5

Hydropower

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Executive Summary

Hydropower offers significant potential for carbon emissions reductions. The installed capacity of hydropower by the end of 2008 contributed 16% of worldwide electricity supply, and hydropower remains the largest source of renewable energy in the electricity sector. On a global basis, the technical potential for hydropower is unlikely to constrain further deployment in the near to medium term. Hydropower is technically mature, is often economically competitive with current market energy prices and is already being deployed at a rapid pace. Situated at the crossroads of two major issues for development, water and energy, hydro reservoirs can often deliver services beyond electricity supply. The significant increase in hydropower capacity over the last 10 years is anticipated in many scenarios to continue in the near term (2020) and medium term (2030), with various environmental and social concerns representing perhaps the largest challenges to continued deployment if not carefully managed.

Hydropower is a renewable energy source where power is derived from the energy of water moving from higher to lower elevations. It is a proven, mature, predictable and typically price-competitive technology. Hydropower has among the best conversion efficiencies of all known energy sources (about 90% efficiency, water to wire). It requires relatively high initial investment, but has a long lifespan with very low operation and maintenance costs. The levelized cost of electricity for hydropower projects spans a wide range but, under good conditions, can be as low as 3 to 5 US cents$_{2005}$ per kWh. A broad range of hydropower systems, classified by project type, system, head or purpose, can be designed to suit particular needs and site-specific conditions. The major hydropower project types are: run-of-river, storage- (reservoir) based, pumped storage and in-stream technologies. There is no worldwide consensus on classification by project size (installed capacity, MW) due to varying development policies in different countries. Classification according to size, while both common and administratively simple, is—to a degree—arbitrary: concepts like 'small' or 'large hydro' are not technically or scientifically rigorous indicators of impacts, economics or characteristics. Hydropower projects cover a continuum in scale and it may ultimately be more useful to evaluate hydropower projects based on their sustainability or economic performance, thus setting out more realistic indicators.

The total worldwide technical potential for hydropower generation is 14,576 TWh/yr (52.47 EJ/yr) with a corresponding installed capacity of 3,721 GW, roughly four times the current installed capacity. Worldwide total installed hydropower capacity in 2009 was 926 GW, producing annual generation of 3,551 TWh/y (12.8 EJ/y), and representing a global average capacity factor of 44%. Of the total technical potential for hydropower, undeveloped capacity ranges from about 47% in Europe and North America to 92% in Africa, which indicates large opportunities for continued hydropower development worldwide, with the largest growth potential in Africa, Asia and Latin America. Additionally, possible renovation, modernization and upgrading of old power stations are often less costly than developing a new power plant, have relatively smaller environment and social impacts, and require less time for implementation. Significant potential also exists to rework existing infrastructure that currently lacks generating units (e.g., existing barrages, weirs, dams, canal fall structures, water supply schemes) by adding new hydropower facilities. Only 25% of the existing 45,000 large dams are used for hydropower, while the other 75% are used exclusively for other purposes (e.g., irrigation, flood control, navigation and urban water supply schemes). Climate change is expected to increase overall average precipitation and runoff, but regional patterns will vary: the impacts on hydropower generation are likely to be small on a global basis, but significant regional changes in river flow volumes and timing may pose challenges for planning.

In the past, hydropower has acted as a catalyst for economic and social development by providing both energy and water management services, and it can continue to do so in the future. Hydro storage capacity can mitigate freshwater scarcity by providing security during lean flows and drought for drinking water supply, irrigation, flood control and navigation services. Multipurpose hydropower projects may have an enabling role beyond the electricity sector as a financing instrument for reservoirs that help to secure freshwater availability. According to the World Bank, large hydropower projects can have important multiplier effects, creating an additional USD$_{2005}$ 0.4 to 1.0 of indirect benefits for every dollar of value generated. Hydropower can serve both in large, centralized and small, isolated grids, and small-scale hydropower is an option for rural electrification.

Environmental and social issues will continue to affect hydropower deployment opportunities. The local social and environmental impacts of hydropower projects vary depending on the project's type, size and local conditions and are often controversial. Some of the more prominent impacts include changes in flow regimes and water quality, barriers to fish migration, loss of biological diversity, and population displacement. Impoundments and reservoirs stand out as the source of the most severe concerns but can also provide multiple beneficial services beyond energy supply. While lifecycle assessments indicate very low carbon emissions, there is currently no consensus on the issue of land use change-related net emissions from reservoirs. Experience gained during past decades in combination with continually advancing sustainability guidelines and criteria, innovative planning based on stakeholder consultations and scientific know-how can support high sustainability performance in future projects. Transboundary water management, including the management of hydropower projects, establishes an arena for international cooperation that may contribute to promoting sustainable economic growth and water security.

Technological innovation and material research can further improve environmental performance and reduce operational costs. Though hydropower technologies are mature, ongoing research into variable-speed generation technology, efficient tunnelling techniques, integrated river basin management, hydrokinetics, silt erosion resistive materials and environmental issues (e.g., fish-friendly turbines) may ensure continuous improvement of future projects.

Hydropower can provide important services to electric power systems. Storage hydropower plants can often be operated flexibly, and therefore are valuable to electric power systems. Specifically, with its rapid response load-following and balancing capabilities, peaking capacity and power quality attributes, hydropower can play an important role in ensuring reliable electricity service. In an integrated system, reservoir and pumped storage hydropower can be used to reduce the frequency of start-ups and shutdowns of thermal plants; to maintain a balance between supply and demand under changing demand or supply patterns and thereby reduce the load-following burden of thermal plants; and to increase the amount of time that thermal units are operated at their maximum thermal efficiency, thereby reducing carbon emissions. In addition, storage and pumped storage hydropower can help reduce the challenges of integrating variable renewable resources such as wind, solar photovoltaics, and wave power.

Hydropower offers significant potential for carbon emissions reductions. Baseline projections of the global supply of hydropower rise from 12.8 EJ in 2009 to 13 EJ in 2020, 15 EJ in 2030 and 18 EJ in 2050 in the median case. Steady growth in the supply of hydropower is therefore projected to occur even in the absence of greenhouse gas (GHG) mitigation policies, though demand growth is anticipated to be even higher, resulting in a shrinking percentage share of hydropower in global electricity supply. Evidence suggests that relatively high levels of deployment over the next 20 years are feasible, and hydropower should remain an attractive renewable energy source within the context of global GHG mitigation scenarios. That hydropower can provide energy and water management services and also help to manage variable renewable energy supply may further support its continued deployment, but environmental and social impacts will need to be carefully managed.

5.1 Introduction

This chapter describes hydropower technology. It starts with a brief historical overview of how the technology has evolved (Section 5.1), a discussion of resource potential and how it may be affected by climate change (Section 5.2), and a description of the technology (Section 5.3) and its social and environmental impacts (Section 5.6). Also included is a summary of the present global and regional status of the hydropower industry (Section 5.4) and the role of hydropower in the broader energy system (Section 5.5), as well as a summary of the prospects for technology improvement (Section 5.7), cost trends (Section 5.8), and potential deployment in both the near term (2020) and long term (2050) (Section 5.9). The chapter also covers the integration of hydropower into broader water management solutions (Section 5.10). In this chapter, the focus is largely on the generation and storage of electrical energy from water; the use of hydropower in meeting mechanical energy demands is covered only peripherally.

5.1.1 Source of energy

Hydropower is generated from water moving in the hydrological cycle, which is driven by solar radiation. Incoming solar radiation is absorbed at the land or sea surface, heating the surface and creating evaporation where water is available. A large percentage—close to 50% of all the solar radiation reaching the Earth's surface—is used to evaporate water and drive the hydrological cycle. The potential energy embedded in this cycle is therefore huge, but only a very limited amount may be technically developed. Evaporated water moves into the atmosphere and increases the water vapour content in the air. Global, regional and local wind systems, generated and maintained by spatial and temporal variations in the solar energy input, move the air and its vapour content over the surface of the Earth, up to thousands of kilometres from the origin of evaporation. Finally, the vapour condenses and falls as precipitation, about 78% on oceans and 22% on land. This creates a net transport of water from the oceans to the land surface of the Earth, and an equally large flow of water back to the oceans as river and groundwater runoff. It is the flow of water in rivers that can be used to generate hydropower, or more precisely, the energy of water moving from higher to lower elevations on its way back to the ocean, driven by the force of gravity.

5.1.2 History of hydropower development

Prior to the widespread availability of commercial electric power, hydropower was used for irrigation and operation of various machines, such as watermills, textile machines and sawmills. By using water for power generation, people have worked with nature to achieve a better lifestyle. The mechanical power of falling water is an old resource used for services and productive uses. It was used by the Greeks to turn water wheels for grinding wheat into flour more than 2,000 years ago. In the 1700s, mechanical hydropower was used extensively for milling and pumping. During the 1700s and 1800s, water turbine development continued. The first hydroelectric power plant was installed in Cragside, Rothbury, England in 1870. Industrial use of hydropower started in 1880 in Grand Rapids, Michigan, when a dynamo driven by a water turbine was used to provide theatre and storefront lighting. In 1881, a brush dynamo connected to a turbine in a flour mill provided street lighting at Niagara Falls, New York. The breakthrough came when the electric generator was coupled to the turbine and thus the world's first hydroelectric station (of 12.5 kW capacity) was commissioned on 30 September 1882 on Fox River at the Vulcan Street Plant, Appleton, Wisconsin, USA, lighting two paper mills and a residence.[1]

Early hydropower plants were much more reliable and efficient than the fossil fuel-fired plants of the day (Baird, 2006). This resulted in a proliferation of small- to medium-sized hydropower stations distributed wherever there was an adequate supply of moving water and a need for electricity. As electricity demand grew, the number and size of fossil fuel, nuclear and hydropower plants increased. In parallel, concerns arose around environmental and social impacts (Thaulow et al., 2010).

Hydropower plants (HPP) today span a very large range of scales, from a few watts to several GW. The largest projects, Itaipu in Brazil with 14,000 MW[2] and Three Gorges in China with 22,400 MW,[3] both produce between 80 to 100 TWh/yr (288 to 360 PJ/yr). Hydropower projects are always site-specific and thus designed according to the river system they inhabit. Historical regional hydropower generation from 1965 to 2009 is shown in Figure 5.1.

The great variety in the size of hydropower plants gives the technology the ability to meet both large centralized urban energy needs as well as decentralized rural needs. Though the primary role of hydropower in the global energy supply today is in providing electricity generation as part of centralized energy networks, hydropower plants also operate in isolation and supply independent systems, often in rural and remote areas of the world. Hydro energy can also be used to meet mechanical energy needs, or to provide space heating and cooling. More recently hydroelectricity has also been investigated for use in the electrolysis process for hydrogen fuel production, provided there is abundance of hydropower in a region and a local goal to use hydrogen as fuel for transport (Andreassen et al., 2002; Yumurtacia and Bilgen, 2004; Silva et al., 2005)

Hydropower plants do not consume the water that drives the turbines. The water, after power generation, is available for various other essential uses. In fact, a significant proportion of hydropower projects are designed for multiple purposes (see Section 5.10.2). In these instances, the dams help to prevent or mitigate floods and droughts, provide the possibility to irrigate agriculture, supply water for domestic, municipal and industrial use, and can improve conditions for navigation, fishing, tourism or leisure

1 United States Bureau of Reclamation: www.usbr.gov/power/edu/history.html.

2 Itaipu Binacional hydroelectric power plant (www.itaipu.gov.br).

3 China Three Gorges Project Corporation Annual Report 2009 (www.ctgpc.com).

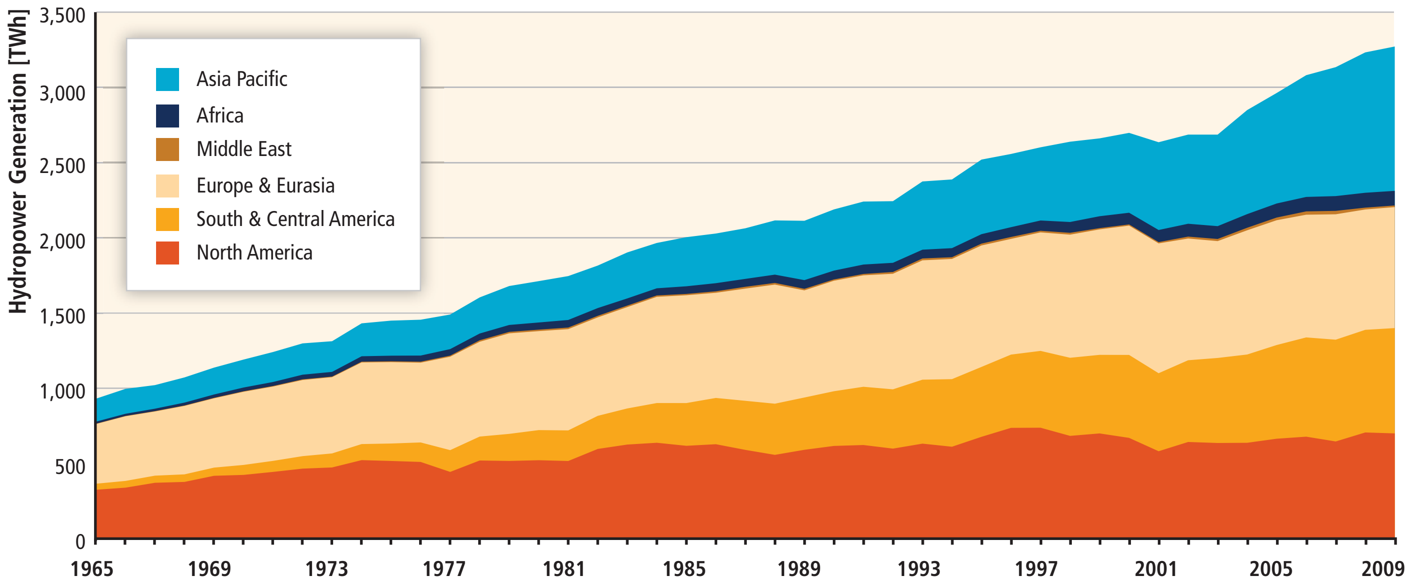


Figure 5.1 | Hydropower generation (TWh) by region (BP, 2010).

activities. One aspect often overlooked when addressing hydropower and the multiple uses of water is that the power plant, as a generator of revenue, in some cases can help pay for the facilities required to develop other water uses that might not generate sufficient direct revenues to finance their construction.

5.2 Resource potential

Hydropower resource potential can be derived from total available flow multiplied by head and a conversion factor. Since most precipitation usually falls in mountainous areas, where elevation differences (head) are the largest, the largest potential for hydropower development is in mountainous regions, or in rivers coming from such regions. The total annual runoff has been estimated as 47,000 km^3, out of which 28,000 km^3 is surface runoff, yielding a theoretical potential for hydropower generation of 41,784 TWh/yr (147 EJ/yr) (Rogner et al., 2004). This value of theoretical potential is similar to a more recent estimate of 39,894 TWh/yr (144 EJ/yr) (IJHD, 2010) (see Chapter 1).

Section 5.2.1 discusses the global technical potential, considering that gross theoretical potential is of no practical value and what is economically feasible is variable depending on energy supply and pricing, which can vary with time and by location.

5.2.1 Global Technical Potential

The International Journal on Hydropower & Dams *2010 World Atlas & Industry Guide* (IJHD, 2010) provides the most comprehensive inventory of current hydropower installed capacity and annual generation, and hydropower resource potential. The Atlas provides three measures of hydropower resource potential, all in terms of annual generation (TW/yr): gross theoretical, technically feasible,[4] and economically feasible. The total worldwide technical potential for hydropower is estimated at 14,576 TWh/yr (52.47 EJ/yr) (IJHD, 2010), over four times the current worldwide annual generation.[5]

This technical potential corresponds to a derived estimate of installed capacity of 3,721 GW.[6] Technical potentials in terms of annual generation and estimated capacity for the six world regions[7] are shown in Figure 5.2. Pie charts included in the figure provide a comparison of current annual generation to technical potential for each region and the percentage of undeveloped potential compared to total technical potential. These charts illustrate that the percentages of undeveloped potential range from 47% in Europe and North America to 92% in Africa, indicating large opportunities for hydropower development worldwide.

There are several notable features of the data in Figure 5.2. North America and Europe, which have been developing their hydropower resources for more than a century, still have sufficient technical potential to double their hydropower generation, belying the perception that the hydropower resources in these highly developed parts of the world are

4 Equivalent to the technical potential definition provided in Annex I (Glossary).

5 Chapter 1 presents current and future technical potential estimates for all RE sources as assessed by Krewitt et al. (2009), based on a review of several studies. There, hydropower technical potential by 2050 is estimated to be 50 EJ/y. However, this chapter will exclusively rely on IJHD (2010) for technical potential estimates.

6 Derived value of potential installed nameplate capacity based on regional generation potentials and average capacity factors shown in Figure 5.3.

7 The Latin America region includes Central and South America, consistent with the IEA world regions. This differs from the regions in IJHD (2010), which includes Central America as part of North America. Data from the reference have been re-aggregated to conform to regions used in this document.

