightly higher in many years to replace flexible generation capabilities lost when hydropower displaces flexible natural gas-based capacity. Across these scenarios, coal usage ranges from a 1.8 quadrillion Btu reduction to a 4.3 quadrillion Btu increase. With *High Fossil Fuel Costs* or *Low VG Costs*, however, new hydropower generation more persistently results in reduced coal usage, with a 2017–2050 reduction of 3.1–5.6 quadrillion Btu. Consistent with the generation displacement results shown in Figure 3-32, natural gas usage is lower for scenarios when improved hydropower economics lead to substantial new deployment.

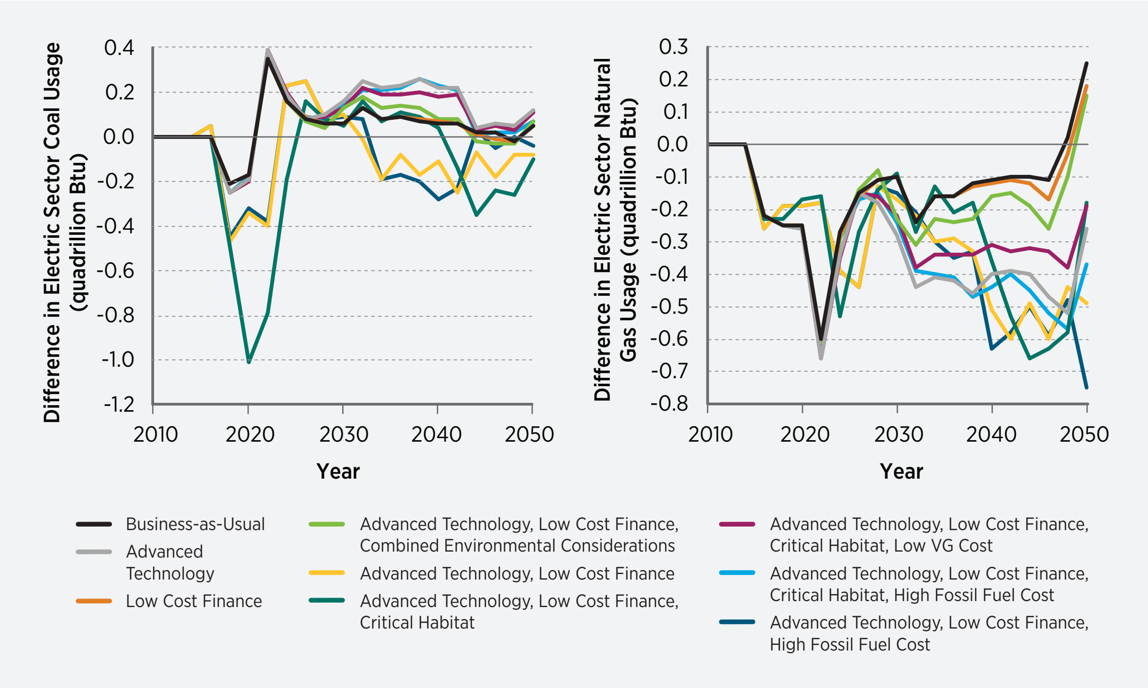



**Figure 3-39.** Differences in electric sector fossil fuel usage in selected hydropower generation and pumped storage hydropower deployment scenarios relative to a no new hydropower baseline (differences taken as scenario value minus baseline value)

ReEDS does not contain a full fossil fuel supply sector model, but it does incorporate natural gas supply curves to represent price elasticity to natural gas demand in the electric sector.[22] This framework produces modeled natural gas prices, which are then used to produce Figure 3-40 plotting differences in national average natural gas prices between each scenario and a no new hydropower baseline. Trends follow those in natural gas usage, with lower gas usage corresponding to lower prices for a given set of electricity market conditions[23]. Gas prices vary from approximately $5/MMBtu (one million British Thermal Units) in 2018 to $9/MMBtu in 2050 for scenarios with reference fossil fuel costs and reach $11.5/MMBtu with *High Fossil Fuel Costs*, making price differences in Figure 3-40 within 3% of the baseline in all years and scenarios. Though this change is small, the absolute impact can be more noticeable given the large volumes of natural gas used. For instance, if the ReEDS gas price reductions were applied to AEO 2015 Reference Case projections of non-electric sector natural gas usage, the result is a net present value range across scenarios (from 2017 to 2050 discounted at 3% real) of $11 billion to $31 billion in natural gas cost savings to consumers outside of the electric power sector [19].[24]

22. Coal prices are exogenously specified in ReEDS as described in Section 3.1 and Appendix D.

23. For example, scenarios with *High Fossil Fuel Costs*, while having higher absolute natural gas prices, are compared to a *High Fossil Fuel Cost* baseline, so the price changes are of the same order as other scenarios.

24. This consumer savings constitutes primarily a transfer from producers (including owners and investors) to consumers, and, as such, it does not necessarily represent an economy-wide increase in disposable income. In addition, this calculation does not take into account any possible increase in natural gas demand due to reduced prices. A detailed economic analysis that fully accounts for fuel supply and demand equilibrium is outside the scope of this report, but the calculations herein demonstrate that the *Hydropower Vision* could allow fossil fuel cost savings both within and outside the electric sector, particularly to consumers.

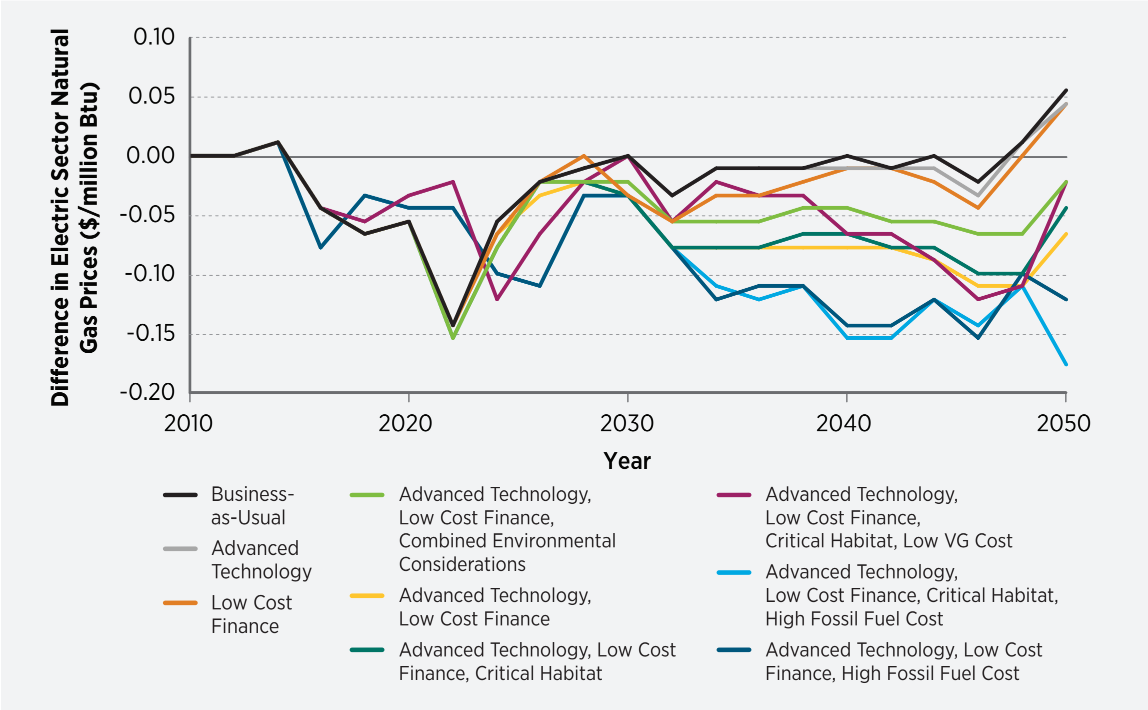



**Figure 3-40.** Differences in electric sector natural gas prices in selected hydropower generation and pumped storage hydropower deployment scenarios relative to a no new hydropower baseline (differences taken as scenario value minus baseline value)

## 3.5.6 Greenhouse Gas Emissions Reductions

The majority of scientists agree that significant changes will occur to the Earth's climate on both multi-decadal and multi-century scales as a result of past and future anthropogenic GHG emissions [16]. Renewable energy (including hydropower) could be deployed to reduce projected GHG emissions, which, in turn, could help to decrease the likelihood and potential severity of future climate-related damages [20, 21].

This section discusses estimates of the potential GHG reductions resulting from new hydropower growth within the nine selected scenarios explored in detail within the *Hydropower Vision* analysis. All scenarios are considered relative to a baseline scenario with no new hydropower construction. The impact of potential GHG emissions avoided by retaining the existing hydropower fleet is also assessed by assuming that, if existing hydropower were not available, it would be replaced by the average generation mix in the remainder of the fleet, in a given region, in a given ReEDS solve year (see also Section 3.1). GHG impacts are estimated on a life cycle basis and are based on a review of peer-reviewed publications and knowledge as of 2016 of GHG emissions from hydropower and other electricity generation technologies.[25] The economic value of the GHG reductions associated with

25. A life cycle-based assessment considers upstream emissions, ongoing combustion and non-combustion emissions, and downstream emissions. Upstream and downstream emissions include emissions resulting from raw materials extraction, materials manufacturing, component manufacturing, transportation from the manufacturing facility to the construction site, on-site construction, project decommissioning, disassembly, transportation to the waste site, and ultimate disposal and/or recycling of the equipment and other site material. For more information on the life cycle emissions (and associated uncertainties) for a range of renewable and non-renewable electricity generating technologies, see Appendix G, which includes results from an extensive database of published life cycle assessments on electricity generation technologies available through the National Renewable Energy Laboratory's Life Cycle Assessment Harmonization project: *www.nrel.gov/harmonization*. Direct combustion-related emissions for ReEDS scenarios are calculated but not reported quantitatively in this section of the *Hydropower Vision*.

reduced carbon dioxide emissions are then estimated based on a range of independently developed social cost of carbon (SCC) estimates, in terms of present value dollars [22, 23].[26]

The *Hydropower Vision* acknowledges that there are important scientific questions surrounding the potential for GHG emissions from bacterial processes in waters and soils (hereafter "biogenic GHG emissions") of any freshwater systems, including impoundment systems such as hydropower reservoirs. However, given the state of scientific understanding and discourse, the *Hydropower Vision* does not attempt to address hydropower-related biogenic GHG emissions given persistent, large uncertainties. Instead, an introduction to biogenic GHG emissions and a review of the literature focused in this field are described in Text Box 3-1. This limitation is acknowledged as a source of uncertainty generally in the estimation of life cycle GHG emissions as a function of hydropower deployment.

In addition to GHG emissions, this chapter also considers another related metric—energy return on investment (or EROI)—that is often used to compare energy technologies on a life cycle basis, and one in which hydropower electricity performs well in comparison to other electricity generation sources. The literature on the EROI of different electricity generation technologies, including hydropower, is also summarized (Text Box 3-2).

### *Hydropower Electricity and Reduced Greenhouse Gas Emissions*

Maintaining the existing fleet and achieving the hydropower deployment levels of the nine selected scenarios explored here will generally reduce fossil energy use, leading to reduced fossil fuel-based GHG emissions in the electric sector. At a sub-national level, existing fleet contributions to avoided combustion emissions are concentrated in the Pacific Northwest and in New York. Similarly, combustion GHG emissions avoided with new hydropower are concentrated in portions of Arkansas and New York, as well as parts of the Southeast, Midwest, and West Coast.

On a life cycle basis, GHG emissions from hydropower electricity generation are lower than fossil fuels and similar to other renewable technologies (see Appendix G). As a result, the nine scenarios evaluated for the *Hydropower Vision* result in life cycle GHG emission reductions larger in absolute terms than combustion-only carbon dioxide ($CO_2e$) reductions. Figure 3-41 and Table 3-6 show the life cycle emissions reductions associated with the selected scenarios through time, relative to a baseline scenario.

Initially, the existing hydropower fleet avoids annual emissions of around 0.25 gigatonnes (GT) of carbon dioxide equivalent ($CO_2e$)/year near 2016. This value gradually declines to near zero by 2050 as carbon intensity of the remaining non-hydropower generation mix declines. Cumulative avoided GHG emissions by the existing fleet from 2017–2050 are estimated at 4.9 GT $CO_2e$. Annual emissions reductions from new hydropower deployment scenarios vary from 0—0.10 GT $CO_2e$/year between 2017–2050. Cumulative GHG emission reductions (2017–2050) from new hydropower deployment range from 0.2–1.3 GT $CO_2e$, with increased hydropower deployment and high fossil fuel prices contributing to outcomes with greater GHG reductions.

While estimates in Figure 3-41 and Table 3-6 suggest potential for hydropower electricity in reducing GHG emissions, there are two key factors that introduce some uncertainty in these results and may affect the actual emissions savings from hydropower growth. First, as discussed in Text Box 3-1, all freshwater systems have potential for biogenic GHG emissions. Second, GHG reductions in the electric sector may induce secondary impacts throughout the economy, including economy-wide rebound[27] and spillover[28] effects. Moreover, the model used for the *Hydropower Vision* analysis focuses on the electric sector, and the analysis is intentionally policy-agnostic.

26. The SCC methods applied here are consistent not only with those used by U.S. regulatory agencies [24], but also with those used in the academic literature [25, 26, 27, 28, 29].

27. The rebound effect is a reduction in expected gains from the use of new technologies due to several potential economic reactions. Increased use of the new technology lowers the costs of alternatives that can be substituted, decreased new technology costs allow increased household consumption of other goods and services, and new technologies allow for the new technological possibilities that build on the new technology

28. Spillover effects are a specific instance in which the use of a new technology within a defined geographic area leads to rebound effects specifically outside that geographic area.

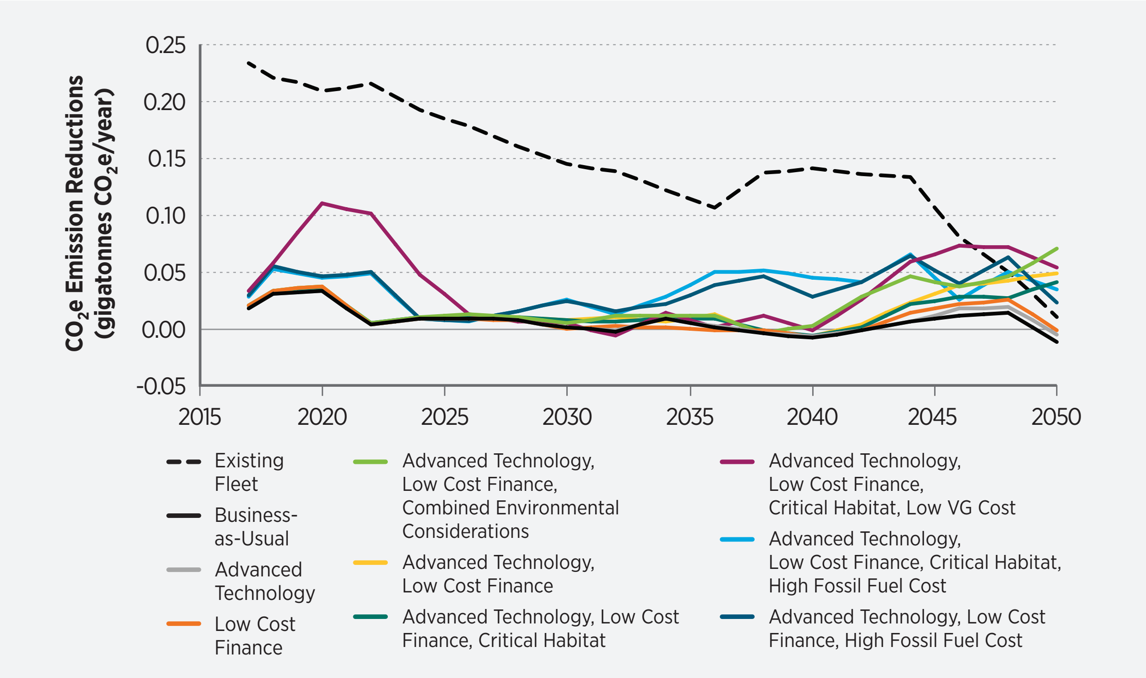



**Figure 3-41.** Annual life cycle greenhouse gas emissions avoided by the existing fleet and emission reductions of the selected scenarios

**Table 3-6.** Total Cumulative Life Cycle Emissions Reductions

| Scenario | 2017–2030 | | 2017–2050 | |
|---|---|---|---|---|
| | Reduction (GT $CO_2e$) | Percent Change | Reduction (GT $CO_2e$) | Percent Change |
| *Existing Fleet* | 2.7 | (8.9%) | 4.9 | (7.2%) |
| *Business-as-Usual* | 0.2 | (0.6%) | 0.2 | (0.3%) |
| *Advanced Technology* | 0.2 | (0.6%) | 0.3 | (0.4%) |
| *Low Cost Finance* | 0.2 | (0.7%) | 0.3 | (0.5%) |
| *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* | 0.2 | (0.8%) | 0.7 | (1.1%) |
| *Advanced Technology, Low Cost Finance, Critical Habitat* | 0.2 | (0.8%) | 0.5 | (0.7%) |
| *Advanced Technology, Low Cost Finance* | 0.2 | (0.8%) | 0.5 | (0.8%) |
| *Advanced Technology, Low Cost Finance, Critical Habitat, High Fossil Fuel Cost* | 0.4 | (1.4%) | 1.2 | (1.9%) |
| *Advanced Technology, Low Cost Finance, High Fossil Fuel Cost* | 0.4 | (1.3%) | 1.2 | (2.0%) |
| *Advanced Technology, Low Cost Finance, Critical Habitat, Low VG Cost* | 0.7 | (2.4%) | 1.3 | (2.0%) |

Literature has shown that spillover and rebound effects can impact GHG savings, as can the specific policy mechanisms used to support renewable energy deployment [21]. Depending on how policies are deployed,[29] the significance of rebound and spillover effects, and the potential for biogenic emissions, actual GHG reductions estimated may either be higher or lower than the results presented here.

### *Economic Benefits of Hydropower in Limiting Climate Change Damages*

The economic benefits of hydropower energy resulting from its ability to limit damages from climate change can be estimated through the use of the SCC. The SCC reflects, among other things, monetary damages resulting from the future impacts of climate change on agricultural productivity, human health, property damages, and ecosystem services [81]. The methodology for estimating the benefits from reduced GHG emissions involves multiplying the emissions reduction (on a life cycle, $CO_2e$ basis) in any given year by the SCC for that year, and then discounting those yearly benefits to the present.[30] Because of the significant role that the existing hydropower fleet plays in carbon abatement, benefits are calculated for new hydropower under the nine selected scenarios as well as for the existing fleet.

Estimating the magnitude and timing of climate change impacts, damages, and associated costs is challenging, especially given the many uncertainties involved [20, 23, 44, 47, 48, 49, 50, 81]. Models of climate response to GHG emissions and damage functions associated with that response are imperfect. Even when looking to events over the several decades leading up to 2014, such as the upward trend in damage costs associated with extreme environmental events [51], caution is necessary to separate causation from correlation [52]. In addition, because the majority of effects will be felt decades and even centuries in the future, the choice of discount rate becomes a key concern when estimating the present value of future damages. The choice of discount rate can greatly influence the relative benefits and timing of alternative strategies to reduce carbon emissions [53, 54].

In part as a result of these challenges, a number of widely ranging estimates of the SCC are available [21, 49, 55]. Key uncertainties about the SCC result from: (1) difficulties in estimating future damages associated with different climate-related causes, as well as uncertainties about the likelihood, timing, and potential impact of (nonlinear) tipping points; (2) the high sensitivity of the SCC to assumptions about growth in world population, gross domestic product, and greenhouse gas emissions; and (3) large differences in the present value of estimated damages depending upon choice of discount rate [49, 56, 57].

Though these uncertainties have led to some suggestions of possible improvements to SCC estimates [54, 58, 59, 60] and to questions about the use of these estimates [57], U.S. government regulatory bodies regularly use SCC estimates when formulating policy [24, 59]. Under Executive Order 12866, U.S. agencies are required, to the extent permitted by law, to assess monetary costs and benefits—even though these are considered difficult to quantify—during regulatory proceedings. To that effect, in 2010, the U.S. Interagency Working Group (IWG) on the SCC[31] used three integrated assessment models to estimate the SCC under four scenarios [22]. The IWG SCC reflects *global* damages from GHGs, and IWG recommends use of global damages. That approach is followed in the *Hydropower Vision* analysis, recognizing that lower values are obtained if only damages within the United States are considered.[32] In 2013, the IWG updated its estimates based on improvements in the integrated assessment models, which led to an increase in SCC values [23]. These numbers were revised again in 2015 [61]. IWG SCC estimates have been widely used in regulatory impact analyses in the United States, including in numerous proposed or final rules from the U.S. Environmental Protection Agency (EPA), DOE, and others [24].

29. In particular, there is general agreement that GHG savings will be greater and/or achieved at lower cost when met, at least in part, through economy-wide carbon pricing, and lower when met solely through sector-specific financial incentives for low-carbon technologies [21, 30, 31, 32, 33, 34, 35, 36, 37]

30. The discount rate varies for any individual calculation to be consistent with that assumed in the SCC estimate.

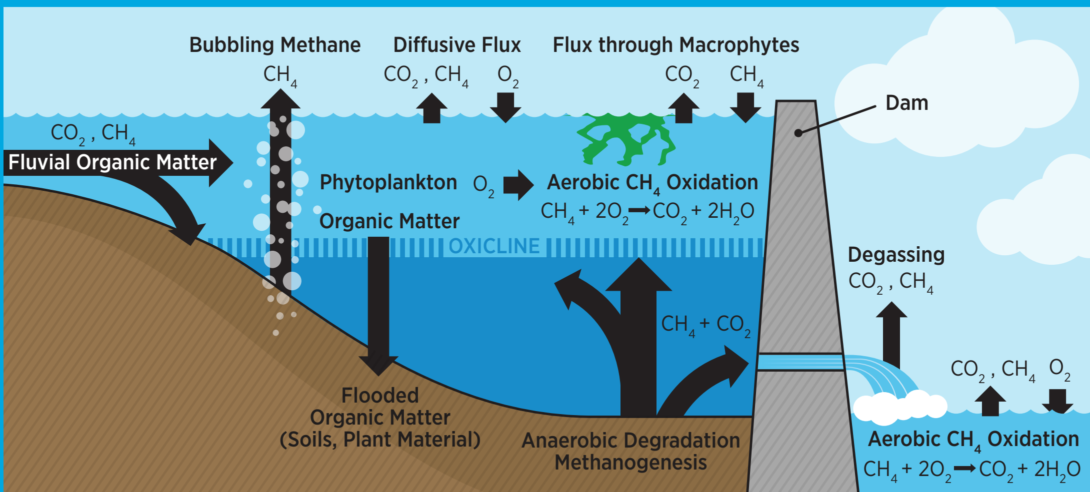
31. U.S. agencies actively involved in the process included the EPA and the Departments of Agriculture, Commerce, Energy, Transportation, and Treasury. The process was convened by the Council of Economic Advisors and the Office of Management and Budget, with active participation from the Council of Environmental Quality, National Economic Council, Office of Energy and Climate Change, and Office of Science and Technology Policy.

32. The IWG notes that a range of values from 7–23% should be used to adjust the global SCC to calculate domestic effects, but also cautions that these values are approximate, provisional, and highly speculative [22].

Text Box 3-1.

## Freshwater biogenic greenhouse gas emissions

All freshwater systems, whether natural or manmade,[a] emit biogenic GHG emissions as a result of bacterial processes in waters and soils (see figure). Carbon in organic matter, either submerged under water or in the water column, is decomposed by bacteria to produce $CO_2$ and methane ($CH_4$); the produced $CH_4$ can then be oxidized by bacteria to $CO_2$. Nitrogen in organic matter forms nitrous oxide ($N_2O$) through bacterial denitrification. There are generally three pathways for emission of GHGs oxidization. GHG emissions related to decommissioning of a dam arise from the disturbance of sediments collected over the life of the structure that exposes accumulated carbon. $N_2O$ emissions have not been well studied but may be important for systems with large inundation areas or in tropical areas [38]. The potential for biogenic GHG emissions from new water retaining structures and for hydropower-generating and non-powered dams is a complex issue and the subject of continuing scientific research.




**Carbon dioxide and methane pathways in a freshwater reservoir.**

Note: The light tan represents soils present prior to constructing the reservoir. The above processes illustrate gross GHG emissions. Many of these pathways would have been active without the reservoir, but the reservoir could increase and accelerate these pathways.

Source: Intergovernmental Panel on Climate Change

from hydropower systems to the atmosphere: diffusive flux,[b] degassing,[c] and bubbling [38].[d] All freshwater systems also bury some carbon in the sediments, where eventual exposure of these accumulated carbons to the atmosphere also can lead to the formation of biogenic GHG emissions [39, 40].

Any water retaining structure has the potential to lead to biogenic GHG emissions. Biogenic $CO_2$ and $CH_4$ emissions occur during two phases in the life cycle. GHG emissions related to the on-going operation of the water retaining structure arise from bacterial decomposition of inundated carbon and from $CH_4$

Existing literature suggests that ***gross*** GHGs emitted from reservoirs[e] are non-zero and variable [39]. Research suggests that newly impounded tropical reservoirs may emit significant amounts of methane with low to negligible emissions in cold and temperate climates, respectively [38]. Uncertainties still remain in the measurement methods and the scope of measurement needs to account for gross emissions [41].

Estimating ***net*** emissions from new reservoirs—the emissions that arise owing to the retaining structure and not what would have been emitted if the structure were not in place—is more challenging [42]. Inundation areas are collection points for material flowing downstream, including organic matter from terrestrial ecosystems and anthropogenic sources such as agricultural run-off and domestic sewage.

Estimating ***net*** GHG emissions requires knowing the local context such as emissions from natural and anthropogenic sources before and after building the water retaining structure. An assessment of ***net*** emissions involves: a) an estimation of natural emissions from the terrestrial ecosystem, wetlands, rivers, and lakes that were located in the area before impoundment; and b) an estimation of the effect of carbon inflow from the terrestrial ecosystem from natural and anthropogenic activities on ***net*** emissions before and after building the structure. Such quantification is a major topic of new research.

Uncertainty is leading to a lack of scientific consensus on methods for estimating ***net*** emissions from freshwater reservoirs [38]. Few existing studies assess ***net*** emissions from on-going or decommissioning activities [38], and uncertainty and the lack of study preclude the consideration of ***net*** emissions in *Hydropower Vision* analysis.

Despite these uncertainties, any new U.S. water retaining structure located mostly in cold or temperate climates are likely to be low emitters of ***net*** GHG relative to fossil fuels [38, 42]. New deployments of low-impact hydropower on undeveloped streams that do not lead to large inundation areas are also likely to have low biogenic GHG emission impacts. Powering of existing NPDs is unlikely to lead to changes in biogenic GHG emissions, since the dam has already been built [43].

The United Nations Educational, Scientific and Cultural Organization and the International Hydropower Association are among those working to standardize measurement techniques and tools for assessing ***net*** biogenic GHG emissions from reservoirs, including those used for hydropower. Those two organizations published the *GHG Measurement Guidelines for Freshwater Reservoirs* in 2010 [43] to enable standardized measurements and calculations worldwide. Subsequently, they aim to develop a database of emissions estimates for a representative set of hydropower systems worldwide. The final outcome of the project will be validated predictive modeling tools to assess the emissions status of unmonitored reservoirs as well as new reservoir sites.

a. Natural systems include rivers, lakes, and wetlands, while manmade systems include reservoirs and canals.
b. Transfer of GHG emissions from surface water to the atmosphere, both upstream and downstream of the water retaining structure.
c. Transfer of GHG emissions from any water retaining structure's outlet water to the atmosphere
d. Methane emissions resulting from carbonation, evaporation or fermentation from a water body
e. These studies are of existing hydropower facilities, which are multi-purpose. Therefore, not all GHG emission can be attributed solely to hydropower.

Text Box 3-2.

## Net energy requirements for different electricity generation technologies

A large body of literature has sought to estimate, on a life cycle basis, the amount of energy required to manufacture and operate energy conversion technologies or fuels (i.e., "input" energy). This concept helps inform decision makers on the degree to which various energy technologies provide a "net" increase in energy supply and is often expressed as ***Energy Return on Investment (EROI)***.

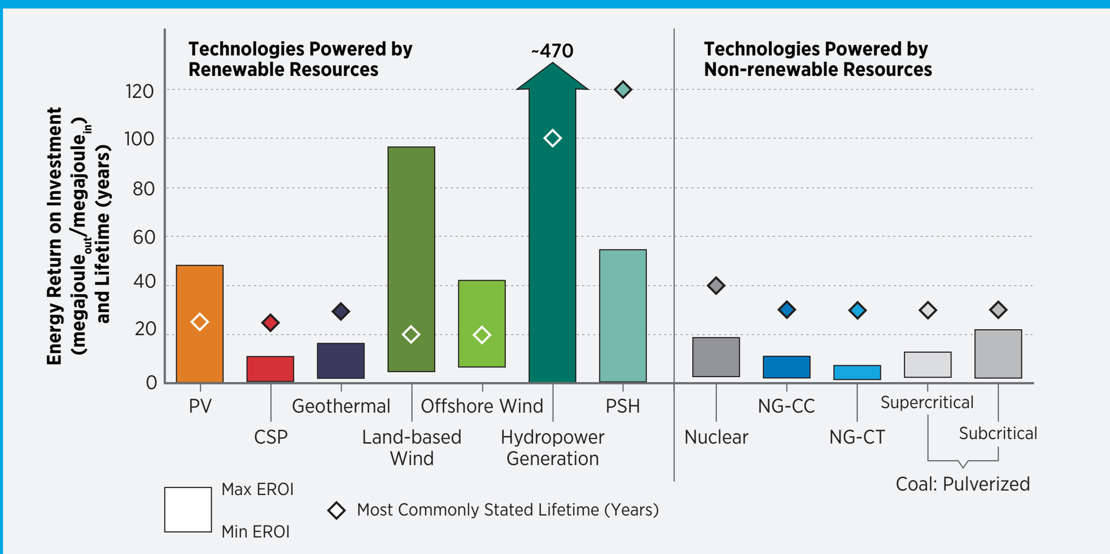
EROI expresses the lifetime amount of energy returned from a system per unit of energy invested (or embodied) in its construction, operation, and decommissioning. EROI indicates the sustainability of an energy system in terms of energy inputs.

This text box summarizes published estimates of this metric for hydropower technologies, in comparison to estimates for other electric generation technologies as presented in a recent report from the Intergovernmental Panel on Climate Change [44] and updated in Mai et al. [45]. Thirteen references reporting more than 30 EROI estimates for hydropower were reviewed using the same literature screening approach as was used for discussing life cycle GHG emissions (see Appendix G). Ranges in EROI estimates reflect current technology as well as future projections in the literature.

The figure below presents a summary of the review. These results are reported from studies that exhibit considerable methodological variability. The literature remains diverse, unconsolidated, and there has been only some analysis of the key issues that can influence results [46]. Variability in the results for hydropower, for example, may in part be due to difference in the assumed system lifetime, capacity factor; and technology evaluated (e.g., size of the dam). Pumped storage hydropower has received little study, but EROI was expected to be highly variable due net electricity generation being highly variable. This variability is related to pumped storage hydropower being used primarily as to store energy rather than as a net energy producer.

Notwithstanding these caveats, the results suggest that EROI is generally higher for renewable technologies (owing to technological advances) while being lower for conventional fossil fuel technologies (owing to resource depletion). In many cases, reservoir-based hydropower has been found to have an EROI higher than many other electricity sources. High hydropower EROI is likely linked to longer lifetimes.

**Review of energy return on investment of electricity generating technologies**




Note: NGCC = Natural gas combined cycle; NGCT = Natural gas combustion turbine; EROI = energy return on investment; IGCC = integrated gasification combined cycle; PSH = pumped storage hydropower.

Note: The range shown in the figure represents minimum and maximum values from the literature review. Counts of the number of literature estimates of EROI are not available as they were not reported in Edenhofer et al. [21].

Source: Non-wind and hydropower estimates from Kumar et al. [44] and updated with wind estimates from NREL [45]; hydropower estimates based on literature review detailed in Appendix G.

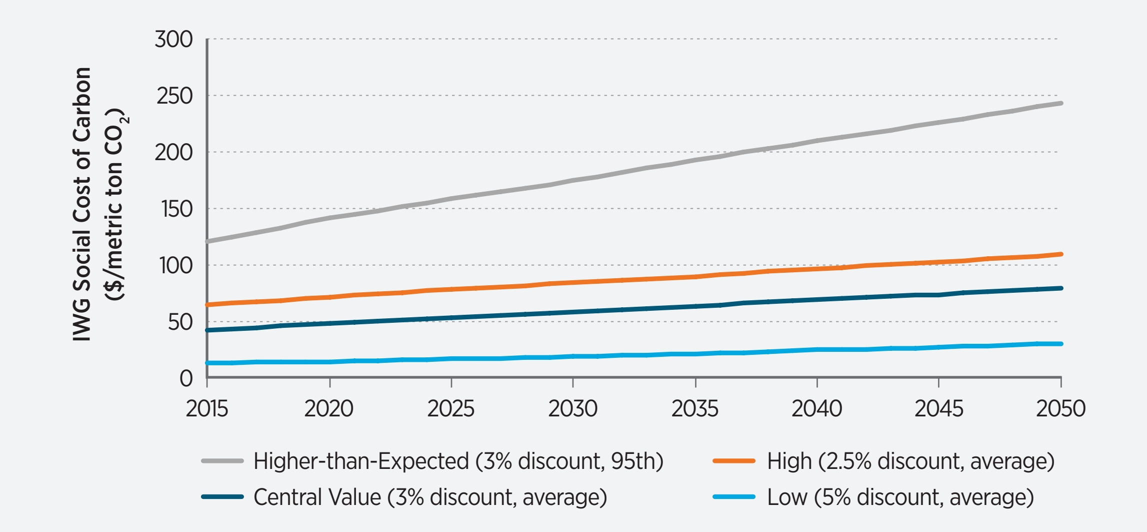



**Figure 3-42.** Interagency Working Group social cost of carbon estimates

To reflect the inherent uncertainties, the IWG [23] has published four SCC trajectories. Figure 3-42 illustrates these four trajectories from 2010 to 2050. Three of the four trajectories are based on the expected value of the SCC (estimated by averaging the results of the three IWG models), assuming discount rates of 2.5%, 3%, and 5% respectively.[33] A fourth trajectory represents a 95th percentile of the SCC estimates across all three models at the central 3% social discount rate. This 95th percentile case is intended to reflect a much less likely outcome, but one with a much higher than expected impact.[34]

As an alternative to valuing GHG reductions based on the SCC, those reductions are also valued based on the possible cost of complying with legal requirements to reduce GHG emissions.[35] Some U.S. states and regions have already enacted carbon reduction policies; the U.S. Congress has considered such policies in the past; and the EPA has established regulations that will limit emissions from existing and new power plants through the CPP [65, 66].[36] Especially when binding cap-and-trade programs are used to limit GHG emissions, as envisioned in part by the CPP, the climate change benefits of hydropower energy may best be valued based on cost of complying with legal requirements to reduce carbon emissions [26, 28]. In this case, the GHG co-benefits of hydropower come in the form of hydropower helping to meet the carbon reduction target, thereby offsetting some of the "marginal" costs of complying with the policy.

GHG reductions are valued in *Hydropower Vision* analysis based on two sets of estimates for this compliance cost. The first is EPA estimates of the average national cost of complying with the CPP under both mass-based and rate-based application [65][37]. Those estimates are provided by EPA for 2020, 2025, and 2030. The *Hydropower Vision* analysis interpolates between these years to estimate costs in intervening periods, and it presumes that the 2030 cost remains

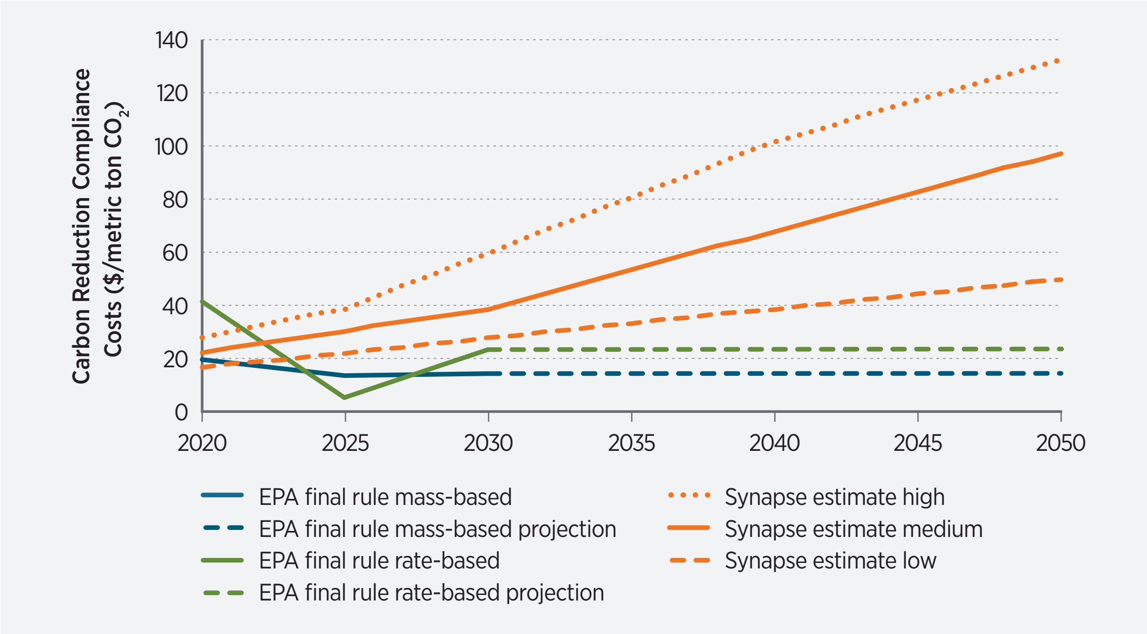
33. The use of this range of discount rates reflects uncertainty among experts about the appropriate social discount rate [22, 55].

34. Each of the integrated assessment models estimates the SCC in any given year by modeling the impact of GHG emissions in that year on climate damages over a multi-century horizon (discounted back to that year). The SCC increases over time because, as IWG explains, "future emissions are expected to produce larger incremental damages as physical and economic systems become more stressed in response to greater climate change" [22].

35. The approach used here and the discussion of incorporating compliance costs (including Figure 3-43) closely follows that used in the recent *On the Path to SunShot* study about the benefits of achieving the DOE's SunShot goals [64].

36.. As a result of the attention to carbon reduction, many utilities already regularly consider the possibility of future policies to reduce GHGs in resource planning, and thereby treat renewable energy sources as options for reducing the possible future costs of climate mitigation [66, 67, 68].

37. Rate-based refers to $CO_2$ emissions per megawatt-hour, while mass-based refers to the total tons emitted.




Source: Wiser et al 2016 [64]

**Figure 3-43.** Estimated social cost of carbon for compliance based on U.S. Environmental Protection Agency estimates and Synapse estimates

constant through 2050. The analysis also uses Synapse Energy Economics [66] estimates of carbon costs under "low," "medium," and "high" trajectories. These estimates consider and assume the possibility of more stringent long-term carbon reduction goals than envisioned by the CPP, and, as such, entail higher costs than those from EPA [65]. Figure 3-43 summarizes both sets of resulting carbon compliance costs.

Using the four IWG SCC estimates and the five compliance scenarios, Figure 3-44 shows the present value of the estimated global benefits of life cycle GHG reductions from 2017 to 2050 from the existing fleet (assuming no rebound or spillover effects). For the IWG central value case, discounted present value benefits are estimated to be $185 billion. Across the three expected-value cases, benefits range from $46 billion (for the 5% discount rate case) to $286 billion (for the 2.5% discount rate case). The fourth case, which accounts for the limited possibility of more extreme global climate damages, results in a benefit estimate of $555 billion.[38] The values for the compliance cases are lower on average and show less variation.

There are notable uncertainties in the benefits associated with existing hydropower (and the different hydropower growth scenarios that follow) that extend beyond alternative estimates of the SCC. This includes uncertainties in the evolution of the electricity system and the corresponding influence on hydropower's ability to reduce GHG emissions. This uncertainty exists for a variety of reasons, including the impact of uncertainty in future fossil prices, the timing and nature of carbon or other regulation, accuracy in assumed financing terms, and assumptions embedded in the ReEDS capacity expansion model. In part for these reasons, the balance of this section focuses on the IWG SCC valuation methods across the full range of the nine selected model scenarios.

Figure 3-45 shows, for the four IWG cases, the present value of the estimated global benefits of life cycle GHG reductions from 2017 to 2050 for the nine selected scenarios explored in depth in the *Hydropower Vision* analysis, compared to their respective

38. Annual benefits reflecting the discounted future benefits of yearly avoided emissions are as follows: (1) low: $2.86 billion (2020), $2.6 billion (2030), $0.31 billion (2050); (2) central: $10.0 billion (2020), $8,26 billion (2030), $0.8 billion (2050); (3) high: $14.8 billion (2020), $12.1 billion (2030), $1.1 billion (2050); (4) higher-than-expected: $29.4 billion (2020), $25.1 billion (2030), $2.43 billion (2050) [2015$].