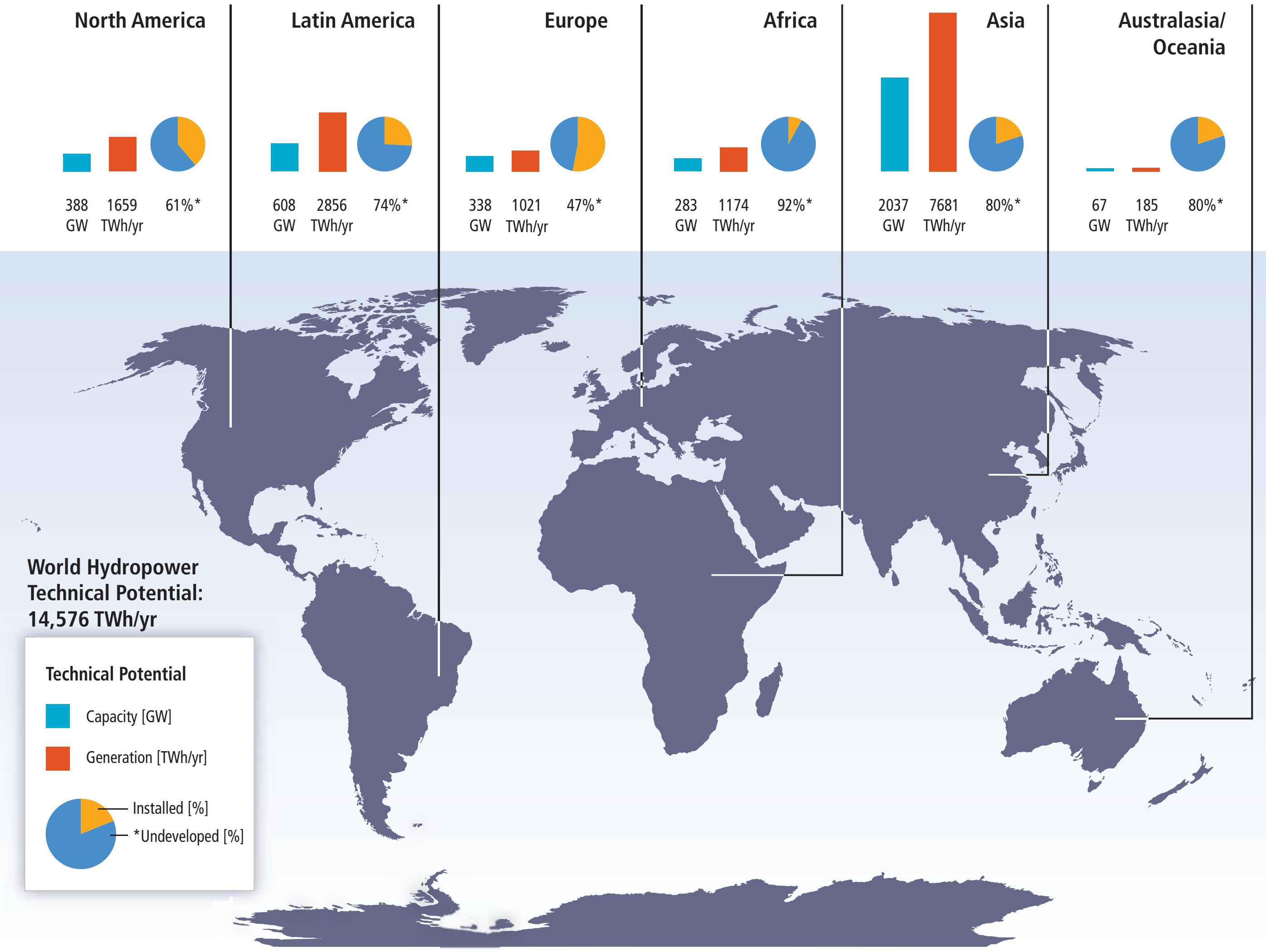


Figure 5.2 | Regional hydropower technical potential in terms of annual generation and installed capacity, and percentage of undeveloped technical potential in 2009. Source: IJHD (2010).

exhausted. However, how much of this untapped technical potential is economically feasible is subject to time-dependent economic conditions. Actual development will also be impacted by sustainability concerns and related policies. Notably, Asia and Latin America have comparatively large technical potentials and, along with Australasia/Oceania, the fraction of total technical potential that is undeveloped is quite high in these regions. Africa has a large technical potential and could develop 11 times its current level of hydroelectric generation in the region. An overview of regional technical potentials for hydropower is given in Table 5.1.

Understanding and appreciation of hydropower technical potential can also be obtained by considering the current (2009) total regional hydropower installed capacity and annual generation shown in Figure 5.3. The reported worldwide total installed hydropower capacity is 926 GW producing a total annual generation of 3,551 TWh/yr (12.8 EJ/yr) in 2009. Figure 5.3 also includes regional average capacity factors calculated using current regional total installed capacity and annual generation (capacity factor = generation/(installed capacity x 8,760 hrs)).

It is interesting to note that North America, Latin America, Europe and Asia have the same order of magnitude of total installed capacity while Africa and Australasia/Oceania have an order of magnitude less—Africa due in part to the lack of available investment capital and Australasia/Oceania in part because of size, climate and topography. The average capacity factors are in the range of 32 to 55%. Capacity factor can be indicative of how hydropower is employed in the energy mix (e.g., peaking versus base-load generation), water availability, or an opportunity for increased generation through equipment upgrades and operation optimization. Generation increases that have been achieved by equipment upgrades and operation optimization have generally not been assessed in detail, but are briefly discussed in Sections 5.3.4 and 5.8.

The regional technical potentials presented above are for conventional hydropower corresponding to sites on natural waterways where there is significant topographic elevation change to create useable hydraulic head. Hydrokinetic technologies that do not require hydraulic head but rather extract energy in-stream from the current of a waterway are being developed. These technologies increase the potential for energy

Table 5.1 | Regional hydropower technical potential in terms of annual generation and installed capacity (GW); and current generation, installed capacity, average capacity factors in percent and resulting undeveloped potential as of 2009. Source: IJHD (2010).

World region	Technical potential, annual generation TWh/yr (EJ/yr)	Technical potential, installed capacity (GW)	2009 Total generation TWh/yr (EJ/yr)	2009 Installed capacity (GW)	Un-developed potential (%)	Average regional capacity factor (%)
North America	1,659 (5.971)	388	628 (2.261)	153	61	47
Latin America	2,856 (10.283)	608	732 (2.635)	156	74	54
Europe	1,021 (3.675)	338	542 (1.951)	179	47	35
Africa	1,174 (4.226)	283	98 (0.351)	23	92	47
Asia	7,681 (27.651)	2,037	1,514 (5.451)	402	80	43
Australasia/Oceania	185 (0.666)	67	37(0.134)	13	80	32
World	**14,576 (52.470)**	**3,721**	**3,551 (12.783)**	**926**	**75**	**44**

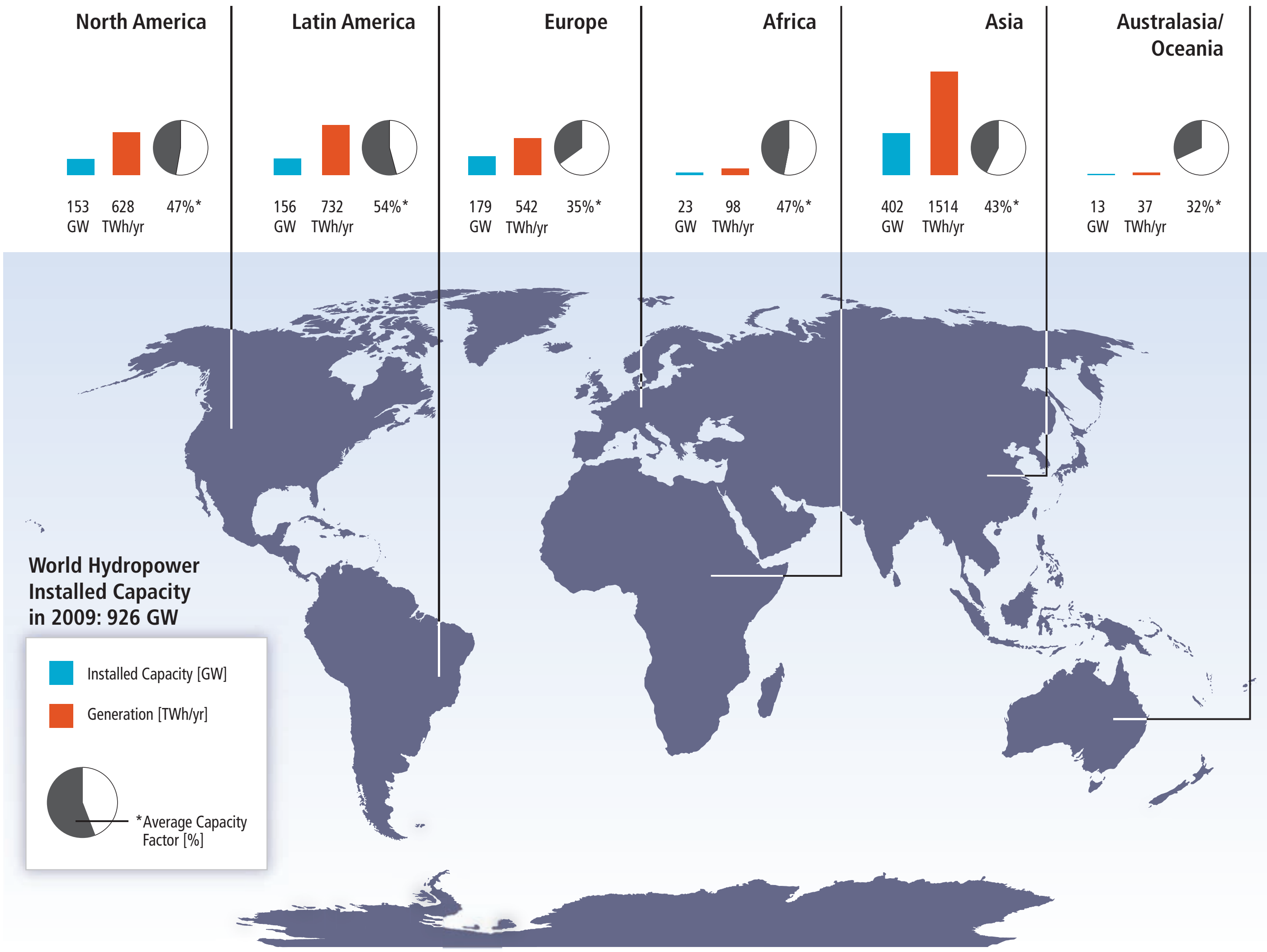


Figure 5.3 | Total regional installed hydropower capacity and annual generation in 2009, and average regional capacity factors (derived as stated above). Source: IJHD (2010).

production at sites where conventional hydropower technology cannot operate. Non-traditional sources of hydropower are also not counted in the regional technical potentials presented above. Examples are constructed waterways such as water supply and treatment systems, aqueducts, canals, effluent streams and spillways. Applicable conventional and hydrokinetic technologies can produce energy using these resources.

While the total technical potentials of in-stream and constructed waterway resources have not been assessed, they may prove to be significant given their large extent.

5.2.2 Possible impact of climate change on resource potential

The resource potential for hydropower is currently based on historical data for the present climatic conditions. With a changing climate, this resource potential could change due to:

- Changes in river flow (runoff) related to changes in local climate, particularly in precipitation and temperature in the catchment area. This may lead to changes in runoff volume, variability of flow and seasonality of the flow (e.g., by changing from spring/summer high flow to more winter flow), directly affecting the resource potential for hydropower generation.
- Changes in extreme events (floods and droughts) may increase the cost and risk for the hydropower projects.
- Changes in sediment loads due to changing hydrology and extreme events. More sediment could increase turbine abrasions and decrease efficiency. Increased sediment load could also fill up reservoirs faster and decrease the live storage, reducing the degree of regulation and decreasing storage services.

The work of IPCC Working Group II (reported in IPCC, 2007b) includes a discussion of the impact of climate change on water resources. Later, a technical paper on water was prepared based on the material included in the previous IPCC reports as well as other sources (Bates et al., 2008). The information presented in this section is mostly based on these two sources, with a few additions from more recent papers and reports, as presented, for example, in a recent review by Hamududu et al. (2010).

5.2.2.1 Projected changes in precipitation and runoff

A wide range of possible future climatic projections have been presented, with corresponding variability in projection of precipitation and runoff (IPCC, 2007c; Bates et al., 2008). Climate projections using multi-model ensembles show increases in globally averaged mean water vapour, evaporation and precipitation over the 21st century. At high latitudes and in part of the tropics, nearly all models project an increase in precipitation, while in some subtropical and lower mid-latitude regions, precipitation is projected to decrease. Between these areas of robust increase or decrease, even the sign of projected precipitation change is inconsistent across the current generation of models (Bates et al., 2008).

Changes in river flow due to climate change will primarily depend on changes in volume and timing of precipitation, evaporation and snowmelt. A large number of studies of the effect on river flow have been published and were summarized in IPCC (2007b). Most of these studies use a catchment hydrological model driven by climate scenarios based on climate model simulations. Before data can be used in the catchment hydrological models, it is necessary to downscale data, a process where output from the global climate model is converted to corresponding climatic data in the catchments. Such downscaling can be both temporal and spatial, and it is currently a high priority research area to find the best methods for downscaling.

A few global-scale studies have used runoff simulated directly by climate models (Egré and Milewski, 2002; IPCC, 2007b). The results of these studies show increasing runoff in high latitudes and the wet tropics and decreasing runoff in mid-latitudes and some parts of the dry tropics. Figure 5.4 illustrates projected changes in runoff by the end of the century, based on the IPCC A1B scenario[8] (Bates et al., 2008).

Uncertainties in projected changes in the hydrological systems arise from internal variability in the climatic system, uncertainty about future greenhouse gas and aerosol emissions, the translations of these emissions into climate change by global climate models, and hydrological model uncertainty. Projections become less consistent between models as the spatial scale decreases. The uncertainty of climate model projections for freshwater assessments is often taken into account by using multi-model ensembles (Bates et al., 2008). The multi-model ensemble approach is, however, not a guarantee of reducing uncertainty in mathematical models.

Global estimates as shown in Figure 5.4 represent results at a large scale, and cannot be applied to shorter temporal and smaller spatial scales. In areas where rainfall and runoff are very low (e.g., desert areas), small changes in runoff can lead to large percentage changes. In some regions, the sign of projected changes in runoff differs from recently observed trends. Moreover, in some areas with projected increases in runoff, different seasonal effects are expected, such as increased wet season runoff and decreased dry season runoff. Studies using results from fewer climate models can be considerably different from the results presented here (Bates et al., 2008).

5.2.2.2 Projected impacts on hydropower generation

Though the average global or continent-wide impacts of climate change on hydropower resource potential might be expected to be relatively small, more significant regional and local effects are possible. Hydropower resource potential depends on topography and the volume, variability and seasonal distribution of runoff. Not only are these regionally and locally determined, but an increase in climate variability,

8 Four scenario families or 'storylines' (A1, A2, B1 and B2) were developed by the IPCC and reported in the IPCC *Special Report On Emission Scenarios* (SRES) as a basis for projection of future climate change, where each represents different demographic, social, economic, technological and environmental development over the 21st century (IPCC, 2000). Therefore, a wide range of possible future climatic projections have been presented based on the resulting emission scenarios, with corresponding variability in projections of precipitation and runoff (IPCC, 2007b).

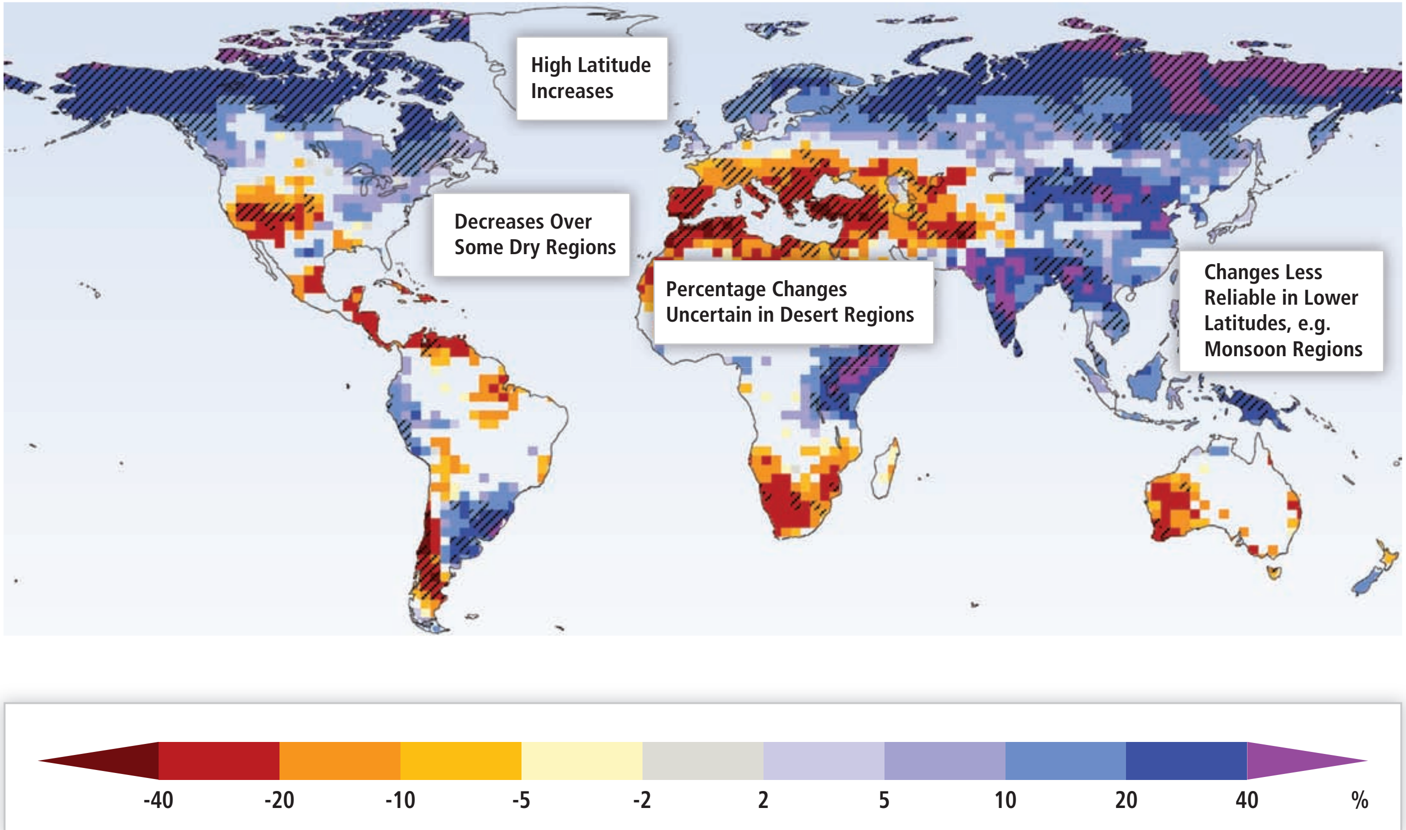


Figure 5.4 | Large-scale changes in annual runoff (water availability, in percent) for the period 2090 to 2099, relative to 1980 to 1999. Values represent the median of 12 climate model projections using the SRES A1B scenario. White areas are where less than 66% of the 12 models agree on the sign of change and hatched areas are where more than 90% of models agree on the sign of change. Source: IPCC (2007a).

even with no change in average runoff, can lead to reduced hydropower production unless more reservoir capacity is built and operations are modified to account for the new hydrology that may result from climate change.

In order to make accurate quantitative predictions of regional effects it is therefore necessary to analyze both changes in average flow and changes in the temporal distribution of flow, using hydrological models to convert time series of climate scenarios into time series of runoff scenarios. In catchments with ice, snow and glaciers it is of particular importance to study the effects of changes in seasonality, because a warming climate will often lead to increasing winter runoff and decreasing runoff in spring and summer. A shift in winter precipitation from snow to rain due to increased air temperature may lead to a temporal shift in peak flow and winter conditions (Stickler and Alfredsen, 2009) in many continental and mountain regions. The spring snowmelt peak would then be brought forward or eliminated entirely, with winter flow increasing. As glaciers retreat due to warming, river flows would be expected to increase in the short term but decline once the glaciers disappear (Bates et al., 2008; Milly et al., 2008).

Summarizing available studies up to 2007, IPCC (2007b) and Bates et al. (2008) found examples of both positive and negative regional effects on hydropower production, mainly following the expected changes in river runoff. Unfortunately, few quantitative estimates of the effects on technical potential for hydropower were found. The regional distribution of studies was also skewed, with most studies done in Europe and North America, and a weak literature base for most developing country regions, in particular for Africa. The summary below is based on findings summarized in Bates et al. (2008) and IPCC (2007b) unless additional sources are given.