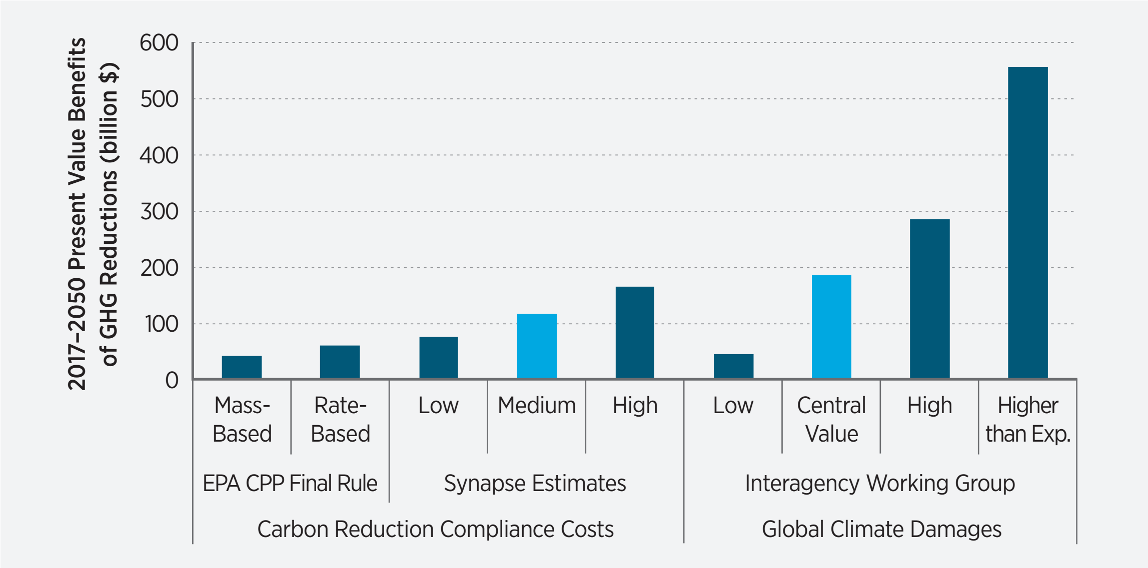



**Figure 3-44.** Estimated benefits of the existing fleet based on estimated avoided climate change damages and estimated avoided compliance costs

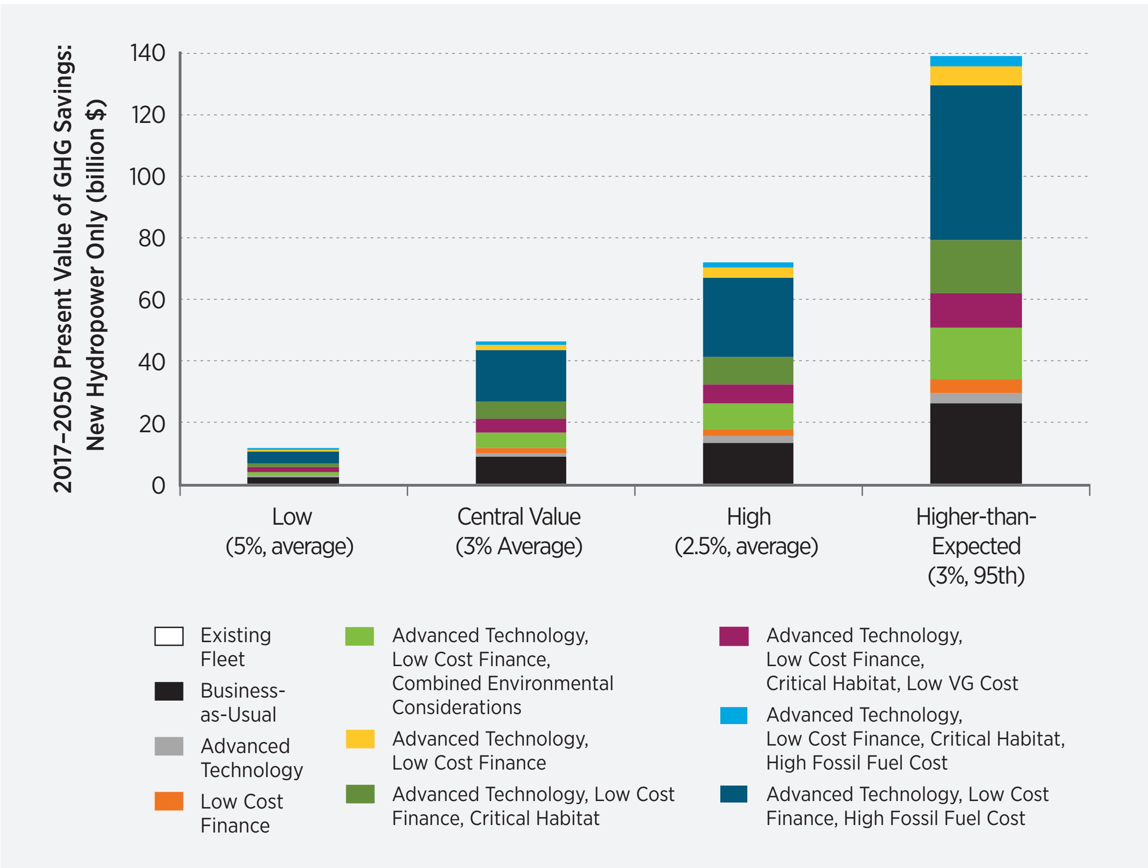



**Figure 3-45.** Estimated benefits of the nine selected scenarios due to avoided climate change damages

baseline scenario. Figure 3-46 shows the same information, but includes the present value of social benefits of the existing fleet.[39] The present values of the benefits associated with the existing hydropower fleet are larger than those anticipated for new hydropower under any of the new hydropower scenarios explored, as the existing fleet produces the majority of hydropower energy across all scenarios.

The present value of the estimated global benefits of life cycle GHG reductions from 2017 to 2050 from new hydropower growth in the nine selected scenarios varies substantially. For the IWG central value case, discounted present value benefits are estimated to be in the range from $8.8 billion for *Business-as-Usual* to $46.4 billion for *Advanced Technology, Low Cost Finance, Critical Habitat, Low VG Cost* scenario. Under the IWG central value case assumptions, new hydropower deployment increases the total present value of GHG benefits by 5% to 25% over that achieved from existing hydropower alone.

Across the three expected-value cases, benefits range from $2.3 billion to $11.2 billion for the 5% discount rate case and from $13.5 billion to $72.0 billion for the 2.5% discount rate case. The fourth case, which accounts for the limited possibility of more extreme global climate damages, results in a benefit estimate ranging from $26.1 billion to $139 billion.[40]

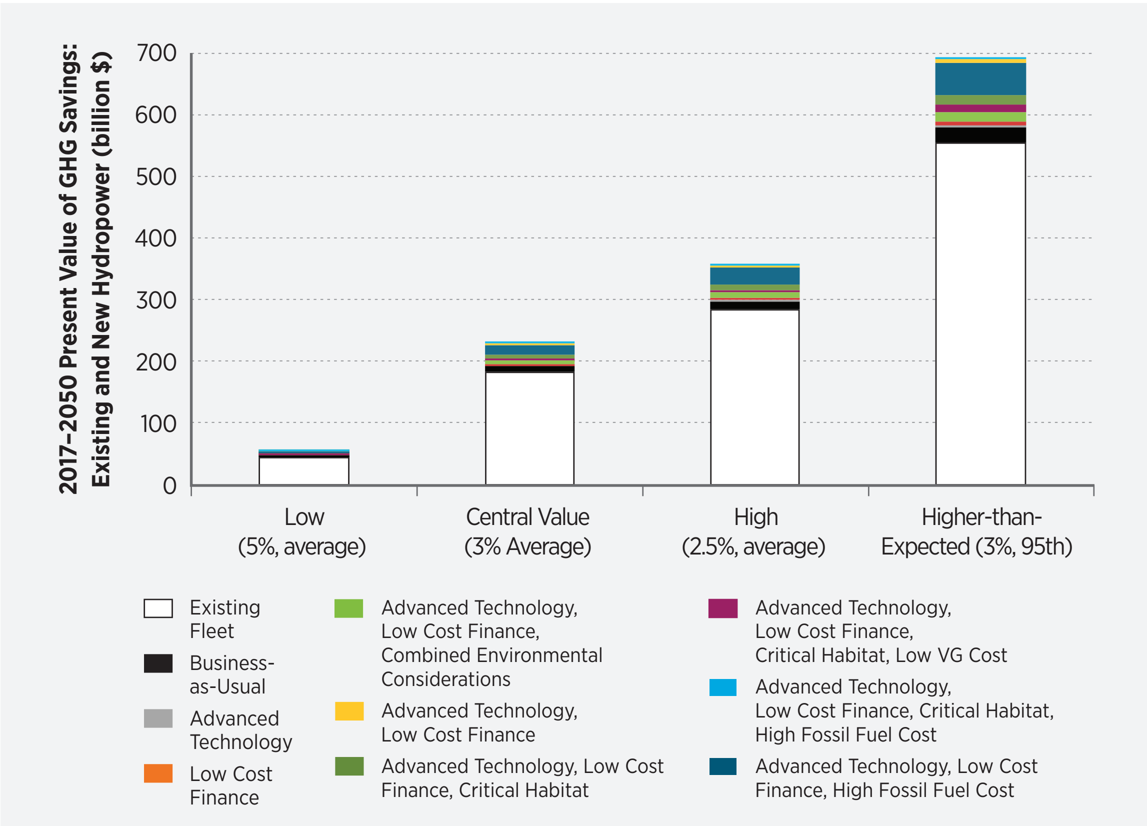



**Figure 3-46.** Estimated benefits of the nine selected scenarios and the existing fleet due to avoided climate change damages

39. Compliance cases are not included, as the similarity and differences of compliance to IWG cases are shown in Figure 3-44 (including the similarity of the median Synapse case to the central IWG case).

40. As suggested by the IWG, domestic benefits might be 7–23% of these global estimates [22]

### 3.5.7 Air Pollution Emissions, Human Health, and Environmental Benefits

Combusting fuels to generate electricity produces air pollutants that harm human health and cause environmental damage [69]. Epidemiological studies have shown a causal association between increased mortality (and morbidity) and exposure to air pollution (for examples of the association with mortality, see Dockery et al. 1993 [70]; Krewski et al. 2009 [71]; Lepeule et al. 2012 [72]). Lim et al. [73] estimate more than 3 million premature deaths globally, each year, are attributable to outdoor particulate air pollution.

In the United States, a number of studies have evaluated the potential air quality and public health benefits of reducing combustion-based electricity generation. For example, Driscoll et al. [74] found that policies aimed at reducing power-sector $CO_2$ emissions would also reduce fine particulate matter ($PM_{2.5}$) and ozone, preventing as many as 3,500 premature mortalities in 2020. Siler-Evans et al. [26] value the health and environmental benefits of displaced conventional generation from new solar and wind power at 1¢/kWh to 10¢/kWh, with the range largely reflecting locational differences. The EPA has estimated that its CPP would provide $14 billion to $34 billion of monetized health co-benefits in 2030, based mostly on reductions in premature mortality [65].

Though all energy sources have environmental impacts, most renewable and non-combustion based electricity sources—including hydropower—have no direct air pollution emissions and low life cycle air pollution emissions [44, 75]. Therefore, the existing and new hydropower generation resource estimated by ReEDS has the potential to reduce air pollution emissions into the future.

To evaluate the air quality benefits of existing hydropower and new hydropower deployment in the nine modeled scenarios, the changes in emissions of $SO_2$, $NO_x$, and $PM_{2.5}$ from 2017 to 2050 due to hydropower electricity generation are estimated. Based on the emission changes, the public health and environmental impacts are quantified in the form of mortality and morbidity outcomes, as well as in monetary terms. Given uncertainty in pollutant transport, transformation, and exposure as well as uncertainty in the human response to ambient $PM_{2.5}$ and ozone, multiple established methods are used to quantify the health and environmental outcomes and monetary benefits of the emissions changes. The overall approach used to calculate the benefits of new capacity under the capacity expansion scenarios is similar to that used in DOE's *Wind Vision* report [3], and is broadly consistent with methods used in Cullen [28], Driscoll et al. [74], EPA [65], Fann et al. [76], Johnson et al. [25], Novan [77], NRC [69], McCubbin and Sovacool [27], and Siler-Evans et al. [26]. In addition to calculating the benefits of new capacity, a modified approach is used to calculate the benefits of maintaining the existing fleet. The two approaches are described below.

The emission benefits of new capacity under each future scenario is found as the difference between ReEDS-estimated, power-sector combustion-related $SO_2$ and $NO_x$ emissions in each of the nine selected scenarios relative to a baseline scenario with no new hydropower growth. Power-sector $PM_{2.5}$ emission benefits are calculated similarly, except they are a function of ReEDS generation by power plant type and location.[41] Incorporated in these estimates are assumptions about power sector regulations that apply to emissions of $SO_2$, $NO_X$, and/or $PM_{2.5}$, such as the Mercury Air Toxics Rule (MATS) and the Cross-State Air Pollution Rule (CSAPR).[42] Of particular importance to this analysis, EPA's CPP has been incorporated into ReEDS. The CPP limits $CO_2$ emissions but does not directly address emissions of criteria pollutants.

41. $PM_{2.5}$ emission estimates are developed for both scenarios as a function of the product of ReEDS generation outputs (MWh, by generation type and vintage) and average emission rates (grams/MWh, by generation type). Average $PM_{2.5}$ emissions rates (reported by Argonne National Laboratory [78, 79]) are differentiated by generation type (coal, gas, or oil) and U.S. state. Additionally, $PM_{2.5}$ emission factors are adjusted over time to comply with scheduled $PM_{2.5}$ MATS limits for existing plants (for more details see Appendix L of the Wind Vision report [3]).

42. Although CSAPR is represented in ReEDS, it is essentially non-binding due to the $SO_2$ reductions required for MATS and due to the long-term substitution of natural gas and other generation sources for coal power generation. Although MATS and CSAPR are both under some legal uncertainty, it is assumed that MATS or something like MATS will remain as an active regulation (supporting this assumption, to a significant degree, the effect of MATS has already been seen, though actual and announced coal plant retirements).

The emissions benefits of the existing fleet are calculated solely for a baseline "no new hydropower" scenario. Specifically, the average non-hydropower emission rate (in grams per megawatt-hour (MWh)-non-hydropower) for $SO_2$, $NO_X$, and $PM_{2.5}$ is calculated for each year (2017–2050) over three large regions defined by EPA [65]. Following this step, the electricity generated by hydropower within each region and for each year is multiplied by the corresponding non-hydropower emission rate, providing a total emission benefit.[43]

Based on these emission changes, two different peer-reviewed approaches are used to calculate a range of health and environmental benefits (including reduced morbidity and mortality outcomes and total monetary value). Each approach accounts for pollutant transport and chemical transformation as well as population exposure and response: (1) the Air Pollution Emission Experiments and Policy analysis model (AP2, formerly APEEP; created by and described in Muller et al. [80]), and (2) EPA's benefit-per-ton methodology developed for the Clean Power Plan [65].[44] The EPA CPP approach includes two estimates of the health impacts in order to span the uncertainty in the underlying epidemiological studies.[45] The two outputs from the EPA CPP approach are identified as 'EPA Low' and 'EPA High.' The 'low' and 'high' classifications correspond to differences only between the underlying health impact functions employed by EPA, and EPA notes they do not favor either of its estimates over the other. The simple average of all three benefit estimates is used as the "central" value. One important assumption across all methods used is the monetary value of preventing a premature mortality (or the Value of Statistical Life). Consistent with the broader literature, all use a Value of Statistical Life of approximately $6 million dollars in year 2000.[46]

Several additional aspects of the methodology, and possible related limitations, warrant noting:

- The focus is on a subset of air emissions impacts: $SO_2$, $NO_x$, and $PM_{2.5}$. Non-quantified impacts include heavy metal releases, radiological releases, waste products, and land use impacts associated with power and upstream fuel production, as well as noise, aesthetics, and others. Only emissions from power plant operations are considered, ignoring the smaller upstream and downstream life-cycle impacts.
- The air emissions impact estimates are inherently uncertain, in part due to the impact of uncertain policy and market factors on those reductions.
- The methodology presumes that the MATS is maintained or replaced with a similar regulation such that $SO_2$ and $NO_x$ cap-and-trade programs, such as CSAPR, are essentially non-binding over time. Otherwise, the benefits of the new capacity in the

43. The benefits of the existing fleet were also calculated with the AP2 model, following a similar methodology. In this case, the emissions in the baseline without the existing fleet needed to be calculated for each of the 134 ReEDS regions to match the resolution of the AP2 model. The percentage emission increase for each of the pollutants, across the three EPA regions and for each year, was applied to each of the corresponding ReEDS regions. In this way, the total emission changes found at the EPA region were simply distributed to each smaller ReEDS region and weighted by the baseline level of emissions.

44. Benefits calculated by AP2 and EPA CPP differ in a number of respects. For example, the AP2 model accounts for not only mortality and morbidity, but also air pollution-induced decreases to timber and agriculture yields, visibility reductions, accelerated materials degradation, and reductions in recreation services; while benefits calculated with the EPA CPP benefit-per-ton approach include only mortality and morbidity. Both the EPA CPP benefit-per-ton approach and the AP2 model include the benefits from primary and secondary particulate reductions and from ozone reductions; however, the exact pollutants considered in terms of primary particulate exposure varies.

45. EPA Low is based on research summarized in Krewski et al. [71] and Bell et al. [82], whereas EPA High is based on research presented in Lepeule et al. [72] and Levy et al. [83]. Both sets of epidemiological research have different strengths and weaknesses, and EPA indicates that it does not favor one result over the other.

46. The AP2 model contains monetized benefit-per-ton estimates based on emissions in the year 2008, so damages from AP2 are scaled over time based on Census population projections [85] and per capita income growth projections used by AEO [85], using an elasticity of the value of statistical life to income growth consistent with NRC [69]. EPA benefit-per-ton (BPT) values are developed for each year, within each of three regions, by linearly extrapolating EPA's provided BPT values. In this manner, there is implicit representation of the population and income growth assumptions incorporated in the EPA's analysis. The 2017–2025 BPT values are based on the linear trend established by EPA's 2020 and 2025 BPT values. The 2026–2050 BPT values are based on the linear trend established by EPA's 2025 and 2030 BPT values. The same process is used for EPA's health incidence-per-ton (mortality and morbidity outcomes) estimates.

future scenarios should arguably be calculated based on allowance prices to reflect savings in the cost of complying with the cap [26].[47]

- Estimates of the health and environmental benefits associated with emissions reductions are inherently uncertain. Some, but not all, of those uncertainties are reflected by calculating benefits using two approaches (AP2, EPA) leading to three different estimates (AP2, EPA Low and High).

### Air Pollution Reduction Benefits from New Hydropower Capacity

New hydropower deployment provided cumulative air quality benefits in scenarios combining *Advanced Technology, Low Cost Finance* with the following assumptions: 1) *High Fossil Fuel Cost*; 2) *Critical Habitat, High Fossil Fuel Cost*; and 3) *Critical Habitat, Low VG Cost*. In the *Low VG Cost* scenario, the additional hydropower generation allowed for greater new non-hydropower renewable generation, primarily wind. Under these conditions, combined new hydropower and new non-hydropower renewables led to reduced total criteria pollutant emissions and associated public health burdens. In the *High Fossil Fuel Cost* scenarios, the additional hydropower offsets both coal and natural gas, providing air quality benefits. In contrast, new hydropower in the remaining scenarios reduced natural gas generation but facilitated additional coal generation along with non-hydropower renewables. On balance, this increased total criteria pollutant emissions, causing a slight increase to air quality burdens.

Representation of EPA's CPP influences the sign and magnitude of the air quality impacts. The CPP limits total carbon emissions, but does not directly limit $SO_2$, $NO_x$, and $PM_{2.5}$ emissions. As the combustion emissions of $CO_2$ associated with coal generation are larger than that of natural gas generation (on a per-MWh basis), the implementation of the CPP within ReEDS limits generation from coal in both the baseline and new hydropower scenarios. However, in the new hydropower scenarios, the new deployment of combustion-free hydropower allows for the ratio of coal to natural gas generation to increase without increasing total $CO_2$ emissions. In fact, relative to the baseline scenarios, the new hydropower scenarios (with the exception of the *High Fossil Fuel Cost* and *Low VG Cost* scenarios) show higher absolute coal generation along with lower absolute natural gas generation.

This analysis does not suggest the CPP causes any air quality damages; in fact, the CPP is estimated to provide substantial air quality benefits [65]. However, after those CPP benefits are realized, the addition of new hydropower can allow for additional coal generation in the specific scenarios analyzed here.

Figure 3-47 shows emission impacts from 2017–2050. The figure illustrates that, as the CPP becomes more restrictive closer to 2030, all the selected scenarios have increased emissions of $SO_2$, $NO_x$ and $PM_{2.5}$ compared to their baselines. The *High Fossil Fuel Cost* scenarios show reduced emissions again soon after 2030, and the *Advanced Technology, Low Cost Finance, Critical Habitat, Low VG Cost* scenario shows reduced emissions by roughly 2040. Table 3-7 shows cumulative emission changes (new hydropower deployment, relative to the respective baseline scenario) for 2017–2025. The largest reductions were seen for *Advanced Technology, Low Cost Finance, Critical Habitat, Low VG Cost* scenario, with $SO_2$, $NO_x$, and $PM_{2.5}$ reduced by 460,000; 801,000; and 71,000 metric tons or 1.5%, 2.2%, and 1.3%, respectively, over 2017–2050. The largest increases to emissions were found in the *Advanced Technology, Low Cost Finance, Critical Habitat* scenario*.* In that scenario in 2017–2050, $SO_2$, $NO_x$, and $PM_{2.5}$ emissions increased by 226,000; 160,000; and 41,000 metric tons or 0.7%, 0.5%, and 0.1%, respectively.

47. This is because under strictly binding caps, renewable electricity does not reduce emissions per se, but it instead alleviates the need to reduce emissions elsewhere in order to achieve the cap. In this instance, the benefits of hydropower electricity derive not from reduced health and environmental damages but instead from reducing the cost of complying with the air-pollution regulations. As mentioned above, ReEDS simulations indicate CSAPR $SO_2$ and $NO_x$ caps are largely non-binding over time, due to the presumed existence of MATS. This result also follows historical experience, as the largest regional $SO_2$ and $NO_x$ cap-and-trade program (EPA's Clean Air Interstate Rule) was non-binding in 2013 [86, 87]. Therefore, estimates are not calculated for the benefits of new capacity in the *Hydropower Vision* from the perspective of reducing pollution regulation compliance costs. Nonetheless, this alternative valuation approach is mentioned because it is possible that future cap-and-trade regulations applied either nationally or regionally could impact the size and nature of the benefits from the scenarios analyzed here. It is also possible that our emissions treatment may not incorporate some more-localized ***existing*** binding cap-and-trade programs; however, the geographic extent of these programs is limited, so this limitation will not substantially bias the results.

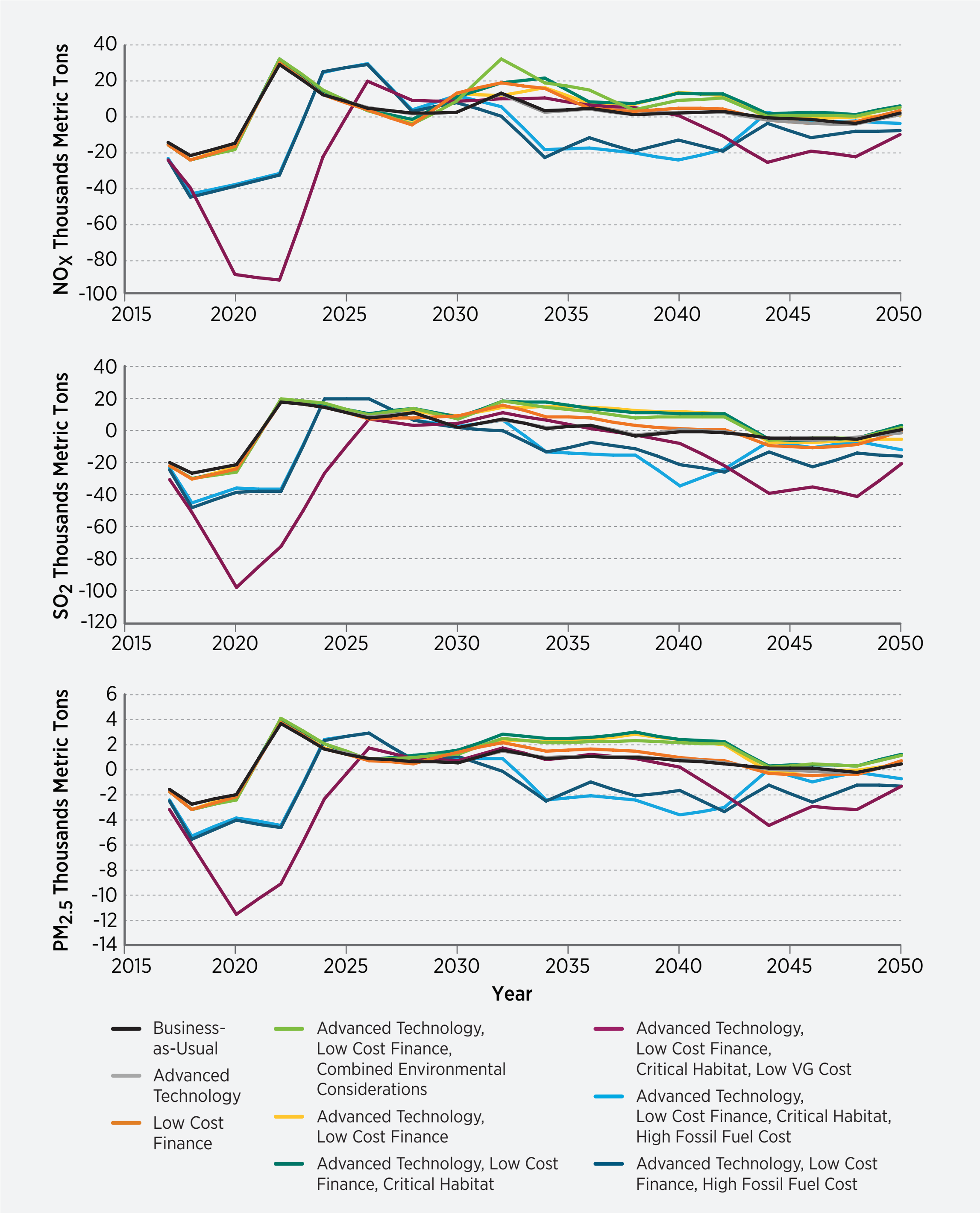



**Figure 3-47.** Power sector $SO_2$, $NO_x$, and $PM_{2.5}$ emissions impacts of new hydropower capacity

**Table 3-7.** Cumulative Power Sector $SO_2$, $NO_x$, and $PM_{2.5}$ Emissions Impacts of New Hydropower Capacity

| | $SO_2$ (metric tons) | Percent Change | $NO_X$ (metric tons) | Percent Change | $PM_{2.5}$ (metric tons) | Percent Change |
|---|---|---|---|---|---|---|
| *Business-as-Usual* | 81,000 | 0.2% | -10,000 | 0.0% | 16,000 | 0.3% |
| *Advanced Technology* | 69,000 | 0.2% | -10,000 | 0.0% | 16,000 | 0.3% |
| *Low Cost Finance* | 124,000 | 0.4% | 17,000 | 0.0% | 20,000 | 0.4% |
| *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* | 222,000 | 0.7% | 129,000 | 0.4% | 36,000 | 0.7% |
| *Advanced Technology, Low Cost Finance, Critical Habitat* | 226,000 | 0.7% | 160,000 | 0.5% | 41,000 | 0.8% |
| *Advanced Technology, Low Cost Finance* | 171,000 | 0.5% | 128,000 | 0.4% | 34,000 | 0.6% |
| *Advanced Technology, Low Cost Finance, Critical Habitat, Low VG Cost* | -506,000 | -1.5% | -761,000 | -2.2% | -70,000 | -1.3% |
| *Advanced Technology, Low Cost Finance, Critical Habitat, High Fossil Fuel Cost* | -323,000 | -1.0% | -436,000 | -1.3% | -48,000 | -0.9% |
| *Advanced Technology, Low Cost Finance, High Fossil Fuel Cost* | -274,000 | -0.9% | -396,000 | -1.2% | -43,000 | -0.8% |

To summarize the emission impacts, the *Hydropower Vision* analysis scenarios only provide cumulative air quality benefits under conditions that favor additional, non-hydropower, renewable energy deployment, or in scenarios with higher fossil fuel prices. Criteria pollutants are found to increase in the remainder of the new hydropower deployment scenarios. These patterns are a result of the inclusion of the CPP within the modeling framework.

These emission changes would lead to changes in air quality and health outcomes across the continental United States. Specifically, the cumulative, discounted present value of the U.S. health and environmental impacts range from a ***penalty*** of $6.4 billion to a ***benefit*** of $26.5 billion across the central estimates of the nine scenarios (in 2015$). Figures 3-48 and 3-49 and Table 3-8 show the range of total health and environmental impacts values across all the scenarios. The central estimates[48] of premature mortality incidences ranges from an ***increase*** of 1,600 to a ***decrease*** of 5,400.

While these results indicate a range of potential air quality impacts from new deployment of hydropower, there is no attempt to pick a 'most likely' scenario or create an overall average impact estimate. As such, the conclusion must be a qualified statement: Given the constraints of the CPP, air quality impacts from new deployment of hydropower are positive only under conditions that either favor additional non-hydropower renewable deployment or that discourage additional fossil fuel generation, including additional coal generation.

48. The central estimate of mortality incidences is the simple average mortality estimate between EPA Low and EPA High (as mortality incidences were not available for AP2).

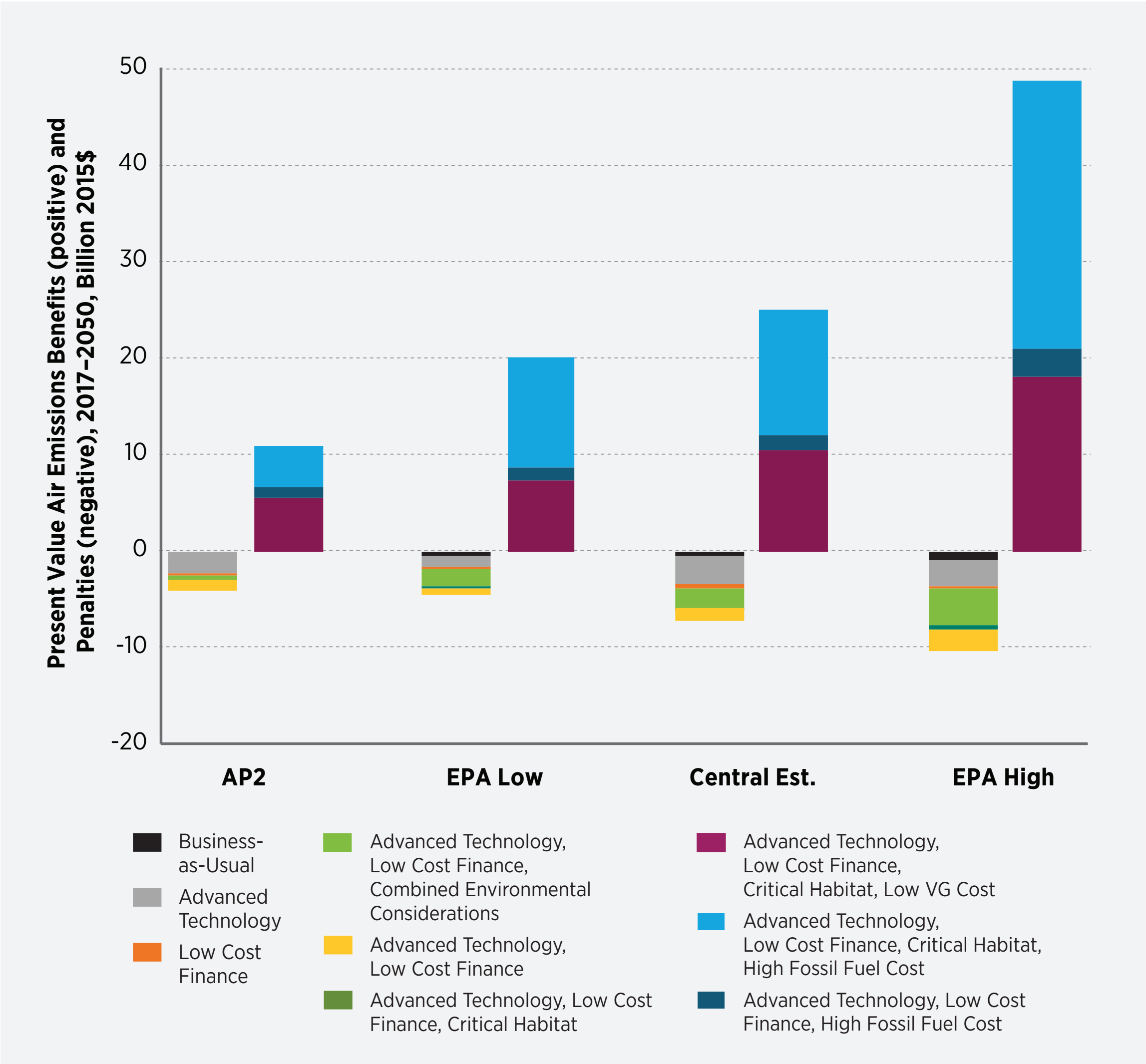



**Figure 3-48.** Estimated value of $SO_2$, $NO_X$, and $PM_{2.5}$ impacts of new capacity with benefits and penalties stacked separately

### *Air Pollution Reduction Benefits from Existing Hydropower Capacity*

The air quality impacts of the existing hydropower fleet are calculated as a function of the average regional emission rates of non-hydropower generation within the baseline scenario. The existing fleet is found to reduce emissions of $SO_2$, $NO_x$ and $PM_{2.5}$ by 1.6, 2.8, and 0.3 million metric tons (or 5%, 9%, and 6%), respectively, over 2017–2050. These emission reductions lead to improved air quality and health outcomes across the continental United States. Specifically, total U.S. health and environmental benefits from the existing fleet fall in the range of $39 billion–$94 billion on a discounted, present-value basis, depending on the method used to quantify those benefits (see Figure 3-50).

Reduction of $SO_2$ and the subsequent reduction of particulate sulfate concentrations account for a majority of the monetized benefits. For example, the reduction of $SO_2$ emissions accounted for 55%, 69%, and 64% of the AP2, EPA Low, and EPA High benefits. The benefits of reduced tropospheric ozone (due to reduced $NO_x$ emissions) account for 8% and 15% of the EPA Low and High benefit estimates, respectively.[49]

49. An estimate of ozone benefits, separate from the total benefits and corresponding to the AP2 valuation, was not available within the model.

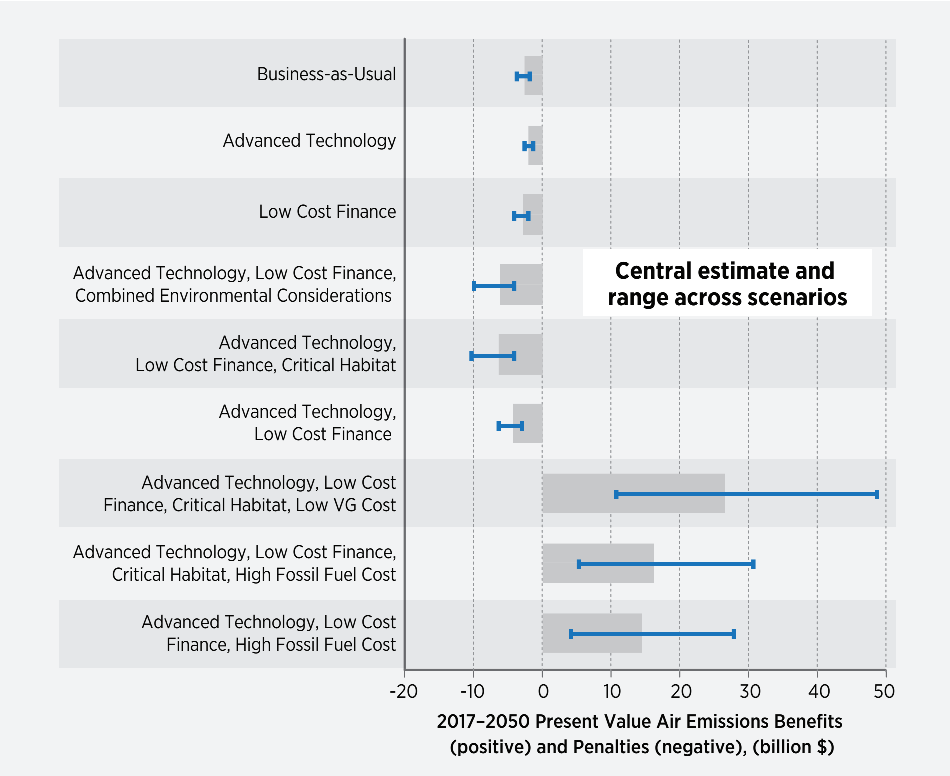



**Figure 3-49.** Estimated central value and range of $SO_2$, $NO_X$, and $PM_{2.5}$ impacts of new capacity

**Table 3-8.** Estimated cumulative, 2017–2050, discounted value of $SO_2$, $NO_X$, and $PM_{2.5}$ impacts of new capacity (million 2015$)

| | AP2 | EPA Low | Central Estimate | EPA High |
|---|---|---|---|---|
| *Business-as-Usual* | -2,300 | -1,800 | -2,600 | -3,700 |
| *Advanced Technology* | -2,200 | -1,300 | -2,100 | -2,600 |
| *Low Cost Finance* | -2,600 | -2,000 | -2,900 | -4,000 |
| *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* | -4,000 | -4,600 | -6,200 | -10,000 |
| *Advanced Technology, Low Cost Finance, Critical Habitat* | -4,100 | -4,700 | -6,400 | -10,400 |
| *Advanced Technology, Low Cost Finance* | -3,600 | -2,900 | -4,200 | -6,300 |
| *Advanced Technology, Low Cost Finance, Critical Habitat,Low VG Cost* | 10,800 | 20,000 | 26,500 | 48,700 |
| *Advanced Technology, Low Cost Finance, Critical Habitat, High Fossil Fuel Cost* | 5,300 | 12,800 | 16,300 | 30,800 |
| *Advanced Technology, Low Cost Finance, High Fossil Fuel Cost* | 4,100 | 11,500 | 14,500 | 27,900 |

The data suggest that exposure to particulates (directly or indirectly from emissions of $SO_2$, $NO_x$ and $PM_{2.5}$) is the primary driver of health outcomes.

Most of the health benefits come from avoided premature mortality, again associated primarily with reduced chronic exposure to ambient $PM_{2.5}$ (which derive largely from the transformation of $SO_2$ to sulfate and $NO_x$ to nitrate particles). Based on the EPA approach, the existing fleet is found to prevent 6,700 to 16,200 premature mortalities in total from 2017 to 2050. It is also estimated that the existing fleet would reduce numerous forms of morbidity outcomes (see Table 3-9), including 8,500 hospital admissions for respiratory and cardiovascular symptoms, 0.7 million lost work days, and 0.9 million missed school days.

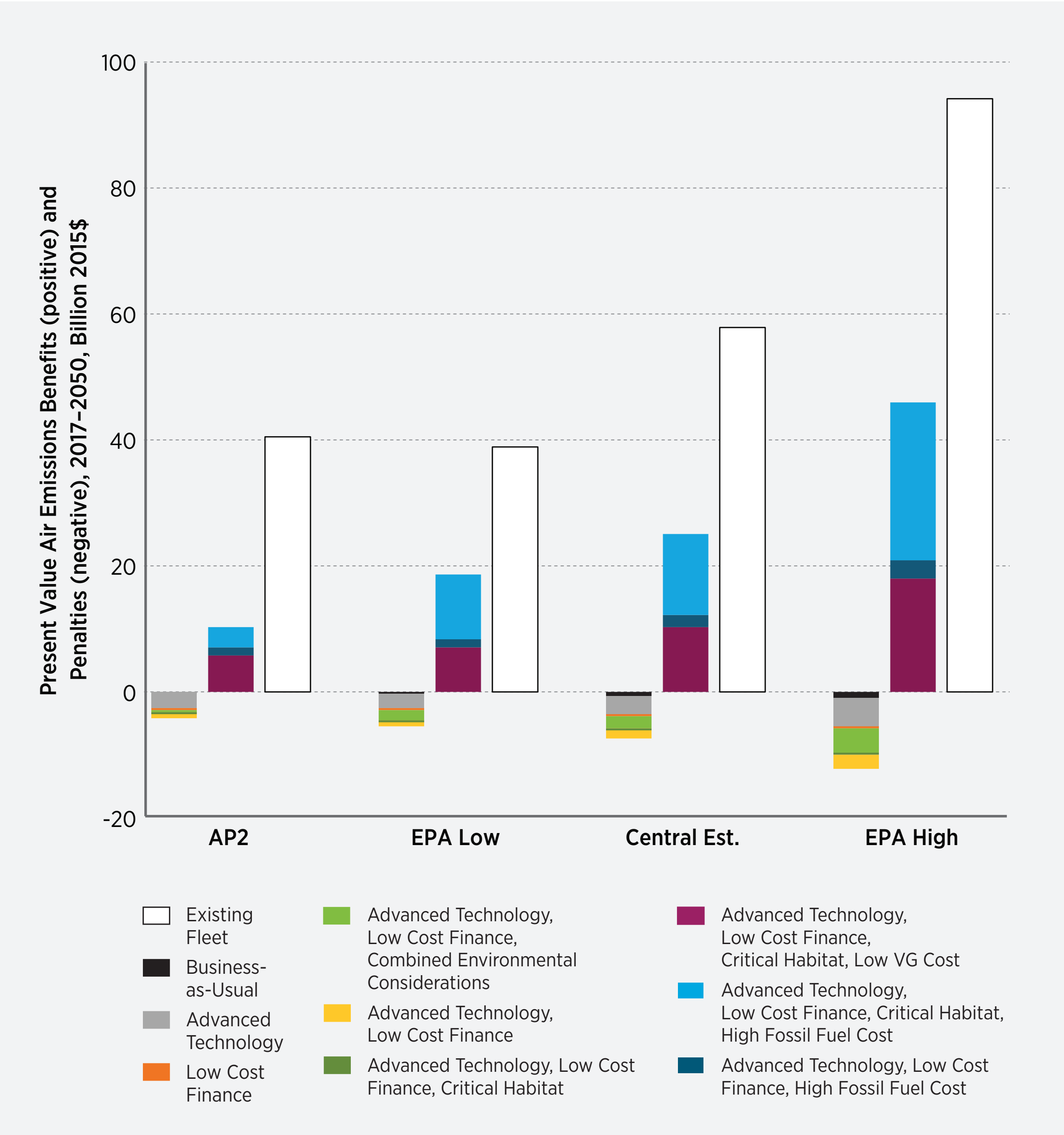



**Figure 3-50.** Estimated value of $SO_2$, $NO_x$, and $PM_{2.5}$ impacts of new capacity with benefits and penalties stacked separately and with the existing fleet benefits for comparison

**Table 3-9:** Emissions Reductions, Monetized Benefits, and Mortality and Morbidity Benefits over 2017–2050 for the Existing Fleet

| Impacts | $SO_2$ | $NO_x$ | $PM_{2.5}$ | Total |
|---|---|---|---|---|
| **Emissions Reductions (millions metric tons)** | | | | |
| Existing Fleet impacts | 1.64 | 2.76 | 0.33 | — |
| **Existing Fleet Total Monetized Benefits (Present Value)** | | | | |
| EPA Low benefits (Billions 2015$) | 27 | 7 | 5 | 39 |
| EPA High benefits (Billions 2015$) | 60 | 22 | 12 | 94 |
| AP2 benefits (Billions 2015$) | 22 | 12 | 6 | 40 |
| **Existing Fleet EPA Total Mortality Reductions** | | | | |
| EPA Low mortality reductions (count) | 4,700 | 1,100 | 900 | 6,700 |
| EPA High mortality reductions (count) | 10,600 | 3,500 | 2,100 | 16,200 |
| **Existing Fleet EPA Morbidity Reductions from Primary and Secondary PM2.5 Impacts** | | | | |
| Emergency department visits for asthma (all ages) | 1,500 | 200 | 300 | 2,000 |
| Acute bronchitis (age 8–12) | 6,700 | 1,100 | 1,300 | 9,100 |
| Lower respiratory symptoms (age 7–14) | 85,100 | 13,800 | 17,200 | 116,100 |
| Upper respiratory symptoms (asthmatics age 9–11) | 127,800 | 20,000 | 24,600 | 172,400 |
| Minor restricted-activity days (age 18–65) | 3,247,200 | 484,900 | 625,000 | 4,357,100 |
| Lost work days (age 18–65) | 538,700 | 81,200 | 104,600 | 724,500 |
| Asthma exacerbation (age 6–18) | 295,900 | 49,400 | 58,500 | 403,800 |
| Hospital Admissions-Respiratory (all ages) | 1,400 | 200 | 300 | 1,900 |
| Hospital Admissions-Cardiovascular (age > 18) | 1,700 | 200 | 300 | 2,200 |
| Non-fatal Heart Attacks | 5,300 | 700 | 1,000 | 7,000 |
| Non-fatal Heart Attacks (Pooled estimates—4 studies) | 600 | 100 | 100 | 800 |
| **Existing Fleet EPA Morbidity Reductions from NOx — Ozone Impacts** | | | | |
| Hospital Admissions, Respiratory (ages > 65) | — | 2,900 | — | 2,900 |
| Hospital Admissions, Respiratory (ages < 2) | — | 1,500 | — | 1,500 |
| Emergency Room Visits, Respiratory (all ages) | — | 1,300 | — | 1,300 |
| Acute Respiratory Symptoms (ages 18–65) | — | 2,723,700 | — | 2,723,700 |
| School Loss Days | — | 943,900 | — | 943,900 |

Notes: All values accumulated from 2017–2050. All monetized benefits are discounted at 3%; however, the mortality and morbidity values are simply accumulated over the time period. EPA and AP2 $ benefits include mortality and morbidity estimates from primary and secondary $PM_{2.5}$ effects from $SO_2$, $NO_X$, and direct $PM_{2.5}$ emissions and ozone benefits from reduced $NO_X$ emissions during the ozone season (May–September). AP2 benefits also include environmental effects such loss of visibility and crop damage. Both AP2 and EPA benefit estimates are dominated by mortality benefits.

## 3.5.8 Power-Sector Water Usage Reduction

The electric sector beyond hydropower relies on readily available supplies of water for reliable operations. Most water requirements in the energy sector are for thermal power plant cooling, but all life cycle stages of energy production require water. Although energy supply can also affect water resources through changes in water quality and temperature, water use is typically categorized into two metrics: withdrawal and consumption. Withdrawals are defined as the amount of water removed or diverted from a water source for use, while consumption is the amount of water evaporated, transpired, incorporated into products or crops, or otherwise removed from the immediate water environment [88]. The U.S. power sector is the largest withdrawer of water in the nation, at 38% of total withdrawals [89]. Its share of consumption is much lower, around 3% nationally, but can be regionally important [90].

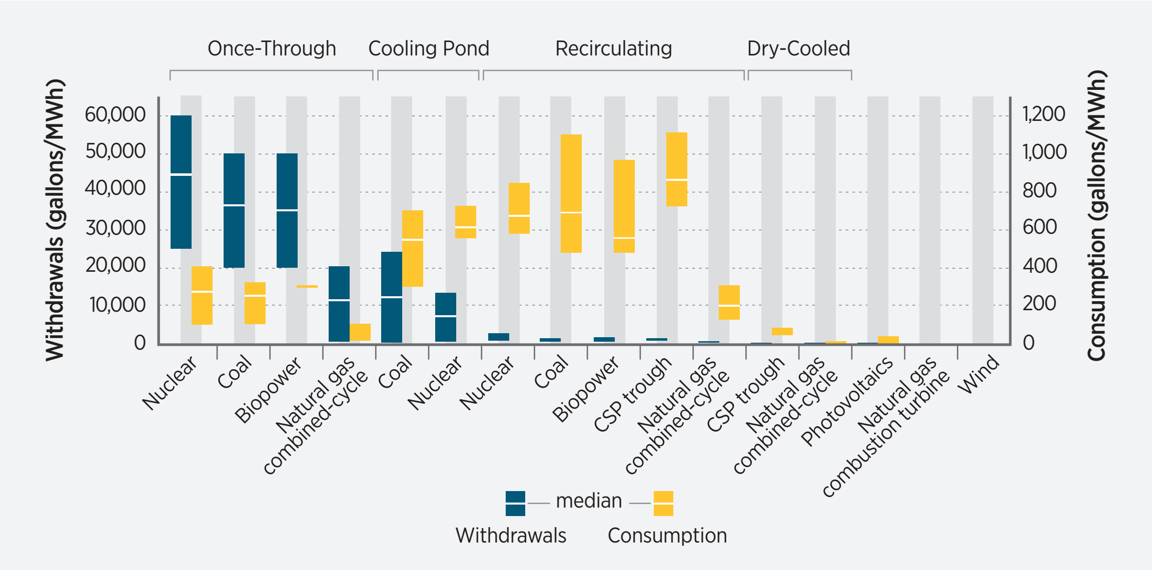
Prior studies have evaluated the impact of a range of U.S. electric sector futures on water demands [2, 91, 92, 93, 94, 95, 96, 97]. Many renewable energy technologies have low operational (see Macknick et al. [98] and *Methodology* discussion in the next section) and life cycle (see Meldrum et al. [99]) water use compared to fossil and nuclear technologies. As a result, prior work generally found that future scenarios designed to meet carbon reduction goals also result in water savings, particularly when renewable-based pathways are envisioned [94, 100]. No studies to date have evaluated the potential changes in water use that could result from scenarios of high hydropower deployment.

Hydropower technologies are unique in that water is not diverted away from a water body in the same way it is for other uses; water is used for hydropower operations and generally remains in, or is returned to, the water body. However, characterizing withdrawal metrics is not uniform across all forms of hydropower and at the national scale. Consumption metrics, which could be measured by evaporation and loss from reservoirs, also have challenges associated with the geometric and geographic diversity of reservoirs; temporal variations in water levels and evaporation rates; and inter-year variations in operational releases and water levels that can affect evaporation rates. Withdrawal and consumption metrics are also complicated by the multiple uses of reservoirs (e.g., water supply, recreation, flood control) and the different methods of allocating evaporation to electricity production or other uses [101, 102, 103]. Given that this modeling analysis, along with many others, does not project any new large hydropower reservoirs to be built or to be retired, this impact analysis does not consider withdrawal or consumption from existing reservoirs that contain hydropower technologies. This modeling analysis focuses on run-of-river hydropower technologies as well as upgrades to existing facilities or powering non-powered dams, which entail little to no increase in water consumption above current levels.

Notwithstanding the uncertainties noted previously, new hydropower deployment is expected to reduce thermal cooling water use in some areas, potentially providing economic and environmental benefits. Some states have already proposed measures to reduce the water intensity of the electricity produced in their states, and EPA has invoked the Clean Water Act to propose various measures to limit the impacts of thermal power plant cooling on aquatic habitats [104]. To the extent that new hydropower deployment considered in this analysis can reduce power-sector water demands, it might also reduce the cost of meeting future policies intended to manage water use. The rest of this section details calculations of the water withdrawal and consumption impacts of the nine selected scenarios explored in greater depth within the *Hydropower Vision* analysis, both nationally and regionally. The economic benefits of water-use reductions are described qualitatively due to limitations in monetary quantification.

### *Methodology*

ReEDS was used to compute power-sector water withdrawal and consumption in each scenario and its corresponding baseline scenario with no new unannounced hydropower construction. ReEDS incorporates the cost, performance, and water use characteristics of different generation technology and cooling system combinations, and the model considers water availability as a limiting condition for new power plant construction [105]. Cooling systems for thermal power plants implemented in ReEDS fall into four categories:




Source: Averyt et al. [110]

**Figure 3-51.** Operational water withdrawal and consumption requirements by generation technology and cooling system

once-through, pond, recirculating, and dry cooling.[50] Consistent with prior studies and proposed EPA regulations, this analysis does not allow new power plants in ReEDS to employ once-through cooling technologies [94, 96]. The basic approach used here has been applied in multiple studies evaluating the national and regional water impacts of the U.S. electricity sector [3, 94, 100, 105, 106].

Water withdrawal and consumption impacts of the existing hydropower fleet are calculated as a function of the baseline scenarios. Avoided water withdrawal and consumption are calculated utilizing regional average water use rates (gallons per MWh of electricity generated) for non-hydropower generation. The electricity generated by hydropower within each region and for each year is multiplied by the regional water withdrawal and consumption rate to provide water impact results.

The *Hydropower Vision* analysis focuses exclusively on operational water-use requirements. These requirements can vary depending on fuel type, power plant type, and cooling system, and many renewable energy technologies have relatively low operational water withdrawal and consumption intensities (Figure 3-51). Thermal power plants using once-through cooling withdraw more water for every MWh of electricity generated than do plants using recirculating cooling systems. For water consumption, however, once-through cooling has lower demands than recirculating systems. Dry cooling can be used to reduce both water withdrawal and consumption for thermal plants, but at a cost and efficiency penalty [107]. Non-thermal renewable energy technologies (such as PV, wind, and the hydropower technologies considered in this analysis) do not require water for cooling and, thus, have low operational water-use intensities. These water requirements for non-thermal technologies are, however, included in the calculations. Several additional aspects of the methodology, and possible related limitations, deserve note:

- This analysis does not estimate full life cycle water uses, including upstream processes such as construction, manufacturing, and fuel supply. Including these requirements would likely increase the water savings from many scenarios, but associating upstream water uses to specific geographic regions is challenging. Moreover, prior work has

50. Cooling systems for the existing fleet are assigned to ReEDS balancing area generating capacity based on an analysis of individual electric-generating units aggregated at the ReEDS balancing-authority level, as described elsewhere [108, 109].

demonstrated that thermoelectric water withdrawals and consumption during plant operations are orders of magnitude greater than the demands from other life cycle stages [99].

- Power-sector water use will be impacted by various possible changes in the electric sector, such as coal plant retirements, new combined-cycle natural gas plant construction, and increased use of dry cooling. These changes may be driven in part by future, uncertain water policies, and they could affect the estimated water savings under the scenarios analyzed.
- Although water resource impacts are described regionally at the state level, there can be considerable variation in water resource availability and impacts within a given state; evaluating water impacts on a smaller watershed level could partially address this limitation.
- The benefits of water-use reductions are not quantified in monetary terms owing to challenges associated with quantifying the value of water resource services [3].

### *Results*

Both the existing hydropower fleet and new hydropower deployment reduce national power-sector water withdrawal and consumption, when compared with historical use and across selected scenarios.

The existing hydropower fleet contributed to approximately 1,450 billion gallons of water withdrawal savings per year and 100 billion gallons of water consumption savings per year as of 2016, representing a 4.1% and 7.3% reduction in water withdrawals and consumption, respectively. Over time, water withdrawal and consumption savings decline as water-intensive energy technologies (e.g., coal, nuclear) and cooling systems (e.g., once-through cooling), are replaced by lower water intensity natural gas and renewable energy technologies. In 2050, the existing hydropower fleet contributes to a 2.9% reduction in water withdrawals (200 billion gallons) and a 4.6% reduction in water consumption (40 billion gallons) due to the existing fleet. Cumulative water savings for 2017–2050 total 30.1 trillion gallons of withdrawals and 2.2 trillion gallons of consumption.

Regionally, the existing fleet provides different benefits depending on the water intensity of the non-hydropower fleet. In the arid West, where many existing hydropower projects are concentrated, water withdrawal and consumption rates of the non-hydropower fleet tend to be lower than in the East. Figure 3-52 shows national water withdrawal and consumption savings associated with the existing hydropower fleet.

Figure 3-53 shows the decline in annual power-sector water withdrawals for all scenarios considered. On a national level, withdrawals decline substantially over time under all scenarios, largely owing to the retirement and reduced operations of once-through-cooled thermal facilities and the assumed replacement of those plants with newer, less water-intensive generation and cooling technologies. In all scenarios, once-through-cooled plants are largely replaced by new thermal plants using recirculating cooling and a combination of renewable energy technologies. Although national-level withdrawal estimates are relatively similar across scenarios with reference electricity market conditions within each set of baseline scenarios (no more than 1% difference across scenarios for all years), withdrawal estimates have greater variation across scenarios with different market conditions. The *Advanced Technology, Low Cost Finance, Critical Habitat, Low VG Cost* scenario has greater penetrations of wind and solar PV technologies than the *Business-as-Usual* scenario, and the low water intensity of wind and PV have the effect of reducing national level water withdrawals in 2050 by 9.6% (~680 billion gallons) from *Business-as-Usual* (680 billion gallons represents the annual water usage of approximately 4.8 million U.S. households). This effect is amplified in scenarios with *High Fossil Fuel Cost*, where increases in fossil fuel costs lead to a sharper reduction in fossil fuel generation, also resulting in greater penetrations of non-thermal electricity technologies. Withdrawal estimates in the *High Fossil Fuel* scenarios in 2050 are approximately 33% (2.3 trillion gallons) lower than those in *Business-as-Usual*.

Across the nine selected scenarios, 2050 water withdrawal impacts relative to their respective baseline range from a 0.5% increase (in the *Low Cost Finance* scenario) to a 4% decrease (in the two *High Fossil Fuel Cost* scenarios). Table 3-10 and Figure 3-54 highlight the range of results for all scenarios as they relate to their corresponding baseline. Cumulative withdrawal reductions for 2017–2050 range from a 0.1% increase for several scenarios, to a 1.2% decrease in the *Advanced Technology, Low Cost Finance, Critical Habitat, Low VG Cost* scenario.

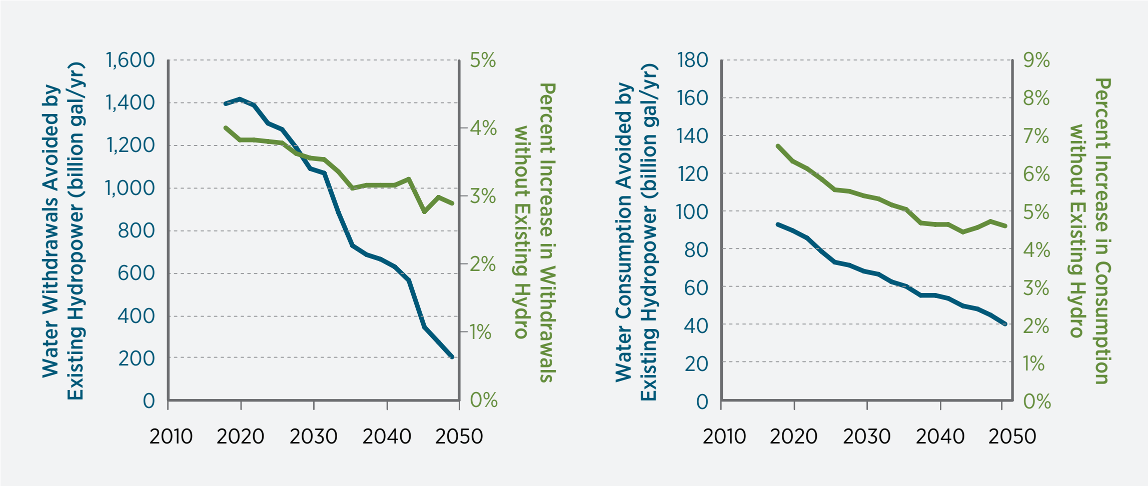



**Figure 3-52.** Water withdrawal savings (left) and water consumption savings (right) of the existing fleet

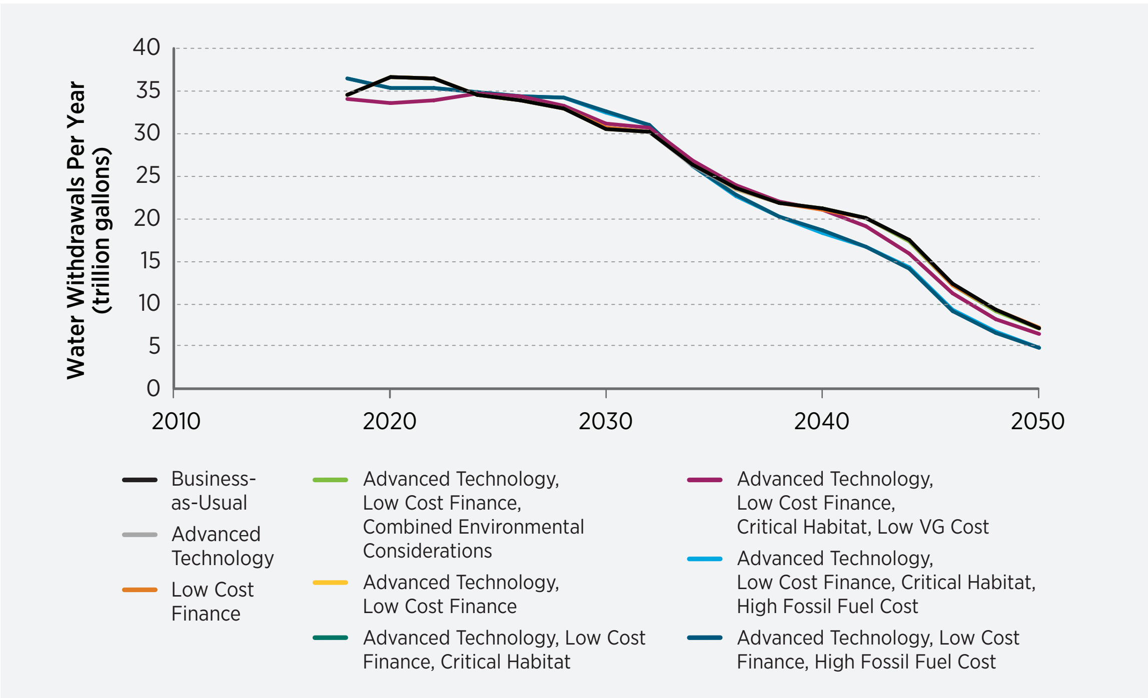



**Figure 3-53.** Power-sector water withdrawal impacts of selected scenarios

**Table 3-10.** Water Withdrawal in 2050 under Multiple Scenarios Relative to the Baseline

| | 2050 Withdrawal (trillion gallons) | Reduction in 2050 Withdrawal from baseline | | Reduction in 2017–2050 Withdrawal from baseline | |
|---|---|---|---|---|---|
| | | (trillion gallons) | (%) | (trillion gallons) | (%) |
| *Business-as-Usual* | 7.02 | -0.03 | -0.4% | -1.1 | -0.1% |
| *Advanced Technology* | 7.01 | -0.02 | -0.3% | -0.5 | -0.1% |
| *Advanced Technology, Low Cost Finance* | 6.97 | 0.02 | 0.3% | -0.4 | -0.1% |
| *Advanced Technology, Low Cost Finance, Critical Habitat* | 6.99 | 0.00 | 0.0% | -0.7 | -0.1% |
| *Advanced Technology, Low Cost Finance, Critical Habitat, High Fossil Fuel Cost* | 4.71 | 0.20 | 4.0% | 7.7 | 0.9% |
| *Advanced Technology, Low Cost Finance, Critical Habitat, Low VG Cost* | 6.35 | 0.22 | 3.3% | 10.2 | 1.2% |
| *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* | 6.99 | 0.00 | 0.1% | -0.8 | -0.1% |
| *Advanced Technology, Low Cost Finance, High Fossil Fuel Cost* | 4.71 | 0.20 | 4.0% | 7.2 | 0.9% |
| *Low Cost Finance* | 7.03 | -0.03 | -0.5% | -0.4 | 0.0% |

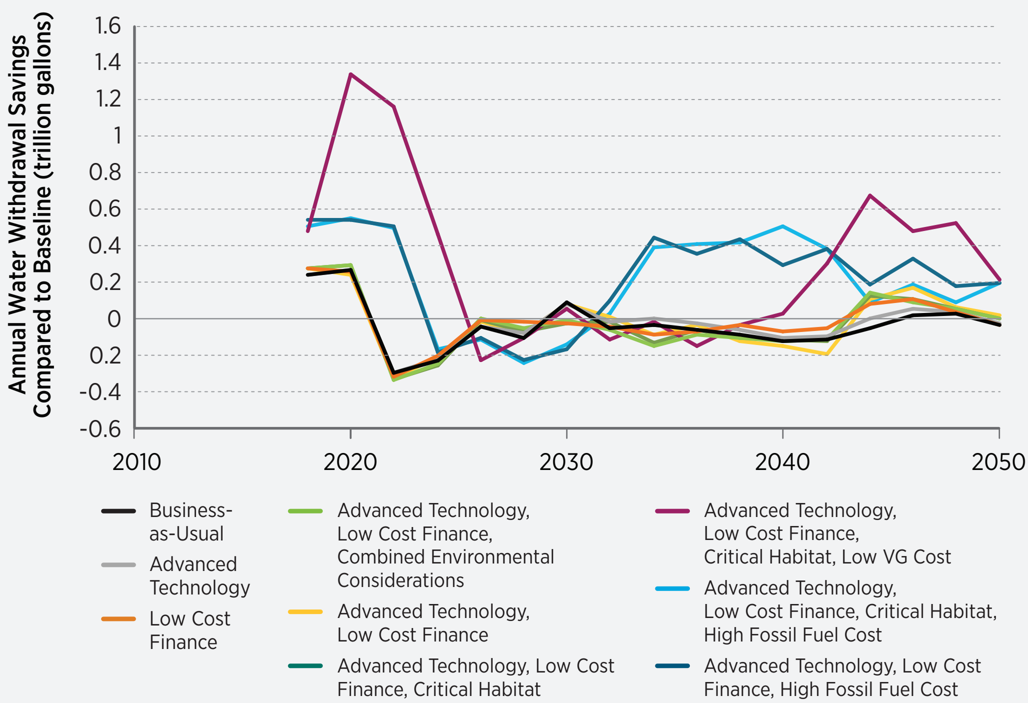



**Figure 3-54.** Annual water withdrawal savings under selected scenarios

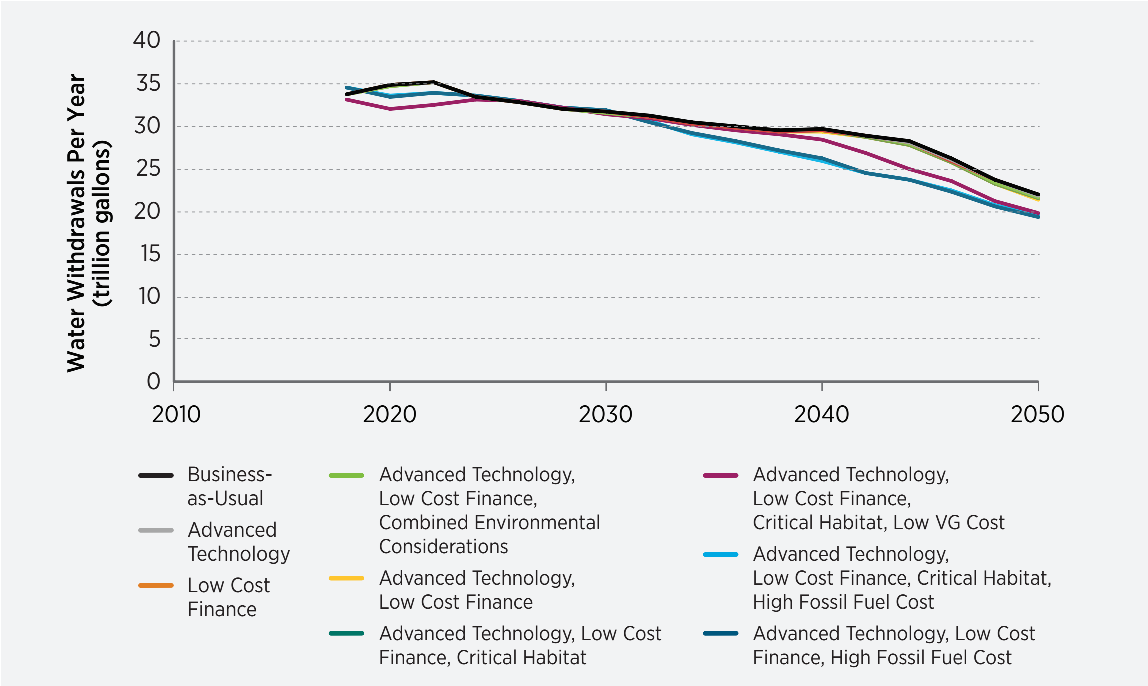



**Figure 3-55.** Power-sector water consumption impacts of selected scenarios

Figure 3-55 shows the change in annual power-sector water consumption for the selected scenarios. National power-sector water consumption declines over time in all scenarios, but to a lesser extent than water withdrawals. Similar to withdrawals, there is little variability in national water consumption across scenarios using reference fossil fuel and VG costs (no more than 3% difference across scenarios and years). The scenario with *Low VG Cost* leads to national reductions in consumption in 2050 of 9.7% (85 billion gallons), relative to *Business-as-Usual*. Under scenarios with *High Fossil Fuel Cost*, national reductions in consumption in 2050 are 11–12% (~100 billion gallons). As with withdrawals, these changes can be attributed to the amount of low-water-intensity renewable generation sources that are deployed, as compared with high-water-intensity thermal technologies. Consumption differences are smaller than withdrawal differences due to the transition from once-through-cooled to recirculating-cooled thermal technologies, with the latter having a higher water consumption rate.

There is greater variation in impacts on national water consumption than there is for withdrawal. Across selected scenarios, water consumption impacts range from a 2.3% increase (in *Business-as-Usual*) to a 7.6% decrease (in the *Advanced Technology, Low Cost Finance, Critical Habitat, High Fossil Fuel Cost* scenario) in 2050 compared to the baseline scenarios. Cumulative 2017–2050 consumption impacts range from a 0.4% increase (in the *Business-as-Usual* and *Advanced Technology* scenarios) to a 2.6% decrease in scenarios with *High Fossil Fuel Cost*. Table 3-11 and Figure 3-56 highlight the water consumption impacts for all selected scenarios. Consumption reductions in 2050 are seen only for the *High Fossil Fuel Cost* scenarios and the *Advanced Technology, Low Cost Finance* scenario, when compared with the baseline. The *Advanced Technology, Low Cost Finance, Critical Habitat* scenario and the scenario with *Low VG Cost* achieve consumption reductions over the 2017–2050 time frame.

Water withdrawal impacts under all scenarios are not uniform throughout the continental United States, and considerable regional differences can mask relatively small national-level differences. Figure 3-57 shows state water withdrawal differences in 2050 for representative low, mid, and high hydropower deployment scenarios, compared with the baseline. In the *Business-as-Usual* scenario, only 18 states show withdrawal savings compared with the baseline, yet for the *Advanced Technology, Low Cost Finance, High*

**Table 3-11.** Water Consumption in 2050 Compared across Multiple Scenarios and Relative to the Baseline

| | 2050 Withdrawal (trillion gallons) | Reduction in 2050 Withdrawal from baseline | | Reduction in 2017–2050 Withdrawal from baseline | |
|---|---|---|---|---|---|
| | | (trillion gallons) | (%) | (trillion gallons) | (%) |
| *Business-as-Usual* | 0.88 | -0.02 | -2.3% | -0.17 | -0.4% |
| *Advanced Technology* | 0.87 | -0.02 | -1.9% | -0.15 | -0.4% |
| *Advanced Technology, Low Cost Finance* | 0.86 | 0.00 | 0.3% | 0.06 | 0.2% |
| *Advanced Technology, Low Cost Finance, Critical Habitat* | 0.86 | 0.00 | -0.5% | 0.05 | 0.1% |
| *Advanced Technology, Low Cost Finance, Critical Habitat, High Fossil Fuel Cost* | 0.77 | 0.06 | 7.6% | 1.04 | 2.6% |
| *Advanced Technology, Low Cost Finance, Critical Habitat, Low VG Cost* | 0.79 | -0.01 | -0.7% | 0.40 | 1.0% |
| *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* | 0.87 | -0.01 | -1.0% | 0.00 | 0.0% |
| *Advanced Technology, Low Cost Finance, High Fossil Fuel Cost* | 0.78 | 0.06 | 7.1% | 1.05 | 2.6% |
| *Low Cost Finance* | 0.88 | -0.02 | -2.2% | -0.08 | -0.2% |

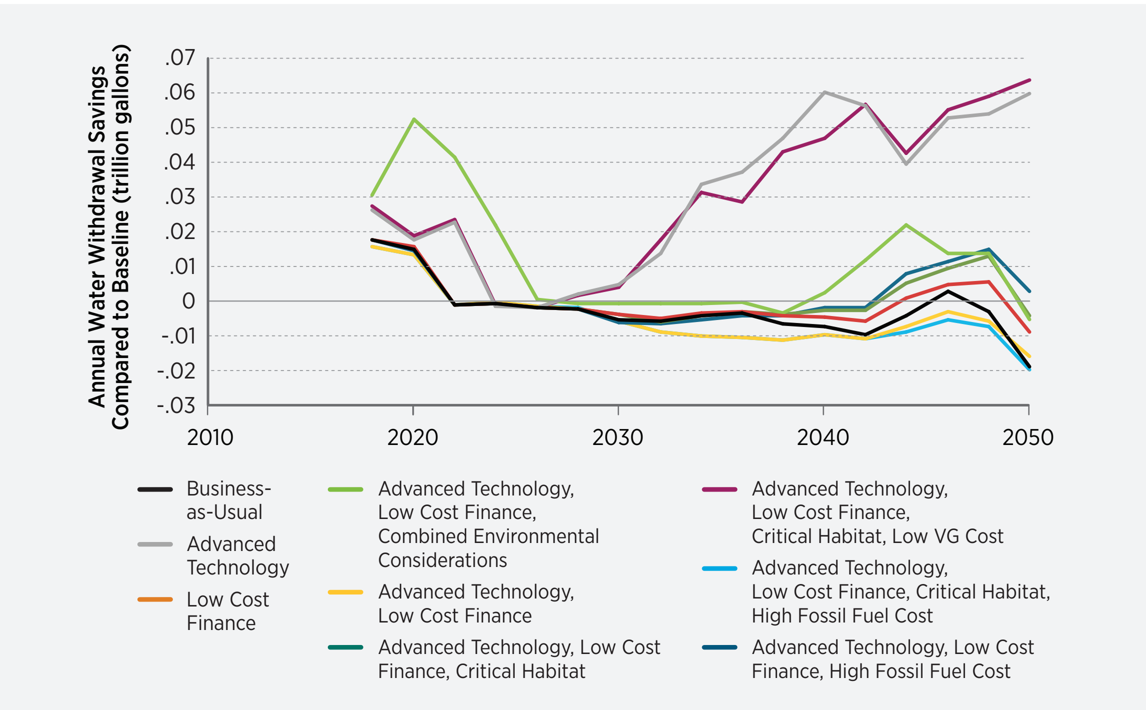



**Figure 3-56.** Annual water consumption under selected scenarios

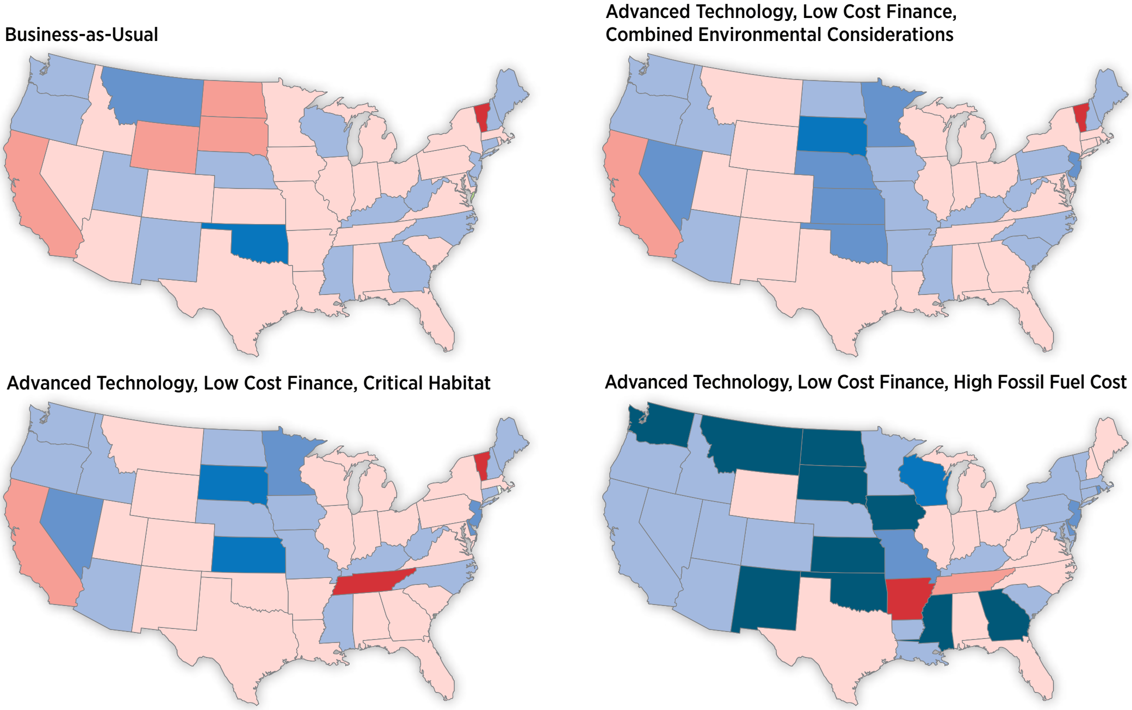
*Fossil Fuel Cost* scenario, there are 33 states with withdrawal savings. This is largely a reflection of where new hydropower capacity is deployed, where other renewable energy technologies are deployed, and where the most water-intensive thermal plants are offset. Certain states, such as Mississippi, Nebraska, and New Jersey, show withdrawal savings across all scenarios. Other states, such as Illinois, Tennessee, and Texas, show withdrawal increases across all scenarios. Most states, however, including California, show either withdrawal increases or decreases depending on the scenario considered and the regional deployment of technologies. The largest changes in magnitude for water withdrawals are concentrated in the areas with high levels of once-through cooling (e.g., Midwest, Southeast, Texas).

Water consumption impacts under all scenarios are also diverse throughout the continental United States, showing substantial regional differences that are not apparent in national level results. Figure 3-58 shows state water consumption differences in 2050 for representative low, mid, and high deployment scenarios compared with the baseline. In the *Business-as-Usual* scenario, only 17 states show consumption savings compared with the baseline; yet for the *Advanced Technology, Low Cost Finance, High Fossil Fuel Cost* scenario, 39 states show consumption savings. Regionally, more states show water consumption savings for all scenarios than for withdrawal savings, and fewer states show consumption increases for all scenarios than withdrawal increases. Notably, many water-stressed states (e.g., Texas, California, and other parts of the arid West), show larger water consumption savings than withdrawal savings. The largest increases in consumption tend to be located in the Southeast, whereas the largest reductions in consumption tend to be located in the arid West.

The ability of new hydropower to reduce power-sector water withdrawals and consumption in certain regions offers economic and environmental benefits, especially in regions where water is scarce. By reducing power-sector water use, hydropower technologies considered in this analysis can reduce the vulnerability of electricity supply to the availability or temperature of water, potentially avoiding power-sector reliability events and/or the effects of reduced thermal plant efficiencies—concerns that might otherwise grow as the climate changes [111]. Additionally, increased non-consumptive hydropower deployment can free up water for other productive purposes (e.g., agricultural, industrial, or municipal use) or to strengthen local ecosystems (e.g., benefiting wildlife owing to greater water availability and lack of temperature change). Reducing the quantities of fossil fuels used can help alleviate other power-sector impacts on water resource quality and quantity that occur during upstream fuel production [110].

Quantifying in monetary terms the societal value of these water-use reductions is difficult, however, as no standardized methodology exists in the literature. One potential approach is to consider hydropower deployment as avoiding the *possible* need to otherwise employ thermal power plants with lower water use, or to site power plants where water is available and less costly. ReEDS already includes the cost and performance characteristics of different cooling technologies in its optimization, as well as the availability and cost of water supply; these costs and considerations are embedded in the results presented earlier. If water becomes scarcer in the future and/or if water policy becomes stricter, however, additional costs might be incurred. In such an instance, a possible upper limit of the incremental cost of water-use reductions associated with conventional thermal generation can be estimated by comparing the cost of traditional wet cooling with the cost of dry cooling. Dry cooling adds capital expense to thermal plants and reduces plant efficiencies. The total cost increase of dry cooling for coal generation has been estimated at 0.32–0.64¢/kWh [112]. For natural gas combined cycle plants, Maulbetsch and DiFilippo [113] estimate an "effective cost" of saved water at $3.80–$6.80 per 1,000 gallons, corresponding to approximately 0.06–0.17¢/kWh [3]. These estimated incremental costs for dry cooling are relatively small, and they likely set an upper limit on the water-related cost savings of hydropower or any other power technology intended, in part, to reduce water withdrawal and consumption.[51]

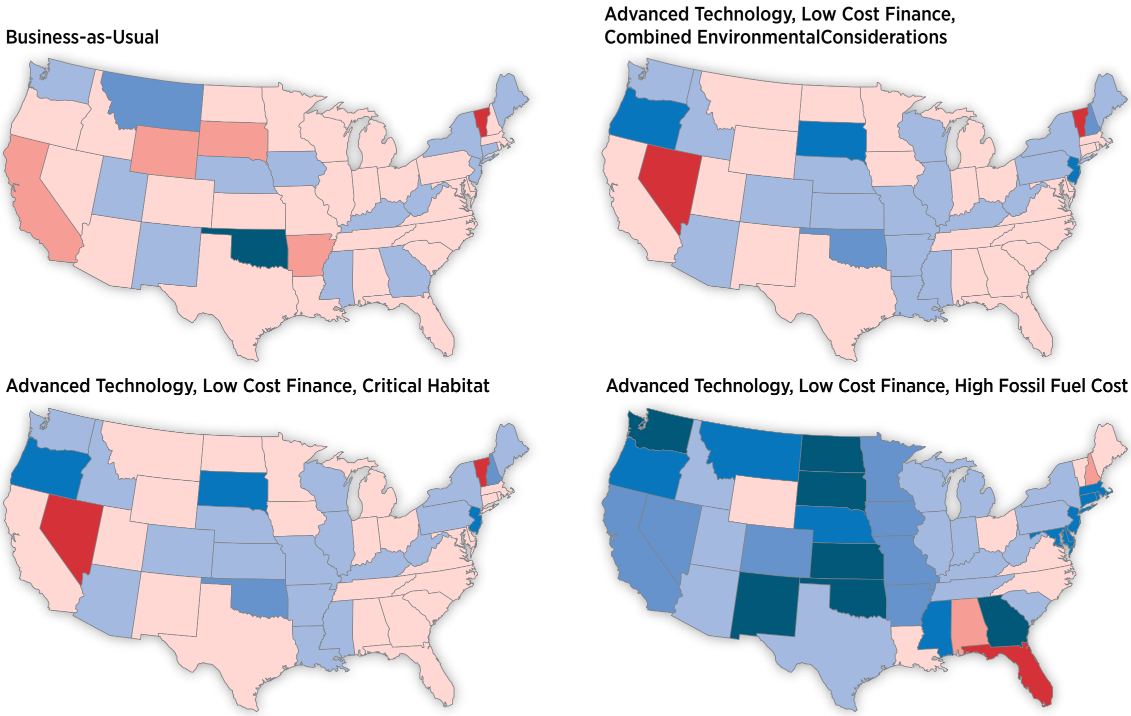
51. The actual benefits, in terms of cost savings, would be lower than these figures for a few reasons. First, many regions of the country are not facing water scarcity, so the economic benefits of reduced water use are geographically limited. Second, to the extent that hydropower offsets more electricity supply (kilowatt-hours) than electricity capacity (kilowatts), it may not be able to offset the full capital and operating cost of less water-intensive cooling technologies. Third, few plants to date have been required or chosen to implement dry cooling; alternative, lower-cost means of obtaining and/or reducing water have predominated, including simply locating plants where water is available. Alternative water resources, such as municipal wastewater or shallow brackish groundwater, could also be more cost-effective than dry cooling in some regions [114]. These lower-cost methods of reducing water use are likely to dominate for the foreseeable future.




**Annual Withdrawal Savings in 2050** (% Change from Baseline)

< -20% | -20% – -10% | -10% – 0% | 0% – 10% | 10% – 20% | 20% – 30% | > 30%

**Figure 3-57.** Water withdrawals savings in 2050 for representative low, mid, and high deployment scenarios




**Annual Consumption Savings in 2050** (% Compared with Comparable Baseline)

< -20% | -20% – -10% | -10% – 0% | 0% – 10% | 10% – 20% | 20% – 30% | > 30%

**Figure 3-58.** Water consumption savings in 2050 in representative low, mid, and high deployment scenarios

## 3.5.9 Workforce and Economic Development Impacts

Many studies have been conducted that seek to quantify potential jobs and economic activity supported by the construction and operation of energy facilities [3, 121, 122, 123, 124, 125, 126, 127, 128, 129, 130]. This section continues and builds on these efforts by quantifying future gross jobs[52], earnings, gross domestic product (GDP), and economic output supported by the hydropower industry.

Jobs estimates include employment resulting from servicing and maintaining the existing fleet as well as potential additional employment resulting from new hydropower plant development, construction, and operation. Replacement needs within the current workforce through 2030 are also estimated. Economic activity is similarly quantified based on: (1) new investment in maintenance of the existing hydropower fleet, and (2) new investment in facility upgrades, powering of non-powered dams and new hydropower facilities (hydropower generation and PSH).