In Africa, the electricity supply in a number of states is largely based on hydroelectric power. However, few available studies examine the impacts of climate change on hydropower resource potential in Africa. Observations deducted from general predictions for climate change and runoff point to a reduction in hydropower resource potential with the exception of East Africa (Hamududu et al., 2010).

In major hydropower-generating Asian countries such as China, India, Iran, Tajikistan etc., changes in runoff are found to potentially have a significant effect on the power output. Increased risks of landslides and glacial lake outbursts, and impacts of increased variability, are of particular concern to Himalayan countries (Agrawala et al., 2003). The possibility of accommodating increased intensity of seasonal precipitation by increasing storage capacities may become of particular importance (Iimi, 2007).

In Europe, by the 2070s, hydropower potential for the whole of Europe has been estimated to potentially decline by 6%, translated into a 20 to 50% decrease around the Mediterranean, a 15 to 30% increase in northern and Eastern Europe, and a stable hydropower pattern for western and central Europe (Lehner et al., 2005).

In New Zealand, increased westerly wind speed is very likely to enhance wind generation and spill over precipitation into major South Island watersheds, and to increase winter rain in the Waikato catchment. Warming is virtually certain to increase melting of snow, the ratio of rainfall to snowfall, and to increase river flows in winter and early spring. This is very likely to increase hydroelectric generation during the winter peak demand period, and to reduce demand for storage.

In Latin America, hydropower is the main electrical energy source for most countries, and the region is vulnerable to large-scale and persistent rainfall anomalies due to El Niño and La Niña, as observed in Argentina, Colombia, Brazil, Chile, Peru, Uruguay and Venezuela. A combination of increased energy demand and droughts caused a virtual breakdown of hydroelectricity in most of Brazil in 2001 and contributed to a reduction in gross domestic product (GDP). Glacier retreat is also affecting hydropower generation, as observed in the cities of La Paz and Lima.

In North America, hydropower production is known to be sensitive to total runoff, to its timing, and to reservoir levels. During the 1990s, for example, Great Lakes levels fell as a result of a lengthy drought, and in 1999, hydropower production was down significantly both at Niagara and Sault St. Marie. For a 2°C to 3°C warming in the Columbia River Basin and BC Hydro service areas, the hydroelectric supply under worst-case water conditions for winter peak demand is likely to increase (high confidence). Similarly, Colorado River hydropower yields are likely to decrease significantly, as will Great Lakes hydropower. Northern Québec hydropower production would be likely to benefit from greater precipitation and more open-water conditions, but hydropower plants in southern Québec would be likely to be affected by lower water levels. Consequences of changes in the seasonal distribution of flows and in the timing of ice formation are uncertain.

In a recent study (Hamududu and Killingtveit, 2010), the regional and global changes in hydropower generation for the existing hydropower system were computed, based on a global assessment of changes in river flow by 2050 (Milly et al., 2005, 2008) for the SRES A1B scenario using 12 different climate models. The computation was done at the country or political region (USA, Canada, Brazil, India, China, Australia) level, and summed up to regional and global values (see Table 5.2).

Table 5.2 | Power generation capacity in GW and TWh/yr (2005) and estimated changes (TWh/yr) due to climate change by 2050. Results are based on an analysis using the SRES A1B scenario in 12 different climate models (Milly et al., 2008), UNEP world regions and data for the hydropower system in 2005 (US DOE, 2009) as presented in Hamududu and Killingtveit (2010).

REGION	Power Generation Capacity (2005)		Change by 2050 TWh/yr (PJ/yr)
	GW	TWh/yr (PJ/yr)	
Africa	22	90 (324)	0.0 (0)
Asia	246	996 (3,586)	2.7 (9.7)
Europe	177	517 (1,861)	-0.8 (-2.9)
North America	161	655 (2,358)	0.3 (≈1)
South America	119	661 (2,380)	0.3 (≈1)
Oceania	13	40 (144)	0.0 (0)
TOTAL	737	2931 (10,552)	2.5 (9)

In general the results given in Table 5.2 are consistent with the (mostly qualitative) results given in previous studies (IPCC, 2007b; Bates et al., 2008). For Europe, the computed reduction (-0.2%) has the same sign, but is less than the -6% found by Lehner et al. (2005). One reason could be that Table 5.2 shows changes by 2050 while Lehner et al. (2005) give changes by 2070, so a direct comparison is difficult.

It can be concluded that the overall impacts of climate change on the existing global hydropower generation may be expected to be small, or even slightly positive. However, results also indicated substantial variations in changes in energy production across regions and even within countries (Hamududu and Killingtveit, 2010).

Insofar as a future expansion of the hydropower system will occur incrementally in the same general areas/watersheds as the existing system, these results indicate that climate change impacts globally and averaged across regions may also be small and slightly positive.

Still, uncertainty about future impacts as well as increasing difficulty of future systems operations may pose a challenge that must be addressed in the planning and development of future HPP (Hamududu et al., 2010).

Indirect effects on water availability for energy purposes may occur if water demand for other uses such as irrigation and water supply for households and industry rises due to the climate change. This effect is difficult to quantify, and it is further discussed in Section 5.10.

5.3 Technology and applications

Head and also installed capacity (size) are often presented as criteria for the classification of hydropower plants. The main types of hydropower, however, are run-of-river, reservoir (storage hydro), pumped storage, and in-stream technology. Classification by head and classification by size are discussed in Section 5.3.1. The main types of hydropower are presented in Section 5.3.2. Maturity of the technology, status and current trends in technology development, and trends in renovation and modernization follow in Sections 5.3.3 and 5.3.4 respectively.

5.3.1 Classification by head and size

A classification by head refers to the difference between the upstream and the downstream water levels. Head determines the water pressure on the turbines that together with discharge are the most important parameters for deciding the type of hydraulic turbine to be used. Generally, for high heads, Pelton turbines are used, whereas Francis turbines are used to exploit medium heads. For low heads, Kaplan and Bulb turbines are applied. The classification of what 'high head' and 'low head are varies widely from country to country, and no generally accepted scales are found.

Classification according to size has led to concepts such as 'small hydro' and 'large hydro', based on installed capacity measured in MW as the defining criterion. Small-scale hydropower plants (SHP) are more likely to be run-of-river facilities than are larger hydropower plants, but reservoir (storage) hydropower stations of all sizes will utilize the same basic components and technologies. Compared to large-scale hydropower, however, it typically takes less time and effort to construct and integrate small hydropower schemes into local environments (Egré and Milewski, 2002). For this reason, the deployment of SHPs is increasing in many parts of the world, especially in remote areas where other energy sources are not viable or are not economically attractive.

Nevertheless, there is no worldwide consensus on definitions regarding size categories (Egré and Milewski, 2002). Various countries or groups of countries define 'small hydro' differently. Some examples are given in Table 5.3. From this it can be inferred that what presently is named 'large hydro' spans a very wide range of HPPs. IJHD (2010) lists several more examples of national definitions based on installed capacity.

This broad spectrum in definitions of size categories for hydropower may be motivated in some cases by national licensing rules (e.g., Norway[9]) to determine which authority is responsible for the process or in other cases by the need to define eligibility for specific support schemes (e.g., US Renewable Portfolio Standards). It clearly illustrates that different countries have different legal definitions of size categories that match their local energy and resource management needs.

Regardless, there is no immediate, direct link between installed capacity as a classification criterion and general properties common to all HPPs above or below that MW limit. Hydropower comes in manifold project types and is a highly site-specific technology, where each project is a tailor-made outcome for a particular location within a given river basin to meet specific needs for energy and water management services. While run-of-river facilities may tend to be smaller in size, for example, large numbers of small-scale storage hydropower stations are also in operation worldwide. Similarly, while larger facilities will tend to have lower costs on a USD/kW basis due to economies of scale, that tendency will only hold on average. Moreover, one large-scale hydropower project of 2,000 MW located in a remote area of one river basin might have fewer negative impacts than the cumulative impacts of 400 5-MW hydropower projects in many river basins (Egré and Milewski, 2002). For that reason, even the cumulative relative environmental and social impacts of large versus small hydropower development remain unclear, and context dependent.

All in all, classification according to size, while both common and administratively simple, is—to a degree—arbitrary: general concepts like 'small' or 'large hydro' are not technically or scientifically rigorous indicators of impacts, economics or characteristics (IEA, 2000c). Hydropower projects cover a continuum in scale, and it may be more useful to evaluate a hydropower project on its sustainability or economic performance (see Section 5.6 for a discussion of sustainability), thus setting out more realistic indicators.

Table 5.3 | Small-scale hydropower by installed capacity (MW) as defined by various countries

Country	Small-scale hydro as defined by installed capacity (MW)	Reference Declaration
Brazil	≤30	Brazil Government Law No. 9648, of May 27, 1998
Canada	<50	Natural Resources Canada, 2009: canmetenergy-canmetenergie.nrcan-rncan.gc.ca/eng/renewables/small_hydropower.html
China	≤50	Jinghe (2005); Wang (2010)
EU Linking Directive	≤20	EU Linking directive, Directive 2004/101/EC, article 11a, (6)
India	≤25	Ministry of New and Renewable Energy, 2010: www.mnre.gov.in/
Norway	≤10	Norwegian Ministry of Petroleum and Energy. Facts 2008. Energy and Water Resources in Norway; p.27
Sweden	≤1.5	European Small Hydro Association, 2010: www.esha.be/index.php?id=13
USA	5–100	US National Hydropower Association. 2010 Report of State Renewable Portfolio Standard Programs (US RPS)

9 Norwegian Water Resources and Energy Directorate, Water resource act and regulations, 2001.

5.3.2 Classification by facility type

Hydropower plants are often classified in three main categories according to operation and type of flow. Run-of-river (RoR), storage (reservoir) and pumped storage HPPs all vary from the very small to the very large scale, depending on the hydrology and topography of the watershed. In addition, there is a fourth category called in-stream technology, which is a young and less-developed technology.

5.3.2.1 Run-of-River

A RoR HPP draws the energy for electricity production mainly from the available flow of the river. Such a hydropower plant may include some short-term storage (hourly, daily), allowing for some adaptations to the demand profile, but the generation profile will to varying degrees be dictated by local river flow conditions. As a result, generation depends on precipitation and runoff and may have substantial daily, monthly or seasonal variations. When even short-term storage is not included, RoR HPPs will have generation profiles that are even more variable, especially when situated in small rivers or streams that experience widely varying flows.

In a RoR HPP, a portion of the river water might be diverted to a channel or pipeline (penstock) to convey the water to a hydraulic turbine, which is connected to an electricity generator (see Figure 5.5). RoR projects may form cascades along a river valley, often with a reservoir-type HPP in the upper reaches of the valley that allows both to benefit from the cumulative capacity of the various power stations. Installation of RoR HPPs is relatively inexpensive and such facilities have, in general, lower environmental impacts than similar-sized storage hydropower plants.

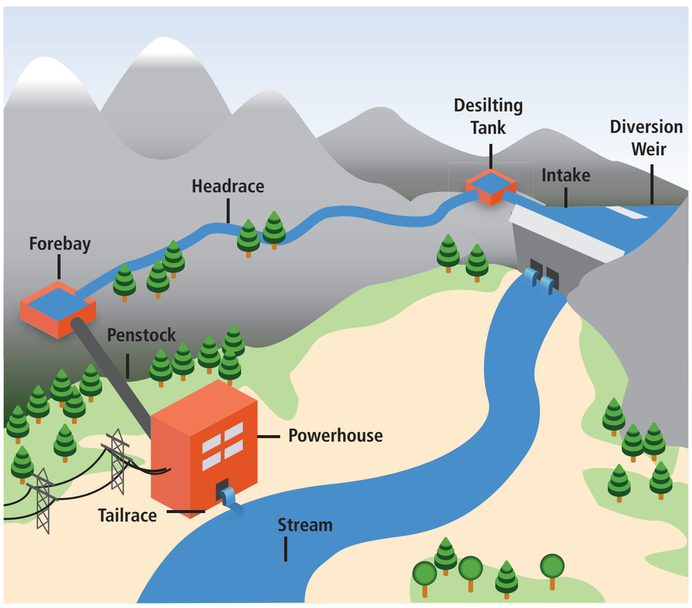


Figure 5.5 | Run-of-river hydropower plant.

5.3.2.2 Storage Hydropower

Hydropower projects with a reservoir are also called storage hydropower since they store water for later consumption. The reservoir reduces the dependence on the variability of inflow. The generating stations are located at the dam toe or further downstream, connected to the reservoir through tunnels or pipelines. (Figure 5.6). The type and design of reservoirs are decided by the landscape and in many parts of the world are inundated river valleys where the reservoir is an artificial lake. In geographies with mountain plateaus, high-altitude lakes make up another kind of reservoir that often will retain many of the properties of the original lake. In these types of settings, the generating station is often connected to the lake serving as reservoir via tunnels coming up beneath the lake (lake tapping). For example, in Scandinavia, natural high-altitude lakes are the basis for high pressure systems where the heads may reach over 1,000 m. One power plant may have tunnels coming from several reservoirs and may also, where opportunities exist, be connected to neighbouring watersheds or rivers. The design of the HPP and type of reservoir that can be built is very much dependent on opportunities offered by the topography.

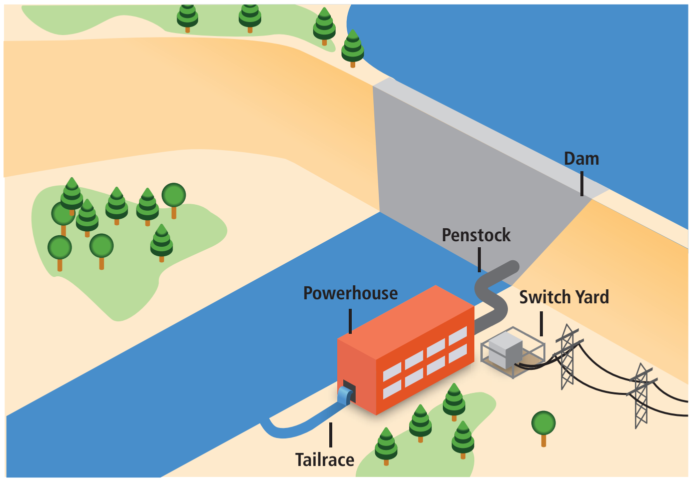


Figure 5.6 | Typical hydropower plant with reservoir.

5.3.2.3 Pumped storage

Pumped storage plants are not energy sources, but are instead storage devices. In such a system, water is pumped from a lower reservoir into an upper reservoir (Figure 5.7), usually during off-peak hours, while flow is reversed to generate electricity during the daily peak load period or at

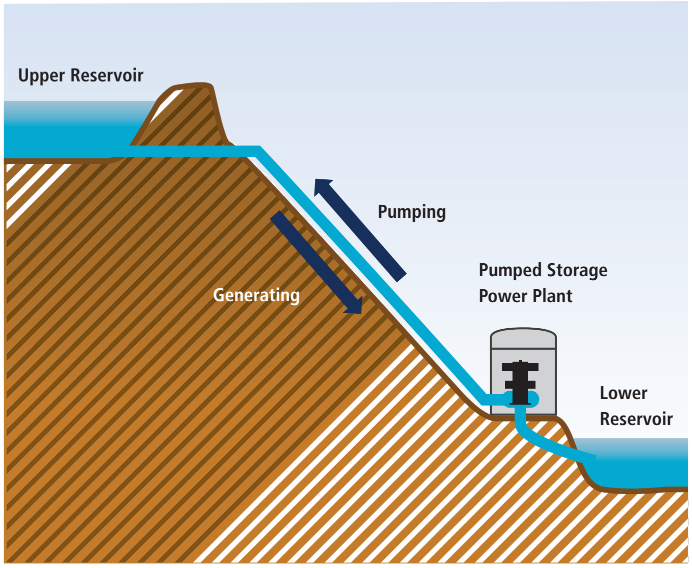


Figure 5.7 | Typical pumped storage project.

other times of need. Although the losses of the pumping process make such a plant a net energy consumer overall, the plant is able to provide large-scale energy storage system benefits. In fact, pumped storage is the largest-capacity form of grid energy storage now readily available worldwide (see Section 5.5.5).

5.3.2.4 In-stream technology using existing facilities

To optimize existing facilities like weirs, barrages, canals or falls, small turbines or hydrokinetic turbines can be installed for electricity generation. These basically function like a run-of-river scheme, as shown in Figure 5.8. Hydrokinetic devices being developed to capture energy from tides and currents may also be deployed inland in both free-flowing rivers and in engineered waterways (see Section 5.7.4).

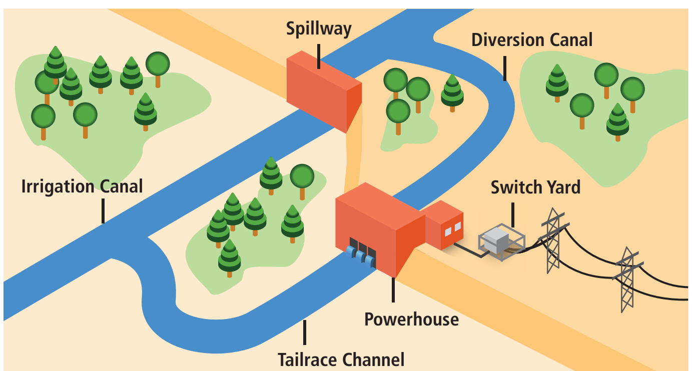


Figure 5.8 | Typical in-stream hydropower plant using existing facilities.

5.3.3 Status and current trends in technology development

Hydropower is a proven and well-advanced technology based on more than a century of experience—with many examples of hydropower plants built in the 19th century still in operation today. Hydropower today is an extremely flexible power technology with among the best conversion efficiencies of all energy sources (~90%, water to wire) due to its direct transformation of hydraulic energy to electricity (IEA, 2004). Still, there is room for further improvements, for example, by improving operation, reducing environmental impacts, adapting to new social and environmental requirements and by developing more robust and cost-effective technological solutions. The status and current trends are presented below, and options and prospects for future technology innovations are discussed in Section 5.7.

5.3.3.1 Efficiency

The potential for energy production in a hydropower plant is determined by the following parameters, which are dependent on the hydrology, topography and design of the power plant:

- The amount of water available;
- Water loss due to flood spill, bypass requirements or leakage;
- The difference in head between upstream intake and downstream outlet;
- Hydraulic losses in water transport due to friction and velocity change; and
- The efficiency in energy conversion of electromechanical equipment.

The total amount of water available at the intake will usually not be possible to utilize in the turbines because some of the water will be lost or will not be withdrawn. This loss occurs because of water spill during high flows when inflow exceeds the turbine capacity, because of bypass releases for environmental flows, and because of leakage.

In the hydropower plant the potential (gravitational) energy in water is transformed into kinetic energy and then mechanical energy in the turbine and further to electrical energy in the generator. The energy transformation process in modern hydropower plants is highly efficient, usually with well over 90% mechanical efficiency in turbines and over 99% in the generator. The inefficiency is due to hydraulic loss in the water circuit (intake, turbine and tailrace), mechanical loss in the turbo-generator group and electrical loss in the generator. Old turbines can have lower efficiency, and efficiency can also be reduced due to wear and abrasion caused by sediments in the water. The rest of the potential energy is lost as heat in the water and in the generator.

In addition, some energy losses occur in the headrace section where water flows from the intake to the turbines, and in the tailrace section taking water from the turbine back to the river downstream. These losses, called head loss, reduce the head and hence the energy potential for the power plant. These losses can be classified either as friction losses or singular losses. Friction losses depend mainly on water velocity and the roughness in tunnels, pipelines and penstocks.

The total efficiency of a hydropower plant is determined by the sum of these three loss components. Hydraulic losses can be reduced by increasing the turbine capacity or by increasing the reservoir capacity to get better regulation of the flow. Head losses can be reduced by increasing the area of headrace and tailrace, by decreasing the roughness in these and by avoiding too many changes in flow velocity and direction. The efficiency of electromechanical equipment, especially turbines, can be improved by better design and also by selecting a turbine type with an efficiency profile that is best adapted to the duration curve of the inflow. Different turbine types have quite different efficiency profiles when the turbine discharge deviates from the optimal value (see Figure 5.9). Improvements in turbine design by computational fluid dynamics software and other innovations are discussed in Section 5.7.

5.3.3.2 Tunnelling capacity

In hydropower projects, tunnels in hard and soft rock are often used for transporting water from the intake to the turbines (headrace), and from the turbine back to the river, lake or fjord downstream (tailrace). In addition, tunnels are used for a number of other purposes when the power station is placed underground, for example for access, power cables, surge shafts

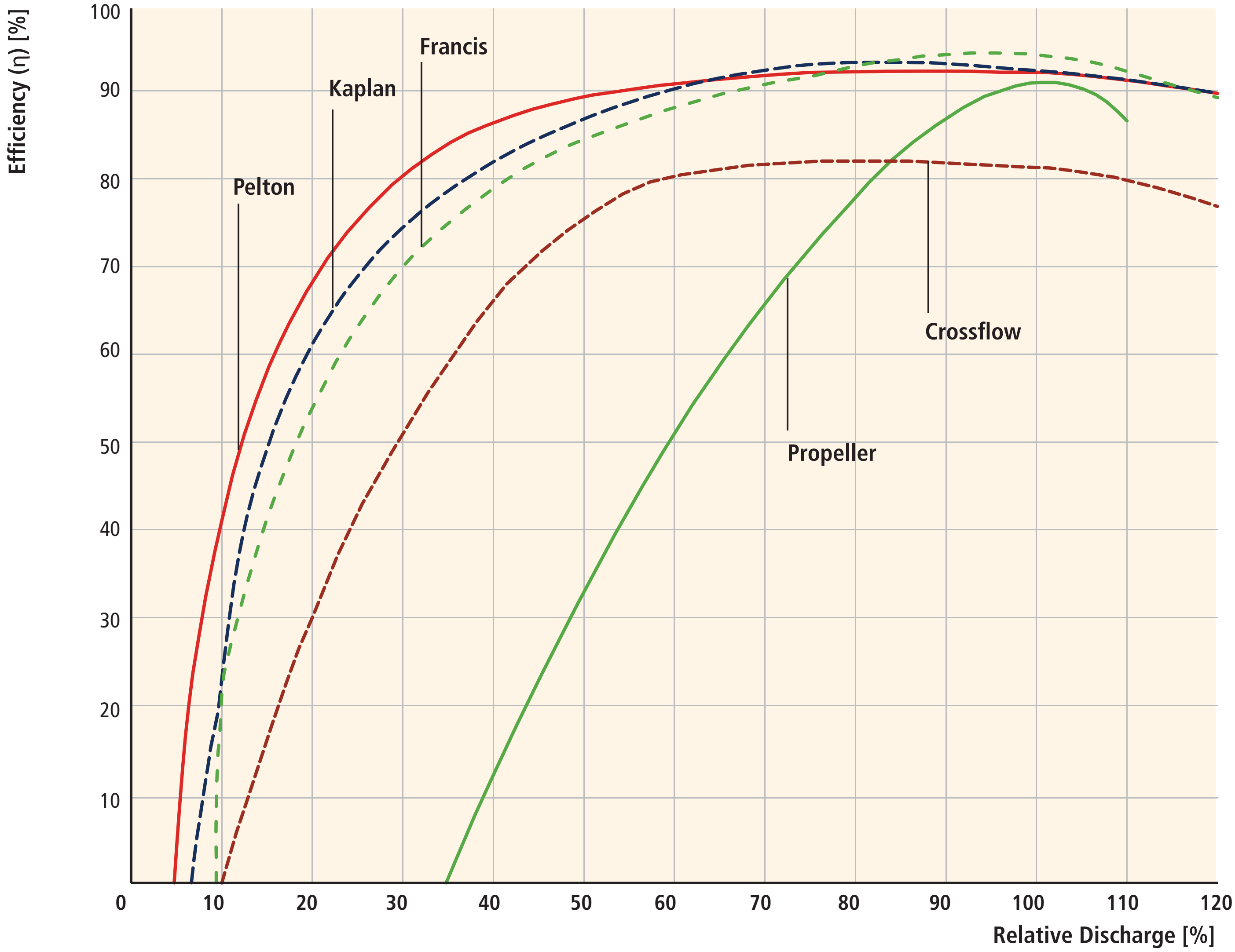


Figure 5.9 | Typical efficiency curves for different types of hydropower turbines (Vinogg and Elstad, 2003).

and ventilation. Tunnels are increasingly favoured for hydropower construction as a replacement for surface structures like canals and penstocks.

Tunnelling technology has improved greatly due to the introduction of increasingly efficient equipment, as illustrated by Figure 5.10 (Zare and Bruland, 2007). Today, the two most important technologies for hydropower tunnelling are the drill and blast method and the use of tunnel-boring machines (TBM).

The drill and blast method is the conventional method for tunnel excavation in hard rock. Thanks to the development in tunnelling technology, excavation costs have been reduced by 25%, or 0.8%/yr, over the past 30 years (see Figure 5.10).

TBMs excavate the entire cross section in one operation without the use of explosives. TBMs carry out several successive operations: drilling, support of the ground traversed and construction of the tunnel. The diameter of tunnels constructed can be from <1 m ('micro tunnelling') up to 15 m. The excavation progress of the tunnel is typically from 30 up to 60 m/day.

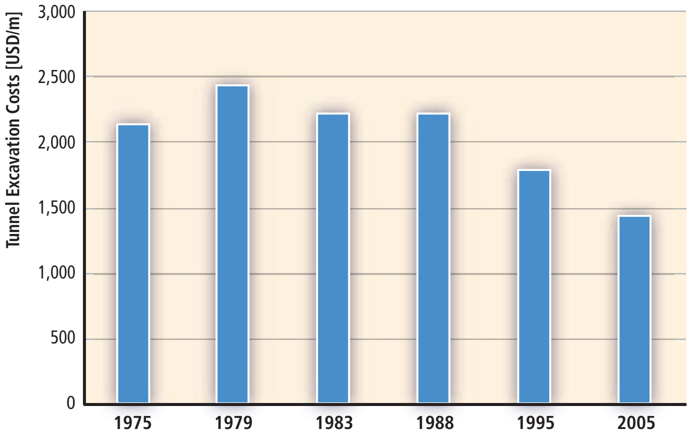


Figure 5.10 | Developments in tunnelling technology: the trend in excavation costs for a 60 m^2 tunnel, in USD_{2005} per metre (adapted from Zare and Bruland, 2007).

5.3.3.3 Technical challenges related to sedimentation management

Although sedimentation problems are not found in all rivers (see Section 5.6.1.4), operating a hydropower project in a river with a large sediment load comes with serious technical challenges.

Specifically, increased sediment load in the river water induces wear on hydraulic machinery and other structures of the hydropower plant. Deposition of sediments can obstruct intakes, block the flow of water through the system and also impact the turbines. The sediment-induced wear of the hydraulic machinery is more serious when there is no room for storage of sediments.

In addition, for HPPs with reservoirs, their storage capacity can be filled up by sediments, which requires special technical mitigation measures or plant design.

Lysne et al. (2003) reported that the effects of sediment-induced wear of turbines in power plants can be, among others:

- Generation loss due to reduction in turbine efficiency;
- Increase in frequency of repair and maintenance;
- Increase in generation losses due to downtime;
- Reduction in lifetime of the turbine; and
- Reduction in regularity of power generation.

All of these effects are associated with revenue losses and increased maintenance costs. Several promising concepts for sediment control at intakes and mechanical removal of sediment from reservoirs and for settling basins have been developed and practised. A number of authors (Mahmood, 1987; Morris and Fan, 1997; ICOLD, 1999; Palmieri et al., 2003; White, 2005) have reported measures to mitigate the sedimentation problems by better management of land use practices in upstream watersheds to reduce erosion and sediment loading, mechanical removal of sediment from reservoirs and design of hydraulic machineries aiming to resist the effect of sediment passing through them.

5.3.4 Renovation, modernization and upgrading

Renovation, modernization and upgrading (RM&U) of old power stations is often less costly than developing a new power plant, often has relatively smaller environment and social impacts, and requires less time for implementation. Capacity additions through RM&U of old power stations can therefore be attractive. Selective replacement or repair of identified hydro powerhouse components like turbine runners, generator windings, excitation systems, governors, control panels or trash cleaning devices can reduce costs and save time. It can also lead to increased efficiency, peak power and energy availability of the plant (Prabhakar and Pathariya, 2007). RM&U may allow for restoring or improving environmental conditions in already-regulated areas. Several national programmes for RM&U are available. For example, the Research Council of Norway recently initiated a program with the aim to increase power production in existing hydropower plants and at the same time improve environmental conditions.[10] The US Department of Energy has been using a similar approach to new technology development since 1994 when it started the Advanced Hydropower Turbine Systems Program that emphasized simultaneous improvements in energy and environmental performance (Odeh, 1999; Cada, 2001; Sale et al., 2006a).

Normally the life of hydroelectric power plants is 40 to 80 years. Electromechanical equipment may need to be upgraded or replaced after 30 to 40 years, however, while civil structures like dams, tunnels

10 Centre for Environmental Design of Renewable Energy: www.cedren.no/.

etc. usually function longer before they requires renovation. The lifespan of properly maintained hydropower plants can exceed 100 years. Using modern control and regulatory equipment leads to increased reliability (Prabhakar and Pathariya, 2007). Upgrading hydropower plants calls for a systematic approach, as a number of hydraulic, mechanical, electrical and economic factors play a vital role in deciding the course of action. For techno-economic reasons, it can also be desirable to consider up-rating (i.e., increasing the size of the hydropower plant) along with RM&U/life extension. Hydropower generating equipment with improved performance can also be retrofitted, often to accommodate market demands for more flexible, peaking modes of operation. Most of the existing worldwide hydropower equipment in operation will need to be modernized to some degree by 2030 (SER, 2007). Refurbished or up-rated hydropower plants also result in incremental increases in hydropower generation due to more efficient turbines and generators.

In addition, existing infrastructure without hydropower plants (like existing barrages, weirs, dams, canal fall structures, water supply schemes) can also be reworked by adding new hydropower facilities. The majority of the world's 45,000 large dams were not built for hydropower purposes, but for irrigation, flood control, navigation and urban water supply schemes (WCD, 2000). Retrofitting these with turbines may represent a substantial potential, because only about 25% of large reservoirs are currently used for hydropower production. For example, from 1997 to 2008 in India, about 500 MW have been developed on existing facilities. A recent study in the USA indicated some 20 GW could be installed by adding hydropower capacity to 2,500 dams that currently have none (UNWWAP, 2006).

5.4 Global and regional status of market and industry development

5.4.1 Existing generation

In 2008, the generation of electricity from hydroelectric plants was 3,288 TWh (11.8 EJ)[11] compared to 1,295 TWh (4.7 EJ) in 1973 (IEA, 2010a), which represented an increase of roughly 25% in this period, and was mainly a result of increased production in China and Latin America, which reached 585 TWh (2.1 EJ) and 674 TWh (2.5 EJ), respectively (Figures 5.11 and 5.12).

Hydropower provides some level of power generation in 159 countries. Five countries make up more than half of the world's hydropower production: China, Canada, Brazil, the USA and Russia. The

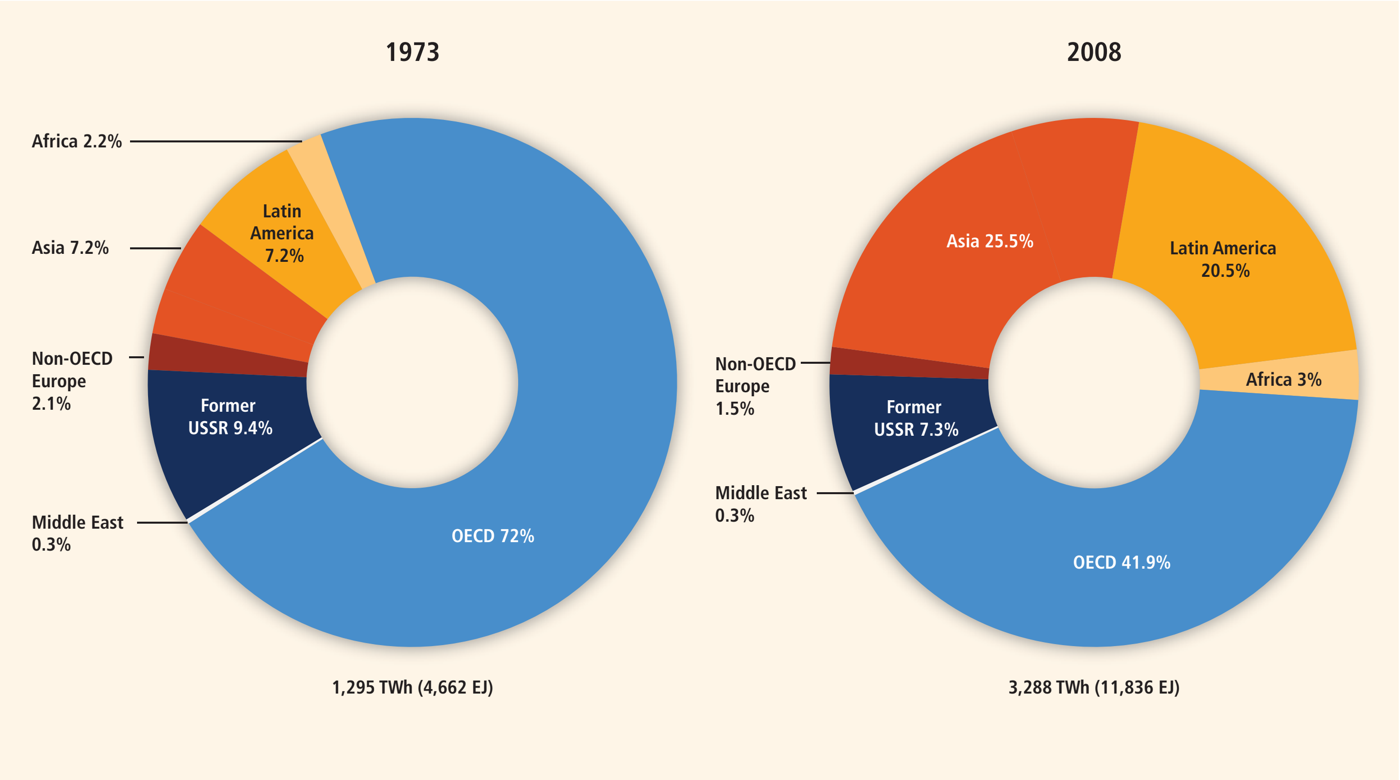


Figure 5.11 | 1973 and 2008 regional shares of hydropower production (IEA, 2010a).

11 These figures differ slightly from those presented in Chapter 1.

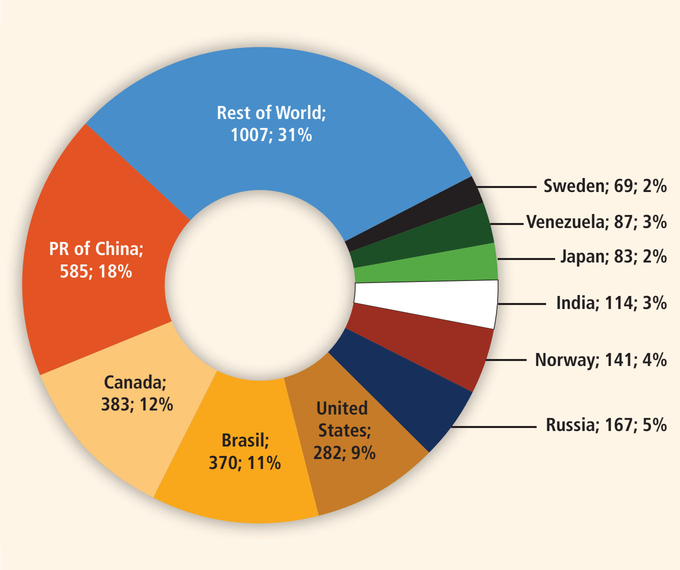


Figure 5.12 | Hydropower generation in 2008 by country, indicating total generation (TWh) and respective global share (IEA, 2010a).

importance of hydroelectricity in the electricity mix of these countries is, however, different (Table 5.4). On the one hand, Brazil and Canada are heavily dependent on this source, with a percentage share of total domestic electricity generation of 83.9% and 59%, respectively, whereas in Russia the share is 19.0% and in China 15.5%.

China, Canada, Brazil and the USA together account for over 46% of the production (TWh/EJ) of hydroelectricity in the world and are also the four largest in terms of installed capacity (GW) (IEA, 2010a). Figure 5.12 shows hydropower generation by country. It is noteworthy that 5 out of the 10 major producers of hydroelectricity are among the world's most industrialized countries: Canada, the USA, Norway, Japan and Sweden. This is no coincidence, given that the possibility of drawing on the hydroelectric resource was important for the introduction and consolidation of the main electro-intensive sectors on which the industrialization process in these countries was based during a considerable part of the 20th century.

Despite the significant growth in hydroelectric production, the percentage share of hydroelectricity on a global basis has dropped during the last three decades (1973 to 2008), from 21 to 16%. This is because electricity demand and the deployment of other energy technologies have increased more rapidly than hydropower generating capacity.

5.4.2 The hydropower industry

In developed markets such as the Europe, the USA, Canada, Norway and Japan, where many hydropower plants were built 30 to 60 years ago, the hydropower industry is focused on re-licensing and renovation as well as on adding new hydropower generation to existing dams. In emerging markets such as China, Brazil, Ethiopia, India, Malaysia, Iran, Laos, Turkey, Venezuela, Ecuador and Vietnam, utilities and private developers are pursuing large-scale new hydropower construction (116 GW of capacity is under construction; IJHD, 2010). Canada is still on the list of the top five hydropower markets for new installations worldwide. Orders for hydropower equipment were lower in 2009 and 2010 compared to the peaks in 2007 and 2008, though the general high level after 2006, when the hydropower market almost doubled, is anticipated to continue for the near future. With increasing policy support of governments for new hydropower (see Sections 5.4.3 and 5.10.3) construction, hydropower industrial activity is expected to be higher in the coming years compared to the average since 2000 (IJHD, 2010). As hydropower and its industry are mature, it is expected that the industry will be able to meet the demand that materializes (see Section 5.9). In 2008, the hydropower industry installed more than 40 GW of new capacity worldwide (IJHD, 2010), with 31 GW added in 2009 (REN21, 2010; see Chapter 1).