### *Methodology*

The National Renewable Energy Laboratory's Hydropower Jobs and Economic Development Impacts, or JEDI, model is used to estimate job impacts from the construction and operation of facilities in the modeled scenarios. Appendix H contains a more detailed description of JEDI, including detail on how the model works and its limitations. To better illustrate the trends through time, economic impacts for any given year are reported as a 4-year moving average. Estimates are inclusive of new investments in both hydropower generation and PSH.

The number of U.S. jobs, especially those supported throughout the supply chain, depends on the portion of expenditures made by developers and operators that accrue to companies within the United States. Proportions are estimated from two proprietary sources. First, public- and private-sector contributors to this study contacted manufacturers and other companies within the hydropower supply chain to acquire information about where those respondents operate and the factors that influence location decisions. Second, Oak Ridge National Laboratory surveyed hydropower operators in 2013 about where components are sourced. These two sources of information provide a range of potential local expenditures. Based on these data, a low domestic content and a high domestic content result was estimated for each modeled hydropower scenario. Domestic content proportions are shown in Tables 3-12 and 3-13. While this range of potential results helps to illustrate the uncertainty inherent in these estimates, it is not intended to show the lowest and highest possible impact. It is also not intended to assert a potential probability or likelihood associated with either of these scenarios.

The proportions of domestic content are assumed to be constant throughout the period of analysis. This simplifying assumption is applied due to substantial uncertainty regarding factors that could lead to increases or decreases in local content. Such factors include changes in technology, international trade, economic development incentives, hydropower development outside of the United States, and the preferences of producers and developers.

Workforce replacement estimates come from a demographic cohort-component model. Cohort-component models are often used to project changes in populations in which age, sex,[53] and factors that influence entry and exit from the population are reasonably known. The U.S. Census Bureau, for example, uses a cohort-component model in its population projections. Entry and exit from the population are determined by estimating births, deaths, and in- and out-migration [116]. The cohort-component model used in this study splits the workforce into groups, or cohorts, characterized by occupation, age, and sex. Each cohort is aged over time, and members are removed based on estimates of mortality and retirement. The analysis assumes that workers who are removed need to be replaced; i.e., as workers age, they are more likely to retire or potentially pass away.

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52. The difference between gross and net impacts is discussed more thoroughly in Appendix H. The gross impacts estimated in this study solely consider impacts supported by expenditures made by hydropower operators and developers. They do not consider a full range of impacts such as utility rate changes, changes in land values, taxes, or displaced economic activity.

53. Demographers use the term "sex" to refer to biological differences between males and females, which differs from the meaning of "gender." In this case, "sex" is more accurate. For more information, see the U.S. Census Bureau's "About Age and Sex" [115].

**Table 3-12.** Domestic Content of Construction Expenditures

| | Low | High |
|---|---|---|
| Land Purchases | 100% | 100% |
| Preparation, Prefabricated Structures, Site Access | 60% | 100% |
| Turbines and Generators | 20% | 80% |
| Balance of Plant | 30% | 80% |
| Transformers, Switchyard, and Interconnection | 0% | 0% |
| Installation Labor | 80% | 100% |
| Mitigation | 80% | 95% |
| Licensing, Permitting, Interconnection | 80% | 100% |
| Engineering and Other Professional Services | 15% | 50% |
| Insurance and Other Development Costs | 75% | 100% |

**Table 3-13.** Domestic Content of Operations and Maintenance Expenditures

| | Low | High |
|---|---|---|
| Onsite operations labor | 100% | 100% |
| Supplies, tools, vehicles | 40% | 80% |
| Replacement parts | 25% | 80% |
| Regulatory compliance | 80% | 95% |

Retirements are estimated based on changes in labor force participation over time. Labor force participation can be seen decreasing as older workers age, reflecting both a smaller absolute size of the older population due to mortality and workers choosing to retire.[54] Retirement in this report refers to workers who exit the labor force by ceasing to work or actively seek employment. Retirement estimates by year, age, and sex are derived from Bureau of Labor Statistics projections [116]. These projections contain existing and forecasted labor force participation rates by age and sex through 2022. It is assumed that annual average changes in labor force participation by age and sex beyond 2022 continue on the same linear trajectory as the Bureau of Labor Statistics forecasts between 2012 and 2022.

54. This definition of retirement does not describe financial arrangements such as pensions or social security. For example, a worker who formally retires to begin collecting a pension and then returns to work as a contractor does not exit the labor force. Despite technically retiring from a specific employer, this worker would not be considered a retiree because she or he remains in the labor force

**Table 3-14.** Jobs (Full-time Equivalents) in 2030 and 2050 Supported by New Hydropower Deployment Scenario with Low and High Domestic Content

| | 2030 | | 2050 | |
|---|---|---|---|---|
| | Low Domestic Content | High Domestic Content | Low Domestic Content | High Domestic Content |
| *Business as Usual* | 137,800 | 140,600 | 137,600 | 139,000 |
| *Advanced Technology* | 132,600 | 135,200 | 137,200 | 140,300 |
| *Low Cost Finance* | 173,500 | 197,100 | 144,800 | 149,200 |
| *Advanced Technology, Low Cost Finance, Critical Habitat, Low VG Cost* | 203,600 | 238,900 | 219,700 | 251,100 |
| *Advanced Technology, Low Cost Finance, Critical Habitat* | 214,700 | 260,500 | 190,000 | 208,000 |
| *Advanced Technology, Low Cost Finance* | 252,700 | 297,200 | 270,300 | 290,400 |
| *Advanced Technology, Low Cost Finance, High Fossil Fuel Cost, Critical Habitat* | 271,800 | 325,000 | 274,300 | 300,500 |
| *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* | 214,100 | 250,800 | 191,500 | 202,300 |
| *Advanced Technology, Low Cost Finance, High Fossil Fuel Cost* | 329,700 | 410,000 | 317,500 | 352,500 |

Mortality estimates in this analysis are from the Centers for Disease Control and Prevention's Wide-ranging Online Data for Epidemiologic Research database. These are present-day mortality rates by age and sex, not forecasts. This analysis assumes no change in mortality rates into the future.

### Results

Total hydropower-derived employment estimates have been calculated as function of all future investments in hydropower facilities (on-site, supply chain, induced jobs) under conditions with varying levels of new hydropower deployment. More specifically, total hydropower-derived estimates have been made for each of the nine scenarios identified and described in Section 3.4 and under both the low and high domestic content assumptions noted in Tables 3-12 and 3-13.

Total hydropower investment employment estimates for 2030 and 2050 are shown in Table 3-14. Under *Business-as-Usual* conditions, the existing labor force grows to approximately 137,800 to 140,600 jobs (full-time equivalents) in 2030 and holds essentially steady at that level through 2050. The scenario with the largest hydropower capacity expansion—*Advanced Technology, Low Cost Finance, High Fossil Fuel Cost*—consistently supports the highest number of jobs, with impacts in 2030 and 2050 ranging from a low of 317,500 (2050 low domestic content) to a high of 410,000 (2030 high domestic content).

Earnings, gross domestic product, and economic output (total economic activity) are also associated with operation and expansion of hydropower facilities. Table 3-15 highlights these results across representative low, mid, and high hydropower deployment scenarios for 2030. Table 3-16 highlights these results across the same four scenarios for 2050. Relative to the baseline, new hydropower deployment supports 76,000 new jobs (averaged across low and high domestic content estimates) in the *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* Scenario. Estimates of jobs supported by the existing fleet change over time, with 119,600–119,700 jobs supported in 2030 and 120,300–120,700 jobs supported in 2050 (ranges are across low and high domestic content).

**Table 3-15.** Jobs, Earnings, Output, and Gross Domestic Product Impacts of Representative Low, Mid, and High Deployment Scenarios in 2030, Showing Low and High Domestic Content (dollars in $2015 millions)

| 2030 | | Domestic Content | Onsite | Supply Chain | Induced | Total |
|---|---|---|---|---|---|---|
| *Business as Usual* | Jobs | Low | 25,000 | 60,200 | 52,700 | 137,800 |
| | | High | 25,600 | 61,400 | 53,700 | 140,600 |
| | Earnings | Low | $31,370 | $75,540 | $66,130 | $172,910 |
| | | High | $32,130 | $77,040 | $67,380 | $176,420 |
| | Output | Low | $2,350 | $4,110 | $3,290 | $9,740 |
| | | High | $2,400 | $4,280 | $3,330 | $10,010 |
| | GDP | Low | $2,410 | $15,370 | $9,990 | $27,750 |
| | | High | $2,490 | $15,800 | $10,100 | $28,390 |
| *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* | Jobs | Low | 49,500 | 81,300 | 83,400 | 214,100 |
| | | High | 60,900 | 93,400 | 96,400 | 250,700 |
| | Earnings | Low | $4,430 | $5,490 | $5,110 | $15,020 |
| | | High | $5,370 | $6,500 | $5,840 | $17,700 |
| | Output | Low | $5,500 | $20,810 | $15,530 | $41,840 |
| | | High | $7,190 | $23,990 | $17,740 | $48,910 |
| | GDP | Low | $4,580 | $13,210 | $9,100 | $26,880 |
| | | High | $5,630 | $14,700 | $10,400 | $30,710 |
| *Advanced Technology, Low Cost Finance, Critical Habitat* | Jobs | Low | 56,400 | 74,500 | 83,900 | 214,600 |
| | | High | 70,900 | 89,400 | 100,200 | 260,400 |
| | Earnings | Low | $5,030 | $5,490 | $5,190 | $15,690 |
| | | High | $6,240 | $6,660 | $6,100 | $18,990 |
| | Output | Low | $6,350 | $17,910 | $15,770 | $40,020 |
| | | High | $8,500 | $22,070 | $18,530 | $49,090 |
| | GDP | Low | $5,210 | $10,730 | $9,240 | $25,180 |
| | | High | $6,570 | $12,760 | $10,860 | $30,180 |
| *Advanced Technology, Low Cost Finance, High Fossil Fuel Cost* | Jobs | Low | 84,300 | 122,000 | 123,500 | 329,700 |
| | | High | 111,200 | 146,700 | 152,100 | 409,900 |
| | Earnings | Low | $7,500 | $7,990 | $7,410 | $22,880 |
| | | High | $9,800 | $9,930 | $9,030 | $28,750 |
| | Output | Low | $9,710 | $31,650 | $22,510 | $63,850 |
| | | High | $13,650 | $37,840 | $27,440 | $78,920 |
| | GDP | Low | $7,830 | $20,100 | $13,190 | $41,110 |
| | | High | $10,410 | $23,190 | $16,080 | $49,670 |

**Table 3-16.** Jobs, Earnings, Output, and GDP Impacts of Representative Low, Mid, and High Deployment Scenarios in 2050, Showing Both Low and High Local Content (dollars in $2015 millions)

| 2050 | | Domestic Content | Onsite | Supply Chain | Induced | Total |
|---|---|---|---|---|---|---|
| *Business as Usual* | Jobs | Low | 24,200 | 60,500 | 53,000 | 137,600 |
| | | High | 24,200 | 61,200 | 53,500 | 138,900 |
| | Earnings | Low | $2,280 | $4,130 | $3,310 | $9,700 |
| | | High | $2,280 | $4,270 | $3,320 | $9,860 |
| | Output | Low | $2,280 | $15,450 | $10,060 | $27,790 |
| | | High | $2,300 | $15,780 | $10,080 | $28,150 |
| | GDP | Low | $2,280 | $10,060 | $5,900 | $18,220 |
| | | High | $2,290 | $10,070 | $5,910 | $18,250 |
| *Advanced Technology, Low Cost Finance, Combined Environmental Considerations* | Jobs | Low | 31,600 | 78,900 | 81,000 | 191,400 |
| | | High | 34,400 | 83,000 | 84,900 | 202,200 |
| | Earnings | Low | $2,910 | $5,250 | $5,040 | $13,190 |
| | | High | $3,140 | $5,650 | $5,240 | $14,030 |
| | Output | Low | $3,170 | $20,510 | $15,300 | $38,980 |
| | | High | $3,590 | $21,640 | $15,920 | $41,140 |
| | GDP | Low | $2,950 | $13,380 | $8,970 | $25,280 |
| | | High | $3,200 | $13,820 | $9,330 | $26,340 |
| *Advanced Technology, Low Cost Finance, Critical Habitat* | Jobs | Low | 37,900 | 68,400 | 83,900 | 190,000 |
| | | High | 42,900 | 74,900 | 90,300 | 207,900 |
| | Earnings | Low | $3,500 | $5,100 | $5,300 | $13,900 |
| | | High | $3,900 | $5,600 | $5,700 | $15,200 |
| | Output | Low | $3,900 | $16,600 | $16,100 | $36,500 |
| | | High | $4,600 | $18,600 | $17,200 | $40,300 |
| | GDP | Low | $3,600 | $10,200 | $9,500 | $23,100 |
| | | High | $4,000 | $11,200 | $10,100 | $25,200 |
| *Advanced Technology, Low Cost Finance, High Fossil Fuel Cost* | Jobs | Low | 51,700 | 137,800 | 128,200 | 317,500 |
| | | High | 62,400 | 149,600 | 140,600 | 352,400 |
| | Earnings | Low | $4,670 | $8,820 | $7,780 | $21,260 |
| | | High | $5,570 | $9,790 | $8,480 | $23,830 |
| | Output | Low | $5,530 | $36,510 | $23,640 | $65,670 |
| | | High | $7,080 | $39,520 | $25,750 | $72,350 |
| | GDP | Low | $4,780 | $24,020 | $13,850 | $42,650 |
| | | High | $5,780 | $25,500 | $15,100 | $46,360 |

In 2030, total contributions to output could be as high as $78.9 billion and contributions to GDP could be as high as $49.7 billion. In 2050, total contributions to output could be as high as $72.4 billion and contributions to GDP could be as high as $46.4 billion.

Communities will often be most interested in local impacts. To illustrate the potential geographic distribution of on-site jobs, Figure 3-59 details on-site jobs by state for representative low, mid, and high hydropower deployment scenarios: *Business-as-Usual*; *Advanced Technology; Low Cost Finance; All Environmental Considerations*; *Advanced Technology, Low Cost Finance, Critical Habitats Consideration*; and *Advanced Technology, Low Cost Finance, High Fossil Fuel Cost*. Data presented in Figure 3-59 assume that all onsite jobs occur within the states where facilities are built and operated. Supply chain and induced employment impacts are not estimated on a state or regional basis, as they may be procured from local or non-local suppliers.

As shown in Section 2.8, the hydropower industry supported approximately 118,000 total full-time equivalent jobs from O&M investments related to the existing fleet (based on estimated 2013 annual expenditures). Approximately 23,200 of these are identified as direct onsite hydropower industry jobs. These jobs and associated impacts are expected to continue throughout the duration of the modeled hydropower scenarios and are included in the total hydropower-related employment estimates shown in Figure 3-59. However, some portion of existing fleet workers will need to be replaced as the workforce ages.

The occupational distribution of the share of existing hydropower-supported jobs that are direct onsite jobs (approximately 20%) is summarized in Table 3-17. Figure 3-60 subsequently shows the age distribution of all U.S. workers, as well as the workers in the hydropower industry jobs categories in Table 3-17.

Note that many hydropower workers are older than 36 years, especially those in managerial or supervisory occupations, and the greatest concentration is in the 46- to 55-year-old cohort. These occupations will thus be the most affected by retirements in the next 10–20 years.

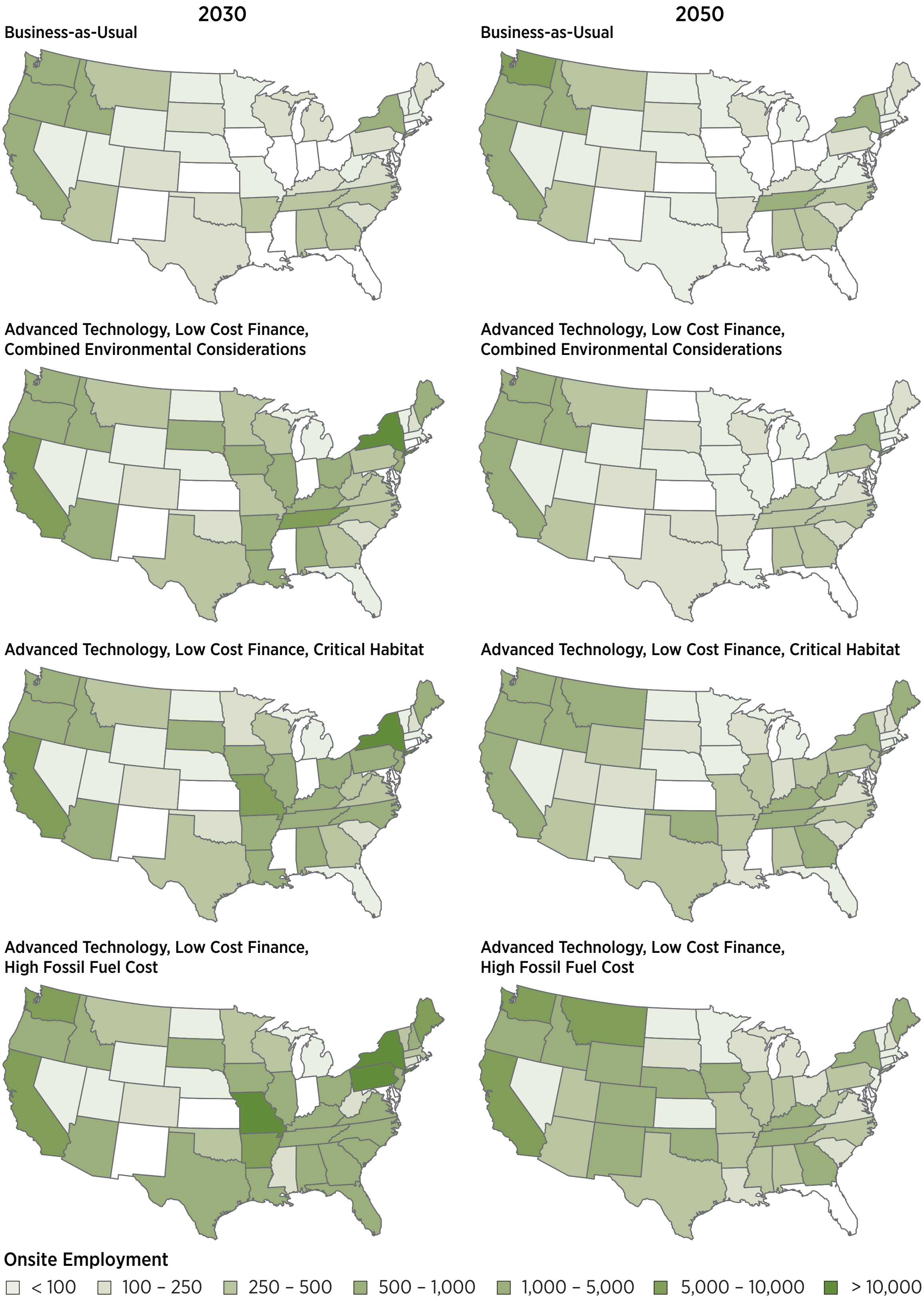


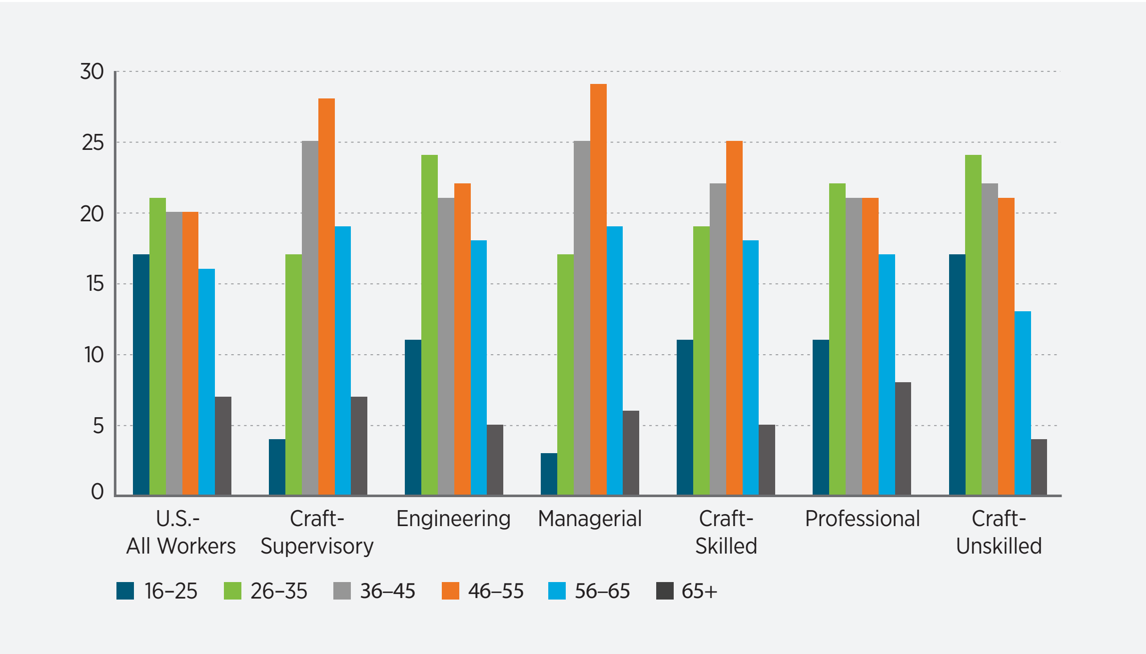

**Figure 3-59.** Onsite employment (full-time equivalents) by state under representative low, mid, and high deployment scenarios

**Table 3-17.** Distribution of 2013 Onsite Hydropower Operations and Maintenance Workers by Occupation[a]

| Occupation Category | Sample Jobs | Employment (2013) |
|---|---|---|
| Craft workers, unskilled | Construction laborers, helpers | 1,500 |
| Craft workers, skilled | Heavy equipment operators, mechanics | 6,200 |
| Supervisory craft workers | Managers of electricians, mechanics | 1,500 |
| Managers | Program manager, operations manager | 1,100 |
| Engineering | Civil, electrical, environmental | 2,800 |
| Administration | Accountant, clerical workers | 3,000 |
| Professional | Biologists, hydrologists, regulatory, compliance support workers | 7,100 |

a. Appendix I-Workforce contains further detail about specific occupations included in each category.

Source: DOE [118]




Source: DOE [118]

**Figure 3-60.** Age and occupational distribution of the existing hydropower workforce

**Table 3-18.** Cumulative Projected Workforce Replacement Needs by Occupation

| | 2025 | 2030 |
|---|---|---|
| Craft—Supervisory | 460 | 650 |
| Engineering | 800 | 1,110 |
| Managerial | 340 | 480 |
| Craft—Skilled | 1,650 | 2,320 |
| Professional | 2,070 | 2,800 |
| Craft—Unskilled | 330 | 480 |
| Administration | 750 | 1,040 |
| **Total** | **6,400** | **8,880** |

Source: DOE [118]

Based on these data, Table 3-18 summarizes projected retirements and subsequent replacement needs for the onsite workers through 2030. On a cumulative basis, the most significant workforce replacement needs are for skilled craft laborers and professional occupations, each representing approximately 2,500 jobs. Cumulative total jobs replacements through 2030 are estimated at approximately 8,880 on-site O&M-related jobs. Although managerial and supervisory staff tend to be older, absolute replacement totals for these staff suggest that this not necessarily problematic. These individuals also may start out in other fields and eventually become supervisors or managers, further reducing workforce concerns for this group.

Meeting both the replacement and incremental employment needs of the hydropower workforce may present challenges, especially if existing operators must compete with new operators for talented workers. Many positions require advanced educational backgrounds in science, technology, engineering, and mathematics fields, while others require post-secondary vocational training or trade certification. Workers may be hesitant to relocate to remote rural locations that offer limited employment alternatives if workers choose to leave their jobs [119, 120]. At same time, both the overall magnitude of potential workforce needs and the timing of incremental demand suggest that securing the requisite labor for the hydropower industry will be manageable.

In summary, the existing hydropower fleet provides a substantial workforce foundation to replenish and build from over time. Total employment supported by the existing fleet is estimated at approximately 118,000. Approximately 38% of these jobs are expect to require replacement by 2030. Opportunities for new hydropower deployment (hydropower generation and PSH) present further demand to expand the hydropower workforce. Under *Business-as-Usual* conditions, the hydropower-supported workforce could expand by 17–19% by 2030 and remain largely at that level through 2050. Under the largest new hydropower growth considered in modeling analysis, the hydropower workforce could grow 180–250% by 2030 before declining slightly and stabilizing at levels that are approximately 170–200% larger than the current workforce. Under the largest new hydropower growth scenario considered in modeling analysis, total annual contributions to GDP could approach levels of $40 billion–$50 billion per year by 2030 and remain at that level through 2050.

# Chapter 3 References

[1] Short, W.; Sullivan, P.; Mai, T.; Mowers, M.; , C.; Blair, N.; Heimiller, D.; Martinez, A. Regional Energy Deployment System (ReEDS). 2011.NREL Report No. TP-6A20-46534. National Renewable Energy Laboratory, Golden, CO (US). Accessed June 15, 2016. *http://www.nrel.gov/analysis/reeds/documentation.html*.

[2] Sullivan, P.; Cole, W.; Blair, N.; Lantz, E.; Krishnan, V.; Mai, T.; Mulcahy, D.; Porro, G.2015 Standard Scenarios Annual Report: U.S. Electric Sector Scenario Exploration. 2015. NREL Report No. TP-6A20-64072. National Renewable Energy Laboratory, Golden, CO (US). Accessed June 15, 2016. *http://www.nrel.gov/docs/fy15osti/64072.pdf*.

[3] U.S. Department of Energy 2015. Wind Vision: A New Era for Wind Power in the United States. DOE/GO-102015-4557. Washington, D.C.: U.S. Department of Energy. Accessed June 16, 2016. *http://www.energy.gov/eere/wind/maps/wind-vision*.

[4] National Energy Board (NEB). 2013. Canada's Energy Future 2013–Energy Supply and Demand Projections to 2035–An Energy Market Assessment. Cat. No. NE2-12/2013E-PDF. Calgary, Alberta, Canada: National Energy Board, 2013; Accessed June 15, 2016. *https://www.neb-one.gc.ca/nrg/ntgrtd/ftr/2013/index-eng.html.*

[5] McFarland, J., Zhou, Y., Clarke, L., Schultz, P., Sullivan, P., Colman, J., Patel, P., Eom, J., Kim, S., Kyle, G.P., Jaglom, W., Venkatesh, B., Haydel, J., Miller, R., Creason, J., and Perkins, B. 2015. Climate change impacts on electricity demand and supply in the United States: a multi-model comparison. Climatic Change. Accessed July 6, 2016. *https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=252232*.

[6] U.S. Bureau of Reclamation. March 2012. Site Inventory and Hydropower Energy Assessment of Reclamation Owned Conduits: Supplement to the "Hydropower Resource Assessment at Existing Reclamation Facilities Report." Accessed May 24, 2016. *http://www.usbr.gov/power/CanalReport/*.

[7] Sale, M.J., N.A. Bishop, Jr., S.L. Reiser, K. Johnson, A.C. Bailey, A. Frank, and B.T. Smith. 2014. Opportunities for Energy Development in Water Conduits: A Report Prepared in Response to Section 7 of the Hydropower Regulatory Efficiency Act of 2013. ORNL/TM-2014/272. Prepared for the U.S. Department of Energy by the ORNL Water Power Technologies Team. September.

[8] "Canada's Energy Future 2016: Energy Supply and Demand Projections to 2040," Government of Canada, National Energy Board. © January 2016. Accessed June 24, 2016. *https://www.neb-one.gc.ca/nrg/ntgrtd/ftr/2016/index-eng.html*

[9] Lopez, A., B. Roberts, D. Heimiller, N. Blair, and G. Porro. 2012. *U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis.* NREL/ TP-6A20-51946. Golden, CO: National Renewable Energy Laboratory. Accessed June 25, 2016. *http://primo-pmtna01.hosted.exlibrisgroup.com/Pubs:PUBS:NREL_HORIZON83030*.

[10] Montgomery, Watson, Harza (MWH), 2009. Hydropower Modernization Initiative, Phase I, Needs and Opportunities Evaluation and Ranking. Report prepared for the U.S. Army Corps of Engineers Northwest Division Hydroelectric Design Center, Contract No. W9127N-08-D-0003, Task Order 0013.

[11] Zhang, Q.; Smith, B. T. 2015. Final Report: Demonstration Assessments of the Hydropower Advancement Project. Oak Ridge, TN: Oak Ridge National Laboratory. Accessed June 28, 2016. *http://hydropower.ornl.gov/research/hydropower/*.

[12] National Research Council (NRC), 2012. *Corps of Engineers Water Resources Infrastructure: Deterioration, Investment, or Divestment?* The National Academies Press, Washington, DC. Accessed June 28, 2016. *http://www.nap.edu/catalog/13508/corps-of-engineers-water-resources-infrastructure-deterioration-investment-or-divestment*.

[13] Hadjerioua, B.; Wei, Y.; Kao, S.C. An Assessment of Energy Potential at Non-Powered Dams in the United States. GPO DOE/EE-0711. Washington, DC, 2012.

[14] Kao, S-C., R.A. McManamay, K.M. Stewart, N.M. Samu, B. Hadjerioua, S.T. DeNeale, D. Yeasmin, M. Fayzul, K. Pasha, A.A. Oubeidillah, and B.T. Smith. 2014. New Stream-Reach Development: A Comprehensive Assessment of Hydropower Energy Potential in the United States. GPO DOE/EE-1063. U.S. Department of Energy Wind and Water Power Program, Washington, DC. Accessed April 26, 2016. *http://nhaap.ornl.gov/nsd.*

[15] US. Army Corps of Engineers. 1981. National Hydroelectric Power Resources Study Vol X: An Assessment of Hydroelectric Pumped Storage. U.S. Army Corps of Engineers Institute for Water Resources.

[16] IPCC (Intergovernmental Panel on Climate Change) 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp. Accessed June 14, 2016. *http://www.ipcc.ch/report/ar5/syr/*.

[17] Ashfaq, M., S. Ghosh, S.-C. Kao, L.C. Bowling, P. Mote, D. Touma, S.A. Rauscher, and N.S. Diffenbaugh, “Near-Term Acceleration Of Hydroclimatic Change In The Western U.S.,” Journal Of Geophysical Research: Atmospheres 118 (19) (2013): 10,676-10,693. Accessed July 6, 2016. *http://dx.doi.org/10.1002/jgrd.50816*.

[18] U.S. Energy Information Administration (EIA). 2015. Annual Energy Outlook 2015. DOE/EIA-0383(2015). U.S. Energy Information Administration, Washington, D.C. (US). Accessed June 15, 2016: *http://www.eia.gov/forecasts/aeo/*.

[19] U.S. Energy Information Administration (EIA). (2015c). *Annual Energy Outlook 2015.* Accessed June 16, 2016. *http://www.eia.gov/oiaf/aeo/tablebrowser/.*

[20] Field, C.B.; Barros, V.R.; Dokken, D.J.; Mach, K.J.; Mastrandrea, M.D.; Bilir, T.E.; Chatterjee, M.; Ebi, K.L.; Estrada, Y.O.; Genova, R.C.; Girma, B.; Kissel, E.S.; Levy, A.N.; MacCracken, S.; Mastrandrea, P.R.; White, L.L., eds. *Climate Change 2014: Impacts, Adaptation, and Vulnerability: Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK, and New York: Cambridge University Press, 2014. Accessed June 16, 2016. *http://ipcc-wg2.gov/AR5/*.

[21] Edenhofer, O.; Pichs-Madruga, R.; Sokona, Y.; Farahani, E.; Kadner, S.; Seyboth, K.; Adler, A.; Baum, I.; Brunner, S.; Eickemeier, P.; Kriemann, B.; Savolainen, J.; Schlömer, S.; von Stechow, C.; Zwickel, T.; Minx, J.C., eds. *Climate Change 2014: Mitigation of Climate Change: Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK, and New York: Cambridge University Press, 2014b. Accessed June 15, 2016. *http://mitigation2014.org/*.

[22] Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866. 2010. Interagency Working Group on Social Cost of Carbon. Washington, DC (US). Accessed June 16, 2016. *http://www.whitehouse.gov/sites/default/files/omb/inforeg/scc-tsd-final-july-2015.pdf*

[23] Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866. November 2013 revision. 2013. 78 FR 70586. Interagency Working Group on Social Cost of Carbon. Washington, DC: (US). Accessed June 16, 2016. *https://federalregister.gov/a/2013-28242*.

[24] Regulatory Impact Analysis: Development of Social Cost of Carbon Estimates. 2014. GAO-14-663. U.S. Government Accountability Office, Washington, DC (US). Accessed June 16, 2016. *http://www.gao.gov/products/GAO-14-663*.

[25] Johnson, L.T., S. Yeh, and C. Hope, “The Social Cost Of Carbon: Implications For Modernizing Our Electricity System”. Journal Of Environmental Studies And Sciences 3 (4) (2013): 369-375. doi:10.1007/s13412-013-0149-5. Accessed June 14, 2016. *http://www.researchgate.net/publication/263492370_The_social_cost_of_carbon_implications_for_modernizing_our_electricity_system.*

[26] Siler-Evans, K., I. L. Azevedo, M. G. Morgan, and J. Apt. 2013. “Regional Variations In The Health, Environmental, And Climate Benefits Of Wind And Solar Generation”. Proceedings Of The National Academy Of Sciences 110 (29): 11768-11773. doi:10.1073/pnas.1221978110. Accessed June 16, 2016. *http://www.ncbi.nlm.nih.gov/pubmed/23798431*.

[27] McCubbin, D. and B.K. Sovacool. 2013. “Quantifying the Health and Environmental Benefits of Wind Power to Natural Gas.” Energy Policy 53 (February): 429–41. Accessed June 23, 2016. *http://dx.doi.org/10.1016/j.enpol.2012.11.004*.

[28] Cullen, J., “Measuring The Environmental Benefits Of Wind-Generated Electricity”. American Economic Journal: Economic Policy 5 (4) (2013): 107-133. doi:10.1257/pol.5.4.107. Accessed June 14, 2016. *https://www.aeaweb.org/articles.php?doi=10.1257/pol.5.4.107*.

[29] Kaffine, D., McBee, B. and Lieskovsky, J. 2012. Emissions Savings from Wind Power Generation: Evidence from Texas, California and the Upper Midwest. Working Paper 2012-03. Colorado School of Mines, Golden, CO (US). Accessed June 16, 2016. *http://econpapers.repec.org/paper/mnswpaper/wp201203.htm*.

[30] Fell, H. and J. Linn. 2013. “Renewable Electricity Policies, Heterogeneity, And Cost Effectiveness”. Journal Of Environmental Economics And Management 66 (3): 688-707. doi:10.1016/j.jeem.2013.03.004. Accessed June 14, 2016. *https://www.researchgate.net/publication/259095992_Renewable_electricity_policies_heterogeneity_and_cost_effectiveness*.

[31] Fischer, C. and R.G. Newell, “Environmental And Technology Policies For Climate Mitigation”. Journal Of Environmental Economics And Management 55 (2) (2008): 142-162. doi:10.1016/j.jeem.2007.11.001. Accessed June 14, 2016. *http://www.sciencedirect.com/science/article/pii/S0095069607001064*.

[32] Edenhofer, O., L. Hirth, B. Knopf, M. Pahle, S. Schlömer, E. Schmid and F. Ueckerdt, “On the Economics of Renewable Energy Sources.” Energy Economics (40) (2013); pp. S12–S23. DOI: 10.1016/j.eneco.2013.09.015. Accessed June 14, 2016. *http://www.researchgate.net/publication/259097121_On_the_economics_of_renewable_energy_sources*.

[33] Kalkuhl, M., O. Edenhofer, and K. Lessmann. “Renewable Energy Subsidies: Second-Best Policy Or Fatal Aberration For Mitigation?”. September 2013. Resource and Energy Economics, Volume 35, Issue 3: 217–234. doi:10.2139/ssrn.1873197. Accessed July 6, 2016. *http://www.sciencedirect.com/science/article/pii/S0928765513000043*.

[34] McKibbin, W.J., A.C. Morris, and P.J. Wilcoxen, “Pricing Carbon In The U.S.: A Model-Based Analysis Of Power-Sector-Only Approaches”. Resource And Energy Economics 36 (1) (2014): 130-150. doi:10.1016/j.reseneeco.2013.11.007. Accessed June 14, 2016. *https://www.infona.pl/resource/bwmeta1.element.elsevier-4f146c3d-43e3-3440-bacd-79d64acfc198*.

[35] Borenstein, S. “The Private and Public Economics of Renewable Electricity Generation.” Journal of Economic Perspectives (26:1), 2012; pp. 67–92. Accessed June 14, 2016. *http://www.nber.org/papers/w17695*.

[36] Rausch, S.; Karplus, V.J. “Markets versus Regulation: The Efficiency and Distributional Impacts of U.S. Climate Policy Proposals.” The Energy Journal, Special Issue (35:1), 2014. Accessed June 14, 2016. *http://www.iaee.org/en/publications/ejarticle.aspx?id=2595*.

[37] Tuladhar, S.D.; Mankowski, S.; Bernstein, P. “Interaction Effects of Market-Based and Command-and-Control Policies.” The Energy Journal, Special Issue (35:1), 2014. Accessed June 14, 2016. *http://www.iaee.org/en/publications/ejarticle.aspx?id=2588*.

[38] Kumar, A., T. Schei, A. Ahenkorah, R. Caceres Rodriguez, J.-M. Devernay, M. Freitas, D. Hall, Å. Killingtveit, Z. Liu. “Hydropower.” In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2011. Accessed June 16, 2016. *http://www.ipcc.ch/report/srren/*.

[39] Hertwich, E.G. 2013. “Addressing Biogenic Greenhouse Gas Emissions from Hydropower in LCA.” Environmental Science and Technology, 2013(47), 9604–9611. Accessed April 1, 2016. *http://pubs.acs.org/doi/abs/10.1021/es401820p*.

[40] Cole, J. J., Y. T. Prairie, N. F. Caraco, W. H. McDowell, L. J. Tranvik, R. G. Striegl, and C. M. Duarte et al, “Plumbing The Global Carbon Cycle: Integrating Inland Waters Into The Terrestrial Carbon Budget”. Ecosystems 10 (1) (2007): 172-185. doi:10.1007/s10021-006-9013-8. Accessed July 6, 2016. *http://dx.doi.org/10.1007/s10021-006-9013-8*.

[41] Beaulieu, J.J.; Smolenski,R.L.; Nietch, C.T.; Townsend-Small,A.; Elovitz, M.S. 2014. "High Methane Emissions from a Midlatitude Reservoir Draining an Agricultural Watershed." Environmental Science and Technology, 2014(48), 11100–11108. Accessed April 1, 2016. *http://pubs.acs.org/doi/pdf/10.1021/es501871g*.

[42] Teodoru et al. 2012. "The net carbon footprint of a newly created boreal hydroelectric reservoir." American Geophysical Union, 26(GB2016), 1-14. Accessed April 1, 2016. *http://onlinelibrary.wiley.com/doi/10.1029/2011GB004187/abstract*.

[43] United Nations Educational, Scientific and Cultural Organization / International Hydropower Association. 2010. GHG Measurement Guidelines for Freshwater Reservoirs. Accessed June 14, 2016. *http://www.hydropower.org/sites/default/files/publications-docs/GHG%20Measurement%20Guidelines%20for%20Freshwater%20Reservoirs.pdf*.

[44] Kumar, A., T. Schei, A. Ahenkorah, R. Caceres Rodriguez, J.-M. Devernay, M. Freitas, D. Hall, Å. Killingtveit, Z. Liu, 2011. Hydropower. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[45] Mai, T.; Wiser, R.; Sandor. D.; Brinkman, G.; Heath, G.; Denholm, P.; Hostick, D.; Darghouth, N.; Schlosser, A.; Strzepek, K. Exploration of High-Penetration Renewable Electricity Futures. June 2012. Vol. 1 of Renewable Electricity Futures Study. NREL REPORT NO. TP-6A20-52409-1. National Renewable Energy Laboratory, Golden, CO (US). Accessed June 15, 2016. *http://www1.eere.energy.gov/library/viewdetails.aspx?productid=5846*.

[46] Lenzen, M. 2008. Life cycle energy and greenhouse gas emissions of nuclear energy: A review. Energy Conversion and Management 49, 2178-2199. Original publication 2006. Accessed July 6, 2016. *http://www.isa.org.usyd.edu.au/publications/documents/ISA_Nuclear_Report.pdf*.

[47] Parry, M.L.; Canziani, O.F.; Palutikof, J.P.; van der Linden, P.J.; Hanson, C.E., eds. *Climate Change 2007: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press, 2007. Accessed June 15, 2016. *http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg2_report_impacts_adaptation_and_vulnerability.htm*.

[48] Melillo, J.M., T.C. Richmond, and G.W. Yohe. 2014. *Climate Change Impacts in the United States: The Third National Climate Assessment*. Washington, DC: U.S. Global Change Research Program. Accessed June 16, 2016. *http://www.globalchange.gov/browse/reports/climate-change-impacts-united-states-third-national-climate-assessment-0*.

[49] Metz, B.; Davidson, O.R.; Bosch, P.R.; Dave, R.; Meyer, L.A., eds. *Climate Change 2007: Mitigation of Climate Change: Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK, and New York: Cambridge University Press, 2007. Accessed June 16, 2016. *https://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml*.

[50] Weitzman, M.L. "GHG Targets as Insurance Against Catastrophic Climate Damages." *Journal of Public Economic Theory* (14:2), 2012; pp. 221–244. Accessed June 16, 2016: *http://onlinelibrary.wiley.com/doi/10.1111/jpet.2012.14.issue-2/issuetoc*.

[51] MunichRE 2014. *2013 Natural Catastrophe Year in Review.* (2014). Munich, Germany: Webinar. Accessed Feb. 22, 2015 (recording no longer available).

[52] Sander, J.; Eichner, J.F.; Faust, E.; Steuer, M. 2013. "Rising Variability in Thunderstorm-Related U.S. Losses as a Reflection of Changes in Large-Scale Thunderstorm Forcing." *Weather, Climate, and Society* (5:4), 2013; pp. 317–331. Accessed June 16, 2016. *http://journals.ametsoc.org/doi/abs/10.1175/WCAS-D-12-00023.1*.

[53] Weitzman, M.L. "A Review of the *Stern Review on the Economics of Climate Change*." *Journal of Economic Literature* (45), September 2007; pp. 703–724. Accessed June 16, 2016. *https://www.aeaweb.org/articles.php?doi=10.1257/jel.45.3.703*.

[54] Johnson, L.T.; Hope, C. "The Social Cost of Carbon in U.S. Regulatory Impact Analyses: An Introduction and Critique." *Journal of Environmental Studies and Sciences* (2:3), 2012; pp. 205–221. Accessed June 16, 2016. *http://link.springer.com/article/10.1007%2Fs13412-012-0087-7#page-1*.

[55] Tol, R.S.J. "The Social Cost of Carbon." *Annual Review of Resource Economics* (3), October 2011; pp. 419–443. Accessed June 16, 2016. *http://www.annualreviews.org/doi/abs/10.1146/annurev-resource-083110-120028*.

[56] Kopp, R.E.; Golub, A.; Keohane, N.O.; Onda, C. 2012. "The Influence of the Specification of Climate Change Damages on the Social Cost of Carbon." *Economics: The Open-Access, Open-Assessment E-Journal* (6:2012–13), 2012. Accessed June 16, 2016. *http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2056944*.

[57] Pindyck, R.S. "Climate Change Policy: What Do the Models Tell Us?" *Journal of Economic Literature* (51:3), 2013; pp. 860–872. Accessed June 23, 2016. *http://dx.doi.org/10.3386/w19244*.

[58] Arrow, K.; Cropper, M.; Gollier, C.; Groom, B.; Heal, G.; Newell, R.; Nordhaus, W.; et al. 2013. "Determining Benefits and Costs for Future Generations." *Science* (341:6144), 2013; pp. 349–350. Accessed June 16, 2016. *http://comments.sciencemag.org/content/10.1126/science.1235665*.

[59] Kopp, R.E.; Mignone, B.K. 2012. "The U.S. Government's Social Cost of Carbon Estimates After Their First Two Years: Pathways for Improvement." *Economics: The Open-Access, Open-Assessment E-Journal* (6:2012–15), 2012; pp. 1–41. Accessed June 16, 2016. *http://www.economics-ejournal.org/economics/journalarticles/2012-15*.

[60] Ackerman, F.; Stanton, E.A. "Climate Risks and Carbon Prices: Revising the Social Cost of Carbon." *Economics: The Open-Access, Open-Assessment E-Journal* (6:2012-10), 2012; pp. 1–25. Accessed June 16, 2016. *http://www.economics-ejournal.org/economics/journalarticles/2012-10.*

[61] Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866. July 2015 revision. Interagency Working Group on Social Cost of Carbon. Washington, DC: (US). Accessed July 6, 2016. *https://www3.epa.gov/climatechange/EPAactivities/economics/scc.html*.

[62] U.S. Energy Information Administration (EIA). (2015a). *Electricity Data Browser*. Accessed June 16, 2016. *http://www.eia.gov/electricity/data/browser/.*

[63] U.S. Energy Information Administration (EIA). (2015b). *Electric Power Monthly with Data for December 2014*. February 2015 Issue. Accessed June 16, 2016. *http://www.eia.gov/electricity/monthly/current_year/february2015.pdf.*

[64] Wiser, R., Mai, T., Millstein, D., Macknick, J., Carpenter, A., Cohen, S., Cole, W., Frew, B., and Heath, G. 2016. On the Path to SunShot: The Environmental and Public Health Benefits of Achieving High Penetrations of Solar Energy in the United States. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-65628. Accessed July 6, 2016. *http://primo-pmtna01.hosted.exlibrisgroup.com/Pubs:PUBS:NREL_HORIZON102095*.

[65] EPA (Environmental Protection Agency). 2015. Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units. Washington, D.C.: Environmental Protection Agency. Accessed July 6, 2016. *https://www.federalregister.gov/articles/2014/06/18/2014-13726/carbon-pollution-emission-guidelines-for-existing-stationary-sources-electric-utility-generating*.

[66] Luckow, P., E. Stanton, S. Fields, B. Biewald, S. Jackson, J. Fisher and R. Wilson. 2015. 2015 Carbon Dioxide Price Forecast. Cambridge, MA: Synapse Energy Economics, Inc. Accessed June 16, 2016. *http://www.synapse-energy.com/sites/default/files/2015%20Carbon%20Dioxide%20Price%20Report.pdf*.

[67] Barbose, G., R. Wiser, A. Phadke, and C. Goldman. 2008. "Managing Carbon Regulatory Risk In Utility Resource Planning: Current Practices In The Western United States". Energy Policy 36 (9): 3300-3311. doi:10.1016/j.enpol.2008.04.023. Accessed June 16, 2016. *http://eetd.lbl.gov/publications/managing-carbon-regulatory-risk-in-utility-resource-planning-current-practices-in-the-w.*

[68] Bokenkamp, K., H. LaFlash, V. Singh, and D.B. Wang, "Hedging Carbon Risk: Protecting Customers And Shareholders From The Financial Risk Associated With Carbon Dioxide Emissions". The Electricity Journal 18 (6) (2005): 11-24. doi:10.1016/j.tej.2005.05.007. Accessed July 6, 2016. *http://dx.doi.org/10.1016/j.tej.2005.05.007*.

[69] NRC (National Research Council). 2010. Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use. National Research Council of the National Academies. Washington, DC: National Academies Press. Accessed June 23, 2016. *http://www.nap.edu/catalog/12794/hidden-costs-of-energy-unpriced-consequences-of-energy-production-and*.

[70] Dockery D. W., Pope C. A., Xu X., Spengler J. D., Ware J. H., Fay M. E., Ferris B. G., and F. E. Speizer. 1993. "An association between air pollution and mortality in six U.S. cities." N. Engl. J. Med. 329, 1753–1759. Accessed June 16, 2016. *http://www.nejm.org/doi/full/10.1056/NEJM199312093292401#t=article*.

[71] Krewski D., Jerrett M., Burnett R. T., Ma R., Hughes E., Shi Y., Turner M. C., Pope C. A., Thurston G., Calle E. E., Thun M. J., Beckerman B., DeLuca P., Finkelstein N., Ito K., Moore D. K., Newbold K. B., Ramsay T., Ross Z., Shin H., and B. Tempalski. 2009. "Extended follow-up and spatial analysis of the American Cancer Society study linking particulate air pollution and mortality." Research report 140, Boston, MA, June, 2009. Accessed June 16, 2016. *http://pubs.healtheffects.org/view.php?id=315*.

[72] Lepeule J., Laden F., Dockery D., and J. Schwartz. 2012. "Chronic exposure to fine particles and mortality: An extended follow-up of the Harvard Six Cities Study from 1974 to 2009." Environ. Health Perspect. 120, 965–970. Accessed June 16, 2016. *http://ehp.niehs.nih.gov/1104660/*.

[73] Lim S. et al. 2012. "A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: A systematic analysis for the Global Burden of Disease Study." Lancet. 380, 2224–2260. Accessed June 16, 2016. *http://www.thelancet.com/journals/lancet/article/PIIS0140-6736(12)61766-8/abstract*.

[74] Driscoll C. T., Buonocore J. J., Levy J. I., Lambert K. F., Burtraw D., Reid S. B., Fakhraei H. and J. Schwartz. 2015. "US power plant carbon standards and clean air and health co-benefits." Nature Climate Change. DOI: 10.1038/NCLIMATE2598. Accessed June 16, 2016. *http://www.nature.com/nclimate/journal/v5/n6/full/nclimate2598.html*.

[75] Turconi R., Boldrin A. , and T. Astrup. 2013. "Life Cycle Assessment (LCA) of Electricity Generation Technologies: Overview, Comparability and Limitations." Renewable and Sustainable Energy Reviews 28, 555–565. doi: 10.1016/j.rser.2013.08.013. Accessed June 16, 2016. *http://orbit.dtu.dk/en/publications/life-cycle-assessment-lca-of-electricity-generation-technologies-overview-comparability-and-limitations(d8c747fb-3774-4f4b-ac09-588f1226d935).html*.

[76] Fann N., Baker K. R., and C. M. Fulcher. 2012. "Characterizing the PM2.5-Related Health Benefits of Emission Reductions for 17 Industrial, Area and Mobile Emission Sectors Across the U.S." Environment International. (49) 141–151. Accessed June 23, 2016. *http://dx.doi.org/10.1016/j.envint.2012.08.017*.

[77] Novan, Kevin. 2015. "Valuing the Wind: Renewable Energy Policies and Air Pollution Avoided." American Economic Journal: Economic Policy, 7(3): 291-326. Accessed July 6, 2016. *http://dx.doi.org/10.1257/pol.20130268*

[78] Cai H., Wang M., Elgowainy A., and J. Han. 2012. Updated Greenhouse Gas and Criteria Air Pollutant Emission Factors and Their Probability Distribution Functions for Electric Generating Units. ANL/ESD/12-2. Lemont, IL: Argonne National Laboratory. Accessed June 16, 2016. *http://www.osti.gov/scitech/biblio/1045758*.

[79] Cai H., Wang M., Elgowainy A., and J. Han. 2013. Updated Greenhouse Gas and Criteria Air Pollutant Emission Factors of the U.S. Electric Generating Units in 2010. Lemont, IL: Argonne National Laboratory. Accessed July 7, 2016. *https://greet.es.anl.gov/publication-electricity-13*.

[80] Muller N. Z., Mendelsohn R., and W. Nordhaus. 2011. "Environmental Accounting for Pollution in the United States Economy." American Economic Review. (101:5). 1649–1675. DOI: 10.1257/aer.101.5.1649. Accessed June 16, 2016. *https://www.aeaweb.org/articles?id=10.1257/aer.101.5.1649*.

[81] Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866. Washington, DC: Interagency Working Group on Social Cost of Carbon, February 2010. Accessed July 7, 2016. *https://www3.epa.gov/otaq/climate/regulations/scc-tsd.pdf*.

[82] Bell M. L., McDermott A., Zeger S. L., Samet J. M., and F. Dominici. 2004. "Ozone and Short-Term Mortality in 95 US Urban Communities, 1987–2000." Journal of the American Medical Association. (292:19) 2372–2378. Accessed June 16, 2016. *http://www.ncbi.nlm.nih.gov/pubmed/15547165*.

[83] Levy, J.I., Chemerynski, S.M., Sarnat, J.A. 2005. "Ozone Exposure and Mortality: An Empiric Bayes Metaregression Analysis." Epidemiology. (16:4) 458–468. Accessed June 16, 2016. *http://www.ncbi.nlm.nih.gov/pubmed/15951663*.

[84] U.S. Census Bureau. 2012. 2012 National Population Projections Summary Tables, Table 1. Projections of the Population and Components of Change for the United States: 2015 to 2060. Washington, DC: U.S. Census Bureau Population Division. h Accessed June 16, 2016: *https://www.census.gov/population/projections/data/national/2012/summarytables.html*.

[85] AEO (Annual Energy Outlook). 2014. Annual Energy Outlook with Projections to 2040. DOE/EIA-0383(2014). Washington, DC: U.S. Department of Energy, Energy Information Administration, April 2014a; 269 pp. Accessed June 16, 2016. *http://www.eia.gov/forecasts/aeo/*.

[86] U.S. Environmental Protection Agency. 2013. Progress Report: SO2 and NOX Emissions, Compliance, and Market Analyses. Washington, DC: U.S. Environmental Protection Agency.

[87] Schmalensee R. and R. N. Stavins. 2013. "The SO2 Allowance Trading System: The Ironic History of a Grand Policy Experiment." Journal of Economic Perspectives. (27:1) 103–122. Accessed June 16, 2016. *https://www.aeaweb.org/articles.php?doi=10.1257/jep.27.1.103*.

[88] Kenny, J.F., N.L. Barber, S.S. Hutson, K.S. Linsey, J.K. Lovelace, and M.A. Maupin. 2009. *Estimated Use of Water in the United States in 2005.* No. CIR–1344. Reston, VA: U.S. Geological Survey. Accessed June 16, 2016. *http://pubs.usgs.gov/circ/1344/*.

[89] Maupin, M.A., J.F. Kenny, S.S. Hutson, J.K. Lovelace, N.L. Barber, and K.S. Linsey. 2014. *Estimated Use of Water in the United States in 2010*. U.S. Geological Survey Circular 1405. Washington, DC: U.S. Geological Survey. Accessed June 16, 2016. *http://pubs.usgs.gov/circ/1405/*.

[90] Solley, W.B., R.R. Pierce, and H.A. Perlman. 1998. *Estimated Use of Water in the United States in 1995*. U.S. Geological Survey Circular 1200. Reston, VA: U.S. Geological Survey. Accessed June 16, 2016. *https://pubs.er.usgs.gov/publication/cir1200*.

[91] Arent, D., J. Pless, T. Mai, R. Wiser, M. Hand, S. Baldwin, G. Heath, J. Macknick, M. Bazilian, A. Schlosser, and P. Denholm. 2014. "Implications of High Renewable Electricity Penetration in the US for Water Use, Greenhouse Gas Emissions, Land-Use, and Materials Supply." *Applied Energy* 123: 368–77. Accessed June 16, 2016. *http://www.sciencedirect.com/science/article/pii/S0306261913010210*.

[92] Chandel, M.K., L.F. Pratson, and R.B. Jackson. 2011. "The Potential Impacts of Climate-Change Policy on Freshwater Use in Thermoelectric Power Generation." *Energy Policy* 39: 6234–42. Accessed June 16, 2016. *http://www.sciencedirect.com/science/article/pii/S0301421511005465*.

[93] Clemmer, S., J. Rogers, S. Sattler, J. Macknick, and T. Mai. 2013. "Modeling Low-Carbon US Electricity Futures to Explore Impacts on National and Regional Water Use." *Environmental Research Letters* 8 (015004).

[94] Macknick, J., S. Sattler, K. Averyt, S. Clemmer, and J. Rogers. 2012b. "The Water Implications of Generating Electricity: Water Use across the United States Based on Different Electricity Pathways through 2050." *Environmental Research Letters* 7(4): 045803. Accessed June 16, 2016. *http://iopscience.iop.org/article/10.1088/1748-9326/7/4/045803/meta*.

[95] Roy, S.B., L. Chen, E.H. Girvetz, E.P. Maurer, W.B. Mills, and T.M. Grieb. 2012. "Projecting Water Withdrawal and Supply for Future Decades in the U.S. under Climate Change Scenarios." *Environmental Science and Technology* 46: 2545–56. Accessed June 16, 2016. *http://pubs.acs.org/doi/abs/10.1021/es2030774*.

[96] Tidwell, V.C., L.A. Malczynski, P.H. Kobos, G.T. Klise, and E. Shuster. 2013. "Potential Impacts of Electric Power Production Utilizing Natural Gas, Renewables and Carbon Capture and Sequestration on U.S. Freshwater Resources." *Environmental Science and Technology* 47: 8940–47. DOI: 10.1021/es3052284. Accessed June 16, 2016: *http://pubs.acs.org/doi/abs/10.1021/es3052284*.

[97] van Vliet, M.T.H., J.R. Yearsley, F. Ludwig, S. Vogele, D.P. Lettenmaier, and P. Kabat. 2012. "Vulnerability of US and European Electricity Supply to Climate Change." *Nature Climate Change* 2: 676–81. Accessed June 16, 2016. *http://dx.doi.org/10.1038/nclimate1546*.

[98] Macknick, J., R. Newmark, G. Heath, and K.C. Hallett. 2012a. "Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies: A Review of Existing Literature." *Environmental Research Letters* 7(4): 045802. Accessed June 16, 2016. *http://iopscience.iop.org/article/10.1088/1748-9326/7/4/045802/meta*.

[99] Meldrum, J., S. Nettles-Anderson, G. Heath, and J. Macknick. 2013. "Life Cycle Water Use for Electricity Generation: A Review and Harmonization of Literature Estimates." *Environmental Research Letters* 8: 015031. Accessed June 16, 2016. *http://iopscience.iop.org/article/10.1088/1748-9326/8/1/015031/meta*.

[100] Clemmer, S., J. Rogers, S. Sattler, J. Macknick, and T. Mai, "Modeling Low-Carbon US Electricity Futures To Explore Impacts On National And Regional Water Use". Environ. Res. Lett. 8 (1) (2013): 015004. doi:10.1088/1748-9326/8/1/015004. Accessed June 14, 2016. *http://dx.doi.org/10.1088/1748-9326/8/1/015004*.

[101] Gleick, P. 1992. Environmental consequences of hydroelectric development: the role of facility size and type. *Energy* 17 735–747. Accessed June 16, 2016. *http://www.sciencedirect.com/science/article/pii/036054429290116H*.

[102] Torcellini, P., Long, N., and Judkoff, R. 2003. *Consumptive Water Use for U.S. Power Production* (Golden, CO: National Renewable Energy Laboratory). NREL/TP-550-33905. Accessed June 16, 2016. *http://www.nrel.gov/docs/fy04osti/33905.pdf*.

[103] Pasqualetti, M. J., Kelley, S. 2008. *The Water Costs of Electricity in Arizona.* Arizona Department of Water Resources. Accessed June 16, 2016. *http://www.azwater.gov/AzDWR/StatewidePlanning/Conservation2/Documents/documents/TheWaterCostsofElectricityinArizona.pdf.*

[104] U.S. Environmental Protection Agency. 2011. *Environmental and Economic Benefits Analysis for Proposed Section 316(b) Existing Facilities Rule.* EPA 821-R-11-002. Washington, DC: U.S. Environmental Protection Agency. Accessed June 16, 2016. *http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100B6F8.TXT*.

[105] Macknick, J., Cohen, S., Tidwell, V., Newmark, R., Martinez, A., and Sullivan, S. 2015. *Water Constraints in an Electric Sector Capacity Expansion Model.* NREL/TP-6A20-64270. Golden, CO: National Renewable Energy Laboratory. Accessed June 16, 2016. *http://www.nrel.gov/docs/fy15osti/64270.pdf*.

[106] Rogers, J., Averyt, K., Clemmer, S., Davis, M., Flores-Lopez, F., Kenney, D., Macknick, J., Madden, N., Meldrum, J., Sattler, S., Spanger-Siegfried, E., and Yates, D. 2013. *Water-Smart Power: Strengthening the U.S. Electricity System in a Warming World*. Cambridge, MA: Union of Concerned Scientists. Accessed June 16, 2016. *http://www.ucsusa.org/clean_energy/our-energy-choices/energy-and-water-use/water-smart-power.html#.V2Ks-PkrLIU*.

[107] EPA (U.S. Environmental Protection Agency). 2009. *Cooling Water Intake Structures— CWA 316(b), Phase II—Large Existing Electric Generating Plants*. Washington, DC: U.S. Environmental Protection Agency. Accessed July 7, 2016. *http://www.reginfo.gov/public/do/eAgendaViewRule?pubId=201310&RIN=2040-AE95*.

[108] Averyt, K., J. Macknick, J. Rogers, N. Madden, J. Fisher, J. Meldrum, and R. Newmark. 2013. "Water Use for Electricity in the United States: An Analysis of Reported and Calculated Water Use Information for 2008." *Environmental Research Letters* 8 (015001). Accessed June 23, 2016. *http://dx.doi.org/10.1088/1748-9326/8/1/015001*.

[109] UCS (Union of Concerned Scientists). 2012. *UCS EW3 Energy-Water Database. V.1.3.* Cambridge, MA: Union of Concerned Scientists. Accessed June 16, 2016. *http://www.ucsusa.org/clean_energy/our-energy-choices/energy-and-water-use/ucs-power-plant-database.html#.V2KwbPkrLIU.*

[110] Averyt, K., J. Fisher, A. Huber-Lee, A. Lewis, J. Macknick, N. Madden, J. Rogers, and S. Tellinghuisen. 2011. *Freshwater Use by U.S. Power Plants: Electricity's Thirst for a Precious Resource*. Cambridge, MA: Union of Concerned Scientists. Accessed June 16, 2016. *http://www.ucsusa.org/clean_energy/our-energy-choices/energy-and-water-use/freshwater-use-by-us-power-plants.html#.V2KjovkrLIU*.

[111] DOE (U.S. Department of Energy). 2013. *U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather.* DOE/PI-0013. Washington, DC: U.S. Department of Energy. Accessed June 16, 2016. *http://www.energy.gov/sites/prod/files/2013/07/f2/20130716-Energy%20Sector%20Vulnerabilities%20Report.pdf*.

[112] Zhai, H., and E.S. Rubin. 2010. "Performance and Cost of Wet and Dry Cooling Systems for Pulverized Coal Power Plants with and Without Carbon Capture and Storage." *Energy Policy* 38(10): 5653–60. Accessed June 16, 2016. *http://www.sciencedirect.com/science/article/pii/S0301421510003848*.

[113] Maulbetsch, J.S., and M.N. DiFilippo. 2006. *Cost and Value of Water Use at Combined-Cycle Power Plants.* CEC-500-2006-034. Sacramento, CA: California Energy Commission. Accessed June 23, 2016. *http://www.energy.ca.gov/2006publications/CEC-500-2006-034/*.

[114] Tidwell, V.C., J. Macknick, K. Zemlick, J. Sanchez, and T. Woldeyesus. 2014. "Transitioning to Zero Freshwater Withdrawal in the U.S. for Thermoelectric Generation." *Applied Energy* 131: 508–16. Accessed June 16, 2016. *http://www.sciencedirect.com/science/article/pii/S0306261913009215*.

[115] U.S. Census Bureau. 2013. About Age and Sex. U.S. Census Bureau, Washington, D.C. (US). Accessed July 7, 2016. *http://www.census.gov/population/age/about/*.

[116] U.S. Census Bureau. 2013. Population Estimates and Projections Methodology. U.S. Census Bureau, Washington, D.C. (US). Accessed June 16, 2016. *https://www.census.gov/population/international/data/idb/estandproj.php*

[117] "Employment Projections." U.S. Bureau of Labor Statistics. Accessed July 7, 2016. *http://www.bls.gov/emp/*.

[118] U.S. Department of Energy. Prepared by Navigant Consulting, Inc. , and the National Renewable Energy Laboratory. DOE/EE-1400. Forthcoming (2016). "United States Hydropower Workforce Assessment and Future Scenarios".

[119] Florida, R., C. Mellander, and K. Stolarick, "Inside the Black Box Of Regional Development—Human Capital, The Creative Class And Tolerance". Journal of Economic Geography 8 (5) (2008): 615-649. Accessed July 8, 2016. *http://dx.doi.org/10.1093/jeg/lbn023*.

[120] Waltert, F.; Schläpfer, F. 2007. The role of landscape amenities in regional development: a survey of migration, regional economic and hedonic pricing studies. Working Paper No. 0710. University of Zürich, Socioeconomic Institute, Zürich, Switzerland. Accessed June 16, 2016. *http://www.zora.uzh.ch/52380/1/wp0710.pdf*.

[121] Böhringer, C., N.J. Rivers, T.F. Rutherford, and R. Wigle. 2012. "Green Jobs and Renewable Electricity Policies: Employment Impacts Of Ontario's Feed-In Tariff". The B.E. Journal of Economic Analysis & Policy 12 (1) (2012). Accessed July 11, 2016. *http://dx.doi.org/10.1515/1935-1682.3217*.

[122] Breitschopf, B., C. Nathani, and G. Resch. 2011. Review of Approaches for Employment Impact Assessment of Renewable Energy Deployment. International Energy Agency Renewable Energy Technology Deployment (IEA-RETD). Paris, France. Accessed June 15, 2016. *http://iea-retd.org/wp-content/uploads/2011/11/EMPLOY-task-1.pdf*.

[123] Brown, J.P., J. Pender, R. Wiser, E. Lantz, and B. Hoen. 2012. "Ex Post Analysis Of Economic Impacts From Wind Power Development In U.S. Counties". Energy Economics 34 (6): 1743-1754. Accessed July 11, 2016. *http://dx.doi.org//10.1016/j.eneco.2012.07.010*.

[124] Chien, T. and J.L. Hu, "Renewable Energy: An Efficient Mechanism To Improve GDP". Energy Policy 36 (8) (2008): 3045-3052. Accessed July 11, 2016. *http://dx.doi.org//10.1016/j.enpol.2008.04.012*.

[125] Frondel, M., N. Ritter, C.M. Schmidt, and C. Vance, "Economic Impacts From The Promotion Of Renewable Energy Technologies: The German Experience". Energy Policy 38 (8) (2010): 4048-4056. Accessed July 11, 2016. *http://dx.doi.org/10.1016/j.enpol.2010.03.029*.

[126] Haerer, D., and L. Pratson. 2015. "Employment trends in the U.S. Electricity Sector, 2008-2012," Nicholas School of the Environment, Duke University, Durham, NC (US). Accessed June 15, 2016. *http://www.sciencedirect.com/science/article/pii/S0301421515001123*.

[127] Hillebrand, B., H.G. Buttermann, J.M. Behringer, and M. Bleuel, "The Expansion Of Renewable Energies And Employment Effects In Germany". Energy Policy 34 (18) (2006): 3484-3494. Accessed July 12, 2016. *http://dx.doi.org/10.1016/j.enpol.2005.06.017*.

[128] Marques, A.C. and J.A. Fuinhas, "Is Renewable Energy Effective In Promoting Growth?". Energy Policy 46 (2012).: 434-442. Accessed July 12, 2016. *http://dx.doi.org/10.1016/j.enpol.2012.04.006*.

[129] Meyer, I.; Sommer, M.W. 2014. Employment Effects of Renewable Energy Supply, A Meta Analysis, Policy Paper no 12. THEME SSH.2011.1.2-1. Austrian Institute of Economic Research (WWW For Europe), Vienna, Arsenal. Accessed June 16, 2016. *http://www.wifo.ac.at/jart/prj3/wifo/resources/person_dokument/person_dokument.jart?publikationsid=47225&mime_type=application/pdf*.

[130] Wei, M., S. Patadia, and D.M. Kammen, "Putting Renewables And Energy Efficiency To Work: How Many Jobs Can The Clean Energy Industry Generate In The US?". Energy Policy 38 (2) (2010): 919-931. doi:10.1016/j.enpol.2009.10.044.

# 4 THE *HYDROPOWER VISION* ROADMAP: A Pathway Forward

U.S. DEPARTMENT OF ENERGY

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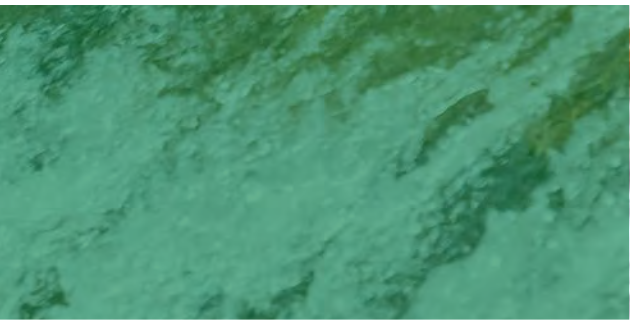
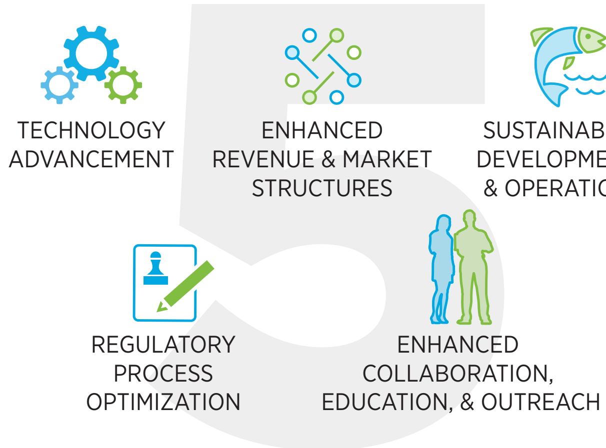


# Overview

This chapter provides a detailed roadmap of potential technical, economic, and institutional actions by the hydropower community to optimize hydropower's continued contribution to a clean, reliable, low-carbon, domestic energy generation portfolio, while also ensuring that the nation's natural resources are adequately protected or conserved. Each of the actions was formulated to address opportunities and challenges presented in Chapter 2.

## 5 ACTION AREAS

64 detailed actions




**The proposed roadmap actions are intended to motivate committed stakeholders to consider specific activities that they are in a position to facilitate or carry out, whether alone or in concert with others.**

Hydropower[1] has important attributes as a flexible, renewable energy source. Despite available generation potential, hydropower growth has lagged for a number of reasons, including the failure of markets to recognize hydropower's value, the long lead time for development, and stakeholder opposition based largely on environmental concerns. The roadmap actions are designed to address many of the challenges that have affected hydropower in recent decades. These actions are intended to stimulate a broadly inclusive multi-stakeholder dialogue that could result in new opportunities to upgrade existing hydropower facilities, utilize existing water infrastructure such as unpowered dams and water conveyances of different types, and stimulate sustainable development of low-impact projects at new sites. Realization of these opportunities will require collaborative efforts by various stakeholder groups, and will be impacted by national and regional policies and priorities as they evolve.

The analysis carried out in support of the *Hydropower Vision* has clearly shown that, of the types of development summarized above, new hydropower projects at previously undeveloped "new stream-reach" sites will continue to face substantial challenges. As such, this type of project will experience very limited growth without transformational changes in technologies and approaches that are able to successfully balance multiple co-objectives, including energy production, other water management requirements, and environmental protection. It is not possible to predict a timetable under which such major changes may be realized. However, the actions in this roadmap, taken as a cohesive body of work building on specific innovative efforts to date, will all contribute in incremental steps to realizing those co-objectives.

The roadmap is the result of a collaborative effort led by the U.S. Department of Energy (DOE), with significant contributions and rigorous peer review from industry, the electric power sector, non-governmental organizations, academia, national laboratories, and representatives of other government agencies. The roadmap is intended to be the beginning of an evolving, collaborative, and necessarily dynamic process. It would thus benefit from periodic reviews and adaptive updates at approximately three-year intervals, informed by its objective analysis activities. These reviews and related feedback loops will hopefully lead to the evolution of specific mechanisms for collaboration among stakeholders, and prioritization of individual and joint efforts.

**Roadmap actions are identified in five topical areas, introduced below:**

### *Technology Advancement*

Cost reduction, improved performance, and environmental stewardship are critical to the optimization and growth of hydropower in the United States. Innovative technology and system design concepts, such as standardized powertrain components, biologically-based turbine design and evaluation, modular civil structures, and alternative closed-loop pumped storage hydropower (PSH) systems will be essential to attaining those objectives. Continued operation of existing facilities and deployment of new facilities will depend on demonstration and acceptance of environmental mitigation technologies for facilities of all sizes. Mechanisms to test and validate performance of hydropower and PSH innovations are critical for introducing nascent technologies into the market. With the growing integration of variable renewable generation technologies into the electric grid, hydropower and PSH technologies and systems will also need to accommodate demands for greater operational flexibility in the grid.

### *Sustainable Development and Operation*

Increasing the amount of hydropower for meeting the nation's electricity needs will require a holistic approach to project development that incorporates sustainability principles by balancing environmental, social, and economic factors associated with hydropower. Development and operation at new and existing

1. Hydropower, as assessed in this report, includes new or conventional technologies that use diverted or impounded water to create hydraulic head to power turbines, and pumped storage hydropower facilities in which stored water is released to generate electricity and then pumped to replenish a reservoir. Throughout this report, the term "hydropower" generally encompasses all categories of hydropower. If a distinction needs to be made, the term "hydropower generation" distinguishes other types of projects from "pumped storage hydropower" (PSH).

hydropower facilities must be compatible with social, environmental, and economic values that prepare the United States for a future in which climate change may influence water supply and other flow- or water-dependent resources, as demand for renewable energy increases. Extensive stakeholder collaboration will be necessary to address these challenges. Such collaboration should examine and consider interactions of a particular hydropower project with other hydropower projects and other water uses within and among basins or watersheds to achieve optimum delivery of power and non-power benefits. Additionally, reservoir operations and other basin/watershed factors or competing uses and demands should be evaluated during planning processes to ensure that new development is compatible with and supports multiple objectives under changing energy demands and hydrologic conditions, both in the near or longer term.

### *Enhanced Revenue and Market Structures*

Hydropower plays a vital role in grid operation through its unique performance attributes and long-lasting facilities. In addition to providing energy production, capacity, and ancillary grid support services (as designated by the Federal Energy Regulatory Commission [FERC]), hydropower offers operational flexibility, energy storage, and other services essential to the continued reliability of the entire power system. Improved market structures and compensation mechanisms could more appropriately reward new and existing hydropower for the numerous services and benefits it provides. Important actions in this area include determining how much flexibility is provided by hydropower in existing grid operations, exploring opportunities to enhance market valuation of that flexibility, and examining how and at what time scale settlement of prices in energy markets could facilitate better use of hydropower flexibility to support integration of variable renewable generation resources. Additionally, improving the valuation and revenue of PSH services would help optimize PSH facility operation to benefit the entire electric system and stimulate new projects through improved economic performance.

### *Regulatory Process Optimization*

The continued development of unified, well-established mechanisms for collaboration and dissemination of the best available scientific procedures and findings could allow participants and regulators to realize mutual benefits by increasing approval process efficiency. For example, costs, risks, and implementation timeframes may be reduced by providing hydropower stakeholders with an increased knowledge base, easier access to information relevant to their projects, and increased mechanisms for collaboration. Additionally, achieving the same outcomes more rapidly and predictably can reduce the risks and costs to developers and encourage investment in new projects by the financial community, without a reduction in environmental protection. Benefits in environmental and energy generation performance could also be realized if cutting edge science were better disseminated and integrated into fulfillment of regulatory processes, while greater consideration of scientific advances could inform policy decisions. Successfully addressing the actions outlined in this topic area could result in both better performance and increased environmental protection, and could contribute to improved cohesion within the regulatory framework for hydropower.

### *Enhanced Collaboration, Education, and Outreach*

There are significant opportunities for improved communication and collaboration within the hydropower community, as well as with interested external stakeholders. Objective and verified information regarding hydropower as an established reliable, low-carbon, renewable energy source should be articulated and disseminated in order to increase the awareness of its benefits as well as its impacts. Hydropower facility owners and developers would also benefit from a national-scale effort to identify and regularly update best practices for maintaining, operating, and constructing hydropower facilities. These ongoing best practices and benchmarking programs will enable the industry to achieve its full potential as a reliable and low-cost renewable energy source. Finally, in order maintain the industry and have it grow to the potential levels of deployment analyzed in the *Hydropower Vision*, the United States will need to sustain and expand its highly qualified and well-trained workforce. Hydropower-specific curricula can be implemented within vocational and university programs for students interested in technical skills, engineering, and development of renewable energy to motivate new professionals to enter the hydropower field.

# 4.0 Introduction

This chapter provides a detailed roadmap consisting of potential actions necessary to optimize hydropower's economically and environmentally sustainable[2] contribution to a cleaner, more reliable domestic portfolio for energy generation and grid stability.

The roadmap is the result of a collaborative effort led by DOE, with significant contributions and rigorous peer review from industry, power generation owners/operators, non-governmental organizations, academia, national laboratories, and other government agencies.[3]

The proposed actions are intended to inform stakeholders to consider specific activities that they are in a position to facilitate or carry out, whether alone or in concert with others. However, the roadmap is not prescriptive; it does not detail how suggested actions are to be accomplished or by whom.

Further, while the roadmap provides a range of actions to inform the evaluation of policy options, it is beyond the scope of the *Hydropower Vision* to suggest policy preferences and no attempt is made to do so.

The *Hydropower Vision* modeling analysis of a range of potential scenarios (Chapter 3) supports the conclusion that, under certain assumed conditions, extensive industry growth between 2015 and 2050 is feasible. The analysis also indicates that new hydropower projects at previously undeveloped sites will continue to face significant challenges without transformational changes in technologies and approaches that are able to successfully balance multiple co-objectives including energy production, other water management requirements, and environmental protection. In aggregate, the roadmap actions are aimed at achieving the potential progress implied by these assumptions, though it is not possible to predict a timetable under which such major changes can be realized.

Growth is categorized into five technical areas, or "sectors of potential growth" (see Chapter 3, Section 3.1.4.1 for more details):

- Expanding, upgrading, and/or improving efficiency of existing hydropower facilities;
- Adding power generation capabilities at existing but non-powered dams;
- Installing hydropower in existing water conveyance infrastructure, such as canals and conduits;
- Developing new hydropower projects requiring new water diversions or impoundments; and
- Developing new PSH projects.

Although DOE supports research on marine and river hydrokinetic technologies[4] that convert the energy of waves, tides, and currents into electricity, those technologies are not addressed in this report, as explained in Chapter 1.

## The Roadmap Approach

The *Hydropower Vision* roadmap outlines actions grounded in three distinct yet complementary objectives that link to the three foundational "pillars" of the *Hydropower Vision*. The three key roadmap objectives are:

1. **Optimization:** Advance the nation's hydropower fleet by maintaining its long-standing economic value, energy contribution, and critical water management infrastructure while modernizing and optimizing its facilities, operations, and environmental performance.
2. **Growth:** Expand hydropower through innovative technologies, utilization of existing infrastructure, enhanced value recognition in electricity and environmental markets, and improved efficiency in regulatory processes.
3. **Sustainability:** Maintain the overall value of hydropower to the nation through balancing economic, social, and energy-related factors with the co-objective of responsible environmental stewardship.

2. For purposes of the *Hydropower Vision,* sustainable hydropower is defined as a project or interrelated projects that are sited, designed, constructed, and operated to balance social, environmental, and economic objectives at multiple or applicable geographic scales (e.g., national, regional, basin, site).

3. The authors acknowledge other reports that outline potential actions related to future developments in hydropower, including: the Hydro Research Foundation's *Blue Gold: Building New Hydropower with Existing Infrastructure*; the New Hydropower Innovation Collaborative's *New Pathways for Hydropower: Getting Hydropower Built—What Does It Take?;* and the International Energy Agency's *Technology Roadmap: Hydropower*.

4. See the DOE website (*http://energy.gov/eere/water/marine-and-hydrokinetic-energy-research-development*) for more information.

**The challenges and opportunities of realizing each of these objectives are separated into five Action Areas of the roadmap:**

**4.1: Technology Advancement**

**4.2: Sustainable Development and Operation**

**4.3: Enhanced Revenue and Market Structures**

**4.4: Regulatory Process Optimization**

**4.5: Enhanced Collaboration, Education, and Outreach**

As noted, the actions outlined in the roadmap specifically and intentionally do not include policy recommendations. However, by addressing market barriers and process inefficiencies, roadmap actions have the potential to reduce the cost and timelines of complying with existing and future policies, and can help improve the market competitiveness of hydropower.

The *Hydropower Vision* roadmap is intended to be a living document that will be modified using an evolving and collaborative process. It thus suggests an approach of periodic reviews of progress toward the roadmap objectives approximately every three years, informed by analysis activities and resulting in regular updates. These reviews would assess impacts of and suggest adjustments to the outlined actions as necessary and appropriate through 2050 to optimize adaptation to changing technologies, markets, public priorities, and policy factors.

As feedback loops develop during the follow-up roadmap review process, it will likely become increasingly advantageous for stakeholder groups to collaborate in prioritizing actions to attain mutual objectives. For example, a national laboratory project to evaluate the potential for science-based metrics of environmental sustainability to be applied to hydropower development, as outlined in Action 4.2.4, was initiated by DOE in response to needs identified during formulation of the *Hydropower Vision*. This collaborative project provides an early example of stakeholders initiating roadmap actions that will be subsequently reviewed for progress and effectiveness in future years.

The linkages between key objectives and the action areas of the roadmap are summarized in Table 4-1, and activities included within each action area are presented in Text Box 4-1.

**Table 4-1.** *Hydropower Vision* Roadmap Strategic Position and Approach Summary

| Core Challenge | Facilitate and leverage the existing hydropower fleet and sustainable hydropower growth to increase and support the nation's renewable energy portfolio, economic development, environmental stewardship, and effective use of resources. | | |
|---|---|---|---|
| **Key Objectives** | **Optimization**<br>Advance the nation's hydropower fleet by maintaining its long-standing economic value, energy contribution, and critical water management infrastructure, while modernizing and optimizing its facilities, operations, and environmental performance. | **Growth**<br>Expand hydropower through innovative technologies, utilization of existing infrastructure, enhanced value recognition in electricity and environmental markets, and improved efficiency in regulatory processes. | **Sustainability**<br>Maintain the overall value of hydropower to the nation through balancing economic, social, and energy-related factors with the co-objective of responsible environmental stewardship. |
| **Intended Results** | Investment in technology advancement, modernization, and environmental performance to ensure that the existing wide range of high-value, multi-use benefits of the hydropower fleet do not diminish. | Development of the next generation of hydropower facilities—and a trained workforce to support them—that leverage untapped infrastructure, technology advancement, plant modernization, improved environmental performance, and cost reduction pathways. | Capture and increase of the enduring economic and social value of hydropower through reduction of environmental impacts and continuous improvement of power systems and other project resources to ensure that sustainability objectives are incorporated throughout the full hydropower facility life cycle. |

*Continues next page*

*Table 4-1. continued*

| Core Challenge | Facilitate and leverage the existing hydropower fleet and sustainable hydropower growth to increase and support the nation's renewable energy portfolio, economic development, environmental stewardship, and effective use of resources. |
|---|---|
| **Linkage to *Hydropower Vision*** | The modeling within the *Hydropower Vision* presents potential hydropower development scenarios based on varying assumptions about key factors influencing growth over a 35-year period and beyond. Activities undertaken within the five Action Areas listed below and designed to incorporate the Core Challenge, Key Objectives, and Intended Results, and can significantly affect which of those development scenarios will ultimately be realized. |
| **Roadmap Action Areas** | 4.1 Technology Advancement<br>4.2 Sustainable Development and Operation<br>4.3 Enhanced Revenue and Market Structures<br>4.4 Regulatory Process Optimization<br>4.5 Enhanced Collaboration, Education, and Outreach |
| **Sectors of Potential Growth** | • Upgrades to existing hydropower facilities (Upgrades)<br>• Powering of existing non-powered dams (NPD)<br>• Installations in existing water conveyance infrastructure (Conduits)<br>• New stream-reach development (NSD)<br>• Pumped storage hydropower (PSH)<br>*Each action in the roadmap indicates the specific growth sector(s) to which it applies.* |

## Risks of Inaction

The characterization of the state of hydropower in Chapter 2 of the *Hydropower Vision* and the analytical results detailed in Chapter 3 reveal potential benefits and ongoing challenges for the hydropower community. These challenges must be met in order to realize the benefits that both existing hydropower plants and new projects could contribute to meeting grid flexibility needs; stimulating job growth and economic stability; protecting public health and reducing greenhouse gas emissions; and meeting environmental and societal needs related to watershed protection and management. Lack of well-informed, coordinated actions to meet these challenges may reduce the likelihood of each of those potential contributions of hydropower being fully realized.