Table 5.4 | Major hydroelectricity producer countries with total installed capacity and percentage of hydropower generation in the electricity mix. Source: IJHD (2010).

Country	Installed Capacity (GW)	Country Based on Top 10 Producers	Percent of Hydropower in Total Domestic Electricity Generation (%)
China	200	Norway	99
Brazil	84	Brazil	83.9
USA	78.2	Venezuela	73.4
Canada	74.4	Canada	59.0
Russia	49.5	Sweden	48.8
India	38	Russia	19.0
Norway	29.6	India	17.5
Japan	27.5	China	15.5
France	21	Italy	14.0
Italy	20	France	8.0
Rest of the world	301.6	Rest of the world[1]	14.3
World	**926.1**	**World**	**15.9**

Note: 1. Excluding countries with no hydropower production.

5.4.3 Impact of policies[12]

Hydropower infrastructure development is closely linked to national, regional and global development policies. Beyond its role in contributing to a secure energy supplysecurity and reducing a country's dependence on fossil fuels, hydropower offers opportunities for poverty alleviation and sustainable development. Hydropower also can contribute to regional cooperation, as good practice in managing water resources requires a river basin approach regardless of national borders (see also Section 5.10). In addition, multipurpose hydropower can strengthen a country's ability to adapt to climate change-induced hydrological variability (World Bank, 2009).

The main challenges for hydropower development are linked to a number of associated risks such as poor identification and management of environmental and social impacts, insufficient hydrological data, unexpected adverse geological conditions, lack of comprehensive river basin planning, shortage of financing, scarcity of local skilled human resources and lack of regional collaboration. These challenges can be and are being addressed to varying degrees at the policy level by a number of governments, international financing institutions, professional associations and nongovernmental organizations (NGOs). Examples of policy initiatives dealing with the various challenges can be found in Sections 5.6.2 and 5.10.

Challenges posed by various barriers can be addressed and met by public policies, bearing in mind the need for an appropriate environment for investment, a stable regulatory framework and incentives for research and technological development (Freitas and Soito, 2009; see Chapter 11). A variety of policies have been enacted in individual countries to support certain forms and types of hydropower, as highlighted generally in Chapter 11. More broadly, in addition to country-specific policies, several larger policy issues have been identified as particularly important for the development of hydropower, including carbon markets, financing, administration and licensing procedures, and size-based classification schemes.

5.4.3.1 International carbon markets

As with other carbon reduction technologies, carbon credits can benefit hydropower projects by bringing additional funding and thus helping to reduce project risk and thereby secure financing. Though the Clean Development Mechanism (CDM) is not unique to hydropower, hydropower projects are one of the largest contributors to the CDM and Joint Implementation (JI) mechanisms and therefore to existing carbon credit markets. In part, this is due to the fact that new hydropower development is targeted towards developing countries that are in need of investment capital, and international carbon markets offer one possible route to that capital. Out of the 2,062 projects registered by the CDM Executive Board (EB) by 1 March 2010, 562 were hydropower projects. When considering the predicted volumes of Certified Emission Reductions to be delivered, registered hydropower projects are expected to avoid more than 50 Mt of carbon dioxide (CO_2) emissions per year by 2012. China, India, Brazil and Mexico represent roughly 75% of the hosted projects.

5.4.3.2 Project financing

Hydropower projects can often deliver electricity at comparatively low costs relative to existing market energy prices (see Section 5.8). Nonetheless, many otherwise economically feasible hydropower projects are financially challenging because high upfront costs are often a deterrent to investment. Related to this, hydropower projects tend to have lengthy lead times for planning, permitting and construction, increasing development risk and delaying revenue generation. A key challenge, then, is to create sufficient private sector confidence in hydropower investment, especially prior to project permitting. Deployment policies of the types described in Chapter 11 are being used in some countries to encourage investment. Also, in developing regions such as Africa, interconnection between countries and the formation of larger energy markets is helping to build investor confidence by reducing the risk of a monopsony buyer. Feasibility and impact assessments carried out by the public sector, prior to developer tendering, can also help ensure greater private sector interest in hydropower development (WEC, 2007; Taylor, 2008). Nonetheless, the development of appropriate financing models that consider the uncertainty imposed by long planning and regulatory processes, and finding the optimum roles for the public and private sectors, remain key challenges for hydropower development.

5.4.3.3 Administrative and licensing process

Hydropower is often regarded as a public resource (Sternberg, 2008), emphasized by the operating life of a reservoir that may be more than 100 years. Legal frameworks vary from country to country, however, including practices in the award and structuring of concessions, for instance, regarding concession periods, royalties, water rights etc. Environmental licensing procedures also vary greatly. With growing involvement of the private sector in what was previously managed by public sector, contractual arrangements surrounding hydropower have become increasingly complex. There are now more parties involved and much greater commercial accountability, with a strong awareness of environmental and social indicators and licensing processes. Clearly, the policies and procedures established by governments in granting licenses and concessions will impact hydropower development outcomes.

12 Non-technology-specific policy issues are covered in Chapter 11 of this report.

5.4.3.4 Classification by size

Finally, many governments and international bodies have relied upon various distinctions between 'small' and 'large' hydro, as defined by installed capacity (MW), in establishing the eligibility of hydropower plants for certain programs. While it is well known that large-scale HPPs can create conflicts and concerns (WCD, 2000), the environmental and social impacts of a HPP cannot be deduced by size in itself, even if increasing the physical size may increase the overall impacts of a specific HPP (Egré and Milewski, 2002; Sternberg, 2008). Despite their lack of robustness (see Section 5.3.1), these classifications have had significant policy and financing consequences (Egré and Milewski, 2002).

In the UK Renewables Obligation,[13] eligible hydropower plants must be below 20 MW in size. Likewise, in several countries, feed-in tariffs are targeted only towards smaller projects. For example, in France, only projects with an installed capacity not exceeding 12 MW are eligible,[14] and in Germany, a 5 MW maximum capacity has been established.[15] In India, projects below 5 and 25 MW in capacity obtain promotional support that is unavailable to projects of larger sizes. Similar approaches exist in many developed and developing countries around the world, for example, in Indonesia.[16] Because project size is neither a perfect indicator of environmental and social impact nor of the financial need of a project for addition policy support, these categorizations may, at times, impede the development of socially beneficial projects.

Similar concerns have been raised with respect to international and regional climate policy. Though hydropower is recognized as a contributor to reducing GHG emissions and is included in the Kyoto Protocol's flexible mechanisms, those mechanisms differentiate HPPs depending on size and type. The United Nations Framework Convention on Climate Change (UNFCCC) CDM EB, for example, has established that storage hydropower projects are to follow the power density indicator (PDI), W/m^2 (installed capacity/reservoir area), to be eligible for CDM credits. The PDI indicates tentative GHG emissions from reservoirs. The CDM Executive Board stated (February 2006) that "Hydroelectric power plants with power densities greater than 4 W/m^2 but less than or equal to 10 W/m^2 can use the currently approved methodologies, with an emission factor of 90 g CO_2eq/kWh for projects with reservoir emissions", while "less than or equal to 4 W/m^2 cannot use current methodologies". There is little link, however, between installed capacity, the area of a reservoir and the various biogeochemical processes active in a reservoir. Hypothetically, two identical storage HPPs would, according to the PDI, have the same emissions independent of climate zones or of inundated biomass and carbon fluxes (see Section 5.6.3). As such, the PDI rule may inadvertently impede the development of socially beneficial hydropower projects, while at the same time supporting less beneficial projects. The European Emission Trading Scheme and related trading markets similarly treat small- and large-scale hydropower stations differently.[17]

13 The Renewables Obligation Order 2006, No. 1004 (ROO 2006): www.statutelaw.gov.uk.

14 Décret n°2000-1196, Decree on capacity limits for different categories of systems for the generation of electricity from renewable sources that are eligible for the feed-in tariff: www.legifrance.gouv.fr.

15 EEG, 2009 - Act on Granting Priority to Renewable Energy and Mineral Sources: bundesrecht.juris.de/eeg_2009/.

16 Regulation of the Minister of Energy and Mineral Resources, No.31, 2009.

5.5 Integration into broader energy systems

Hydropower's large capacity range, flexibility, storage capability when coupled with a reservoir, and ability to operate in a stand-alone mode or in grids of all sizes enables hydropower to deliver a broad range of services. Hydropower's various roles in and services to the energy system are discussed below (see also Chapter 8).

5.5.1 Grid-independent applications

Hydropower can be delivered through national and regional interconnected electric grids, through local mini-grids and isolated grids, and can also serve individual customers through captive plants. Water mills in England, Nepal, India and elsewhere, which are used for grinding cereals, for lifting water and for powering machinery, are early testimonies of hydropower being used as captive power in mechanical and electrical form. The tea and coffee plantation industries as well as small islands and developing states have used and still make use of hydropower to meet energy needs in isolated areas.

Captive power plants (CPPs) are defined here as plants set up by any person or group of persons to generate electricity primarily for the person or the group's members (Indian Electricity Act, 2003). CPPs are often found in decentralized isolated systems and are generally built by private interests for their own electricity needs. In deregulated electricity markets that allow open access to the grid, hydropower plants are also sometimes installed for captive purposes by energy-intensive industries such as aluminium smelters, pulp and paper mills, mines and cement factories in order to weather short-term market uncertainties and volatility (Shukla et al., 2004). For governments of emerging economies such as India facing shortages of electricity, CPPs are also a means to cope with unreliable power supply systems and higher industrial tariffs by encouraging decentralized generation and private participation (Shukla et al., 2004).

5.5.2 Rural electrification

According to the International Energy Agency (IEA, 2010c), 1.4 billion people have no access to electricity (see Section 9.3.2). Related to the discussion in Section 5.5.1, small-scale hydropower (SHP) can sometimes be an economically viable supply source in these circumstances, as SHP can provide a decentralized electricity supply in those rural areas

17 Directive 2004/101/E, C article 11a(6), www.eur-lex.europa.eu.

that have adequate hydropower technical potential (Egré and Milewski, 2002). In fact, SHPs already play an important role in the economic development of some remote rural areas. Small-scale hydropower-based rural electrification in China has been one of the most successful examples, where over 45,000 small hydropower plants totalling 55 GW have been built that are producing 160 TWh (0.58 EJ) annually. Though many of these plants are used in centralized electricity networks, SHPs constitute one-third of China's total hydropower capacity and are providing services to over 300 million people (Liu and Hu, 2010). More generally, SHP is found in isolated grids as well as in off-grid and central-grid settings. As 75% of costs are site-specific, proper site selection is a key challenge. Additionally, in isolated grid systems, natural seasonal flow variations might require that hydropower plants be combined with other generation sources in order to ensure continuous supply during dry periods (World Bank, 2008) and may have excess production during wet seasons; such factors need to be considered in the planning process (Sundqvist and Wårlind, 2006).

In general, SHPs

- Are often but certainly not always RoR schemes;
- Can use existing infrastructure such as dams or irrigation channels;
- Are located close to villages to avoid expensive high-voltage distribution equipment;
- Can use pumps as turbines and motors as generators for a turbine/generator set; and
- Have a high level of local content both in terms of materials and work force during the construction period and local materials for the civil works.

A recent example from western Canada[18] shows that SHP might also be a solution for remote communities in developed countries by replacing fossil-fired diesel generation with hydropower generation.

All in all, the development of SHP for rural areas involves environmental, social, technical and economic considerations. Local management, ownership and community participation, technology transfer and capacity building are basic issues for sustainable SHP plants in such circumstances.

5.5.3 Power system services provided by hydropower

Hydroelectric generation differs from thermal generation in that the quantity of 'fuel' (i.e., water) that is available at any given time is determined by river flows leading to the hydroelectric plant. Run-of-river HPPs lack a reservoir to store large quantities of water, though large RoR HPPs may have some limited ability to regulate river flow. Storage hydropower, on the other hand, can largely decouple the timing of hydropower generation and variable river flows. For large storage reservoirs, the storage may be sufficient to buffer seasonal or multi-seasonal changes in river flows, whereas for smaller reservoirs the storage may buffer river flows on a daily or weekly basis.

With a very large reservoir relative to the size of the hydropower plant (or very consistent river flows), HPPs can generate power at a near-constant level throughout the year (i.e., operate as a base-load plant). Alternatively, in the case that the hydropower capacity far exceeds the amount of reservoir storage, the hydropower plant is sometimes referred to as energy-limited. An energy-limited hydropower plant would exhaust its 'fuel supply' by consistently operating at its rated capacity throughout the year. In this case, the use of reservoir storage allows hydropower generation to occur at times that are most valuable from the perspective of the power system rather than at times dictated solely by river flows. Since electrical demand varies during the day and night, during the week and seasonally, storage hydropower generation can be timed to coincide with times where the power system needs are the greatest. In part, these times will occur during periods of peak electrical demand. Operating hydropower plants in a way that generates power during times of high demand is referred to as peaking operation (in contrast to base-load). Even with storage, however, hydropower generation will still be limited by the size of the storage, the rated electrical capacity of the hydropower plant, and downstream flow constraints for irrigation, recreation or environmental uses of the river flows. Hydropower peaking may, if the outlet is directed to a river, lead to rapid fluctuations in river flow, water-covered area, depth and velocity. In turn this may, depending on local conditions, lead to negative impacts in the river (see Section 5.6.1.5) unless properly managed.

Hydropower generation that consistently occurs during periods with high system demand can offset the need for thermal generation to meet that same demand. The ratio of the amount of demand that can be reliably met by adding hydropower to the nameplate capacity of the hydropower plant is called the capacity credit. Even RoR hydropower that consistently has river flows during periods of high demand can earn a high capacity credit, while adding reservoir storage can increase the capacity credit to levels comparable to thermal power plants (see Section 8.2.1.2).

In addition to providing energy and capacity to meet electrical demand, hydropower generation often has several characteristics that enable it to provide other services to reliably operate power systems. Because hydropower plants utilize gravity instead of combustion to generate electricity, hydropower plants are often less susceptible to the sudden loss of generation than is thermal generation. Hydropower plants also offer operating flexibility in that they can start generating electricity with very short notice and low start-up costs, provide rapid changes in generation, and have a wide range of generation levels over which power can be generated efficiently (i.e., high part-load efficiency) (Haldane and Blackstone, 1955; Altinbilek et al., 2007). The ability to rapidly change

18 Natural Resources Canada. 2009. Isolated-grid case study: the Hluey Lake project in British Columbia: www.retscreen.net/ang/case_studies_2900kw_isolated_grid_internal_load_canada.php.

output in response to system needs without suffering large decreases in efficiency makes hydropower plants well suited to providing the balancing services called regulation and load-following. RoR HPPs operated in cascades in unison with storage hydropower in upstream reaches may similarly contribute to the overall regulating and balancing ability of a fleet of HPPs. With the right equipment and operating procedures, hydropower can also provide the ability to restore a power station to operation without relying on the electric power transmission network (i.e., black start capability) (Knight, 2001).

Overall, with its important load-following and balancing capabilities, peaking capacity and power quality attributes, hydropower can play a significant role in ensuring reliable electricity service (US Department of the Interior, 2005).

5.5.4 Hydropower support of other generation including renewable energy

Electricity systems worldwide rely upon widely varying amounts of hydropower today. In this range of hydropower capabilities, electric system operators have developed economic dispatch methodologies that take into account the unique role of hydropower, including coordinating the operation of hydropower plants with other types of generating units. In particular, many thermal power plants (coal, gas or liquid fuel, or nuclear energy) require considerable lead times (often four hours for gas turbines and over eight hours for steam turbines) before they attain an optimum thermal efficiency at which point fuel consumption and emissions per unit output are minimum. In an integrated system, the considerable flexibility provided by storage HPPs can be used to reduce the frequency of start ups and shut downs of thermal plants; to maintain a balance between supply and demand under changing demand or supply patterns and thereby reduce the load-following burden on thermal plants; and to increase the amount of time that thermal units are operated at their maximum thermal efficiency. In some regions, for instance, hydroelectric power plants are used to follow varying peak load demands while nuclear or fossil fuel power plants are operated as base-load units.

Pumped hydropower storage can further increase the support of other resources. In cases with pumped hydropower storage, pumps can use the output from thermal plants during times that they would otherwise operate less efficiently at part load or be shut down (i.e., low load periods). The pumped storage plant then keeps water in reserve for generating power during peak period demands. Pumped storage has much the same ability as storage HPPs to provide balancing and regulation services.

Pumped storage hydropower is usually not a source for energy, however. The hydraulic, mechanical and electrical efficiencies of pumped storage determine the overall cycle efficiency, ranging from 65 to 80% (Egré and Milewski, 2002). If the upstream pumping reservoir is also used as a traditional reservoir the inflow from the watershed may balance out the energy loss caused by pumping. If not, net losses lead to pumped hydropower being a net energy consumer. A traditional storage HPP may also be retrofitted with pump technologies to combine the properties of storage and pump storage HPPs (SRU, 2010). The use and benefit of pumped storage hydropower in the power system will depend on the overall mix of existing generating plants and the architecture of the transmission system. Pumped storage represents about 2.2% of all generation capacity in the USA, 10.2 % in Japan and 18.7 % in Austria (Deane et al., 2010). Various technologies for storing electricity in the grid are compared by Vennemann et al. (2010) in Figure 5.13 for selected large storage sites in different parts of the world.

In addition to hydropower supporting fossil and nuclear generation technologies, hydropower can also help reduce the challenges of integrating variable renewable resources. In Denmark, for example, the high level of variable wind (>20% of the annual energy demand) is managed in part through strong interconnections (1 GW) to Norway, where there is substantial storage hydropower (Nordel, 2008). More interconnectors to Europe may further support increasing the share of wind power in Denmark and Germany (SRU, 2010; see also Section 11.6.5). From a technical viewpoint, Norway alone has a long-term potential to establish pumped storage facilities in the 10 to 25 GW range, enabling energy storage over periods from hours to several weeks in existing reservoirs, and more or less doubling the present installed capacity of 29 GW (IEA-ENARD, 2010).

Increasing variable generation will also increase the amount of balancing services, including regulation and load following, required by the power system (e.g., Holttinen et al., 2009). In regions with new and existing hydropower facilities, providing these services with hydropower may avoid the need to rely on increased part-load and cycling of thermal plants to provide these services. Similarly, in systems with high shares of variable renewable resources that provide substantial amounts of energy but limited capacity, the potential for a high capacity credit of hydropower can be used to meet peak demand rather than requiring peaking thermal plants.

5.5.5 Reliability and interconnection needs for hydropower

Though hydropower has the potential to offer significant power system services in addition to energy and capacity, interconnecting and reliably utilizing hydropower plants may also require changes to power systems. The interconnection of hydropower to the power system requires adequate transmission capacity from hydropower plants to demand centres. Adding new hydropower plants has in the past required network investments to extend the transmission network (see Section 8.2.1.3). Without adequate transmission capacity, hydropower plant operation can be constrained such that the services offered by the hydropower plant are less than what it could offer in an unconstrained system.