The "Business-as-Usual" scenario in the economic modeling analysis of Chapter 3 illustrates that, when looked at from within the energy sector as a whole, growth of hydropower could be very limited in the next decades without the types of changes that could be precipitated by actions in the roadmap. On a national scale, reduced economic growth and increased energy efficiency measures have slowed the growth of electricity demand and increased the competition among energy technologies to supply new generation capacity. To maintain its share of the energy market, or to compete successfully for a greater share, hydropower will need to become more economically competitive.

Increasing competitiveness will require greater value to be placed on hydropower's essential role within key areas (e.g., grid services and indirect power system-wide benefits) by electricity markets, concurrent with establishing appropriately linked revenue mechanisms and reducing costs. Increasing competitiveness also includes mitigating or avoiding negative environmental impacts, increasing public understanding of progress to date in mitigating those impacts, optimizing regulatory processes, and having hydropower be consistently recognized as a renewable energy technology that offers multiple and varied benefits beyond power production. Otherwise, hydropower could continue to see limited growth—as in the decades leading up to the *Hydropower Vision*—and decreasing energy contribution as a percentage of national generation, with resulting negative impacts on electric grid reliability and efforts to reduce carbon emissions. Reinvestment in existing facilities could also decline over time, leading to a decrease in hydropower generation capacity.

Text Box 4-1.

### *Hydropower Vision* Action Areas

| | |
|---|---|
| **4.1 Technology Advancement** | |
| Action 4.1.1 | Develop Next-Generation Hydropower Technologies |
| Action 4.1.2 | Enhance Environmental Performance of New and Existing Hydropower Technologies |
| Action 4.1.3 | Validate Performance and Reliability of New Hydropower Technologies |
| Action 4.1.4 | Ensure Hydropower Technology Can Support Increased Use of Variable Renewable Generation Resources |
| **4.2 Sustainable Development and Operation** | |
| Action 4.2.1 | Increase Hydropower's Resilience to Climate Change |
| Action 4.2.2 | Improve Coordination among Hydropower Stakeholders |
| Action 4.2.3 | Improve Integration of Water Use within Basins and Watersheds |
| Action 4.2.4 | Evaluate Environmental Sustainability of New Hydropower Facilities |
| **4.3 Enhanced Revenue and Market Structures** | |
| Action 4.3.1 | Improve Valuation and Compensation of Hydropower in Electricity Markets |
| Action 4.3.2 | Improve Valuation and Compensation of PSH in Electricity Markets |
| Action 4.3.3 | Remove Barriers to the Financing of Hydropower Projects |
| Action 4.3.4 | Improve Understanding of and Eligibility/Participation in Renewable and Clean Energy Markets. |
| **4.4 Regulatory Process Optimization** | |
| Action 4.4.1 | Provide Insights into Achieving Improved Regulatory Outcomes |
| Action 4.4.2 | Accelerate Stakeholder Access to New Science and Innovation for Achieving Regulatory Objectives |
| Action 4.4.3 | Analyze Policy Impact Scenarios |
| Action 4.4.4 | Enhance Stakeholder Engagement and Understanding within the Regulatory Domain |
| **4.5 Enhanced Collaboration, Education, and Outreach** | |
| Action 4.5.1 | Increase Acceptance of Hydropower as a Renewable Energy Resource |
| Action 4.5.2 | Compile, Disseminate, and Implement Best Practices and Benchmarking in Operations and Research and Development (R&D) |
| Action 4.5.3 | Develop and Promote Professional and Trade-Level Training and Education Programs |
| Action 4.5.4 | Leverage Existing Research and Analysis of the Federal Fleet in Investment Decisions |
| Action 4.5.5 | Maintain the Roadmap in Order to Achieve the Objectives of the *Hydropower Vision* |

With increasing penetration of variable renewable generation resources such as wind and solar on the grid, the demand for storage and grid support flexibility offered by both traditional hydropower and PSH projects will increase. Failure to address business risks associated with hydropower development costs and development timelines—including uncertainties related to negotiation of interconnect fees and power sales contracts, regulatory process inefficiencies, environmental compliance, financing terms, and revenue sources—may mean that opportunities for renewed deployment of this technology will not be realized. Mitigating these risk factors would help in addressing high initial capital costs and long licensing and permitting timeframes that are often experienced before the benefits of low-cost hydropower generation, grid support, and long project operating life are realized.

As mentioned earlier, the analysis carried out in support of the *Hydropower Vision* has shown that hydropower projects at previously undeveloped sites could provide valuable renewable energy, storage, and grid reliability services, but that very limited growth can be expected without transformational changes in technologies and approaches. Such changes are only likely to come about via the types of actions that this roadmap prescribes.

## 4.1 Technology Advancement

The continued contribution and value of hydropower to the nation's energy portfolio can be furthered by improvements and advancements in technology. Aging infrastructure, untapped low-head hydropower potential, and changing operational demands highlight the need for cost-effective and unique solutions to maintain the existing fleet and assess new opportunities for hydropower energy production. Emerging technologies and other innovations should enhance performance of advanced hydropower and PSH designs at reduced costs, while minimizing environmental effects. To be most effective, these designs should also be responsive to emerging demands for balancing variable renewable generation resources and other requirements for flexibility and diversity within the energy portfolio.

Hydropower technology has progressed in terms of environmental monitoring, mitigation, and protection, with advancements such as fish-friendly turbines that reduce fish injury and mortality, fish passage structures to facilitate upstream and downstream fish movements, auto-venting turbines to ensure availability of adequate oxygen levels in outflows, and closed-loop PSH systems, which are located off-stream and therefore can provide energy storage without degrading aquatic habitats. Research and development (R&D) advancements and innovative technologies should continue to be applied at new and existing facilities to enhance environmental performance and water use efficiency. New hydropower technologies will need to be designed, assessed, and monitored to determine their environmental performance, with improvements adaptively implemented when needed. Developing the environmental and biological design objectives necessary to mitigate adverse effects requires assessing techniques and metrics to evaluate tradeoffs quantitatively and assure that new technologies accommodate both environmental and power generation requirements. These steps could help achieve broader acceptance and use of hydropower by industry and stakeholder groups.

New technologies represent risks to first adopters, making it difficult for equipment manufacturers to bring nascent technologies to market. Those risks can be reduced through validation activities, such as fleet benchmarking and the development of testing facilities, to confirm performance and reliability. Testing and validation of emerging technologies can ensure that biological, physical, and environmental requirements are met. Validation can also increase confidence on the part of investors and decision makers, which, in turn, helps accelerate deployment of new hydropower and PSH technologies.

With the growing integration of variable renewable generation technologies, hydropower technologies and operating systems will need to accommodate needs for greater operational flexibility in the power grid. This will allow hydropower and PSH to continue to support and respond to the increase in variability and uncertainty associated with variable generation. Achieving this objective requires improved reliability and resiliency of new and existing hydropower equipment; operational strategies to accommodate these demands and challenges; and increased sophistication in power system scheduling to blend variable generation with new or existing hydropower, ultimately strengthening the grid. Larger hydropower facilities and operators with robust monitoring systems are in a unique position to share lessons learned and best practices across the industry, benefitting smaller owners who cannot justify the high costs of such systems.

The actions outlined in this section seek to preserve and increase hydropower potential in the United States through advancements in technology that lead to cost reductions, optimized performance, and low environmental impact. Success in these actions will require increased collaboration across the hydropower industry (e.g., original equipment manufacturers, developers, researchers). The efforts will benefit from outreach to other sectors, including construction firms, additive manufacturing facilities, environmental groups, and other renewable energy and energy storage industries.

## ACTION 4.1.1: *Develop Next-Generation Hydropower Technologies.*

**ACTION 4.1.1: Develop Next-Generation Hydropower Technologies**
The next generation of hydropower and PSH technologies must be able to realize high efficiencies and enhanced performance, while minimizing environmental footprint and lowering capital costs.

**Deliverable:** New designs and approaches that will allow developers to tap into previously unrealized potential, while making hydropower more competitive with other generation resources.

**Impact:** Reduced costs and higher reliability.

**Key Objectives:** Optimization, Growth

**Growth Sectors Addressed:** Upgrades, NPD, Conduits, NSD, PSH

**Timeframe:** All actions in this area could commence immediately and simultaneously. Research is already underway by DOE in standard and modular designs (4.1.1.1 and 4.1.1.2), and components manufactured using advanced techniques and materials (4.1.1.3) already exist, but additional applications should continue to be explored. Research and development efforts in new design philosophies (4.1.1.4) will be ongoing and evolving to adapt to new markets, regulatory actions, and unrealized potential. While closed-loop PSH plants already exist, there are opportunities to explore non-conventional designs at perhaps smaller scales (4.1.1.5).

| Action | Deliverable | Impact |
|---|---|---|
| **Action 4.1.1.1**<br>Standardize equipment components. | Standard equipment components that can be mass produced and assembled in a variety of packaged designs. | Reduced costs, expanded manufacturing capabilities, increased industry collaboration. |
| **Action 4.1.1.2**<br>Develop scalable modular civil structure designs. | Modular civil structure designs, manufacturing and implementation plans, database describing performance characteristics of modular designs. | Reduced construction costs, reduced lead time on project construction. |
| **Action 4.1.1.3**<br>Implement additive manufacturing techniques and advanced materials. | Stronger and lighter hydropower components that are more resistant to corrosion and that can be manufactured and installed quickly. | Faster production of turbine components, lower project and maintenance costs. |
| **Action 4.1.1.4**<br>Explore alternative hydropower design philosophies. | Cost-benefit studies and technical reports documenting the feasibility of new design philosophies. | Reduced capital costs, potential deployment at previously unfeasible sites. |
| **Action 4.1.1.5**<br>Demonstrate potential and feasibility of innovative closed-loop PSH design concepts. | Reports and feasibility studies of innovative closed-loop PSH technologies, such as distributed closed-loop PSH systems. | Greater grid flexibility and storage capacity as a result of increased development of PSH. |

### *Rationale for Actions*

To promote hydropower growth and develop new hydropower capacity, the hydropower industry and research community will need to take an innovative approach to designing a suite of generating technologies and civil structures and techniques. This is particularly true with regard to potential new stream-reach facilities, which will require transformational innovation before significant development will occur. For hydropower to remain competitive with other renewable energy resources, next-generation technologies associated with upgrades, new site development (including low-head sites), powering of conduits/canals and non-powered dams, or new or advanced PSH should be designed to reduce equipment and construction costs, improve environmental stewardship, and attain high power efficiencies.

**ACTION 4.1.1.1: Standardize equipment components.**
Existing hydropower technologies are often designed and manufactured to meet the requirements at individual project sites. As such, the majority of total project costs are typically tied to site-specific designs. Developing and design-testing standardized components that can be purchased "off-the-shelf" and can operate in a variety of flows and heads would result in faster deployment of hydropower technologies. Part of the technology research within this action item would be to evaluate the tradeoffs between reduced efficiency and reduced costs of standardized equipment. Reduced costs may be achieved through innovative designs for mass production, economies of scale, and enhanced familiarity of investors and regulators. Standardized components could also drive down long term maintenance costs by making components more readily available and easily replaceable.

**ACTION 4.1.1.2: Develop scalable modular civil structure designs.**
The term "modular" refers to precast, pre-assembled, and/or standardized civil structure components that would otherwise be site-customized in traditional hydropower design approaches. Development and implementation of innovative modular hydraulic structure and foundation concepts have the potential to transform existing designs and streamline construction to reduce overall costs. One goal of this action is to be able to initially develop projects under a least-cost methodology. After a project is on-line and generating revenue, the project owner could then further customize the equipment and operating features to suit their particular needs. For example, a developer may decide to install a turbine-generator unit at a non-powered dam that does not utilize the dam's full hydroelectric potential. Once the project begins generating revenue, the developer can, through a license amendment or during relicensing, add an additional unit and generate more electricity using modular civil structures with minimal infrastructure costs.

**ACTION 4.1.1.3: Implement additive manufacturing[5] techniques and advanced materials.**
Advancements in additive manufacturing techniques hold promise for fast and efficient production of hydropower components. When combined with standardized packages and modular civil structures (Actions 4.1.1.1 and 4.1.1.2), additive manufacturing can lead to accelerated production of off-the-shelf components that are easily deployed, resulting in lower installation time and project costs. Composite materials used in additive manufacturing can be combined to meet a wide variety of material properties. As such, these processes can be used to manufacture drivetrain components that are lighter, stronger, and more corrosion-resistant, therefore reducing maintenance costs.

**ACTION 4.1.1.4: Explore alternative hydropower design philosophies.**
Potential hydropower growth can be achieved by creatively developing technologies that lie outside of the existing design paradigms. Hydropower projects are designed for longevity, with many projects operating for more than 100 years. To the extent that electricity markets are focused on short-term gains, exploring the economic feasibility of and market potential for less expensive hydropower technologies with shorter lifecycles may lead to development of hydropower designs capable of competing under these short-term market drivers. Opportunities to develop modularized hydropower components that may have shorter life cycles—but are lower in cost and easy to replace—should be evaluated and assessed through a variety of tradeoff analyses. Another design philosophy worth examining is powerhouses with an optimal mix or family of turbine sizes to capture energy from variable flows and heads commonly found at low-head sites. The trend in existing projects is a few large machines, all of the same size. Having a

5. Additive manufacturing is a process by which three-dimensional, or 3D, products are built in a layer-by-layer process, i.e., "3D printing."

range of different machine sizes could generate more efficiently over a wide range of flow releases while also meeting environmental flow requirements.

**ACTION 4.1.1.5: Demonstrate potential and feasibility of innovative closed-loop PSH design concepts.** Nearly all PSH development since the mid-1980s has occurred in Europe and Asia. While there is strong interest in the United States in constructing new plants, their development may be hindered by a variety of issues related to cost, limited market for grid services, and regulatory processes. Closed-loop PSH projects are located off-stream and therefore can provide energy storage without degrading aquatic habitats. Incorporating elements of modular design (e.g., using commercial off-the-shelf pumps, turbines, piping, tanks, and valves) may drive down investment costs by compensating the loss of economies of scale with cost reductions achieved through component standardization; reduce development risk; and increase the ease of implementation. Small, modular closed-loop PSH systems could be a competitive option for distributed energy storage applications. Development of this next generation of PSH technologies and validation of the performance and reliability of these new technologies, would increase the prospects of developing PSH in the United States.

## ACTION 4.1.2: *Enhance Environmental Performance of New and Existing Hydropower Technologies.*

### *Rationale for Actions*

Environmental performance refers to the effects hydropower technologies may have on the physical, geological, chemical, biological, ecological, cultural, and social features of the environment. Environmental performance can include, but may not be limited to, flow regimes, water quality, sediment transport, habitat connectivity, fish passage and mortality, and culturally sensitive lands. Because deployment of hydropower technologies is subject to regulatory processes for environmental protection, it will be important to communicate and work with stakeholders to identify, prioritize, and design means to avoid or mitigate adverse environmental effects, and to enhance or promote favorable environmental effects. Doing so earlier in the development process can help minimize expensive redesigns and avoid surprises and unintended consequences of design changes later in the process. Evaluating and improving environmental performance of hydropower technologies, and deploying them within the context of regulatory requirements that ensure environmental performance, can help facilitate acceptance by stakeholders and support hydropower deployment.

**ACTION 4.1.2.1: Develop metrics, monitoring, and measurement methodologies for environmental stressors.**
Key environmental stressors at new or existing hydropower facilities (e.g., habitat connectivity, water quality, flow alterations, in-turbine pressures and shear stresses) can be identified and prioritized for avoidance or mitigation. Metrics and monitoring methodologies will need to be matched and applied to each stressor, or developed if not already available. As each individual circumstance dictates, developers and regulators can apply these metrics and monitoring technologies to the siting, design, and post-construction monitoring phases of new development. Monitoring results will be used to assess compliance with environmental commitments and achievement of environmental performance targets. This action will also produce a consistent and adaptive means to aid assessment of the environmental performance of hydropower facilities by measuring exposure to priority environmental stressors. These assessments can be used to ensure facilities are designed and evaluated with respect to environmental objectives of multiple stakeholders, including regulatory and resource management agencies.

**ACTION 4.1.2.2: Develop biologically-based design and evaluation techniques for hydropower components and associated water control facilities.**
There are concerns related to potential fish injury or mortality caused by hydropower facilities. Industry and regulators recognize these concerns and have made significant improvements in mitigating injury and mortality. To build on this progress, continued improvement is needed in biologically-based design and evaluation tools and information that can be applied during development, deployment, and post-construction by industry, regulators, and natural resource managers.

**ACTION 4.1.2: Enhance Environmental Performance of New and Existing Hydropower Technologies**

Environmental performance (e.g., fish survival rates, water quality) of hydropower and PSH technologies is a significant concern of all parties and should thus be evaluated and, when necessary, modified to ensure continual improvement.

**Deliverables:** Methodologies and metrics to measure environmental performance of hydropower components that are applied during development, deployment, and evaluation of hydropower technologies.

**Impact:** Improved environmental performance due to adaptations of hydropower technology in response to environmental performance findings; acceptance and support from the stakeholder community for individual facilities or projects, resulting in increased deployment of new hydropower technologies.

**Key Objectives:** Optimization, Growth, Sustainability

**Growth Sectors Addressed:** Upgrades, NPD, Conduits, NSD, PSH

**Timeframe:** Actions to assess environmental performance through the development of methodologies (4.1.2.1) and biologically-based designs and evaluation techniques (4.1.2.2) are underway. Findings from the assessments can sequentially be used to identify potential modifications for specific technologies to enhance their environmental performance (4.1.2.3). Baseline studies of environmental metrics (4.1.2.4) are already being performed, but these will be refined with the deliverables from 4.1.2.1 and 4.1.2.2. The existing fleet could be continuously modernized with the latest enhancement technologies to ensure environmental sustainability of hydropower projects (4.1.2.5).

| Action | Deliverable | Impact |
|---|---|---|
| **Action 4.1.2.1**<br>Develop metrics, monitoring, and measurement methodologies for environmental stressors. | Metrics and testing methodologies for environmental stressors. | Improved characterization and quantification of environmental stressors. |
| **Action 4.1.2.2**<br>Develop and apply biologically-based design and evaluation techniques for hydropower components and associated water control facilities. | Biologically-based design and evaluation techniques for hydropower. | Greater prediction and evaluation of environmental performance of hydropower components and associated water control facilities. |
| **Action 4.1.2.3**<br>Apply environmental performance findings within an adaptive management process to prompt modifications to given hydropower technology. | Application of environmental performance findings to drive improvements in hydropower structures and operations. | Improved environmental performance of hydropower technologies. |
| **Action 4.1.2.4**<br>Compare environmental metrics before and after upgrades, new environmental requirements, or deployments at select example facilities to validate and communicate environmental performance improvements. | Comparisons of environmental performance for baseline and post-construction conditions. | Improved documentation and communication of environmental performance. |
| **Action 4.1.2.5**<br>Ensure that enhancing environmental performance is addressed within hydropower fleet modernization efforts. | Comparisons of environmental performance for baseline and post-construction conditions. | Improved documentation and communication of environmental performance. |

The intent of such refinements is to reduce design and regulatory review time, and improve fish survival rates. Biologically-based technologies to predict and measure environmental performance relative to fish passage can apply to any hydraulic structure necessary for hydropower production, as well as operations. Establishing objectives and developing improved tools or methods to assess and improve expected environmental performance of new and rehabilitated facilities and components will build on a subset of the metrics and measurement methodologies developed under Action 4.1.2.1.

**ACTION 4.1.2.3: Apply environmental performance findings within an adaptive management process to prompt modifications to given hydropower technology.**
Focused steps to prompt changes based on the results from Actions 4.1.2.1 and 4.1.2.2 can improve environmental performance of hydropower components. It is not enough to measure performance; the results must be applied and integrated into actions to make new and existing facilities more sustainable and still capable of delivering energy to power system services at marketable prices. The application of environmental performance findings to drive improvements in hydropower structures and operations will improve overall environmental performance of hydropower technologies.

**ACTION 4.1.2.4: Compare environmental metrics before and after upgrades, new environmental requirements, or deployments at select example facilities to validate and communicate environmental performance improvements.**
Collecting baseline data would allow for before and after comparisons of the environmental performance of new hydropower facilities, existing facilities accommodating new environmental requirements or mitigation actions, or new technology deployments. Such studies can be an important communication mechanism in improving and promoting hydropower. This action would build directly from metrics, methodologies, and designs developed in Actions 4.1.2.1 and 4.1.2.2. Validation through comparison of before and after metrics would require baseline and post-modification data collection and assessment. Comparisons should occur at various scales both temporally (e.g., baseline vs. one year or five years) and spatially (e.g., turbine unit, powerhouse, reservoir). The comparisons will spur identification of acceptable mitigation and enhancement measures that stakeholders agree upon as beneficial. Results from such comparisons would spur identification of acceptable mitigation and enhancement measures that stakeholders agree upon be applied as appropriate to modify hydropower structures and operations, as described in Action 4.1.2.3.

**ACTION 4.1.2.5: Ensure that enhancing environmental performance is addressed within hydropower fleet modernization efforts.**
Hydropower industry and researchers regularly carry out R&D efforts to develop innovative technologies that meet environmental objectives. This research takes into account factors such as environmental regulations, changing operating modes, and the effects of climate change. As hydropower owners and operators modernize facilities, equipment, and components, they can help ensure continued environmental compliance and stewardship at existing hydropower facilities by implementing the best available technologies to monitor and mitigate environmental impacts. Even as they do so, owners and operators must also consider the costs of such technologies and the effect of those costs on the viability of hydropower production at the facility. This is particularly important for older facilities that are at or near their relicensing periods, or that may have been designed under less stringent environmental protection regimes.

## ACTION 4.1.3: *Validate Performance and Reliability of New Hydropower Technologies.*

### *Rationale for Actions*

New technologies represent risks to first adopters. These risks must be addressed with validation activities to confirm performance and reliability, such as fleet benchmarking and the development of component and system testing facilities and other mechanisms. Validation will increase confidence on the part of investors and decision makers, which can help accelerate hydropower and PSH deployment.

**ACTION 4.1.3.1: Develop and apply broadly enhanced methodologies for benchmarking and performance assessment across the industry.**
This action will focus on developing methodologies for measuring return on investment as a result of fleet maintenance and optimization. Aspects to be evaluated include hydropower generation, operational performance, equipment efficiency, water efficiencies, and environmental performance testing. Benchmarking can indicate ways to increase reliability and efficiency of the hydropower fleets throughout the industry, while also clarifying financial outlays and addressing future expenditures.

**ACTION 4.1.3.2: Develop test and performance certification mechanisms.**
Developing mechanisms to evaluate new technologies, and providing performance certification to increase product reliability and acceptance, can help ensure a healthy and competitive suite of hydropower technologies for the future. In particular, a facility for full-scale testing of new technologies on the grid would benefit original equipment manufacturers trying to market their technologies, and would give developers reassurance about the performance of nascent technologies.

There may also need to be extensions or supplements to existing turbine performance test codes to address new technologies. A set of industry standards and certifications for emerging technologies (e.g., modular PSH, technologies developed with additive manufacturing) can help maintain standardization across the industry as innovative products are introduced. Improved cost and performance characterization of new hydropower technologies can increase investor confidence, as well as encourage development and adoption of these technologies.

**ACTION 4.1.3: Validate Performance and Reliability of New Hydropower Technologies**
Validating performance of new hydropower and PSH technologies can increase investor confidence, thereby facilitating greater deployment of new capacity.

**Deliverable:** Data, validated models, peer-reviewed studies, and testing mechanisms that provide information on the performance and reliability of new hydropower and PSH technologies.

**Impact:** Improved feasibility and overall performance of new hydropower and PSH projects.

**Key Objectives:** Optimization, Growth

**Growth Sectors Addressed:** Upgrades, NPD, Conduits, NSD, PSH

**Timeframe:** Fleet benchmarking and performance testing (4.1.3.1) are helpful for new technologies, and, as such, efforts to develop and deploy methodologies to perform these actions could begin in the near future. Feasibility studies for performance testing mechanisms (4.1.3.2) are already being explored, and such efforts may continue until the right mechanisms are available to test a variety of new hydropower technologies.

| Action | Deliverable | Impact |
|---|---|---|
| **Action 4.1.3.1**<br>Develop and apply broadly enhanced methodologies for benchmarking and performance assessment across the industry. | New fleet benchmarking tools, new performance standards, new methodologies for performance data collection. | Increased fleet reliability, efficiency gains in fleet operation, improved confidence in financial outlays. |
| **Action 4.1.3.2**<br>Develop test and performance certification mechanisms. | Technology testbeds, standards and methods to certify new designs, accepted certification protocols for emerging technologies, validated models and information on performance and reliability of new technologies. | Accelerated adoption of new hydropower technologies. |

## ACTION 4.1.4: *Ensure Hydropower Technology Can Support Increased Use of Variable Renewable Generation Resources.*

### *Rationale for Actions*

Existing technologies, operational methods, and system-based practices are in place to ensure that hydropower facilities are operated safely, and that equipment wear and tear is minimized. Hydropower provides ancillary grid support services—such as frequency regulation and voltage support—that are prerequisites for reliable grid operation. These capabilities can help support successful integration of large amounts of variable renewable generation. Doing so, however, can result in increased wear and tear on hydropower equipment. The following actions can ensure the existing fleet is prepared to accommodate increased flexible dispatch of hydropower with minimal damage to equipment.

**ACTION 4.1.4.1: Develop new criteria for assessing hydropower equipment performance related to grid support and response.**
A new suite of criteria for assessing hydropower equipment from "water to wire" (generation to interconnection) can aid in understanding the effects of variable renewable generation on the equipment and in identifying common failure modes. Assessing equipment performance under different modes of operation (such as increased frequency of starts and stops) is an important step in mitigating damages and maximizing efficiency when new variable renewable generation resources are incorporated. Such new criteria are likely to require more robust data collection protocols to enable analysis and decision making related to hydropower support of power systems.

**ACTION 4.1.4.2: Share lessons learned and best practices across the hydropower fleet.**
Several hydropower operators have developed "in-house" monitoring systems and other methods and procedures to respond appropriately to changes in operation and to evaluate equipment performance in order to mitigate damage to their facilities. Such practices are often costly; as such, small hydropower

**ACTION 4.1.4: Ensure Hydropower Technology Can Support Increased Use of Variable Renewable Generation Resources**

Technology innovation can minimize increased wear and tear on hydropower and PSH machinery that results from increased penetrations of variable renewable generation resources, such as wind and solar, in power systems.

**Deliverable:** Criteria and guidelines that enable plant owners to assess hydropower equipment performance and make risk-informed operations and maintenance (O&M) plans and investments that accommodate increased flexible dispatch of hydropower; more robust equipment that can withstand demands placed on hydropower as a result of increased penetration of variable renewable generation resources.

**Impact:** Hydropower systems that are adapted to meet variable generation from increasing penetration of variable renewable generation resources, resulting in a more resilient and stable electric grid.

**Key Objectives:** Optimization, Sustainability

**Growth Sectors Addressed:** Upgrades, PSH, NSD

**Timeframe:** Efforts to develop new criteria for assessing hydropower equipment performance as relates to providing grid support (4.1.4.1) could begin immediately. Results from such assessments can then be analyzed and applied in the design of more robust equipment (4.1.4.3). Hydropower operators who have monitoring systems in place and provide existing grid support can begin sharing best practices and lessons learned across the industry (4.1.4.2). Building upon existing research, the value and performance of PSH and other advanced adjustable-speed technologies can be validated and demonstrated (4.1.4.4) on an ongoing basis.

| Action | Deliverable | Impact |
|---|---|---|
| **Action 4.1.4.1** Develop new criteria for assessing hydropower equipment performance related to grid support and response. | New criteria for assessing hydropower equipment performance. | Increased understanding of effects that flexible operation of hydropower in response to variable renewable integration into power systems can have on hydropower equipment. |
| **Action 4.1.4.2** Share lessons learned and best practices across the hydropower fleet. | Workshops and other outreach efforts to communicate lessons learned, peer-reviewed reports, and guidelines on best practices. | Increased collaboration within the hydropower industry, improved reliability of small hydropower plants, increased support for variable renewables. |
| **Action 4.1.4.3** Design more robust technologies and materials to withstand new operating conditions. | New technologies and materials that can better withstand stresses arising from variable and extreme operating conditions. | Reliability improvement, O&M cost reductions, increased support for variable renewables. |
| **Action 4.1.4.4** Demonstrate and validate advanced technologies for adjustable-speed hydropower and PSH units. | Validation studies, implementation of adjustable-speed hydropower and PSH technologies. | Wider adoption of advanced technologies, more flexibility provided to the power system. |

owners may not be able to implement them. There are opportunities for larger hydropower operators to share these methods and procedures with smaller hydropower producers who might benefit from the lessons learned and best practices without incurring high costs. Several industry consortia already exist for sharing of best practices—these forums can be encouraged and enhanced.

**ACTION 4.1.4.3: Design more robust technologies and materials to withstand new operating conditions.** Hydropower units are robust, but their service lives are consumed as they are operated and subjected to cycles of starts and stops. Technologies and materials that extend lifetimes and decrease the frequency of occurrence of equipment failures will also reduce production costs and make hydropower facilities more valuable under existing operating conditions, and under more dynamic conditions caused by increased penetration of variable renewable generation.

**ACTION 4.1.4.4: Demonstrate and validate advanced technologies for adjustable-speed hydropower and PSH units.**
Adjustable-speed units are able to meet varying load requests with greater efficiency than fixed-speed units and provide fast frequency response associated with the expansion of variable renewable generation resources. While there are no adjustable-speed PSH units operating within the United States to date, such units have been deployed successfully in Europe and Asia. Adjustable-speed PSH units typically have greater operational ranges than fixed-speed units and can provide additional regulation service in the pump mode of operation. Opportunities to convert existing fixed-speed units to adjustable-speed technology should be explored. Studies comparing the U.S. context to that of Europe and Asia may yield insight into how adjustable-speed technology may deliver value for U.S. facilities. Ternary pumped storage designs may also be considered to address needs for flexible generation or load.

# 4.2 Sustainable Development and Operation

Increasing the amount of hydropower available to meet the nation's need for electrical energy requires a holistic approach to project development that incorporates sustainability objectives.[6] Development at new and existing hydropower facilities should be compatible with social, environmental, and economic values that account for a future in which climate change may influence water quality and supply, as well as demand for increased amounts of renewable energy. Addressing these challenges will involve extensive stakeholder collaboration, whereby sustainability objectives are implemented in balance during hydropower development. To achieve optimum delivery of power and non-power benefits, such collaboration should examine and consider interactions of a particular hydropower project with other hydropower and water resource projects, as well as other water uses within a basin or watershed. Reservoir operations and other basin/watershed factors or competing uses and demands should be evaluated during regulatory processes associated with development. This can help to ensure that a given project is compatible with and supports multiple objectives under changing energy demands and hydrologic conditions.

Relevant and accessible climate and runoff forecasts will be needed to facilitate planning for possible future conditions. Hydropower operations and water storage management will need to respond to changing climatic conditions and evolving trends in demand for water, as society becomes increasingly interested in more renewable energy and less reliant on carbon-based energy. The use of near- and long-term climate forecasts to predict changes in water availability, temperature regimes, and energy demand at relevant scales for decision making poses a significant challenge; applied research could help advance development of accurate and cost-effective

6. Examples of sustainability objectives related to hydropower include: (1) environmental aspects such as mitigating loss of aquatic connectivity; maximizing persistence of native species and communities; mimicking natural flow, sediment, and water quality regimes; (2) social aspects such as ensuring public health and safety; providing low-cost, reliable energy; and supporting cultural heritages; and (3) economic aspects, such as maximizing market/economic values; providing generation flexibility; providing other attributes such as recreation or flood control; and providing job opportunities.

temperature and runoff forecasting capabilities. Such information will need to be made readily accessible and translatable to a range of stakeholders in order to facilitate collaborative project development.

Hydropower development involves resource balancing; that is, hydropower as a renewable energy source must be balanced with other objectives such as ecosystem health, recreation, transportation, municipal water use, and other energy production. Aspects of hydropower operations, including reservoir elevations, the timing and magnitude of flow releases, downstream target elevations and flows, downstream water quality targets, ramping rates, and other thresholds, can have substantial effects on critical non-power resources. In addition, water uses for hydropower production within a basin are often interdependent—and potentially at odds—with other types of water use facilities or objectives. Accurately characterizing and addressing these interdependencies at new and existing facilities, and within the context of evolving climate conditions, will be necessary to ensure multiple objectives are met as effectively as possible in future development. Therefore, developers and stakeholders should mutually communicate their plans and interests as soon as possible in the development process to ensure tradeoffs and balancing are better understood from the outset. Likewise, stakeholders should become engaged early to fully understand the value and tradeoffs of the proposed development. As demand for water shifts due to population growth and climate change, the need for collaborative balancing of water resources will increase and hydropower can play a significant role in helping to provide a source of reliable and renewable energy.

## ACTION 4.2.1: *Increase Hydropower's Resilience to Climate Change.*

### *Rationale for Actions*

Not only will there be large shifts in water availability and timing as the effects of climate change on weather become more pronounced, but the frequency and severity of extreme events and climate-driven changes (e.g., severe drought or flood/high water) may intensify. Proactive steps can increase hydropower's resilience to climate change and allow hydropower to help mitigate the effects of such extremes. When droughts or other extreme events occur, alternative operational scenarios can be implemented to better align storage and operations with altered water availability and energy demand. Since climate change is a global issue, greater international outreach and sharing of best practices could provide quicker returns on some of these actions.

**ACTION 4.2.1.1: Develop hydropower-focused climate change assessment framework.**
Climate change is expected to affect future hydrologic conditions, such as snow accumulation; amount and timing of runoff; and frequency of extreme temperature, extreme precipitation events, and droughts. How these potential hydrologic changes may influence hydropower operation is not well understood at a scale relevant to site- or project-scale decision making, and the ability to better forecast and plan for future conditions is needed. The rapid evolution of climate science and the heavy computational burden associated with earth system modeling necessitate a shared approach to maintaining understanding of future climate trends. Work is needed to digest pre-processed hydro-climate projection data (e.g., precipitation and temperature) to support quantitative operational assessment at existing or planned hydropower facilities. The River Management Joint Operating Committee study (led by Bonneville Power Administration)[7] for the Pacific Northwest and the DOE-led assessment of the potential impacts of climate change on hydropower at federal facilities [1] are examples of how regional or basin-scale hydropower and climate change assessments could be established and tailored for needs of hydropower stakeholders in different regions. The U.S. Department of the Interior's Bureau of Reclamation (Reclamation) basin studies [2] also provide pertinent examples.

7. The committee, commonly known as RMJOC, is a sub-committee established through direct funding Memorandum of Agreements between Bonneville Power Administration, Reclamation, and the U.S. Army Corps of Engineers. More information is available on the Bonneville Power Administration website (*http://www.bpa.gov/power/pgf/ClimateChange/Part_I_Report.pdf*).

**ACTION 4.2.1: Increase Hydropower's Resilience to Climate Change**

Providing frameworks for assessing climate change impacts can improve the ability of hydropower projects to operate under resultant increases in variability (e.g., temporal and spatial changes in water availability or water use).

**Deliverable:** Tools to forecast water availability and assess changing energy demands.

**Impact:** Improved ability to forecast climate conditions that affect water availability and energy demand.

**Key Objectives:** Optimization, Sustainability

**Growth Sectors Addressed:** Upgrades, NPD, Conduits, NSD, PSH

**Timeframe:** Actions to develop a climate change assessment framework (4.2.1.1) can begin immediately, along with development of the data to populate that framework (4.2.1.2). The climate data repository would transition to the ongoing delivery of data products, with periodic updates as new climate data become available. Development of information on how climate change would influence water demand (4.2.1.3) will depend upon data from the repository and would be updated as climate projections change. Development of operational and storage scenarios that can help offset climate impacts (4.2.1.4) could begin as soon as initial estimates of potential impacts are available (under 4.2.1.3), and would continue until alternatives are defined.

| Action | Deliverable | Impact |
|---|---|---|
| **Action 4.2.1.1**<br>Develop hydropower-focused climate change assessment framework. | Framework for incorporating the effects of climate scenarios on water availability and energy demand into hydropower planning processes. | Improved ability to include future climate scenarios in planning. |
| **Action 4.2.1.2**<br>Develop climate data repository for hydropower operational studies. | Workshops and other outreach efforts to communicate lessons learned, peer-reviewed reports, and guidelines on best practices. | Increased collaboration within the hydropower industry, improved reliability of small hydropower plants, increased support for variable renewables. |
| **Action 4.2.1.3**<br>Develop scientific information on the influence of climate change on water demands. | Tools to improve predictions of operational flexibility and constraints. | Improved understanding of the future effects of climate change on hydropower infrastructure. |
| **Action 4.2.1.4**<br>Evaluate operational and storage scenarios to help offset climate change impacts. | Alternative scenarios for hydropower system configurations and operations. | Enhanced ability for hydropower facilities to respond to and help offset climate change impacts. |

**ACTION 4.2.1.2: Develop climate data repository for hydropower operational studies.**
A common climate data repository, similar to the Downscaled Climate and Hydrology Projections led by Reclamation [3], could be established to streamline the preparation, evaluation, and validation of downscaled climate data for hydropower operational studies. These joint efforts may reduce the duplication of investment by each entity and could help realize regional consensus more efficiently.

**ACTION 4.2.1.3: Develop scientific information on the influence of climate change on water demands.**
Climate change may influence water availability for hydropower generation, as well as for competing water demands and environmental requirements (e.g., household consumption, irrigation, maximum instream temperature, minimum streamflow). This may indirectly affect future hydropower operations. While increasing air temperature may influence competing water demand and instream temperature, quantification of such effects on future hydropower generation is challenging and remains an open scientific question. The existing tools, data, analyses, and concepts that were developed for local operational purposes may not be directly applicable to planning and decision making focused on addressing potential climate change consequences. To increase understanding of how hydropower might have to adapt to future climate conditions, further research efforts should focus on developing an integrated quantitative assessment approach for (1) estimating instream temperature in unregulated stream-reaches

based on the downscaled hydro-climate projections; (2) estimating future competing water usage in the context of climate change; and (3) developing tools to provide credible forecasts of runoff and temperature that can support decision making.

**ACTION 4.2.1.4: Evaluate operational and storage scenarios to offset climate change impacts.** Water systems management aims to meet a number of objectives for existing conditions and usually includes contingencies for extreme conditions. Hydropower facility managers can refine or expand existing operational strategies and water management guidelines to address increasing frequency and severity of extreme events and climate-driven changes in water and electricity demand. A suite of operational and storage scenarios would be useful to inform this process (e.g., co-locating facilities with flood control and water supply). The basis for any changes can center on Actions 4.2.1.1, 4.2.1.2, and 4.2.1.3, and, in particular, on climate model predictions and information that focus on regional or finer scale forecasts to inform management of rivers, river basins, and reservoirs.

## ACTION 4.2.2: *Improve Coordination among Hydropower Stakeholders.*

### *Rationale for Actions*

Water users with a wide variety of objectives share a common resource. The distinct objectives and constraints that govern procedures, rules, and success measures for institutions chartered or authorized to own, operate, market, or regulate hydropower facilities may differ from the objective and constraints of other stakeholders. When multiple hydropower facilities with distinct owners are hydraulically dependent on a basin (meaning that water releases and reservoir

**ACTION 4.2.2: Improve Coordination among Hydropower Stakeholders**

Improved coordination and collaboration among hydropower stakeholders can facilitate better realization of multiple objectives (e.g., social, environmental, electricity generation) through hydropower development planning.

**Deliverable:** Processes that support coordinated water scheduling and planning.

**Impact:** More rapid and less costly development of shared solutions, leading to greater deployment of sustainable hydropower.

**Key Objectives:** Optimization, Growth, Sustainability

**Growth Sectors Addressed:** Upgrades, NPD, Conduits, NSD, PSH

**Timeframe:** Efforts to identify successful water management collaborations (4.2.2.1) can begin immediately and would transition to adding new examples once initial lists are completed. Development of an education and illustration process for complex, multi-owner water scheduling and planning strategies (4.2.2.2) can begin immediately and would transition to demonstration when tools are completed. Seeking opportunities to coordinate licensing within a basin (4.2.2.3) can begin immediately and could continue until a full cycle of license renewals is complete.

| Action | Deliverable | Impact |
|---|---|---|
| **Action 4.2.2.1**<br>Identify examples and lessons learned from successful coordinated water use and management. | List of past collaborations that achieved multiple project purposes. | Greater potential for future collaboration that satisfies multiple objectives. |
| **Action 4.2.2.2**<br>Develop and demonstrate an education and illustration process for complex multi-owner water scheduling and planning strategies. | Tools that improve communication of water use alternatives. | Improved ability to collaborate within a multi-user, multi-stakeholder system. |
| **Action 4.2.2.3**<br>Identify and evaluate opportunities to coordinate licensing outcomes among facilities in the same basin. | List of opportunities for coordination among facilities in a given basin. | Improved overall operational flexibility. |

elevations at one facility affect outcomes at facilities upstream and downstream), these intricacies can create inefficiencies in basin-wide water utilization for hydropower production and other water use benefits, such as recreation and instream flows. Stakeholders who are affected by hydropower facilities typically have discrete values and objectives (e.g., water rights) that govern their response and acceptance of outcomes at individual or multiple facilities. Stakeholders need knowledge of the basin-wide context for water management in order to enable more efficient basin-wide use of water. Although many venues exist for stakeholders to collaborate (e.g., National Hydropower Association regional meetings), continued improved collaboration among stakeholders can lead to satisfactory solutions of multi-use water management situations.

**ACTION 4.2.2.1: Identify examples and lessons learned from successful coordinated water use and management**.

The value of collaboration among hydropower stakeholders has been demonstrated in many hydropower regulatory arenas, most notably through settlement agreements. Success stories from collaboration in multi-objective water management processes should be made available to stakeholders for use within the context of both relicensing existing hydropower facilities and developing new hydropower facilities. For example, in the Vernita Bar Agreement, federal and state agencies, tribes, and utilities collaborated to reach a negotiated solution to protect salmon spawning habitat in the last free-flowing reach of the Columbia River in the United States, above Bonneville Dam.

During collaborative discussions associated with hydropower development, sustainability should be considered in siting, design, and operation. For example, a proposed hydropower location must be screened for its site-scale environmental footprint and its context at the basin scale; without proper planning and siting at the basin scale, opportunities for more optimal and balanced outcomes might be missed. Drawing upon lessons learned will help avoid or mitigate any environmental, cultural, and economic effects of a facility. Lessons learned from water use collaborations should be applied in other settings as appropriate.

**ACTION 4.2.2.2: Develop and demonstrate an education and illustration process for complex multi-owner water scheduling and planning strategies.**

Multi-owner water scheduling, planning, rights, and laws are a challenge due to the complexities involved and the array of possible strategies. Water uses can include irrigation and municipal water supply as well as hydropower. While many forms of reservoir planning and management tools and models exist, the outputs and presentation of such models may be viewed as a "black box" (i.e., the results are not readily available to multiple stakeholders). New tools, or enhancements to existing tools and models, could benefit stakeholders by allowing improved viewing of water use scenarios and a more interactive way to evaluate how scenarios influence multiple objectives. This should allow constraints, competing uses, benefits/costs, and trade-offs to be understood, and could improve the transparency of decision making within a collaborative environment.

**ACTION 4.2.2.3: Identify and evaluate opportunities to coordinate licensing outcomes among facilities in the same basin.**

The single-project approach to licensing can sometimes provide fewer benefits than a jointly optimized approach among projects (federal and non-federal) located in the same basin or watershed. Joint licensing/relicensing processes could lead to better outcomes from power, environmental, and social perspectives. However, not all projects in a basin have coordinated license terms that would facilitate such an approach. The possibility of synchronizing license terms could be a normal consideration in determining future license terms, and could be done so in the context of applicable laws and regulations pertaining to licensing and relicensing. Options to encourage licensees early in their license term to participate in joint water management or mitigation efforts should be explored. Where possible, the opportunity to align license terms among different hydropower projects on a given river or basin could also be examined and pursued. The intent would be to seek better outcomes (e.g., where an action at one project can mitigate the impact of another project). Coordinated approaches have been used in the past and proven beneficial for involved parties. A coordinated watershed plan for a given river or basin could be developed, along with an agreement to implement it and a mechanism for implementation (e.g., synchronizing licenses, joint escrow account for mitigation).

## ACTION 4.2.3: *Improve Integration of Water Use within Basins and Watersheds.*

### *Rationale for Actions*

Planning for hydropower development is a matter of resource balancing. Sustainable hydropower development involves resource management trade-offs among multiple objectives, such as ecosystem management, recreation, commercial navigation, flood control, agricultural and municipal water supply, and other energy production—all while still allowing economic hydropower generation. These trade-offs can be reflected in responses in hydropower operations, such as minimum/maximum reservoir elevations, minimum flow releases, downstream target elevations and flows, downstream water quality targets, ramping rate restrictions on flow releases, and other thresholds. Early communication and integration of plans and interests by developers and stakeholders can help identify constraints and foster balancing of water use objectives so long as new tools are developed in concert with water resource policy to ensure the end products are feasible within the context of real-world water management.

**ACTION 4.2.3.1: Explore options beyond the bounds of individual hydropower projects to mitigate any adverse project effects.**

Limiting mitigation to the area of direct project environmental effects can reduce effectiveness and increase costs in cases where other promising off-site mitigation options might be available. In general, off-site mitigation is considered only when implementation of measures at the project is not feasible.[8] Moreover, FERC's 2006 Settlement Policy states that a relationship must be established between a proposed measure and project effects or purposes, and

**ACTION 4.2.3: Improve Integration of Water Use within Basins and Watersheds**
The development of innovative tools and approaches can increase opportunities for better integration of multiple water uses and objectives.

**Deliverable:** Processes to improve integration of water use within basins and watersheds.

**Impact:** Potential to increase hydropower production with minimal impact to other water uses.

**Key Objectives:** Optimization, Growth

**Growth Sectors Addressed:** Upgrades, NPD, Conduits, NSD

**Timeframe:** Exploring options for mitigation beyond project bounds (4.2.3.1) could begin immediately and continue until options are identified and a list made available. Development of a catalog of basins with potential for hydropower development and mitigation of other impacts (4.2.3.2) would begin immediately and continue until the delivery of a catalog of opportunities. Increasing the contribution of water management, ecological, and mitigation models to water use planning (4.2.3.3) will require starting immediately to ensure that better tools become available in the near term. Additional phases of effort will involve communicating the benefits of those improved models and facilitating their application in water use planning processes.

| Action | Deliverable | Impact |
|---|---|---|
| **Action 4.2.3.1**<br>Explore options beyond the bounds of individual hydropower projects to mitigate any adverse project effects. | Options for more effective and less costly mitigation activities. | Greater flexibility in mitigating for hydropower development. |
| **Action 4.2.3.2**<br>Develop a catalog of basins with potential for both hydropower development and mitigation of related impacts. | A catalog of hydropower development and associated mitigation opportunities. | Reduced environmental impacts of development with a corresponding increase in power production. |
| **Action 4.2.3.3**<br>Increase the contribution of water management, ecological, and mitigation models to water use planning. | Identification of enhancements to existing tools and the development of new tools. | Improved water utilization at basin-wide scales. |

8. See 90 FERC ¶ 61,087 (2000).

actions required under measures should occur physically and geographically as close to the project as possible. If off-site mitigation is appropriate, there are different potential approaches for it within a basin. For example, parties might consider establishment of a mitigation banking-type system in which contributions could be stored for collective restoration as projects come up for relicensing. Such avenues could be explored as part of the development process within the context of what is and is not within FERC jurisdiction and consistent with applicable FERC policy (e.g., on Settlement Agreements), although some settlement provisions may not be enforceable by FERC. Any identification of basin-wide hydropower opportunities would be done in conjunction with basin-wide planning and evaluation of energy, environmental, and social benefits/impacts. While regulatory timelines might increase due to more coordination, outcomes are expected to be more favorable to a wider array of stakeholders.

**ACTION 4.2.3.2: Develop a catalog of basins with potential for both hydropower development and mitigation of related impacts.**
The hydropower community would benefit from better understanding of environmental and other valued characteristics of river basins with development potential. This action would use existing resource assessment reports [4, 5] and information to create an enhanced inventory (such as Reclamation's WaterSMART program [6], or DOE's series of basin scale studies[9]) that identifies not only power generation potential, but also key environmental or other attributes (e.g., potential for water supply, recreation, fisheries). Hydropower developers could then factor these data into project planning. This inventory would feed into tools that help development stakeholders identify the lowest risk sites for successful development and the opportunities for basin-scale collaboration among sites. Doing so would require information about resource values and would ideally be accomplished under a comprehensive effort for watershed planning, i.e., not limited to hydropower development. This catalog of information could define important issues and effective mitigation strategies earlier in the development process and provide better understanding of both. This would aid in determining project costs, benefits, and trade-offs, and could provide for study of needs that would allow new projects to come to fruition more expeditiously. This action can encourage developers to look for win-win opportunities that deliver increased power and improved environmental conditions, recreational opportunities, or benefits to other water users.

**ACTION 4.2.3.3: Improve the contribution of water management, ecological, and mitigation models to water use planning.**
Numerous tools and models exist that allow project and reservoir operations to be modeled at both the project and basin scales. Existing tools should be evaluated to assure they can address future conditions in a manner that enables the most efficient and effective operations to be identified relative to power and non-power resources. Such evaluations could identify improvements to existing tools and models, or identify the need for new tools and models. For example, models for hydraulics and other attributes (e.g., water quality, socioeconomics) already exist. However, capabilities to forecast more complex environmental and socioeconomic outcomes as functions of operational and developmental decisions (e.g., flow regimes, water surface elevations, allocation of storage across seasons, and deployment of mitigation technologies) could enable assessment of likely outcomes of alternatives during regulatory and operational decision making.

## ACTION 4.2.4: *Evaluate Environmental Sustainability of New Hydropower Facilities.*

### *Rationale for Actions*

Energy development of any type involves a certain amount of risk, and it is important that such risk be managed. Unknowns regarding the environmental sustainability of a proposed facility are often a cause of concern for affected stakeholders. Concerns over sustainability issues surrounding hydropower are difficult to address without having agreed upon quantifiable, scientifically defensible sustainability metrics, models, and methods for hydropower. The lack of suitable metrics or best practices make it more difficult and time consuming to demonstrate that a

9. See *http://basin.pnnl.gov/*.

**ACTION 4.2.4: Evaluate Environmental Sustainability of New Hydropower Facilities**
Developing quantifiable environmental sustainability metrics and applying them to the development and operation of new hydropower facilities can lead to greater consistency in permitting processes, and qualification for national, state, and local renewable energy goals.

**Deliverable:** Scientifically rigorous and generally accepted environmental sustainability criteria for new hydropower project development and operation, including potential protocols and assessment tools that are cost effective to implement.

**Impact:** Assure stakeholders and decision makers have consistently defined and scientifically defensible sustainability criteria to support new hydropower development and operations that are responsive to environmental and socioeconomic considerations.

**Key Objectives:** Growth, Sustainability

**Growth Sectors Addressed:** NPD, Conduits, NSD, PSH

**Timeframe:** Continued advancement of hydropower-relevant environmental research (4.2.4.1) is crucial to increasing hydropower sustainability and should continue in perpetuity. The remaining actions should occur consecutively. Metrics for evaluating environmental sustainability (4.2.4.2) of new hydropower development are already being created under DOE-funded efforts. Based on these metrics, tools and protocols (4.2.4.3) could be developed to evaluate environmental sustainability of individual new hydropower facilities. Successful development of sustainability metrics and tools could also be used to support a certification process for new facilities that meet such metrics. Therefore, a review of the potential relationship between existing low-impact hydropower certification processes and opportunities to advance sustainability metrics for new hydropower (4.2.4.4) should be explored.

| Action | Deliverable | Impact |
|---|---|---|
| **Action 4.2.4.1**<br>Continue to conduct research on environmental needs and solutions. | Scientific articles and tools that provide a more precise understanding of hydropower impacts on different environments. | Environmentally-improved technology/plant designs and project/system management. |
| **Action 4.2.4.2**<br>Develop metrics for evaluating environmental sustainability for new hydropower development. | Metrics that effectively measure and track sustainability. | Improved integration of sustainability objectives during development. |
| **Action 4.2.4.3**<br>Develop tools and protocols for assessing and designing for environmental sustainability at new hydropower facilities. | Tools to evaluate and assess sustainability of a specific site. | Ability to identify hydropower and PSH facilities that are environmentally sustainable. |
| **Action 4.2.4.4**<br>Explore benefits, drawbacks, and models in order to develop or expand upon existing certification programs. | Peer-reviewed studies analyzing the pros and cons of a sustainability certification for new hydropower facilities. | Expansion of sustainability certification options for new hydropower development that could result in access to new revenue streams and greater acceptance of hydropower across stakeholders. |

project is sustainable, which can delay the regulatory process and sometimes result in potential new projects being abandoned because the assessment cannot be made or agreed upon. The goal of this action is to develop rigorous and scientifically defensible environmental sustainability metrics for new hydropower development, and the appropriate tools and protocols to measure and assess them. Opportunities to use the developed metrics and tools for new facilities, such as including them within existing sustainability certification processes or creating additional certification processes, should also be evaluated. Existing environmental sustainability certifications already provide benefits to developers, such as greater consistency in permitting processes and qualification for national, state, and local renewable energy goals and targets. An expanded certification could offer the same benefits for new hydropower development.

**ACTION 4.2.4.1: Continue to conduct research on environmental needs and solutions.**
Much of the environmental world is still not understood in enough detail (i.e., scale and resolution) to inform precise technology/plant design or project/system management. The stressor metrics developed in Action 4.1.2.1, for instance, must be underpinned by the environmental science documenting the impacts of the stressors on organisms as well as their effect on the surrounding ecology. Resolving the impacts of hydropower-induced stressors is a prerequisite to developing technologies or management schemes that work to minimize those stressors. Basic and applied environmental research must continue to advance and be published in all realms that affect hydropower, from fish biology to environmental flows, to make hydropower more environmentally sustainable.

**ACTION 4.2.4.2: Develop metrics for evaluating environmental sustainability of new hydropower development.**
A comprehensive set of metrics could achieve a range of objectives. It could promote common understanding of key aspects of sustainable development to inform permitting and licensing processes; build credibility with communities and stakeholders; help avoid actions unlikely to be sustainable; focus new development toward the most sustainable opportunities; and reduce the environmental impacts of future hydropower development. Some metrics would apply at the project level, while others would need to consider a larger basin-scale context. Such metrics could be developed by the scientific community through close collaboration with stakeholders to evaluate whether the objectives the stakeholders have defined are being met.

**ACTION 4.2.4.3: Develop tools and protocols for assessing and designing for environmental sustainability at new hydropower facilities.**
Following the development of the sustainability metrics described in Action 4.2.4.2, tools and protocols to measure sustainability at individual hydropower facilities are suggested to be developed. Measuring environmental sustainability of new hydropower facilities is important not only to recognize those facilities that measure favorably but to identify areas that can be improved. Developers can incorporate such tools and sustainability indicators into their design to gain stakeholder acceptance, facilitate regulatory and permitting process, and ensure environmental stewardship actions are effective.

**ACTION 4.2.4.4: Explore benefits, drawbacks, and operating models in order to develop or expand upon existing certification programs.**
Since 2000, the Low Impact Hydropower Institute has operated a certification program that offers recognition for hydropower projects that meet low impact criteria across a range of environmental benchmarks, such as fish passage and water quality. These criteria were formally revised in March 2016 to include, among other adjustments, a new emphasis on the scientific basis for agency recommendations and mitigation. As of 2015, the Low Impact Hydropower Institute does not consider PSH projects or projects that involve construction of a dam or diversion after August 1998 [7]. Projects that are ineligible for the Low Impact Hydropower Institute may respond to similar incentives to reduce impacts through recognition and certification of responsible operation.

Advancing nationally accepted sustainability certification for new hydropower and PSH facilities could present many opportunities to developers, such as better access to environmental markets and the incentives they provide, qualification in state and national renewable energy goals and targets, and improved stakeholder acceptance. The benefits and drawbacks of such a certification program, along with different potential operating models for one, should be carefully evaluated to determine if it would be overall beneficial to both the environment and the hydropower community. An environmental sustainability certification program could use the metrics, tools, and protocols developed in Actions 4.2.4.2 and 4.2.4.3 to assess the environmental sustainability of new hydropower facilities. Such a program would need to be developed with input from stakeholders, industry, and decision makers, and would acknowledge and be incidental to FERC licensing, which establishes foundational sustainability requirements. The certification program would be for optional certification above and beyond licensing.

# 4.3 Enhanced Revenue and Market Structures

Hydropower and PSH play a pivotal role in grid operation due to unique performance attributes and long-lasting facilities. In addition to providing peaking and baseload energy generation, capacity, and ancillary grid support services, hydropower and PSH offer operational flexibility and dispatchability, energy storage, and essential reliability services benefiting the entire power system. These include on-demand generation supporting integration of variable renewable generation resources, load shifting, greenhouse gas reduction, and increased overall efficiency and reliability of system operation.

Improved market structures and compensation mechanisms could more appropriately reward the services required by an increasingly renewable grid—services which have been provided by existing hydropower and PSH for decades (potentially without compensation), and could be provided in the future by new hydropower projects. Actions in this area include determining how much flexibility is provided by hydropower in existing grid operations, exploring opportunities to enhance market eligibility (particularly eligibility and participation in renewable and clean energy markets), recognition to properly value flexibility, and examining how and at what time scale settling of energy markets can allow better use of hydropower flexibility in integration of variable renewable generation resources.

Decisions to move forward with a prospective hydropower development project (new or existing) rely heavily on the project's pro forma (i.e., benefits/costs, overall financial performance). Because actions identified in this section have the potential to influence project pro forma statements and the decision to proceed with development, the actions that follow are suggested for both near- and long-term implementation.

PSH energy storage technologies are unique because they function as both generation and demand resources. This presents some challenges to their treatment in electricity markets. Historically, most U.S. electricity markets have treated PSH generation and demand functions separately; thus, the operation of PSH may not be fully optimized over its entire generation/demand cycle. This frequently results in the failure to use the full capabilities of PSH to provide maximum benefits to the power system. Improving the valuation and revenue of PSH services would help optimize their operation to benefit the entire system and stimulate new projects through improved economic performance. This may be achieved and validated through modeling and observation of global examples in which enhanced market recognition accommodates the unique contributions of PSH, and through examination of potential approaches for system operators (independent system operators [ISOs] and regional transmission operators [RTOs]) to schedule PSH units within electricity markets.

Actions related to improved valuation and revenue carry cost implications, which in turn can imply the value of potential policy formulations. The actions identified in this section are intended to inform these policy considerations, but such considerations are not incorporated into the actions themselves. Additionally, actions identified in this section can apply to both the federal and non-federal hydropower fleet, as appropriate.

## **ACTION 4.3.1:** *Improve Valuation and Compensation of Hydropower in Electricity Markets.*

### *Rationale for Actions*

Hydropower facilities have many operational characteristics that make them suitable to provide numerous services and contributions to the power system, such as fast ramping and low-cost operating contingency reserves. These characteristics are unique from other energy generation sources, both renewable and conventional. The potential for and benefits of these services need to be better understood, and revenue streams should be established to properly compensate the various types of products and services hydropower provides. Existing proposals for market design enhancements and other emerging trends can be examined and leveraged where appropriate, including recognition in tariffs and rate-setting.

| **ACTION 4.3.1: Improve Valuation and Compensation of Hydropower in Electricity Markets**<br>Enhancing existing market approaches and developing new approaches can help facilitate full recognition and compensation of the suite of grid services, operational flexibility and system-wide benefits offered by new and existing hydropower. | |
|---|---|
| **Deliverable:** Recommendations for new market revenue mechanisms that can compensate hydropower and PSH for operational flexibility and other services.<br>**Impact:** Availability of appropriate financial incentives for the operational flexibility and other services that hydropower can offer. | **Key Objectives:** Optimization, Growth, Sustainability<br>**Growth Sectors Addressed:** Upgrades, NPD, Conduits, NSD, PSH<br>**Timeframe:** The actions in this section can influence the pro forma statements of hydropower projects, and are thus recommended for immediate or near-term implementation and long-term use. |

| Action | Deliverable | Impact |
|---|---|---|
| **Action 4.3.1.1**<br>Quantify operational flexibility of hydropower. | Quantification of hydropower's operational flexibility and its value to the electricity system. | Improved valuation of hydropower's operational flexibility, expanded development of other renewable technologies, and portfolio optimization. |
| **Action 4.3.1.2**<br>Enhance market recognition of flexibility and other services. | A set of recommendations for improved market recognition enhancements and compensation mechanisms. | Improved market treatment of operational flexibility and other services. |
| **Action 4.3.1.3**<br>Increase temporal resolution of electricity markets. | A set of recommendations for improved market settlement. | Better use of hydropower's flexibility for integration of variable renewable generation. |

**ACTION 4.3.1.1: Quantify operational flexibility of hydropower.**
Hydropower and PSH facilities are generally recognized for their fast ramping and flexible operational characteristics, and both are capable of providing significant amounts of operational flexibility to the power grid (flexibility and ramping being similar in terms of ability to start/stop quickly and change output quickly). This flexibility is especially valuable for load/generation balancing and for supporting high levels of variable generation (e.g., ramping capabilities, inertia, and frequency response). However, many hydropower facilities operate under a range of environmental and operational constraints, resulting in actual contributions to power system flexibility that are often lower than their technical capabilities. There is a need to review and build upon existing information and to continue research and analyses to quantify how much operational flexibility and ancillary grid services hydropower provides to the electricity system (e.g., ramping, capacity, storage, voltage regulation/support, reactive power). Similarly, there is a need to determine the value of such flexibility and services in different markets in the United States, including the degree to which flexibility and services are undervalued or not compensated. The science associated with ramping and other avenues to increase use of hydropower's flexibility potential while still satisfying all environmental and other operational constraints also merit investigation. The ability to effectively gather the necessary information will be an important factor in performing these examinations.

**ACTION 4.3.1.2: Enhance market recognition of flexibility and other services.**
With levels of variable renewable generation resources increasing, the power grid requires greater levels of operational flexibility, and, as such, market recognition and compensation mechanisms should keep pace. While most electricity markets include revenue provisions for energy, capacity, and some ancillary grid services, markets could be improved to include revenue mechanisms that recognize and

compensate for some of these services and contributions, including those designated as essential reliability services by the North American Electric Reliability Corporation. The operational flexibility of hydropower facilities is already supporting the transition to greater deployment of variable renewable generation resources and can support and enable even higher levels cost effectively. However, market or other revenue mechanisms that properly value the economics of operational flexibility and provide adequate revenue streams for its contributions to power grid balancing can be examined. Improvements of market recognition or provisions to appropriately compensate power facilities that provide operational flexibility and other system-wide services would assure the long-term viability of hydropower, and contribute to increased integration of variable renewable resources and more reliable operation of the entire power system. Examination and compilation of existing proposals to enhance market design also merit consideration, including recognition in tariffs and rate-setting.

**ACTION 4.3.1.3: Increase temporal resolution of electricity markets.**

While all electricity markets in the United States calculate sub-hourly prices as part of the real-time dispatch, many electricity markets are still cleared (settled or "trued-up") on an hourly basis, making it difficult for flexible generation resources to benefit from their operational flexibility on sub-hourly timescales (e.g., 15 minutes or less). Moving towards sub-hourly markets could inform potential options for greater fidelity at the scale on which the grid actually operates. This would provide financial incentives for hydropower and PSH units to increase use of operational flexibility for intra-hourly load/generation balancing, as well as providing additional energy arbitrage (price differential) opportunities for PSH. Studies conducted under this action (which should involve grid operators, market participants, and regulators) can pertain to sub-hourly markets as well as sub-hourly settlements of markets, since study in both areas can aid in discerning potential options for each pathway.

## ACTION 4.3.2: *Improve Valuation and Compensation of PSH in Electricity Markets.*

### *Rationale for Actions*

As an energy storage technology, PSH provides numerous services and contributions that benefit not only the generation components of the power system, but also transmission, distribution, and demand. For example, incorporating PSH into grid system operations contributes to more efficient dispatch and utilization of other generating units, thus lowering overall electricity generation costs; reduces cycling, ramping, and wear and tear of thermal generating units; reduces curtailments of excess variable renewable generation (by creating load and storage for variable generation); postpones the need for investments into new transmission and distribution facilities; provides significant operational flexibility and reserves that support high penetration of variable renewables; contributes to primary frequency response and voltage support; provides system inertia; and contributes to increased reliability of system operation. While most electricity markets include revenue provisions for energy, capacity, and certain ancillary grid services, market recognition and compensation mechanisms could be improved for these services and contributions to overall grid function and reliability. The treatment and scheduling of PSH in existing electricity markets could be improved to better reflect the value and unique characteristics of PSH and duty cycle (percent of time pumping or generating), which includes both generation and demand functions.

**ACTION 4.3.2.1: Improve the valuation of PSH services.**

PSH is a versatile energy storage technology that provides numerous services and contributions to the power system. In addition to energy, capacity, and ancillary grid services, PSH facilities provide many benefits to the broader power system that are not typically compensated in existing electricity markets. By building upon existing research and information, as well as examining global examples, studies of these benefits can be conducted to determine the full value (revenue potential) of various PSH services, increase understanding of how their contributions to the power system are undervalued, and help improve these valuations.

**ACTION 4.3.2: Improve Valuation and Compensation of PSH Services in Electricity Markets**
Enhanced market rules related to scheduling and operation of PSH in electricity markets can facilitate use of the full value of this energy storage technology.

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|---|---|
| **Deliverable:** New market rules and revenue mechanisms that recognize the unique role and value of PSH in the power system and provide appropriate compensation for PSH services and contributions.<br>**Impact:** Adequate financial incentives for the full range of services and contributions that PSH provides to the power system. | **Key Objectives:** Optimization, Growth, Sustainability<br>**Growth Sectors Addressed:** PSH<br>**Timeframe:** All actions in this section can begin immediately and simultaneously. |

| Action | Deliverable | Impact |
|---|---|---|
| **Action 4.3.2.1**<br>Improve the valuation of PSH services. | Quantification of PSH services and contributions, including system-wide benefits. | Improved understanding of the various benefits that PSH provides to the entire power system, portfolio optimization and expanded development of other renewable technologies. |
| **Action 4.3.2.2**<br>Evaluate enhanced market recognition for PSH. | Report of potential market recognition enhancements. | Accelerated development of new PSH projects or upgrades to existing PSH projects. |
| **Action 4.3.2.3**<br>Investigate potential for RTOs and ISOs to provide input on scheduling PSH units in electricity markets. | Recommendations for improved scheduling of PSH plants in electricity markets. | Better utilization of PSH resources, improved integration of variable renewable generation, and lower electricity generation costs. |

**ACTION 4.3.2.2: Evaluation of enhanced market recognition for PSH.**
Rules for scheduling and compensation of generating resources in electricity markets are not generally favorable for energy storage technologies. For instance, the scheduling and market settlement procedures for PSH and other storage technologies fail to take into account the unique nature of these technologies as both generation and demand technologies. Also, the inadequate valuation and compensation of PSH plants for many system-wide services make it hard for project developers to financially justify new PSH projects. At a minimum, this action would entail a coordinated review with entities having the ability to drive change (e.g., owners, regulators, RTOs/ISOs) and a resulting report identifying services that are not being fully or fairly rewarded. The report would include recommendations regarding development of adequate revenue mechanisms that could properly compensate PSH units for the full suite of services they provide.

**ACTION 4.3.2.3: Investigate potential for RTOs and ISOs to provide input on scheduling PSH units in electricity markets.**
In most RTOs and ISOs, PSH plants provide separate generation and demand bids into day-ahead and hour-ahead markets. Because each PSH plant typically bids into the market individually, there can be a lack of wider system perspective and coordination. Investigating the potential for system operators to provide input on scheduling PSH resources as part of the overall system optimization could help maximize the system benefit created by the energy and other ancillary and essential reliability grid services that PSH plants produce and could lower overall electricity generation costs. This action can include examining and reporting on how PSH plants have historically been handled and scheduled in different ISO/RTOs. This action could also include recognizing that ISO/RTO system operators would not control PSH plants, but rather provide input for their scheduling (e.g., PSH owners would need to retain full control in order to meet other requirements, such as FERC license requirements).

## **ACTION 4.3.3:** *Remove Barriers to the Financing of Hydropower Projects.*

### *Rationale for Actions*

Electricity market conditions are such that few utilities sign power purchase agreements for terms up to or beyond 20 years, which is well short of the 50-year-plus operational life of hydropower assets. The resulting lack of guaranteed revenue over the long life of a hydropower project limits the availability of conventional (i.e., commercial bank) financing sources, as conventional energy sector investors will not provide lower cost debt financing beyond the life of guaranteed revenue streams. Additionally, a lack of standard reporting and loan documentation increases the transaction and due diligence costs of financing site-specific hydropower projects. Regulatory and permitting uncertainty is also an important factor that can affect or delay financing. These problems are particularly acute for developers of smaller projects, because it can be more challenging to obtain lower levels of financing (i.e., $50 million or less). Traditional investors and lenders tend to make financing more available for larger scale projects with funding requirements in the hundreds of millions. As such, the pool of available financing for small hydropower projects may be limited. Additionally, incentives at the state or local level could provide financial support for small projects that have difficulty acquiring traditional financing. Although power purchase agreements for 50 years or more would not be likely on a regular basis for any project, having certainty for a longer revenue stream would be beneficial. Financing for large-scale projects (i.e. $1 billion or more for a merchant PSH project) also faces challenges, such as high upfront risk and long development timeframes. Risk-sharing mechanisms and partnerships warrant an investigation relative to financing and ensuring maximum ratepayer value.

**ACTION 4.3.3: Remove Barriers to the Financing of Hydropower Projects**

The economics of developing new hydropower projects can be improved by facilitating access to low-cost capital and investors with long-term perspective.

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| **Deliverable:** Educational tools, financial instruments, documentation, and outreach activities that improve access to low-cost, long-term financing for small and independent developers and that address small hydropower financing issues.<br><br>**Impact:** Dramatic reductions in the effective cost of bringing new hydropower projects to commercial operation. | **Key Objectives:** Optimization, Growth, Sustainability<br><br>**Growth Sectors Addressed:** Upgrades, NPD, Conduits, NSD, PSH<br><br>**Timeframe:** All actions in this section can begin immediately and simultaneously. |

| Action | Deliverable | Impact |
|---|---|---|
| **Action 4.3.3.1**<br>Standardize documentation for hydropower projects. | Standardized hydropower project documentation, e.g., power purchase agreements, leases, cost and performance reporting. | Reduced due diligence costs (mainly for small developers) and increased confidence on the part of financial institutions regarding investment in hydropower projects. |
| **Action 4.3.3.2**<br>Conduct outreach to municipalities. | Outreach and education programs. | Increased access to lower cost, longer term public capital, resulting in reduced cost of financing for hydropower projects. |
| **Action 4.3.3.3**<br>Conduct outreach to institutional lenders and investors. | Outreach and education programs; possible new financial instruments. | Increased access to lower cost, longer term capital, resulting in reduced cost of financing for hydropower projects. |

**ACTION 4.3.3.1: Standardize documentation for hydropower projects.**
The preparation of documentation, such as power purchase agreements, leases, and other contracts, for hydropower projects (as well as other renewable energy resources) is typically done on an ad-hoc, project-by-project basis. This lengthens the development process and increases the cost of due diligence by financial institutions. This in turn makes investment more difficult, particularly for smaller projects with lower dollar values at stake. Standardized documentation developed collaboratively with investors—inclusive of research and use of existing documentation and mechanisms—can facilitate timely, less expensive evaluation of projects. This would be expected to decrease costs and development time directly for small developers, while lowering the barriers to investment by financial institutions. This action includes assessing potentially applicable examples of standardized documentation (as long as that information can be reasonably shared or exchanged) in other energy generation industries.

**ACTION 4.3.3.2: Conduct outreach to municipalities.**
Municipalities can have access to lower cost capital (such as tax-exempt bonds) and planning horizons that align well with the long productive lifetime of hydropower projects. Creative financing arrangements, such as sale and lease-back arrangements with municipalities and local public power utilities, can extend the availability of this low-cost and potentially long-term financing to privately developed projects. The long life of hydropower assets also generally provides long-term stability in the form of steady energy costs. Outreach activities such as educational documents, media campaigns, workshops, and developer-municipality "matchmaking" could ultimately lower the cost of capital for many new hydropower projects. The standardized documentation from Action 4.3.3.1 could flatten the learning curve for municipalities that might invest in hydropower. Additionally, streamlined or simplified public-private partnerships or other procurement mechanisms can be examined for their applicability to conventional hydropower and PSH development.

**ACTION 4.3.3.3: Conduct outreach to institutional lenders and investors.**
Institutions such as pension funds, banks, and insurance companies seek long-term stable returns on their investments. This long-term view is highly complementary to the long asset life, comparatively lower risk profile, and proven track record of hydropower projects. However, these same organizations are generally attracted to large investment opportunities in the hundreds of millions of dollars. Engagement with this subset of financial institutions can serve a mutual educational purpose and can help hydropower developers begin to identify the information, project features, and investment mechanisms (e.g., securitization or large, multi-project portfolios) necessary to increase the willingness of institutional investors to finance hydropower.

## ACTION 4.3.4: *Improve Understanding of and Eligibility/Participation in Renewable and Clean Energy Markets.*

### *Rationale for Action*

The ability of hydropower facilities to participate in the nation's various renewable and clean energy markets varies widely from state to state and efforts to improve and expand overall recognition and eligibility of hydropower in these markets can result from this action. In addition, initiatives such as the U.S. Environmental Protection Agency's Clean Power Plan will offer states the additional opportunity to incentivize hydropower and participate in state trading programs. Knowledge of the rules and administrative requirements needed to effectively and fully participate in state and federal clean energy market programs requires clear and understandable guidelines for a wide range of business and hydropower ownership types.

**ACTION 4.3.4.1: Create toolkits to assist developers (particularly smaller developers) in understanding what types of renewable and clean energy markets are available, how their projects can qualify, and how to overcome specific barriers.**
The complex eligibility rules surrounding hydropower's participation in renewable and clean energy markets can be difficult for smaller developers to navigate. State- and federal-level policy rules should

| ACTION 4.3.4: Improve Understanding of and Eligibility/Participation in Renewable and Clean Energy Markets<br>Creating a set of tools to better understand policy rules and market eligibility can help reduce confusion and point developers towards the highest value markets for which their hydropower projects are eligible. | | |
|---|---|---|
| **Deliverable:** Transparent standards by which hydropower of all sizes can participate in clean energy markets, replacing existing ad hoc eligibility standards.<br>**Impact:** Improved economics of sustainable hydropower projects through the provision of revenue from environmental markets. | **Key Objectives:** Optimization, Growth, Sustainability<br>**Growth Sectors Addressed:** Upgrades, NPD, Conduits, NSD, PSH<br>**Timeframe:** Toolkits to assist developers in understanding renewable markets can be developed immediately to allow developers to participate in such markets in the near future. | |
| **Action** | **Deliverable** | **Impact** |
| **Action 4.3.4.1**<br>Create toolkits to assist developers (particularly smaller developers) in understanding what types of renewable and clean energy markets are available, how their projects can qualify, and how to overcome specific barriers. | Developer toolkits. | Increased participation of developers in renewable and clean energy markets. |

be documented and compiled into toolkits that can be used by smaller hydropower developers. This centralized repository of market eligibility information (which could also include information on potential off-takers) can help reduce confusion and point smaller developers towards the highest value markets for which their hydropower projects are eligible. This effort can also help improve and expand overall recognition and eligibility of hydropower in such markets.

# 4.4 Regulatory Process Optimization

Existing regulatory processes are intended to ensure that hydropower development is carried out responsibly and consistently. The regulatory processes for hydropower have value to stakeholders to the extent that desired outcomes are achieved or enabled. Those outcomes can include stewardship of natural resources, energy development, socioeconomic improvements, and many other water resource uses, which vary from region to region.

As with many regulatory processes, the broad spectrum of the hydropower regulatory environment has evolved over time rather than having been planned and implemented at one point in time as a unified, fully efficient, integrated process. As a result, hydropower project developers face a complex set of approval and compliance processes administered by various authorities including FERC, federal and state resource agencies, local governments, and tribes. In some cases, agencies operate on an independent schedule outside of the FERC process as required by or allowed under their statutory authority, such as the U.S. Army Corps of Engineers' Section 404 and 408 regulatory processes. Additionally, certain agencies have mandatory conditioning authority. While this complexity can ensure that important potential impacts are assessed and mitigation measures are implemented, it also results in uncertainty in study and administrative costs and schedules that can make it challenging to undertake, finance, and complete projects. The actions described in this section are intended to assist parties in navigating regulatory processes, and not to propose additive components, requirements, or modifications to regulations. The final action proposes evaluating the process from a process improvement perspective, identifying opportunities to make steps more efficient while also being consistent with environmental protection statutes and equally protective of affected resources.

Considering the collective regulatory experience from multiple perspectives may identify opportunities to enhance the effectiveness of the process in terms of both project development and environmental stewardship. Costs, risks, and implementation timeframes may be reduced by providing stakeholders with an increased knowledge base, easier access to information relevant to their projects, and increased capabilities for collaboration. Achieving the same or improved outcomes more quickly and predictably will reduce the risks and costs to developers and encourage investment in new projects by the financial community, without a reduction in environmental protection. Section 2.4.6 in Chapter 2 of the *Hydropower Vision* provides examples of process enhancements that have had positive effects on licensing costs or timelines without changes in regulations.

Because data collection associated with project licensing and relicensing is ultimately the responsibility of hydropower owners, these processes may occur in isolation from others who are carrying out similar efforts. While collaborative groups do share best practices and successes in safety, design, operations, and maintenance,[10] there are opportunities to do more to identify and share best practices for informing and navigating the overall regulatory process.

For example, scientific studies carried out as part of the regulatory process are site-specific, but they may reveal methodologies or findings that could be used by the technical practitioners in other processes to develop answers more efficiently. Benefits in environmental and energy generation performance could be realized if this cutting-edge science were better disseminated and integrated into the the regulatory process. Greater adoption of scientific advances could also inform policy considerations, as has happened in the past with improvements in hydropower operations to meet environmental objectives. For example, Wanapum Dam in eastern Washington on the Columbia River is using best available science to establish fish passage solutions that require less water to meet FERC's fish survival requirements than was required using traditional voluntary spill; sustainability objectives are being addressed with minimal impact on generation capacity. Providing specific actionable alternatives through the *Hydropower Vision* roadmap has the potential to impact other projects similarly in the future. With the establishment of a unified and comprehensive mechanism(s) for collaboration and dissemination of the best available science, mutual benefits could be realized for participants and regulators by increasing approval process efficiency.

## **ACTION 4.4.1:** *Provide Insights into Achieving Improved Regulatory Outcomes.*

### *Rationale for Actions*

The success of hydropower development and energy production, and the role of regulation in that success, are matters of perspectives, values, science, and technology. While future hydropower development and regulation are uncertain and may occur differently than in the past, the historical record can be useful to reveal how desirable and undesirable outcomes—subjective and objective—are correlated with specific practices during regulatory processes. The voluminous public records of hydropower regulation (e.g., FERC's eLibrary, documentation from federal hydropower agencies related to the National Environmental Policy Act) are the sources for such assessments. Disparate perspectives and values of stakeholders embedded in this historical record can be identified, analyzed, and used to classify outcomes according to rubrics for issues such as environmental and human health, environmental disturbance and alteration, economic well-being, cost of energy, energy security, and quality of life. The investigative, assessment, and decision-making processes embedded within this historical record can also be characterized and classified to establish a recurring set of practices that can be correlated with these outcomes.

The objective of this *Hydropower Vision* roadmap action is not to subjectively characterize specific historical development as good or bad overall; rather, it is to provide factual analyses and a summary, based

10. Examples include the National Hydropower Association's Operational Excellence, the Electric Power Research Institute, the Centre for Energy Advancement through Technological Innovation, and the Hydro Research Foundation.

on past experience, of the outcomes stakeholders can expect if certain practices are followed in hydropower regulatory processes. The products of this action could be a set of definitive and peer-reviewed reports, backed by a searchable catalog of hydropower development experiences, that identify multiple indicators of success, identify best (and worst) practices, and quantify the impacts of employing those practices in the regulation of hydropower development and operations. With this information in hand, participants in regulatory processes can choose to implement validated best practices tied to well-defined measures of success and avoid practices that are unlikely to yield benefit. This will provide more consistency, certainty, and clarity of actions, decisions, and outcomes within regulatory processes.

**ACTION 4.4.1.1: Develop indicators to measure outcomes of hydropower regulatory processes.** Stakeholders of hydropower development and operations have different perspectives and values that give rise to different objectives, priorities, and measures of success. Universal agreement on a limited and prioritized list of objectives and associated indicators of success in achieving those objectives is unrealistic. A pragmatic and useful activity would be to assemble—through comprehensive dialogue among stakeholders—a key set of candidate objectives, success indicators, and failure indicators. This effort would be aligned with and contribute to plans for measurable performance in permitting of infrastructure through environmental and social outcome metrics as called for by the White House under Executive Order 13604 in March 2012 [8]. Objectives and indicators are likely

**ACTION 4.4.1: Provide Insights into Achieving Improved Regulatory Outcomes**
Identifying and disseminating best practices can help lead to successful energy, environment-related, and socioeconomic outcomes of the hydropower regulatory process.

**Deliverable:** A series of definitive and peer-reviewed reports, backed by a searchable catalog of hydropower development experiences that identifies indicators of success from multiple perspectives, identifies best (and worst) practices to be encouraged (and avoided), and quantifies the impacts of using best practices to participate in the regulation of hydropower development and operations.

**Impact:** Ability of all participants in regulatory processes to make use of validated best practices tied to well-defined measures of success; more consistency and certainty of actions, decisions, and outcomes, with the goal of further increasing the sustainability of hydropower.

**Key Objectives:** Optimization, Growth, Sustainability

**Growth Sectors Addressed:** Upgrades, NPD, Conduits, NSD, PSH

**Timeframe:** The development of indicators to measure outcomes of regulatory processes (4.4.1.1) could begin immediately and would end when those indicators are published. Cataloging the relationships between practice and outcome in regulatory processes (4.4.1.2) would begin immediately and would end with the delivery of the catalog. Characterization, validation, and dissemination of successful practices (4.4.1.3) would grow out of actions 4.4.1.1 and 4.4.1.2 and continue until those successful approaches are published.

| Action | Deliverable | Impact |
|---|---|---|
| **Action 4.4.1.1** Develop indicators to measure outcomes of hydropower regulatory processes. | Peer-reviewed technical publications that evaluate various indicators of success in meeting the objectives of hydropower regulatory processes. | Greater clarity and consensus in discussions among hydropower regulatory stakeholders. |
| **Action 4.4.1.2** Classify and catalog the relationships between practice and outcome in hydropower regulation. | Searchable catalog, tied to existing databases, of hydropower regulatory experiences enabling investigation of relationships between outcomes and facility, developmental, and regulatory process characteristics. | Data-driven insight and decisions about how to most effectively accomplish hydropower development and relicensing within regulatory processes. |
| **Action 4.4.1.3** Characterize, validate, and disseminate successful practices. | Peer-reviewed technical publication(s) describing the empirical evidence on stakeholder use of best practices. | Evidence-based choices by hydropower developers, owners/operators and regulators on how to scope and execute their work while complying with regulatory processes. |

to address issues such as environmental and human health, environmental disturbance and alteration, economic well-being, cost of regulation or compliance, cost of energy, energy security, and quality of life. These would then be exercised against several historical regulatory test cases to determine which of the objectives or indicators (1) are implementable based on site-specific information in the historical record; (2) provide useful indications of success; and (3) would enhance decision making in the regulatory process.