Aside from network expansion, changes in the river flow between a dry year and a wet year can be a significant concern for ensuring

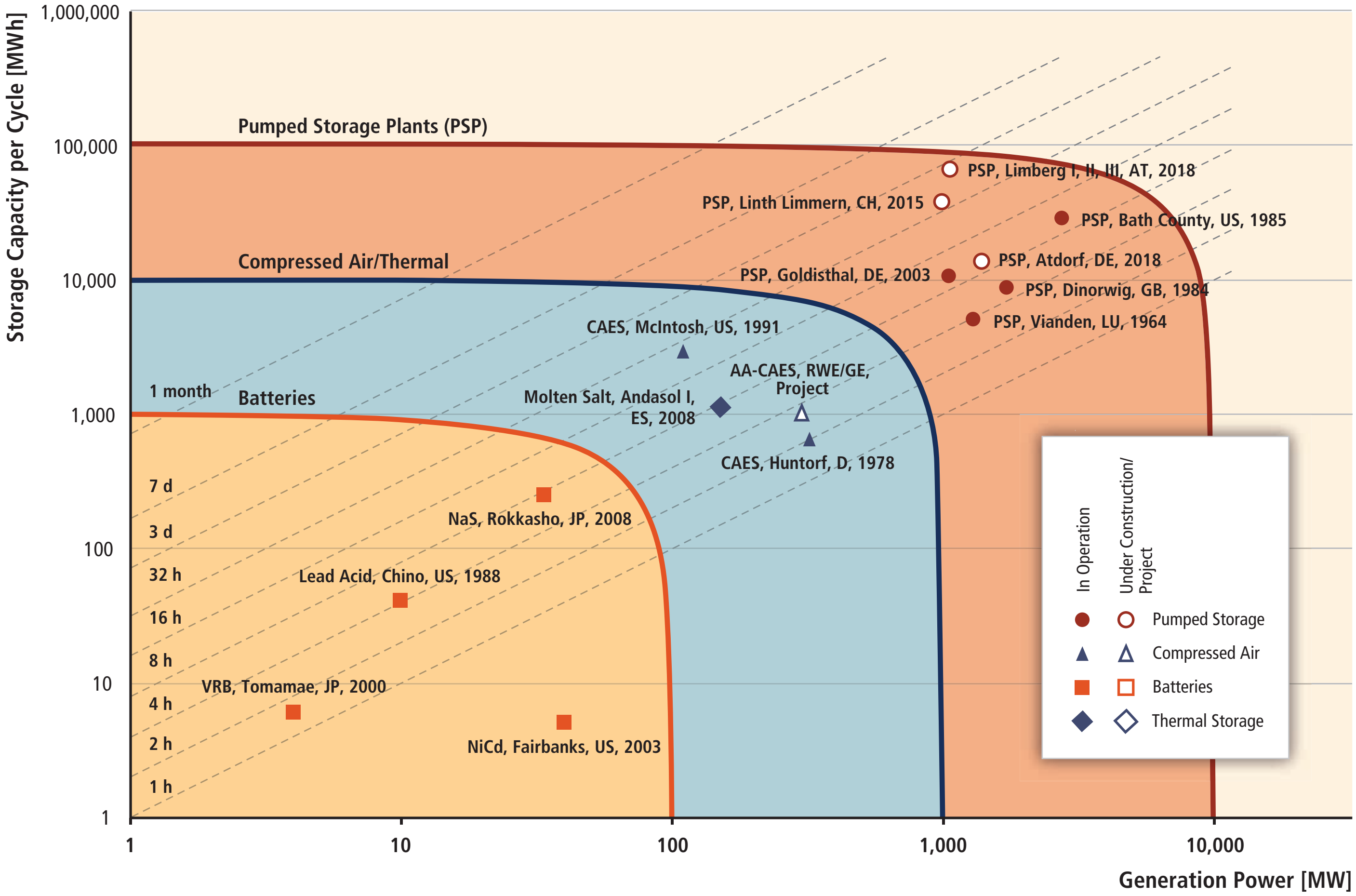


Figure 5.13 | Storage and installed capacity of selected large electricity storage sites (Vennemann et al., 2010).

Note: PSP = Pumped storage plants; CAES = compressed air energy storage, AA-CAES = advanced adiabatic compressed air energy storage; Batteries: NaS = sodium-sulphur, NiCd = nickel cadmium, VRB = vanadium redox battery.

that adequate total annual energy demand can be met. Strong interconnections between diverse hydropower resources or between hydro-dominated and thermal-dominated power systems have been used in existing systems to ensure adequate energy generation (see Section 8.2.1.3). In the future, interconnection to other renewable resources could also ensure adequate energy. Wind and direct solar power, for instance, can be used to reduce demands on hydropower, either by allowing dams to save their water for later release in peak periods or letting storage or pumped storage HPPs consume excess energy produced in off-peak hours.

5.6 Environmental and social impacts[19]

Like all energy and water management options, hydropower projects have negative and positive environmental and social impacts. On the environmental side, hydropower may have a significant environmental footprint at local and regional levels but offers advantages at the macro-ecological level. With respect to social impacts, hydropower projects may entail the relocation of communities living within or nearby the reservoir or the construction sites, compensation for downstream communities, public health issues etc. A properly designed hydropower project may, however, be a driving force for socioeconomic development (see Box 5.1), though a critical question remains about how these benefits are shared.

Because each hydropower plant is uniquely designed to fit the site-specific characteristics of a given geographical site and the surrounding society and environment, the magnitude of environmental and social impacts as well as the extent of their positive and negative effects is highly site dependent. Though the size of a HPP is not, alone, a relevant criterion to predict environmental performance, many impacts are related to the impoundment and existence of a reservoir, and therefore do not apply to all HPP types (see Table 5.5). Section 5.6.1 summarizes

19 A comprehensive assessment of social and environmental impacts of all RE sources covered in this report can be found in Chapter 9.

Box 5.1 | Possible multiplier effects of hydropower projects.

Dam projects generate numerous impacts both on the region where they are located, as well as at an inter-regional, national and even global level (socioeconomic, health, institutional, environmental, ecological and cultural impacts). The World Commission on Dams (WCD) and numerous other studies have discussed the importance and difficulties of evaluating a number of these impacts. One of the issues raised by these studies is the need to extend consideration to indirect benefits and costs of dam projects (Bhatia et al., 2003). According to the WCD's Final Report (WCD, 2000) "a simple accounting for the direct benefits provided by large dams—the provision of irrigation water, electricity, municipal and industrial water supply, and flood control—often fails to capture the full set of social benefits associated with these services. It also misses a set of ancillary benefits and indirect economic (or multiplier) benefits of dam projects". Indirect impacts are called multiplier impacts, and result from both inter-industry linkage impacts (increase in the demand for an increase in outputs of other sectors) and consumption-induced impacts (increase in incomes and wages generated by the direct outputs). Multipliers are summary measures expressed as a ratio of the total effects (direct and indirect) of a project to its direct effects. A multi-country study on multiplier effects of large hydropower projects was performed by the World Bank (2005), which estimates that the multiplier values for large scale hydropower projects vary from 1.4 to 2.0, meaning that for every dollar of value generated by the sectors directly involved in dam-related activities, another 40 to 100 cents could be generated indirectly in the region. Though these multiplier benefits are not unique to hydropower projects, but accompany—to varying degrees—any energy project, they nonetheless represent benefits that might be considered by communities considering hydropower development.

Table 5.5 | Types of hydropower projects, their main services and distinctive environmental and social characteristics (adapted from IEA, 2000d; Egré and Milewski, 2002). The number of subsections within section 5.6.1 that address specific impacts are given in parentheses.

HPP Type	Energy and water management services	Main environmental and social characteristics (corresponding subsection)
All	Renewable electricity generation Increased water management options	Barrier for fish migration and navigation (1,6), and sediment transport (4) Physical modification of riverbed and shorelines (1)
Run-of-river	Limited flexibility and increased variability in electricity generation output profile Water quality (but no water quantity) management	Unchanged river flow when powerhouse in dam toe; when localized further downstream reduced flow between intake and powerhouse (1)
Reservoir (Storage)	Storage capacity for energy and water Flexible electricity generation output Water quantity and quality management; groundwater stabilization; water supply and flood management, see also Section 5.10	Alteration of natural and human environment by impoundment (2), resulting in impacts on ecosystems and biodiversity (1, 5, 6) and communities (7–11) Modification of volume and seasonal patterns of river flow (1), changes in water temperature and quality (3), land use change-related GHG emissions (see Section 5.6.2)
Multipurpose	As for reservoir HPPs; Dependent on water consumption of other uses	As for reservoir HPP; Possible water use conflicts; Driver for regional development (see Box 5.1)
Pumped storage	Storage capacity for energy and water; net consumer of electricity due to pumping No water management options	Impacts confined to a small area; often operated outside the river basin as a separate system that only exchanges the water from a nearby river from time to time

the main environmental and social impacts that can arise from development of the various types of hydropower projects, as well as a number of practicable mitigation measures that can be implemented to minimize negative effects and maximize positive outcomes. More information about existing guidance for sustainable hydropower development is provided in Section 5.6.2. Hydropower creates no direct atmospheric pollutants or waste during operation, and GHG emissions associated with most lifecycle stages are minor. However, methane (CH_4) emissions from reservoirs might be substantial under certain conditions. Thus, there is a need to properly assess the net change in GHG emissions induced by the creation of such reservoirs. The lifecycle GHG emissions of hydropower are discussed in Section 5.6.3, including the scientific status of the carbon balances of reservoirs and other lifecycle aspects.

5.6.1 Typical impacts and possible mitigation measures

Although the type and magnitude of impacts will vary from project to project, it is possible to describe some typical effects, along with the experience that has been gained throughout the past decades in managing and solving problems. Though some impacts are unavoidable, they can be minimized or compensated for, as experience in successful mitigation demonstrates. Information has been systematically gathered on effective assessment and management of impacts related to various types of hydropower (IEA, 2000a; UNEP, 2007). By far the most effective measure is impact avoidance, by weeding out less sustainable alternatives early in the design stage.

All hydroelectric structures affect a river's ecology mainly by inducing a change in its hydrologic characteristics and by disrupting the ecological continuity of sediment transport and fish migration through the building of dams, dikes and weirs. However the extent to which a river's physical, chemical and biological characteristics are modified depends largely on the type of HPP. Whereas run-of-river HPPs do not alter a river's flow regime, the creation of a reservoir for storage hydropower entails a major environmental change by transforming a fast-running fluvial ecosystem into a still-standing lacustrine one. The extent to which a hydropower project has adverse impacts on the riverbed morphology, on water quality and on fauna and flora is highly site-specific and to a certain degree dependent on what resources can be invested into mitigation measures. A more detailed summary of ecological impacts and their possible management measures are discussed in Sections 5.6.1.1 though 5.6.1.6.

Similar to a HPPs environmental effects, the extent of its social impacts on the local and regional communities, land use, the economy, health and safety or heritage varies according to project type and site-specific conditions. While run-of-river projects generally introduce little social change, the creation of a reservoir in a densely populated area can entail significant challenges related to resettlement and impacts on the livelihoods of the downstream populations. Restoration and improvement of living standards of affected communities is a long-term and challenging task that has been managed with variable success in the past (WCD, 2000). Whether HPPs can contribute to fostering socioeconomic development depends largely on how the generated services and revenues are shared and distributed among different stakeholders. As documented by Scudder (2005), HPPs can also have positive impacts on the living conditions of local communities and the regional economy, not only by generating electricity but also by facilitating, through the creation of freshwater storage schemes, multiple other water-dependent activities, such as irrigation, navigation, tourism, fisheries or sufficient water supply to municipalities and industries while protecting against floods and droughts. Yet, inevitably questions arise about the sharing of these revenues among the local affected communities, government, investors and the operator. Key challenges in this domain are the fair treatment of affected communities and especially vulnerable groups like indigenous people, resettlement if necessary, and public health issues, as well as appropriate management of cultural heritage values that will be discussed in more detail in Sections 5.6.1.7 through 5.6.1.11.

All in all, for the sake of sustainability it is important to assess the negative and positive impacts of a hydropower project in the light of a region's needs for energy and water management services. An overview of the main energy and water management services and distinctive environmental characteristics in relation to the different HP project types are presented in the Table 5.5.

According to the results of decade-long IEA research focusing on hydropower and the environment, 11 sensitive issues have been identified that need to be carefully assessed and managed to achieve sustainable hydropower projects. These peer-reviewed reports were produced under the IEA Implementing Agreement on Hydropower Technologies between 1996 and 2006 in collaboration with private agencies, governmental institutions, universities, research institutions and international organizations with relevance to the subject. They are based on more than 200 case studies, involving more than 112 experts from 16 countries, and are considered to be the most comprehensive international information source presently available with regard to managing social and environmental issues related to hydropower. Unless a different reference is mentioned, Sections 5.6.1.1 to 5.6.1.11 are based on the outcomes of these five IEA reports (IEA, 2000a,b,c,d,e).

5.6.1.1 Hydrological regimes

A hydropower project may modify a river's flow regime if the project includes a reservoir. Run-of-river projects change the river's flow pattern marginally, thus creating fewer impacts downstream from the project.

Hydropower plants with reservoirs significantly modify the downstream flow regime (i.e., the magnitude and timing of discharge and hence water levels), and may also alter water temperature over short stretches downstream. Some RoR hydropower projects with river diversions may alter flows along the diversion routes. Physical and biological changes are related to such variations in water level, timing and temperature. Major changes in the flow regime may also cause changes in the river's estuary, where the extent of salt water intrusion depends on the freshwater discharge.

The slope, current velocity and water depth are also important factors influencing sediment-carrying capacity and erosion (Section 5.6.1.4). The construction of a major dam decreases in general the sediment loading to river deltas.

The change in the annual flow pattern may affect significantly natural aquatic and terrestrial habitats in the river and along the shore. The disappearance of heavy natural floods as the result of regulating watercourses alters the natural lifecycle of the floodplains located downstream from the structure. This may affect vegetation species and community structure, which in turn affect the mammalian and avian fauna. On the other hand, frequent (daily or weekly) fluctuations in the water level downstream from a hydropower reservoir and a tailrace area might create problems for both mammals and birds. Sudden water releases could not only drown animals and wash away waterfowl nests, but also represent a public security issue for other water users. The magnitude of these changes can be mitigated by proper power plant operation and discharge management, regulating ponds, information and warning systems as well as access limitations. A thorough flow-management program can prevent loss of habitats and resources. Further possible mitigation measures might be the release of controlled floods in critical periods and building of weirs in order to maintain water levels in rivers with reduced flow or to prevent salt intrusion from the estuary.

5.6.1.2 Reservoir creation

Creating a reservoir entails not only the transformation of a terrestrial ecosystem into an aquatic one, it also makes important modifications to river flow regimes by transforming a relatively fast-flowing water course into a still-standing water body: an artificial lake. For this reason, the most suitable site for a reservoir needs to be thoroughly studied, as the most effective impact avoidance action is to limit the extent of flooding on the basis of technical, economic, social and environmental considerations.

Fluctuations in water levels often lead to erosion of the reservoir shoreline (draw-down zone) and along the downstream riverbanks. Measures to promote vegetation or erosion control following reservoir impoundment include bank restoration, riparian vegetation enhancement, installation of protective structures (e.g., gravel embankments, riprap, gabions) as well as bioengineering for shore protection and enhancement.

The creation of a reservoir causes profound changes in fish habitats. Generally, the transformation of a river into a lake favours species that are adapted to still-standing waters to the detriment of those species requiring faster flowing water (see Section 5.6.1.5).Due to the high phytoplankton productivity of reservoirs, the fish biomass tends to increase overall. However, the impacts of reservoirs on fish species may only be perceived as positive if species are of commercial value or appreciated for sport and subsistence fishing. If water quality proves to be inadequate, measures to enhance the quality of other water bodies for valued species should be considered in cooperation with affected communities. Other options to foster the development of fish communities and fisheries in and beyond the reservoir zone are, for example, to create spawning and rearing habitat; to install fish incubators; to introduce fish farming technologies; to stock fish species of commercial interest that are well adapted to reservoirs as long as this is compatible with the conservation of biodiversity within the reservoir and does not conflict with native species; to develop facilities for fish harvesting, processing and marketing; to build access roads, ramps and landing areas or to cut trees prior to impoundment along navigation corridors and fishing sites; to provide navigation maps and charts; and to recover floating debris.

As reservoirs replace terrestrial habitats, it is also important to protect and/or recreate the types of habitats lost through inundation (WCD, 2000). In general, long-term compensation and enhancement measures have turned out to be beneficial. Further possible mitigation measures might be to protect areas and wetlands that have an equivalent or better ecological value than the land lost; to preserve valuable land bordering the reservoir for ecological purposes and erosion prevention; to conserve flooded emerging forest in some areas for brood-rearing waterfowl; to enhance the habitat of reservoir islands for conservation purposes; to develop or enhance nesting areas for birds and nesting platforms for raptors; to practice selective wood cutting for herbivorous mammals; and to implement wildlife rescue and management plans. Good-practice examples show that some hydropower reservoirs have even been recognized as new, high-value ecosystems by being registered as 'Ramsar' reservoirs in the Ramsar List of Wetlands of International Importance.[20]

5.6.1.3 Water quality

In some densely populated areas with rather poor water quality, RoR hydropower plants are regularly used to improve oxygen levels and filter tonnes of floating waste out of the river, or to reduce high water temperature levels from thermal power generating outlets. However, maintaining the water quality of reservoirs is often a challenge, as reservoirs constitute a focal point for the river basin catchment. In cases where municipal, industrial and agricultural waste waters entering the reservoir are exacerbating water quality problems, it might be relevant that proponents and stakeholders cooperate in the context of an appropriate land and water use plan encompassing the whole catchment area, preventing, for example, excessive usage of fertilizers and pesticides.

Water quality issues related to reservoirs depend on several factors: climate, reservoir morphology and depth, water retention time in the reservoir, water quality of tributaries, quantity and composition of the inundated soil and vegetation, and rapidity of impounding, which affects the quantity of biomass available over time. Also, the operation of the HPP and thus the reservoir can significantly affect water quality, both negatively and positively.

Water quality issues can often be managed by site selection and appropriate design, taking the future reservoir morphology and hydraulic characteristics into consideration. The primary goals are to reduce the submerged area and to minimize water retention in the reservoir. The release of poor-quality water (due to thermal stratification, turbidity and temperature changes both within and downstream of the reservoir) may be reduced by the use of selective or multi-level water intakes. This may also help to reduce oxygen depletion and the volume of anoxic waters. Since the absence of oxygen may contribute to the formation of methane during the first few years after impoundment, especially in warm climates, measures to prevent the formation of anoxic reservoir zones

20 The Ramsar Convention on Wetlands of International Importance is an intergovernmental treaty that provides the framework for national action and international cooperation on the conservation and wise use of wetlands and their resources. The convention was signed in Ramsar, Iran, in 1971 and entered into force in 1975. The Ramsar List of Wetlands of International Importance (2009) and other information is available at http://www.ramsar.org.

will also help mitigate potential methane emissions (see Section 5.6.3 for more details).