**ACTION 4.4.1.2: Classify and catalog the relationships between practice and outcome in hydropower regulation.**
With a useful set of indicators for assessment, a comprehensive and consistent assessment of a representative sample of outcomes (under existing regulations) becomes feasible. Coordinated research among stakeholders can extract from the historical record a database of regulated hydropower projects, regulatory actions, and outcomes suitable for formalized analyses. Such a database could draw from and contribute to the Federal Infrastructure Permitting Dashboard,[11] established to facilitate early collaboration of infrastructure project reviews; synchronize, align, and reduce time associated with permitting and environmental review timelines, when appropriate and practicable; and increase accountability by making more project information available to the public. Combined with increasing availability of hydropower facility and footprint attribute information (i.e., physical, electro-mechanical, ecological, and socioeconomic characteristics), this information can support studies that track trends of the relationships between practice and outcome in hydropower regulation. It should be noted that not all data are public and that the usefulness of such a database must be demonstrated in order to encourage greater information sharing.

**ACTION 4.4.1.3: Characterize, validate, and disseminate successful practices.**
A comprehensive database of regulatory outcomes and the factors that influence those outcomes will enable analyses and yield findings that can underpin regulatory best practices. Examples of candidate best practices could include more emphasis on multi-facility or basin-scale scoping for studies and decision making; explicit incentives for collaboration among disparate stakeholders during the regulatory process; use of standardized designs; and strategies for dealing with the schedule and cost uncertainties (from the developer perspective) engendered by aspects such as mandatory conditioning or potentially redundant/overlapping process characteristics. Within this study effort, researchers can also investigate the variability of outcomes of regulatory processes to understand which factors are most responsible for variation in regulatory outcomes and which led to the most sustainable outcomes. In this way, hypothesized best practices can be validated and distributed, ultimately resulting in a more efficient execution of the regulatory process.

## ACTION 4.4.2: *Accelerate Stakeholder Access to New Science and Innovation for Achieving Regulatory Objectives.*

### *Rationale for Actions*

Science is expected to continue to add to the understanding of ecological response, socioeconomic response, and human reaction to actions such as hydropower development and operation, for both new and existing technologies. Science and technology advancements may also improve the feasibility and robustness of remote sensing and field data collection needed for greater understanding of natural and human systems responses to hydropower development and operations. Incorporating new science and technology for use in specific regulatory processes could contribute to better outcomes.[12] However, these developments may also lead to increased costs, resource requirements, and risks for stakeholders that must be considered. New science may also present new uncertainty, which can translate to increased risk for decision makers. Collaborative frameworks are needed to pilot the use of new science and technology in regulatory process compliance, assess the costs and benefits of such innovative pilot efforts, refine the science and technology, and disseminate the results and guidance to a wide audience of stakeholders nationwide.

11. Available at *https://www.permits.performance.gov/about.*

12. DOE shares new science information with stakeholders through reports and inter-agency collaborations such as the Federal Inland Hydropower Working Group.

| **ACTION 4.4.2: Accelerate Stakeholder Access to New Science and Innovation for Achieving Regulatory Objectives**<br>Improving the ability of stakeholders to use new science and innovation can enhance environmental outcomes; increase the value of hydropower facilities; and reduce costs of permitting, licensing, and compliance. | |
|---|---|
| **Deliverable:** Disseminated unbiased information to stakeholders on the availability and applicability of new citable science findings and the validated performance of innovative technologies.<br>**Impact:** Accelerated, justified, and efficient adoption of scientific developments that may improve outcomes of regulatory processes by increasing confidence in the value of innovative approaches.<br>**Key Objectives:** Optimization, Growth, Sustainability<br>**Growth Sectors Addressed:** Upgrades, NPD, Conduits, NSD, PSH | **Timeframe:** The development of collaborative methodologies to accommodate competing uses for water resources (4.4.2.1) could begin immediately and end with publication. A forum of scientists, practitioners, and stakeholders to assess science and technology innovations (4.4.2.2) could be established immediately and would continue as long as needed. Creating a database of new and emerging technologies and associated studies (4.4.2.3) could begin immediately and would continue to add new technologies as they develop. |

| Action | Deliverable | Impact |
|---|---|---|
| **Action 4.4.2.1**<br>Develop and encourage the use of collaborative methodologies to accommodate competing uses for water resources. | Published research and guidelines for hydropower stakeholders who desire to use collaborative methods in complying with regulatory processes. | More efficient and less contentious pathways to regulatory outcomes. |
| **Action 4.4.2.2**<br>Establish a forum to assess the efficacy and usefulness of new science and technology innovations affecting environmental impact or mitigation. | An established and documented forum wherein participants collectively debate and assess the efficacy and usefulness of new science and technology innovations with the potential to influence regulatory decisions about environmental impact and mitigation. | Much of the disagreement and debates about the efficacy and usefulness of new science and technology will occur outside of and prior to a specific regulatory action. |
| **Action 4.4.2.3**<br>Create a database of new and emerging technologies and associated studies. | A database of performance, economics, and environmental effects of new and emerging hydropower technologies. | Faster acceptance of new technologies by the hydropower community. |

**ACTION 4.4.2.1: Develop and encourage the use of collaborative methodologies to accommodate competing uses for water resources.**

To participate most effectively in decision making, institutional and individual stakeholders should have a fact-based understanding of the relationships between decisions and outcomes. In an ideal forum, they would also have a thorough understanding of the myriad physical, institutional, regulatory, and legislative constraints that limit alternatives for managing hydropower development and associated impacts. Research can draw from existing sources pertaining to a wide array of forums in which decisions are made, or new research could be undertaken to reveal how stakeholders assimilate such complex information, understand motivations, develop trust, negotiate compromises or solutions, and make decisions within their organizations and in collaboration with other institutions. Additional research may provide methodologies for communicating and explaining complex information to stakeholders. It may also provide evidence that greater understanding among stakeholders can improve regulatory decision making and compliance by more quickly identifying alternatives that meet constraints and best deliver on multiple objectives.

**ACTION 4.4.2.2: Establish a forum to assess the efficacy and usefulness of new science and technology innovations affecting environmental impact or mitigation.**

Regulatory processes for hydropower aspire to use the best available science as well as transparency and robust decision rationale. However, the realities of gaps in science—along with limited time, resources, and information—can result in outcomes that are unsatisfactory from the perspectives of some stakeholders. An independent multi-stakeholder forum of experts, functioning outside the jurisdiction of and disinterested from any specific regulatory process or agency, may be able to vet new science (e.g., peer-reviewed journal publications), transparently debate the importance and applicability of that science to classes of water resources and ecological problems, and accelerate the piloting and adoption of new science into specific hydropower development contexts. Such a forum can enable scientific debate to occur unconstrained by the schedule of specific regulatory processes, but would make the results of such debates available to regulatory participants.[13] Recognizing that "one size does not fit all" will be important with respect to assessment of new science or studies not directly related to a specific project.

**ACTION 4.4.2.3: Create a database of new and emerging technologies and associated studies.**
New or emerging technologies may have characteristics that enhance their ability to generate power, improve environmental conditions, or achieve economic viability. Those benefits will only be realized if those technologies are actually identified, selected, and implemented. To accelerate the adoption of promising technologies, a database can be created to capture studies that demonstrate how they have performed from engineering, economic, and environmental perspectives. That body of knowledge could assist developers in objectively selecting equipment that is likely to meet their needs, regulatory requirements, and the objectives of other stakeholders. Regulators and other stakeholders would be able to access the database to make their own evaluations of how technologies are likely to perform.

## ACTION 4.4.3: *Analyze Policy Impact Scenarios.*

### *Rationale for Actions*

Decision makers in government, industry, non-governmental organizations, and the general public at the state and federal levels can benefit from analyses and prognostics that integrate modeled responses of markets, power systems, other infrastructure, river systems, ecosystems, water systems, and socioeconomic conditions with policy alternatives. There is a need for tools and methodologies to aid in evaluating potential impacts of policy options on a variety of factors. These tools could be used to assess proposed regulatory processes for hydropower licensing, new understanding of environmental impacts, new legislation relevant to energy and water systems, availability of new technology to mitigate impacts of hydropower development or reduce costs of deployment, and incentives for deployment of hydropower and other energy generation technologies. Modeled scenarios may need to include multiple objectives at the facility, river system, and power system scales, as well as aggregate effects of those multiple objectives at regional and national scales. Analyses and prognostics should reveal regional variations of responses and illustrate how such responses may vary through time.

**ACTION 4.4.3.1: Develop a coordinated set of models that can reveal the national, regional, and local effects of policy alternatives.**
The *Hydropower Vision* draws heavily on DOE's Regional Energy Deployment System (ReEDS) model to analyze hydropower development scenarios under a least-cost objective for meeting future demands for electricity. The ReEDS model does provide a set of impacts as a consequence of least-cost deployment, but stakeholders and decision makers may desire more information about deployment scenarios based on multiple objectives (e.g., a to-be-defined sustainability objective and a least-cost objective). This added detail will likely require additional modeling and analysis tools that are compatible, complementary, and even coupled with the ReEDS model. As was the case with ReEDS, any of these new models would need to be validated before use. While the least-cost objective is universal for all regions of the United States, other objectives (e.g., sustainability or economic impact) may have regionally varying definitions, importance, and priorities, and thus require different formulations for different regions. Stakeholders could use this common model framework and develop their own objectives and scenarios to initiate

13. The National Wind Coordinating Committee (*www.nationalwind.org*) is one example of this type of forum.

discussions (as described in 4.4.3.2) regarding policy alternatives. Differing perspectives of municipal utilities, investor-owned utilities, and independent power producers also need to be considered in the analysis.

**ACTION 4.4.3.2: Create a framework for developing scenarios, policy alternatives, and predicted outcomes for consideration by all stakeholders.**
Policy analyses require not only models but also development of possible scenarios and strategies for addressing the challenges included in those scenarios. While the *Hydropower Vision* addresses macroeconomic scenario issues such as natural gas price and availability, there are a host of other hydropower-specific challenges that will be relevant to stakeholders and decision makers since hydropower development occurs under evolving regulatory contexts. Examples include revenue and benefits of hydropower, threatened and endangered aquatic species management, and water quality management. Just as modeling capabilities need to become more refined and multi-objective, the scenarios and policies that are translated into modeled objectives, constraints, and other inputs must also be more detailed. Specific institutions and stakeholder groups will have differing priorities for scenarios and policies to be analyzed. However, such priorities can be accommodated into a transparent and common framework for defining, modeling, analyzing, and reporting the outcomes of scenarios, strategies, and policies around hydropower relicensing and new development.

**ACTION 4.4.3.3: Review and report on existing regulatory process and propose potential improvements.**
Because the regulatory process includes agencies at both the state and federal levels, hydropower licensing processes can go beyond original estimated timelines. FERC reported on this issue in its 2001

**ACTION 4.4.3: Analyze Policy Impact Scenarios**

Improving the ability to assess potential impacts of policy options on markets, power systems, ecosystems, and populations—all on local, regional, and national scales—can inform decision makers.

**Deliverable:** An integrated capability to specify and model policy scenarios and anticipate the resulting effects on hydropower capacity, production, value, and impacts within the broad, nationwide energy context.

**Impact:** Realistic projections of the possible outcomes of policy scenarios that enable regional and national decision makers and stakeholders to consider alternatives and make well-informed decisions.

**Key Objectives:** Optimization, Growth, Sustainability

**Growth Sectors Addressed:** Upgrades, NPD, Conduits, NSD, PSH

**Timeframe:** Developing a coordinated set of models able to assess policy alternatives (4.4.3.1) can begin immediately and would continue until models are delivered. Creating a framework for developing scenarios, policy alternatives, and predicted outcomes (4.4.3.2) can also begin immediately. This action will evolve into ongoing application of the framework. Work can begin immediately to report on the causes of delays in the regulatory process and propose solutions (4.4.3.3) and would continue until delivery of a comprehensive report.

| Action | Deliverable | Impact |
|---|---|---|
| **Action 4.4.3.1**<br>Develop a coordinated set of models that can reveal the national, regional, and local effects of policy alternatives. | A transparent collection of models with documentation and guidance on use, and interpretation of results for both the state and federal level. | Ability to capture full effects of policies and educate decision makers on mechanisms to achieve desired impacts. |
| **Action 4.4.3.2**<br>Create a framework for developing scenarios, policy alternatives, and predicted outcomes for consideration by all stakeholders. | A template, methodology, and set of scenarios that are crafted by, transparent to, and understood by hydropower development stakeholders. | Ability to address the sustainability of hydropower through multiple scenarios. |
| **Action 4.4.3.3**<br>Review and report on existing regulatory process and propose potential improvements. | A report presenting data on the variety of causes for regulatory process inefficiencies, with a roadmap addressing opportunities for improvement. | Catalyze changes that lead to efficiency gains in the regulatory process. |

publication, *Report on Hydroelectric Licensing Policies, Procedures, And Regulations Comprehensive Review and Recommendations Pursuant to Section 603 of the Energy Act Of 2000.* This action proposes a report that would seek to update and expand on this aspect of the FERC 603 report to initiate a national dialogue to seek potential improvements. In addition to analyzing data available through FERC and other state, tribal, and federal agencies, the report would gather information from surveys and workshops conducted with the hydropower community to identify opportunities for improvement and propose potential solutions. The report would seek to catalyze changes that can lead to efficiency gains in implementation of regulatory processes.

The proposed national dialogue identified in this action could consist of a collaborative, multi-stakeholder effort led by a neutral entity such as the National Academy of Science. This effort would allow stakeholders to collaboratively brainstorm ideas for achieving the process improvement opportunities with the greatest impact, absent a specific initiative to pursue any of the ideas. Ideas with broad support might be further discussed in terms of how to implement them. The purpose of identifying the highest opportunities for process efficiency improvement and ideas as to how they might be achieved is to inform stakeholders, regulators, and policy makers as to where to focus efforts to have the greatest impact on improving process efficiency.

## ACTION 4.4.4: *Enhance Stakeholder Engagement and Understanding within the Regulatory Domain.*

### *Rationale for Actions*

The crux of this action is to ensure that all stakeholders have knowledge and understanding necessary for them to have trust and participate effectively in hydropower development, decision making, and regulatory processes. Given more than 100 years of hydropower development, there is a wealth of information available from which lessons can be learned, but much of that information is not generally accessible or is not cataloged in ways that make it readily available to inform new undertakings.

**ACTION 4.4.4.1: Develop an enhanced regulatory information portal.**

FERC's website features extensive information with respect to the hydropower industry, including specifics on licensing/relicensing, compliance, administration, and actions that need to be taken.[14] This information from FERC is beneficial to novice and expert users alike. However, since hydropower licensing involves many entities beyond FERC, it may be beneficial to either build upon what FERC has established or develop a new information portal that addresses not only FERC's processes, but also offers links and information with respect to the treatment of hydropower in each U.S. state (particularly if the specific project does not fall under FERC jurisdiction) and those of other federal agencies. Ideally, such a system would afford users a convenient, user-friendly portal that synthesizes regulatory requirements, processes, technical guidance, and findings from multiple jurisdictions, including FERC, the U.S. Army Corps of Engineers, Reclamation, state environmental offices, and state and federal natural resource agencies. The best practices from Action 4.4.1 could eventually be integrated into this portal. The beginnings of this action are reflected in the RAPID (Regulatory and Permitting Information Desktop) toolkit[15] under development at DOE, but go beyond the scope of that project.

**ACTION 4.4.4.2: Facilitate access to relevant historical regulatory information.**

While hydropower development is often characterized as a site-specific undertaking, there are geospatial, ecological, socioeconomic, and political themes that are common to groups of development projects. The commonalities can be leveraged to improve effectiveness and efficiency in designing projects and mitigation strategies for sustainable development and operations (e.g., less novel or extensive studies needed

14. See, for example, *http://www.ferc.gov/industries/hydropower.asp* .
15. RAPID is available via OpenEI at *http://en.openei.org/wiki/RAPID*

**ACTION 4.4.4: Enhance Stakeholder Engagement and Understanding within the Regulatory Domain**
Activities under this action will ensure all stakeholders have access to the knowledge and experience necessary to participate effectively in planning, decision making, and regulatory processes.

**Deliverable:** A user-friendly portal synthesizing hydropower regulatory requirements and processes; a hydropower development knowledge management system for experts; and tools and guidance for enhancing stakeholder understanding of complex water and energy issues.

**Impact:** More robust outcomes, reduced costs, greater efficiency, and better engagement from stakeholders in hydropower development and regulation.

**Key Objectives:** Sustainability

**Growth Sectors Addressed:** Upgrades, NPD, Conduits, NSD, PSH

**Timeframe:** Work to develop an enhanced regulatory information portal (4.4.4.1) can begin immediately and would end with the delivery of that portal. Efforts to facilitate access to relevant historical regulatory information can begin immediately (4.4.4.2) and would continue until a comprehensive knowledge management system is delivered. Development of advanced methods of communicating process complexities to non-technical stakeholders (4.4.4.3) can begin soon and would end with the delivery of guidelines, formats, tools, and facilities.

| Action | Deliverable | Impact |
|---|---|---|
| **Action 4.4.4.1**<br>Develop an enhanced regulatory information portal. | A convenient, user-friendly portal that synthesizes regulatory requirements and processes from multiple jurisdictions, with specific guidance for novice developers. | Reduced cost and less effort required to parse requirements and gather information. |
| **Action 4.4.4.2**<br>Facilitate access to relevant historical regulatory information. | A comprehensive knowledge management system for hydropower development, with advanced geospatial registration and thematic indexing of information content. | Ability for expert stakeholders to quickly and efficiently locate, within the national history and experience, relevant information for a specific proposed hydropower development. |
| **Action 4.4.4.3**<br>Develop advanced methods of communicating process complexities to non-technical stakeholders. | Specific guidelines, formats, software tools, and facilities for conveying water management and power system complexities and scenario outcomes to non-technical stakeholders. | Ability for non-technical stakeholders to better understand issues, develop trust in decision-making processes, and become more effective in helping to craft solutions. |

to satisfy regulators). However, the sources of relevant information are many and varied, which makes searching and assimilating data from those sources difficult even for expert analysts, designers, and regulators. A comprehensive knowledge management system for hydropower development leveraging DOE's investment in the National Hydropower Asset Assessment Program,[16] which has implemented advanced geospatial registration and thematic indexing of a robust set of hydropower information, would address this challenge. Other examples of knowledge discovery efforts include the DOE Bioenergy Knowledge Discovery Framework,[17] and Tethys[18] for marine and offshore wind energy knowledge management.

**ACTION 4.4.4.3: Develop advanced methods of communicating process complexities to non-technical stakeholders.**
Technical complexity can be a barrier to effective and sustained participation by non-technical stakeholders in hydropower development and regulatory processes. River systems, power systems, and ecosystems include network complexities, dynamics, and tradeoffs that can confound even technical analysts in the short term. Enhanced capabilities to visualize and communicate those complexities in ways that are intuitive to stakeholders may lead to greater engagement, trust, and contributions to solutions from stakeholders. Conversely, the absence of understanding

16. More information about the National Hydropower Asset Assessment Program is available at *http://nhaap.ornl.gov/*.
17. More information about the Bioenergy Knowledge Discovery Framework is available at *https://www.bioenergykdf.net/*.
18. More information about Tethys is available at *http://tethys.pnnl.gov/*.

may lead stakeholders to discount objectives and impacts, and can diminish their trust and effective engagement. Such capabilities can be provided through a combination of specific guidelines, formats, software tools, and visualization facilities for conveying water management and power system complexities and scenario outcomes to non-technical stakeholders. An example of this that proved successful was DOE's Basin Scale Opportunity Assessment in Oregon's Deschutes Basin [9]. This assessment used a suite of visualization tools to communicate complex issues to a diverse set of stakeholders so that they might make informed decisions regarding trade-offs in the Basin.

## 4.5 Enhanced Collaboration, Education, and Outreach

The hydropower community is long-standing and complex, comprising many types of companies, organizations, and agencies, each with unique interests, perspectives, and operating mandates. Although the community has continued to work toward individual and common goals, such as regulatory process efficiency and greater environmental sustainability, there are significant opportunities for improved communication and collaboration. Realizing these opportunities can provide mutual benefit within the hydropower community as well as present the value of hydropower to others, including those who rely on hydropower for clean, renewable energy or to support the continued development of variable renewable generation resources like wind and solar.

To increase acceptance of hydropower's benefits and impacts, objective information regarding the technology as an established, reliable, low-carbon renewable energy source, its importance to grid stability and reliability, and its ability to support variable generation should be articulated and disseminated. Since discussions of renewable energy are closely linked to environmental impact, hydropower information should provide fact-based details regarding environmental considerations and existing regulations, and how projects are designed and operated to comply with them in an environmentally responsible manner. Whether or not hydropower (either new or existing) should be included or excluded from renewable or clean energy incentive programs or market compensation mechanisms is dependent upon the goals of specific policies and their related programs.

The fleet of federal hydropower projects produces nearly half of all domestic hydropower generation. A wide range of data exists on the performance, characteristics, and value of these assets. Given the varied objectives of federal hydropower projects, there are different levels of investment that may be applied to maintaining and upgrading these assets for energy generation. To help inform investment decisions, the available data could be compiled to better quantify the full range of contributions and the long-term potential of the federal fleet to help meet the nation's renewable energy supply and grid reliability needs.

Although there are collaborative groups and initiatives—such as those of the International Centre for Energy Advancement through Technological Innovation—that share best operating practices and performance benchmarks, these efforts are not always fully available to the broader hydropower community. Hydropower facility owners and developers could benefit from a national-scale effort to identify and regularly update best practices (including an environmental stewardship component) for maintaining, operating, and constructing generation facilities. Investigation and implementation of ongoing best practices programs and related benchmarking can enable the industry to achieve its full potential as a reliable and low-cost renewable energy source.

To both maintain the industry and have it grow to the potential levels of deployment identified in the *Hydropower Vision,* the United States will need to sustain and increase its qualified, well-trained workforce to maintain and build new hydropower plants. Many of the individuals with the knowledge of how to most effectively design, construct, and operate hydropower plants are nearing retirement. To motivate younger workers to enter the field, hydropower-specific curricula can be implemented within vocational and university programs for students interested in technical skills, engineering, and development of renewable energy. Workforce-needs assessments tied to potential industry growth scenarios would provide baseline data on numbers of required workers with specific skill sets. For detailed information on the hydropower workforce, see Section 2.8 in Chapter 2.

## ACTION 4.5.1: *Increase Acceptance of Hydropower as a Renewable Energy Resource.*

### *Rationale for Actions*

The goal of this action is to articulate and disseminate objective information regarding hydropower as an established and reliable, low-carbon, renewable energy source; its importance to grid stability and reliability; and its ability to support variable generation. This includes information on its existing and historical contribution, as well as its future potential. Discussions of and objectives for clean, renewable energy are linked to considerations of effective environmental stewardship, including avoided or mitigated impacts to affected aquatic resources or impacted lands. This action should highlight hydropower advancements that have been made in addressing environmental considerations, existing environmental regulations with which hydropower projects must comply, and the ongoing need for individual hydropower projects to be designed and operated in as environmentally responsible a way as possible if net-positive clean energy benefits are to be realized.

**ACTION 4.5.1: Increase Acceptance of Hydropower as a Renewable Energy Resource**
Demonstrating and communicating that hydropower is a core renewable energy source can both increase public understanding and encourage inclusion of hydropower in clean energy planning and markets, as appropriate.

| | |
|---|---|
| **Deliverable:** Publication and communication of data and reports highlighting hydropower's benefits as a renewable energy resource as well as how hydropower can be designed and operated within sustainability principles to supply low-carbon energy.<br>**Impact:** General public awareness and acceptance, increased eligibility for energy credits, new low-impact hydropower development. | **Key Objectives:** Optimization, Growth, Sustainability<br>**Growth Sectors Addressed:** Upgrades, NPD, Conduits, NSD, PSH<br>**Timeframe:** The activities in this section could begin as soon as possible. Actions 4.5.1.1 and 4.5.1.2 would be ongoing, while action 4.5.1.3 would be completed when an assessment study is published. |

| Action | Deliverable | Impact |
|---|---|---|
| **Action 4.5.1.1**<br>Conduct outreach and education on hydropower as a renewable energy resource. | Fact-based information disseminated via communication initiatives. | Public, stakeholder, and policy maker awareness and acceptance. |
| **Action 4.5.1.2**<br>Conduct outreach and education regarding the environmental and social considerations of hydropower projects. | Fact-based information disseminated via communication initiatives. | Improved stakeholder perception of hydropower and closed-loop PSH in an environmental context. |
| **Action 4.5.1.3**<br>Assess the inclusion of hydropower in renewable energy markets and incentive programs. | Publication of an assessment study and related workshops. | Refined understanding of whether or when hydropower can be included effectively in broad renewable energy incentives or standards. |

Dissemination of information can support the acknowledgment of hydropower as a renewable energy source and, as such, should be considered in clean energy planning efforts. Whether or not hydropower (either new or existing) should be included or excluded from renewable or clean energy incentive programs or market compensation mechanisms is dependent upon the goals of specific policies and their related programs.

**ACTION 4.5.1.1: Conduct outreach and education on hydropower as a renewable energy resource.**
Outreach should be conducted to increase awareness and acceptance of hydropower's renewable energy attributes. This outreach could share fact-based information and science-based analysis to inform the general public, stakeholders, and policy makers. This outreach can be implemented through published reports, academic channels, webinars, and educational websites, as well as via in-person meetings with decision makers.

**ACTION 4.5.1.2: Conduct outreach and education regarding the environmental and social considerations of hydropower projects.**
This action will raise general awareness of the environmental and social considerations to be addressed in all new hydropower development and existing project modernization, in accordance with existing regulations. This action requires conveying the environmental priorities and challenges, along with appropriate and adequate mitigation techniques, to a range of stakeholders. To facilitate this process, information should be compiled into digestible formats that incorporate examples and success stories, and made available through channels such as public meetings, municipalities and other public agencies, advertisements or service announcements, social media, websites, and fact sheets.

**ACTION 4.5.1.3: Assess the inclusion of hydropower in renewable energy markets and incentive programs.**
To fully understand the existing position of hydropower in renewable energy markets, it is necessary to conduct a full inventory and analysis of renewable energy incentives such as renewable portfolio standards. This study will include assessing whether and why hydropower is or is not considered a renewable technology in each evaluated market, and the impact of renewable energy incentive programs on the growth of hydropower relative to the growth of other technologies. This study can help clarify commonly misunderstood or confusing topics, such as whether a technology needs to be new to qualify as renewable. It can also provide industry and policy makers with a deeper understanding of key factors influencing whether hydropower is, or could be, included to aid in achieving the objectives of such programs or standards. It may include recommendations for increasing the effectiveness and consistency of approaches between incentive programs with similar objectives.

## ACTION 4.5.2: *Compile, Disseminate, and Implement Best Practices and Benchmarking in Operations and R&D.*

### *Rationale for Actions*

A retrospective benchmarking study of hydropower fleet reliability and efficiency can support identification of the leading performance indicators as well as shortfalls in performance, including those related to environmental and social objectives. Several hydropower industry groups have developed best practices for various aspects of the business, but no single industry group has developed or compiled a complete library of these documents. This action will identify best practices that have enabled top performance—including operational, maintenance, environmental mitigation, and water management practices— as well as practices that are needed, including steps for their development and dissemination. Formalized cataloging of best practices can enable more efficient hydropower planning and allow the industry to transfer such knowledge to the future workforce.

| **ACTION 4.5.2: Compile, Disseminate, and Implement Best Practices and Benchmarking in Operations and R&D**<br>Compiling and disseminating methods and best practices from leading performers in all segments of the hydropower industry can drive improvements in hydropower performance. | |
|---|---|
| **Deliverable:** Biannual report on U.S. hydropower fleet performance; compilation of hydropower best practices.<br>**Impact:** Lowered costs and increased revenue for hydropower facility owners and developers.<br>**Key Objectives:** Optimization, Growth, Sustainability | **Growth Sectors Addressed:** Upgrades, NPD, Conduits, NSD, PSH<br>**Timeframe:** The actions in this section are near term and assumed to be sequential. Actions can begin as soon as possible and continue until objectives are met. |

| Action | Deliverable | Impact |
|---|---|---|
| **Action 4.5.2.1**<br>Carry out a retrospective study on operational performance of the hydropower fleet. | A report to benchmark historical hydropower fleet reliability and performance, including identification of highly efficient facilities. | Increased understanding of most effective practices, which can potentially lead to improved performance, lowered costs, and increased revenue. |
| **Action 4.5.2.2**<br>Document and compile proven best practices, as well as processes or procedures for which best practices remain to be developed. | A publicly accessible compilation of existing and required global best practices, incorporating nonproprietary information. | Increased understanding of most effective practices, which can potentially lead to improved performance, lowered costs, and increased revenue. |
| **Action 4.5.2.3**<br>Document best practices to fill gaps identified in Action 4.5.2.2. | Dissemination of previously undocumented best practices. | Increased understanding of most effective practices, which can potentially lead to improved performance, lowered costs, and increased revenue. |

**ACTION 4.5.2.1: Carry out a retrospective study on operational performance of the hydropower fleet.** Benchmarking studies can identify high-performing facilities in the hydropower industry in terms of reliability, safety, efficiency, and environmental performance. Doing so is expected to provide the analytical basis for identifying and characterizing the most effective approaches, methods, and technical solutions, i.e., “best practices.” These studies can also help form a better understanding of the condition of equipment, the future for predictive maintenance and failures, and the impacts of operating equipment in innovative ways in order to respond to increasing amounts of variable generation in the grid.

**ACTION 4.5.2.2: Document and compile proven best practices, as well as processes or procedures for which best practices remain to be developed.** Certain best practices have been previously identified and documented by hydropower industry groups. This action will entail reviewing those practices in the context of the data gathered in Action 4.5.2.1 and developing a list of additional processes and procedures that lack established best practices in order to identify gaps. A publicly accessible compilation or library of existing and required best practices would then be established, incorporating nonproprietary information for use by existing facilities and personnel. The information can also be used to plan future hydropower and to train the future hydropower workforce.

**ACTION 4.5.2.3: Document best practices to fill gaps identified in Action 4.5.2.2.** Characterization and dissemination of previously undocumented best practices to fill gaps identified in Action 4.5.2.2 can provide the industry with a complete set of best practices for developing, maintaining, and operating hydropower facilities.

## ACTION 4.5.3: *Develop and Promote Professional and Trade-Level Training and Education Programs.*

### *Rationale for Actions*

Hydropower owners/operators will need to replace retiring hydropower workers with employees who have knowledge of hydropower, its characteristics, state-of-the-art practices, and developing trends and opportunities for improvement. New workforce members should be inspired and supported by hydropower-specific learning opportunities in education programs, from pre-college to trade, to ensure and maintain a high-quality, well-trained workforce. This includes providing basic information to students and the public about hydropower as a clean, renewable resource; promoting science, technology, engineering, and math education to ensure a highly skilled workforce; training the workforce to be ready for employment so companies have assurance that applicants are prepared; and developing hydropower curricula modeled after successful initiatives in other technologies, such as the KidWind project, the DOE's Wind for Schools project, and the National Energy Education Project.

**ACTION 4.5.3.1: Gather baseline data on the workforce to perform future workforce assessments.** This action entails an in-depth data-gathering effort with industry to assess the labor needs of the U.S. hydropower industry, in collaboration with current DOE efforts on assessing the hydropower workforce. To evaluate progress and future needs, workforce data under potential growth scenarios and new technology deployments will be compiled and analyzed, including analyses to gain a better understanding of the numbers and role of women, minorities, and veterans in the existing workforce. This action will be essential in informing future workforce investments, such as training programs, and tools and techniques to effectively capture and transfer knowledge from workers leaving the workforce.

**ACTION 4.5.3: Develop and Promote Professional and Trade-Level Training and Education Programs**
Evaluating and developing comprehensive training and education programs, with engagement from high school to university and trade school levels, can help encourage and anticipate the technical and advanced-degree workforce required to meet the industry's long-term needs.

| | |
|---|---|
| **Deliverable:** Hydropower-related science, technology, engineering, and math promotions, curricula, and other data and educational materials for education and training programs at community colleges, universities, and training facilities.<br><br>**Impact:** A stable, highly qualified, well-trained workforce for new and existing hydropower projects, including development, construction, O&M, and upgrades. | **Key Objectives:** Optimization, Growth, Sustainability<br><br>**Growth Sectors Addressed:** Upgrades, NPD, Conduits, NSD, PSH<br><br>**Timeframe:** The activities in this section begin with short-term data gathering and curriculum formulation, leading to a set of actions that must be implemented on an ongoing basis to meet industry needs. |

| Action | Deliverable | Impact |
|---|---|---|
| **Action 4.5.3.1**<br>Gather baseline data on the workforce to perform future workforce assessments. | Report on hydropower workforce needs. | Valid baseline from which to identify workforce needs. |
| **Action 4.5.3.2**<br>Develop hydropower-specific curricula. | Curricula specific to hydropower technology. | Inspired, informed students; increased youth interest in hydropower. |
| **Action 4.5.3.3**<br>Promote hydropower as a career choice. | Outreach material such as a Hydropower Career Map. | Consideration by students of hydropower as a prospective career. |
| **Action 4.5.3.4**<br>Encourage greater employment readiness. | Guidebook; training manual/program. | Trained, qualified workers to ensure the responsible operation and development of hydropower projects. |

**ACTION 4.5.3.2: Develop hydropower-specific curricula.**

This action will involve assessing, enhancing, and disseminating hydropower-related curricula based on the baseline data and labor needs assessment in Action 4.5.3.1. The identification of effective existing age- and level-appropriate curricula for high school, university, and trade schools could facilitate targeted education and inspire students to consider hydropower as a professional field. New curricula may also be developed under this action, which would require collaboration between industry and educational institutions to ensure appropriate messaging and the core information to be transferred. Examples of similar efforts include an initiative of the DOE's Wind Program known as Wind for Schools,[19] which reached thousands of students and teachers.

**ACTION 4.5.3.3: Promote hydropower as a career choice.**

This action will promote hydropower as a stable industry with solid job prospects. By applying the curricula developed in Action 4.5.3.2, students in high school, university, and trade schools can be exposed to the field of hydropower and increase the prospects of them selecting hydropower as a career. This will also inspire the next generation of thinkers and innovators to apply their knowledge and ideas to design and develop innovative hydropower technologies. A Hydropower Career Map could be modeled after the existing Wind and Solar Career Maps [10] to show students the variety of jobs available in the field of hydropower. Collaboration among academia and operators, original equipment manufacturers, and federal hydropower owners could facilitate recruiting, internship, and communication efforts for engineering and trade school students.

**ACTION 4.5.3.4: Encourage greater employment readiness.**

To enable the incoming hydropower workforce to be prepared for potential internships or entry-level hydropower positions, rigorous on-site training programs could be collaboratively expanded for greater industry participation in conjunction with universities, community colleges, and vocational schools. Initiatives such as the Hydro Research Foundation's Research Awards Program,[20] a DOE graduate student research program, and the Western Area Power Administration's Electric Power Training Center can stimulate interest in the hydropower field and develop a skilled hydropower workforce.

19. More information about DOE's Wind for Schools program is available at *http://apps2.eere.energy.gov/wind/windexchange/schools_wfs_project.asp*.

20. More information about the Hydro Research Awards Program is available at *http://www.hydrofoundation.org/research-awards-program.html*.

## ACTION 4.5.4: *Leverage Existing Research and Analysis of the Federal Fleet in Investment Decisions.*

### *Rationale for Actions*

DOE estimates that, through hydropower power plants operated under the U.S. Army Corps of Engineers and Reclamation [11], the federal government owns and operates 49% of the installed hydropower capacity in the United States. These facilities contribute significantly to the nation's renewable electric supply. Extensive data about the asset performance and condition can continue to inform federal decisions regarding improvement and modernization of the federal fleet.

**ACTION 4.5.4.1: Compile and disseminate data from existing federal reports and other reports about the condition and performance of the federal fleet.**

The U.S. Army Corps of Engineers, Reclamation, and Power Marketing Administrations already provide extensive publicly available information about the performance of federal hydropower assets and the value of these contributions. These exist in the form of thorough performance goals and data, condition reports, annual financial statements, and plans for infrastructure maintenance and investment. Under this task, data from these various sources would be compiled and presented in a report for use by analysts and decision makers.

**ACTION 4.5.4: Leverage Existing Research and Analysis of the Federal Fleet in Investment Decisions**
Extensive research data about the federal hydropower fleet exist and should be made available in compiled form to be used by policy makers and agency staff in making federal investment decisions.

**Deliverable:** Reports that quantify the condition and performance of the existing hydropower fleet in contributing to the national energy supply and grid stability, including data, validated models, and potential for performance improvement.

**Impact:** Well-informed decision makers able to make investment decisions regarding the existing federal hydropower fleet, including opportunities for performance and the role of the fleet in providing power and grid services in evolving energy markets.

**Key Objectives:** Optimization, Growth, Sustainability

**Growth Sectors Addressed:** Upgrades

**Timeframe:** This action could begin immediately. Resulting report(s) should be updated continuously as the federal fleet evolves and/or new data become available.

| Action | Deliverable | Impact |
|---|---|---|
| **Action 4.5.4.1**<br>Compile and disseminate data from existing federal reports and other reports about the condition and performance of the federal fleet. | Aggregated list of data sources, including agency reports, financial statements, and investment plans. | Greater knowledge of information about the federal fleet and the range of actors involved in the decision-making process. |

## ACTION 4.5.5: *Maintain the Roadmap in Order to Achieve the Objectives of the Hydropower Vision.*

### *Rationale for Actions*

This roadmap is intended to be a living document, regularly modified using an evolving and collaborative process of periodic reviews, informed by analysis activities. Roadmap updates will be used as a means to track progress toward the objectives and principles identified in the *Hydropower Vision.* These reviews will assess effects and suggest redirection of activities as necessary and appropriate through 2050 to optimize adaptation to changes in markets and in policy or regulatory factors. As new types of projects are implemented, knowledge of environmental impacts and mitigation expands, and new industry opportunities and challenges arise, stakeholders of all types should actively engage with DOE to revisit and revise the roadmap. This will allow the roadmap to both reflect changing circumstances and maintain momentum toward a set of mutual benefits for the nation.

**ACTION 4.5.5.1: Regularly update the *Hydropower Vision* Roadmap.**

Accurate tracking and reporting of performance, growth, cost and pricing trends, O&M experience, technology developments, and other data provide a valuable record of progress in hydropower technology and market conditions as well as indication of issues that require attention for national benefit. This record can inform deliberations and analysis of deployment, policies, and R&D priorities, as well as provide ongoing perspective on the status of hydropower deployment in the United States relative to previously proposed roadmap actions. As such, stakeholder effort in assembling a thorough and accurate record of U.S. experience with hydropower—in all of its applications—and updating proposed actions accordingly is valuable.

**ACTION 4.5.5: Maintain the Roadmap in Order to Achieve the Objectives of the *Hydropower Vision***
The *Hydropower Vision* roadmap should be regularly updated by tracking hydropower technology advancement and deployment progress, and prioritizing R&D activities.

**Deliverable:** Periodic publicly available reports that update roadmap actions in response to progress in technology advancement, hydropower deployment, and changes in market conditions.

**Impact:** Ongoing availability of up-to-date information and recommendations to inform DOE and other stakeholders in planning and decision-making efforts.

**Key Objectives:** Optimization , Growth, Sustainability

**Growth Sectors Addressed:** Upgrades, NPD, Conduits, NSD, PSH

**Timeframe:** Maintaining the roadmap will require periodic evaluation of industry progress and roadmap relevance at approximately 3-year intervals, resulting in updates as appropriate.

| Action | Deliverable | Impact |
|---|---|---|
| **Action 4.5.5.1**<br>Regularly update the *Hydropower Vision* roadmap. | Periodic, publicly available reports that update roadmap actions in response to progress in technology advancement, hydropower deployment, and changes in market conditions. | Ongoing availability of up-to-date information and recommendations to inform DOE and other stakeholders in planning and decision making. |

# Chapter 4 References

[1] U.S. Department of Energy. August 2013. Effects of Climate Change on Federal Hydropower. Washington, D.C.: U.S. Department of Energy. Accessed June 3, 2016. *http://energy.gov/eere/water/downloads/effects-climate-change-federal-hydropower-report-congress.*

[2] "WaterSMART Basin Studies Program." Last updated March 16, 2016. U.S. Bureau of Reclamation. Accessed May 31, 2016. *http://www.usbr.gov/watersmart/bsp/*.

[3] "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections." 2014. U.S. Bureau of Reclamation, Climate Analytics Group, Climate Central, Lawrence Livermore National Laboratory, Santa Clara University, Scripps Institution of Oceanography, U.S. Army Corps of Engineers, U.S. Geological Survey, and National Center for Atmospheric Research. *Accessed June 3, 2016. http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html.*

[4] U.S. Bureau of Reclamation. March 2011. Hydropower Program, Hydropower Resource Assessment at Existing Reclamation Facilities eport—March 2011). Accessed June 4, 2016. *http://www.usbr.gov/power/AssessmentReport/index.html.*

[5] U.S. Bureau of Reclamation. March 2012. Site Inventory and Hydropower Energy Assessment of Reclamation Owned Conduits (Final Report—March 2012). Accessed June 4, 2016. *http://www.usbr.gov/power/CanalReport/index.html*.

[6] "WaterSMART." Last updated June 30, 2015. U.S. Bureau of Reclamation. Accessed June 3, 2016. *http://www.usbr.gov/watersmart/water.html*.

[7] "Low Impact Hydropower Certification Handbook, 2nd Edition." 2016. Low Impact Hydropower Institute, Harrington Park, NJ. Accessed June 3, 2016. *http://lowimpacthydro.org/low-impact-criteria/*.

[8] Executive Order 13604 of March 22, 2012, Improving Performance of Federal Permitting and Review of Infrastructure Projects. Federal Register page and date: 77 FR 18887. Accessed June 3, 2016. *https://www.archives.gov/federal-register/executive-orders/2012.html*.

[9] "Basin Scale Opportunity Assessment." 2011. Pacific Northwest National Laboratory. Accessed June 4, 2016. *http://basin.pnnl.gov/Software/Index*.

[10] "Solar Career Map." 2016. Interstate Renewable Energy Council. Accessed June 3, 2016. *http://irecsolarcareermap.org/*.

[11] Uria-Martinez, R.; P. O'Connor; and M. Johnson. 2015. 2014 Hydropower Market Report. DOE/EE 1195. U.S. Department of Energy, Washington, D.C. (US). Accessed May 2, 2016, *http://energy.gov/eere/water/downloads/2014-hydropower-market-report.*

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