Spillways, stilling basins or structures that promote degassing, such as aeration weirs, may help to avoid downstream gas super-saturation. While some specialists recommend pre-impoundment clearing of the reservoir area, this must be carried out carefully because (i) in some cases, significant re-growth may occur prior to impoundment (and will be rapidly degraded once flooded) and (ii) the massive and sudden release of nutrients (in the case of vegetation clearance through burning) may lead to algal blooms and water quality problems. In some situations, filling up and then flushing out the reservoir prior to commercial operation might contribute to water quality improvement. Planning periodic peak flows can increase aquatic weed drift and decrease suitable substrates for weed growth, reducing problems with undesired invasive species. Increased water turbidity can be mitigated by protecting shorelines that are highly sensitive to erosion, or by managing flow regimes in a manner that reduces downstream erosion.

5.6.1.4 Sedimentation

The sediment-carrying capacity of a river depends on its hydrologic characteristics (slope, current velocity, water depth), the nature of the sediments in the riverbed and the material available in the catchment. In general, a river's sediment load is composed of sediments from the riverbed and sediments generated by erosion in the drainage basin. Dams reduce current velocity and the slope of the water body. The result is a decrease in sediment-carrying capacity. Flow reduction contributes to lower sediment transport capacity and increased sediment deposition, which could lead to the raising of riverbed and an increase in flood risk, as, for example, experienced in the lower reaches of the Yellow River (Xu, 2002). The scope of the impact depends on the natural sediment load of the river basin, which varies according to geomorphologic composition of the riverbed, as well as the soil composition and the vegetation coverage of the drainage basin. In areas dominated by rocky granite, such as in Canada and Norway, sedimentation is generally not an issue. Rivers with large sediment loads are found mainly in arid and semi-arid or mountainous regions with fine soil composition. A World Bank study (Mahmood, 1987) estimated that about 0.5 to 1% of the total freshwater storage capacity of existing reservoirs is lost each year due to sedimentation. Similar conditions were also reported by WCD (2000) and ICOLD (2004). Climate change may affect sediment generation, transport processes, sediment flux in a river and sedimentation in reservoirs, due to changes in hydrological processes and, in particular, floods (Zhu et al., 2007).

In countries with extensive sediment control works such as Japan, the riverbed is often lowered in the middle to downstream reaches of rivers, causing serious scoring of bridge piers and disconnection between water use or intake facilities and the lowered river water table (Takeuchi, 2004). Virtually no sediment has been discharged from the Nile River below Aswan High Dam since its construction (completed in 1970), which has resulted in a significant erosion of the riverbed and banks and retreat of its estuary (Takeuchi et al., 1998). The bed of the Nile, downstream of the High Aswan Dam, was reported to be lowered by some 2 to 3 m in the years following completion of the dam, with irrigation intakes left high and dry and bridges undermined (Helland-Hansen et al., 2005).

Besides exposing the machinery and other technical installations to significant wear and tear (see Section 5.3.3.3), sedimentation also has a major impact on reservoirs by depleting not only their storage capacity over time due to sediment deposition, but also by increasing the risk of upstream flooding due to continuous accumulation of sediments in the backwater region (Goodwin et al., 2001; Wang and Hu, 2004).

In order to gain precise knowledge about long-term sediment inflow characteristics and to support proper site selection, the Revised Universal Soil Loss Equation is a method that is widely utilized to estimate soil erosion from a particular land area (Renard et al., 1997). The Geographic Information System (GIS)-based model includes calibration and the use of satellite images to determine vegetation coverage for the entire basin, which determines the erosion potential of the sub-basins as well as the critical areas. If excessive reservoir sedimentation cannot be avoided by proper site selection, appropriate provision of storage volume that is compatible with the required project life has to be planned. If sediment loading occurs, it can be reduced by opening the spillway gates to allow for sediment flushing during flooding or by adding sluices to the main dam. Different sediment-trapping devices or conveyance systems have also been used with success, along with extraction of coarse material from the riverbed and dredging of sediment deposits However, adequate bank protection in the catchment area and the protection of the natural vegetation in the watershed is one of the best ways to minimize erosion and prevent sediment loading.

5.6.1.5 Biological diversity

Although existing literature related to ecological effects of river regulations on wildlife is extensive (Nilsson and Dynesius, 1993; WCD, 2000), the knowledge is mainly restricted to and based on environmental impact assessments. A restricted number of long-term studies have been carried out that enable predictions of species-specific effects of hydropower development on fish, mammals and birds. In general, four types of environmental disturbances are singled out:

- Habitat changes;
- Geological and climatic changes;
- Direct mortality; and
- Increased human use of the area.

Most predictions are, however, very general and only able to focus on the type of change, without quantifying the short- and long-term effects. Thus, it is generally realized that current knowledge cannot provide a basis for precise predictions. The impacts are, however, highly species-, site-, seasonal- and construction-specific.

The most serious causes of ecological effects from hydropower development on wildlife are, in general:

- Permanent loss of habitat and special biotopes through inundation;
- Loss of flooding;
- Fluctuating water levels (and habitat change);
- Introduction and dispersal of exotic species; and
- Obstacles to fish migration.

Fish are among the main organisms of aquatic wildlife to be affected by a HPP. Altered flow regimes, changes in temperature and habitat modifications are known types of negative impacts (Helland-Hansen et al., 2005) impacting fish. Rapidly changing water levels following hydropower peaking operations are another type of impact that may also affect the downstream fish populations. Yet, in some cases, the effects on the river system from various alterations following regulation may also be positive. For instance, L'Abée-Lund et al. (2006) compared 22 Norwegian rivers, both regulated and non-regulated, based on 128 years of catch statistics. For the regulated rivers they observed no significant effect of hydropower development on the annual catch of anadromous salmonids. For two of the regulated rivers the effect was positive. In addition, enhancement measures such as stocking and building fish ladders significantly increased annual catches. A review by Bain (2007) looking at several hydropower peaking cases in North America and Europe indicates clearly that the impacts from HPPs in the operational phase are variable, but may have a positive effect on downstream areas.

On the other hand, peaking may lead to rapid shifts in the water level where the HPP discharges into a river (as opposed to lakes or the ocean). Sudden shutdown of the peaking HPP may lead to a rapid fall in the water table downstream and a possibility for so-called stranding of fish, where especially small species or fry may be locked in pools, between rocks of various sizes, or in the gravel. An example is salmonid fry that may use dewatered areas. Experiments indicate that if the water level, after a shutdown of the HPP, falls at a rate of below 10 to 15 cm/hr, stranding in most cases will not be a problem, depending on local conditions (Saltveit et al., 2001). However, there are individual differences and fish may also be stranded at lower rates (Halleraker et al., 2003), and even survive for several hours in the substrate after dewatering (Saltveit et al., 2001).

A submerged land area loses all terrestrial animals, and many animals will be dispelled or sometimes drown when a new reservoir is filled. This can be partly mitigated through implementation of a wildlife rescue program, although it is generally recognized that these programs may have a limited effect on the wild populations on the long term (WCD, 2000; Ledec and Quintero, 2003). Endangered species attached to specific biotopes require particular attention and dedicated management programs prior to impoundment. Increased aquatic production caused by nutrient leakage from the inundated soil immediately after damming has been observed to affect both invertebrates and vertebrates positively for some time, that is, until the soil nutrients have been washed out. An increase in aquatic birds associated with this damming effect in the reservoir has also been observed.

Whereas many natural habitats are successfully transformed for human purposes, the natural value of certain other areas is such that they must be used with great care or left untouched. The choice can be made to preserve natural environments that are deemed sensitive or exceptional. To maintain biological diversity, the following measures have proven to be effective: establishing protected areas; choosing a reservoir site that minimizes loss of ecosystems; managing invasive species through proper identification, education and eradication; and conducting specific inventories to learn more about the fauna, flora and specific habitats within the studied area.

5.6.1.6 Barriers for fish migration and navigation

Dams may create obstacles for the movement of migratory fish species and for river navigation. They may reduce access to spawning grounds and rearing zones, leading to a decrease in migratory fish populations and fragmentation of non-migratory fish populations. However, natural waterfalls also constitute obstacles to upstream fish migration and river navigation. Dams that are built on such waterfalls therefore do not constitute an additional barrier to passage. Solutions for upstream fish migrations are now widely available: a variety of solutions have been tested for the last 30 years and have shown acceptable to high efficiency. Fish ladders can partly restore the upstream migration, but they must be carefully designed, and well suited to the site and species considered (Larinier and Marmulla, 2004). High-head schemes are usually off limits for fish ladders. Conversely, downstream fish migration remains more difficult to address. Most fish injuries or mortalities during downstream movement are due to their passage through turbines and spillways. In low-head HPPs, improvement in turbine design (for instance 'fish-friendly turbines'), spillway design or overflow design has proven to successfully reduce fish injury or mortality rates, especially for eels, and to a lesser extent salmonids (Amaral et al., 2009). More improvements may be obtained by adequate management of the power plant flow regime or through spillway openings during downstream movement of migratory species. Once the design of the main components (plant, spillway, overflow) has been optimized for fish passage, some avoidance systems may be installed (screens, strobe and laser lights, acoustic cannons, bubbles, electric fields etc.). However, their efficiency is highly site- and species-dependent, especially in large rivers. In some cases, it may be more useful to capture fish in the headrace or upstream and release the individuals downstream. Other common devices include bypass channels, fish elevators with attraction flow or leaders to guide fish to fish ladders and the installation of avoidance systems upstream of the power plant.

To ensure navigation at a dam site, ship locks are the most effective technique available. For small craft, lifts and elevators can be used with success. Navigation locks can also be used as fish ways with some adjustments to the equipment. Sometimes, it is necessary to increase the upstream attraction flow. In some projects, bypass or diversion channels have been dug around the dam.

5.6.1.7 Involuntary population displacement

Although not all hydropower projects require resettlement, involuntary displacement is one of the most sensitive socioeconomic issues surrounding hydropower development (WCD, 2000; Scudder, 2005). It consists of two closely related, yet distinct processes: displacing and resettling people as well as restoring their livelihoods through the rebuilding or 'rehabilitation' of their communities.

When involuntary displacement cannot be avoided, the following measures might contribute to optimize resettlement outcomes:

- Involving affected people in defining resettlement objectives, in identifying reestablishment solutions and in implementing them; rebuilding communities and moving people in groups, while taking special care of indigenous peoples and other vulnerable social groups;
- Publicizing and disseminating project objectives and related information through community outreach programs, to ensure widespread acceptance and success of the resettlement process;
- Improving livelihoods by fostering the adoption of appropriate regulatory frameworks, by building required institutional capacities, by providing necessary income restoration and compensation programs and by ensuring the development and implementation of long-term integrated community development programs;
- Allocating resources and sharing benefits, based upon accurate cost assessments and commensurate financing, with resettlement timetables tied to civil works construction and effective executing organizations that respond to local development needs, opportunities and constraints.

5.6.1.8 Affected people and vulnerable groups

Like in all other large-scale interventions, it is important during the planning of hydropower projects to identify through a proper social impact study who will benefit from the project and especially who will be exposed to negative impacts. Project-affected people are individuals living in the region that is impacted by a hydropower project's preparation, implementation and/or operation. These may be within the catchment, reservoir area, downstream, or in the periphery where project-associated activities occur, and also can include those living outside of the project-affected area who are economically affected by the project.

A massive influx of workers and creation of transportation corridors also have a potential impact on the environment and surrounding communities if not properly controlled and managed. In addition, workers should be in a position once demobilized at least to return to their previous activities, or to have access to other construction sites due to their increased capacities and experience.

Particular attention needs to be paid to groups that might be considered vulnerable with respect to the degree to which they are marginalized or impoverished and their capacity and means to cope with change. Although it is very difficult to mitigate or fully compensate the social impacts of reservoir hydropower projects on indigenous or other culturally vulnerable communities for whom major transformations to their physical environment run contrary to their fundamental beliefs, special attention has to be paid to those groups in order to ensure that their needs are integrated into project design and adequate measures are taken.

Negative impacts can be minimized for such communities if they are willing partners in the development of a hydropower project, rather than perceiving it as a development imposed on them by an outside agency with conflicting values. Such communities require sufficient lead time, appropriate resources and communication tools to assimilate or think through the project's consequences and to define on a consensual basis the conditions in which they would be prepared to proceed with the proposed development. Granting long-term financial support for activities that define local cultural specificities may also be a way to minimize impacts as well as ensure early involvement of concerned communities in project planning in order to reach agreements on proposed developments and economic spin-offs between concerned communities and proponents. Furthermore, granting legal protections so that affected communities retain exclusive rights to the remainder of their traditional lands and to new lands obtained as compensation might be an appropriate mitigation measure as well as to restrict access of non-residents to the territory during the construction period while securing compensation funds for the development of community infrastructure and services such as access to domestic water supply or to restore river crossings and access roads. Also, it is possible to train community members for project-related job opportunities.

5.6.1.9 Public health

In warmer climate zones, the creation of still-standing water bodies such as reservoirs can lead to increases in waterborne diseases like malaria, river blindness, dengue or yellow fever, which need to be taken into account when designing and constructing reservoirs for supply security, which may be one of the most pressing needs in these regions.

In other zones, a temporary increase in mercury may have to be managed in the reservoir, due to the liberation of mercury from the soil through bacteria, which can then enter the food chain in the form of methyl mercury. In some areas, human activities like coal burning (North America) and mining represent a significant contributor.

Moreover, higher incidences of behavioural diseases linked to increased population densities are frequent consequences of large construction sites. Therefore, public health impacts should be considered and addressed from the outset of the project.

Reservoirs that are likely to become the host of waterborne disease vectors require provisions for covering the cost of health care services to improve health conditions in affected communities. In order to manage health effects related to substantial population growth around hydropower reservoirs, options may include controlling the influx of migrant workers or migrant settlers as well as planning the announcement of the project in order to avoid early population migration to an area not prepared to receive them. Moreover, mechanical and/or chemical treatment of shallow reservoir areas could be considered to reduce the proliferation of insects carrying diseases, while planning and implementing disease prevention programs. Additional options include increasing access to good quality medical services in project-affected communities and in areas where population densities are likely to increase as well as establishing detection and epidemiological monitoring programs, establishing public health education programs directed at the populations affected by the project and implementing a health plan for the work force and along the transportation corridor to reduce the risk of transmittable diseases (e.g., sexually transmitted diseases).

5.6.1.10 Cultural heritage

Cultural heritage is the present manifestation of the human past and refers to sites, structures and remains of archaeological, historical, religious, cultural and aesthetic value (World Bank, 1994). Exceptional natural landscapes or physical features of the environment are also an important part of human heritage as landscapes are endowed with a variety of meanings. The creation of a reservoir might lead to the disappearance of valued exceptional landscapes such as spectacular waterfalls and canyons. Long-term landscape modifications can also occur through soil erosion, sedimentation and low water levels in reservoirs as well as through associated infrastructure impacts (e.g., new roads, transmission lines). It is therefore important that appropriate measures be taken to preserve natural beauty in the project area and to protect cultural properties with high historic value.

Possible measures to minimize negative impacts are, for example: ensuring on- site protection; conserving and restoring, relocating and/or re-creating important physical and cultural resources; creating a museum in partnership with local communities to make archaeological findings, documentation and record keeping accessible; including landscape architecture competences into the project design to optimize harmonious integration of the infrastructure into the landscape; using borrow pits and quarries for construction material that will later disappear through impoundment; re-vegetating dumping sites for soil and excavation material with indigenous species; putting transmission lines and power stations underground in areas of exceptional natural beauty; incorporating residual flows to preserve important waterfalls at least during the tourism high season; keeping as much as possible the natural appearance of river landscapes by constructing weirs to adjust the water level using local rocks instead of concrete; and by constructing small islands in impounded areas, which might be of ecological interest for waterfowl and migrating birds.

5.6.1.11 Sharing development benefits

The economic importance of hydropower and irrigation dams for densely populated countries that are affected by scarce water resources for agriculture and industry, limited access to indigenous sources of oil, gas or coal, and frequent shortages of electricity may be substantial. In many cases, however, hydropower projects have resulted both in winners and losers: affected local communities have often born the brunt of project-related economic and social losses, while people outside the project area have benefited from better access to affordable power and improved flood/drought protection. Although the overall economic gains may be substantial, special attention has to be paid to those local and regional communities that have to cope with the negative impacts of a HPP to ensure that they get a faire share of benefits from the project as compensation. This may take many forms including business partnerships, royalties, development funds, equity sharing, job creation and training, jointly managed environmental mitigation and enhancement funds, improvements of roads and other infrastructure, recreational and commercial facilities (e.g., tourism, fisheries), sharing of revenues, payment of local taxes, or granting preferential electricity rates and fees for other water-related services to local companies and project-affected populations.

5.6.2 Guidelines and regulations

The assessment and management of the above impacts represents a key challenge for hydropower development. The issues at stake are complex and have long been the subject of intense controversy (Goldsmith and Hilyard, 1984). Moreover, unsolved socio-political issues, which are often not project related, tend to come to the forefront of the decision-making process in a large-scale infrastructure development (Beauchamp, 1997).

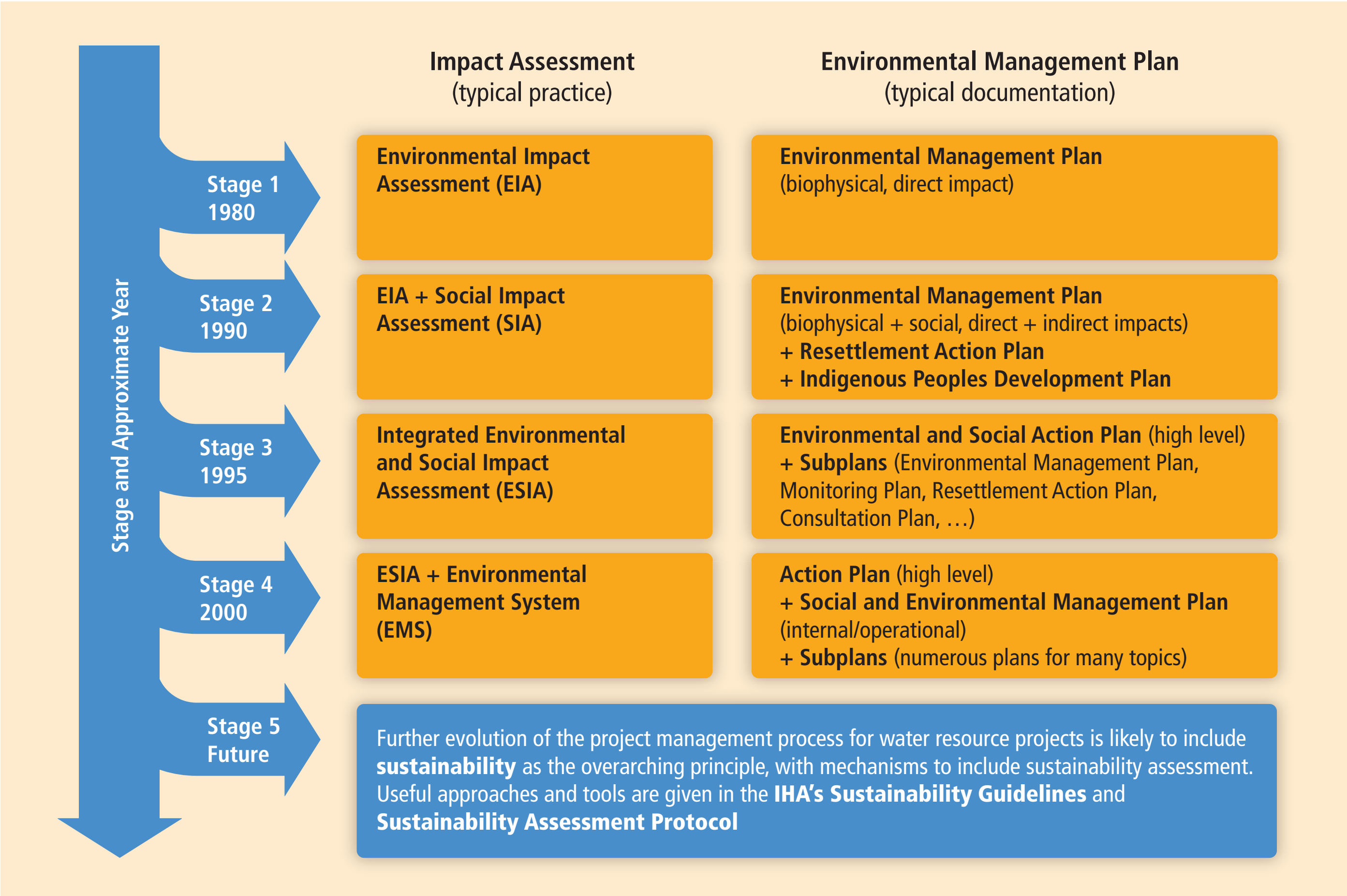


Figure 5.14 | Evolution of environmental and social impact assessment and management (adapted from UNEP, 2007).

Throughout the past decades, project planning has increasingly witnessed a paradigm shift from a technocratic approach to a participative one (Healey, 1992). This shift is also reflected in the evolution of the environmental and social impact assessment and management process that is summarized in Figure 5.14. Today, stakeholder consultation has become an essential tool to improve project outcomes. It is therefore important to identify key stakeholders such as local, national or regional authorities, affected populations, or environmental NGOs, early in the development process in order to ensure positive and constructive consultations, and develop a clear and common understanding of the associated environmental and social impacts, risks and opportunities. Emphasizing transparency and an open, participatory decision-making process, this new approach is driving both present-day and future hydropower projects towards increasingly more environment-friendly and sustainable solutions. At the same time, the concept and scope of environmental and social management associated with hydropower development and operation have changed, moving from a mere impact assessment process to a global management plan encompassing all sustainability aspects.

In particular, the planning of larger hydropower developments mandates guidelines and regulations to ensure that impacts are assessed as objectively as possible and managed in an appropriate manner. In many countries a strong national legal and regulatory framework has been put in place to determine how hydropower projects shall be developed and operated, through a licensing process and follow-up obligations enshrined into the operating permit often also known as concession agreement. Yet, discrepancies between various national regulations as well as controversies have lead to the need to establish international guidelines on how to avoid, minimize or compensate negative impacts while maximizing the positive ones.

Besides the international financing agencies' safeguard policies, one of the first initiatives was launched in 1996 by countries like Canada, Norway, Sweden, Spain and the USA for which hydropower is an important energy resource. Their governments set up, in collaboration with their mainly state-owned hydropower utilities and research institutions, a five-year research program under the auspices of the International Energy Agency (IEA, 2000c) called 'Hydropower and the Environment'. In 1998, the World Commission on Dams (WCD) was established to review the development effectiveness of large dams, to assess alternatives for water and power development, and to develop acceptable criteria, guidelines and standards, where appropriate, for the planning, design, appraisal, construction, operation, monitoring and decommissioning of dams. As a result, 5 core values,[21] 8 strategic priorities[22] and 26 guidelines were suggested (WCD, 2000). While governments, financiers and the industry have widely endorsed the WCD core values and strategic priorities, they consider the guidelines to be only partly applicable to hydropower dams. As a consequence, international financial institutions such as the World Bank, the Asian Development Bank, the African Development Bank and the European Bank for Reconstruction and Development have not endorsed the WCD report as a whole, in particular not its guidelines, but they have kept or developed their own guidelines and criteria (World Bank, 2001). All major export credit agencies have done the same (Knigge et al., 2008). Whereas the WCD's work focused on analyzing the reasons for shortcomings with respect to poorly performing dams, its follow-up initiative, the 'Dams and Development Project' hosted by the UN Environment Programme (UNEP), put an emphasis on gathering good practice into a compendium (UNEP, 2007). With a similar goal, the IEA launched in 2000 a second hydropower-specific five-year research program called 'Hydropower Good Practice' (IEA, 2006) to further document effective management of key environmental and social issues.

Even though each financing agency has developed its own set of quality control criteria to ensure acceptable environmental and social project performance (e.g., World Bank Safeguard, International Finance Corporation's Performance Standards, etc.), there is still no broadly accepted standard to assess the economic, social and environmental performance specifically for hydropower projects. In order to meet this need, the International Hydropower Association (IHA) has produced Sustainability Guidelines (IHA, 2004) and a Hydropower Sustainability Assessment Protocol (IHA, 2006), both of which are based on the broadly shared five core values and seven strategic priorities of the WCD report, taking the hydropower-specific previous IEA study as starting point. This industry-initiated process may be further improved by a multi-stakeholder review initiative called the Hydropower Sustainability Assessment Forum. This cross-sector working group is comprised of representatives from governments of developed and developing countries, as well as from international financial institutions, NGOs and industry groups.[23] A recommended Final Draft Protocol was published in November 2010 (IHA, 2010) and a continuous improvement process has been put in place for its further application and review.

5.6.3 Lifecycle assessment of environmental impacts

Life cycle assessment (LCA) aims at comparing the full range of environmental impacts assignable to products and services, across their lifecycle, including all processes upstream and downstream of operation or use of the product/service. The following subsection focuses on LCA for GHG emissions, while other metrics are briefly discussed in Box 5.2, and more comprehensively in Section 9.3.4.

The lifecycle of hydropower plants consists of three main stages:

- **Construction:** In this phase, GHGs are emitted from the production and transportation of materials (e.g., concrete, steel etc.) and the use of civil work equipment and materials for construction of the facility (e.g., diesel engines).

- **Operation and maintenance:** GHG emissions can be generated by operation and maintenance activities, for example, building

Box 5.2 | Energy payback and lifecycle water use.

The **energy payback** ratio is the ratio of total energy produced during a system's normal lifespan to the energy required to build, maintain and fuel that system. Other metrics that refer to the same basic calculation include the energy returned on energy invested, or the energy ratio (see Annex II). A high energy payback ratio indicates good performance. Lifecycle energy payback ratios for well-performing hydropower plants reach the highest values of all energy technologies, ranging from 170 to 267 for run-of-river, and from 205 to 280 for reservoirs (Gagnon, 2008). However, the range of performances is wider, with literature reporting minimum values of 30 to 50 (Gagnon et al., 2002) or even lower values (Kubiszewski et al., 2010; see also Box 9.2).

Hydropower relies upon water in large quantities, but the majority of this is simply passed through the turbines with negligible losses. As up- and downstream stages require little water, **lifecycle water use** is close to zero for run-of-river hydropower plants (Fthenakis and Kim, 2010). However, consumptive use in the form of evaporation can occur from hydroelectric reservoirs. Global assessments for lifecycle water consumption of reservoirs are not available, and published regional results show high ranges for different climatic and project conditions (Gleick, 1993; LeCornu, 1998; Torcellini et al., 2003; Mielke et al., 2010). Allocation schemes for determining water consumption from various reservoir uses in the case of multipurpose reservoirs can significantly influence reported water consumption values (see also Section 9.3.4.4). Also, research may be needed to determine the net effect of reservoir construction on the evaporation in the specific watershed.

21 Equity, efficiency, participatory decision making, sustainability, and accountability.

22 Gaining public acceptance, comprehensive options assessment, addressing existing dams, sustaining rivers and livelihoods, recognizing entitlements and sharing benefits, ensuring compliance, sharing rivers for peace, development and security.

23 For example, the World Bank, the Equator Principles Financial Institutions, the World Wide Fund for Nature, the Nature Conservancy, Transparency International, Oxfam and the IHA.

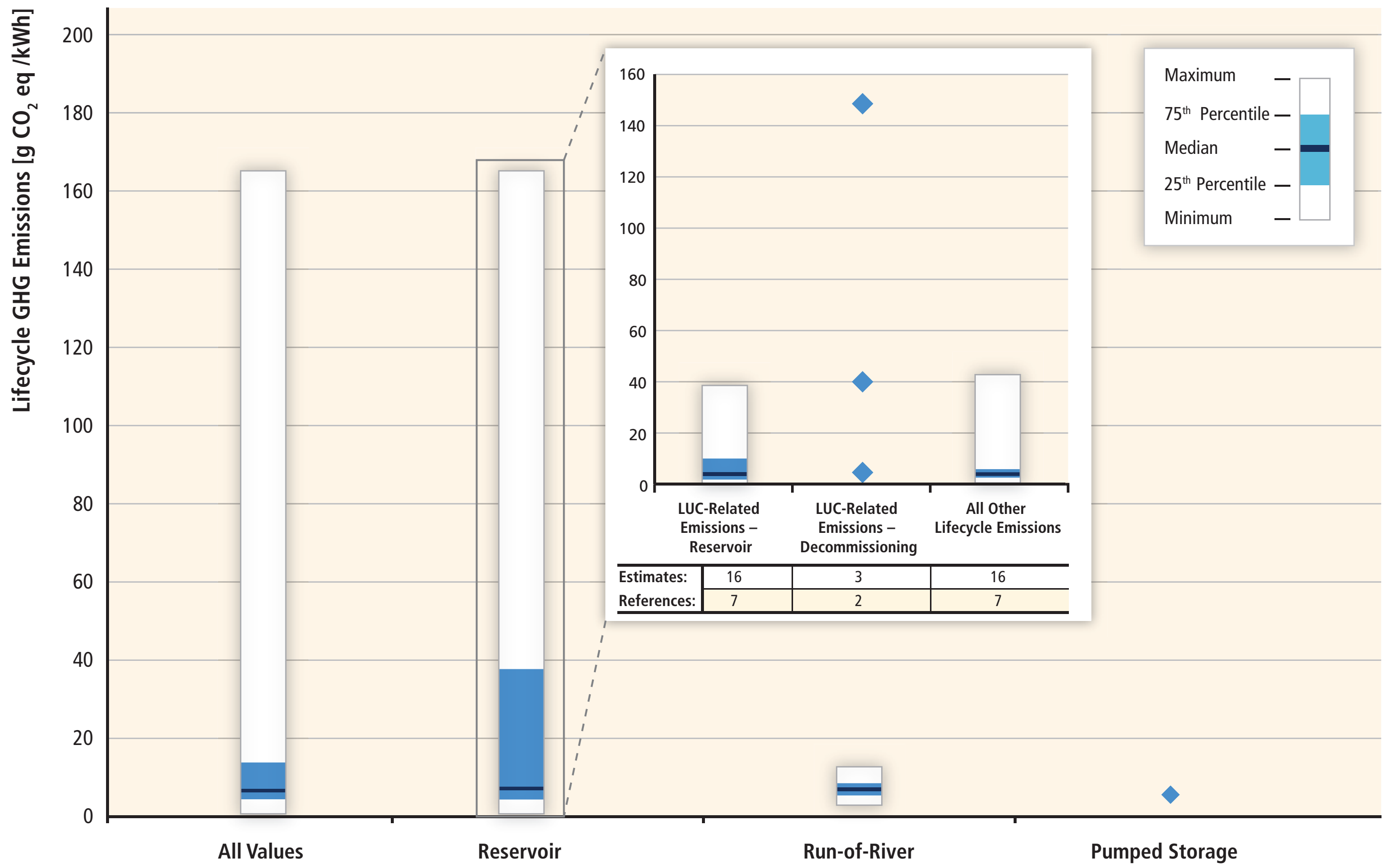
heating/cooling systems, auxiliary diesel generating units, or onsite staff transportation for maintenance activities. Furthermore, land use change induced by reservoir creation and the associated modification of the terrestrial carbon cycle must be considered, and may lead to net GHG emissions from the reservoir during operation (see Section 5.6.3.1).

- **Dismantling:** Dams can be decommissioned for economic, safety or environmental reasons. Up to now, only a small number of small-size dams have been removed, mainly in the USA. Therefore, emissions related to this stage have rarely been included in LCAs so far.

5.6.3.1 Current lifecycle estimates of greenhouse gas emissions

LCAs carried out on hydropower projects up to now have demonstrated the difficulty of generalizing estimates of lifecycle GHG emissions for hydropower projects across climatic conditions, pre-impoundment land cover types and hydropower technologies. An important issue for hydropower is the multipurpose nature of most reservoir projects, and allocation of total impacts to the several purposes that is then required. Many LCAs to date allocate all impacts to the electricity generation function, which in some cases may overstate the emissions for which they are 'responsible'.

Figure 5.15 displays results of a review of the LCA literature reporting estimates of lifecycle GHG emissions from hydropower technologies published since 1980 (see Annex II for further description of review methods and list of references). The majority of lifecycle GHG emission estimates for hydropower cluster between about 4 and 14 g CO_2eq/kWh, but under certain scenarios there is the potential for much larger quantities of GHG emissions, as shown by the outliers. Note that the distributions shown in Figure 5.15 do not represent an assessment of likelihood; the figure simply reports the distribution of currently published literature estimates passing screens for quality and relevance. As depicted in Figure 5.15, reservoir hydropower has been shown to potentially emit over



	All Values	Reservoir	Run-of-River	Pumped Storage
Estimates:	27	18	8	1
References:	11	9	2	1

Figure 5.15 | Lifecycle GHG emissions of hydropower technologies (unmodified literature values, after quality screen). See Annex II for details of literature search and citations of literature contributing to the estimates displayed. Emissions from reservoirs are referred to as gross GHG emissions.

150 g CO_2eq/kWh, which is significantly higher than run-of-river or pumped storage, though fewer GHG emission estimates exist for the latter two technologies.

The outliers stem from studies that included assessments of GHG emissions from land use change (LUC) from reservoir hydropower. While the magnitude of potential LUC-related emissions from reservoir hydropower (caused by inundation) is significant, uncertainty in the quantification of these emissions is also high. LUC emissions can be both ongoing, (i.e., methane emitted from the reservoir from soil and vegetation decomposition), and from decommissioning (release of GHGs from large quantities of silt collected over the life of the plant). The LCAs evaluated in this assessment only accounted for gross LUC-related GHG emissions. Characterizing a reservoir as a net emitter of GHGs implies consideration of emissions that would have occurred without the reservoir, which is an area of active research and currently without consensus (see Section 5.6.4.2). LUC-related emissions from decommissioning have only been evaluated in two studies (Horvath, 2005; Pacca, 2007) that provided three estimates (see Figure 5.15). Both reported significantly higher estimates of lifecycle GHG emissions than the other literature owing to this differentiating factor. However, caution should be used in applying these two estimates of the impact of decommissioning broadly to all hydropower systems as they may not be representative of other technologies, sites, or dam sizes.

Variability in estimates stems from differences in study context (e.g., climate, carbon stock of flooded area), technological performance (e.g., turbine efficiency, lifetime, residence time of water) and methods (e.g., LCA system boundaries) (UNESCO/IHA, 2008). For instance, the assumed operating lifetime of a dam can significantly influence the estimate of lifecycle GHG emissions as it amortizes the construction- and dismantling-related emissions over a shorter or longer period. Completion of additional LCA studies is needed to increase the number of estimates and the breadth of their coverage in terms of climatic zones, technology types, dam sizes etc.

5.6.3.2 Quantification of gross and net emissions from reservoirs

With respect to studies that have explored GHG impacts of reservoirs, research and field surveys on GHG balances of freshwater systems involving 14 universities and 24 countries (Tremblay et al., 2005) have led to the following conclusions:

- All freshwater systems, whether they are natural or manmade, emit GHGs due to decomposing organic material. This means that lakes, rivers, estuaries, wetlands, seasonal flooded zones and reservoirs emit GHGs. They also bury some carbon in the sediments (Cole et al., 2007).
- Within a given region that shares similar ecological conditions, reservoirs and natural water systems produce similar levels of CO_2 emissions per unit area. In some cases, natural water bodies and freshwater reservoirs absorb more CO_2 than they emit.

Reservoirs are collection points for material coming from the whole drainage basin area upstream. As part of the natural cycle, organic matter is flushed into these collection points from the surrounding terrestrial ecosystems. In addition, domestic sewage, industrial waste and agricultural pollution may also enter these systems and produce GHG emissions. Therefore, the assessment of man-made net emissions involves a) appropriate estimation of the natural emissions from the terrestrial ecosystem, wetlands, rivers and lakes that were located in the area before impoundment; and b) abstracting the effect of carbon inflow from the terrestrial ecosystem, both natural and related to human activities, on the net GHG emissions before and after impoundment.

The main GHGs produced in freshwater systems are CO_2 and methane (CH_4). Nitrous oxide (N_2O) may be of importance, particularly in reservoirs with large drawdown zones[24] or in tropical areas, but no global estimate of these emissions presently exists. Results from reservoirs in boreal environments indicate a low quantity of N_2O emissions, while a recent study of tropical reservoirs does not give clear evidence of whether tropical reservoirs act as sources of N_2O to the atmosphere (Guerin et al., 2008).

Two pathways of GHG emissions to the atmosphere are usually studied: diffusive fluxes from the surface of the reservoir and bubbling (Figure 5.16). Bubbling refers to the discharge of gaseous substances resulting from carbonation, evaporation or fermentation from a water body (UNESCO/IHA, 2010). In addition, studies at Petit-Saut, Samuel and Balbina have investigated GHG emissions downstream of the dams (degassing just downstream of the dam and diffusive fluxes along the river course downstream of the dam). CH_4 transferred through diffusive fluxes from the bottom to the water surface of the reservoir may undergo oxidation (i.e., be transformed into CO_2) in the water column nearby the oxycline when methanotrophic bacteria are present. Regarding N_2O, Guerin et al. (2008) have identified several possible pathways for N_2O emissions: these could occur via diffusive flux, degassing and possibly through macrophytes, but this last pathway has never been quantified for either boreal or tropical environments.

Still, for the time being, only a limited amount of studies appraising the net emissions from freshwater reservoirs (i.e., excluding unrelated anthropogenic sources and pre-existing natural emissions) is available, whereas gross fluxes have been investigated in boreal (e.g., Rudd et al.,

24 The drawdown zone is defined as the area temporarily inundated depending on the reservoir level variation during operation.

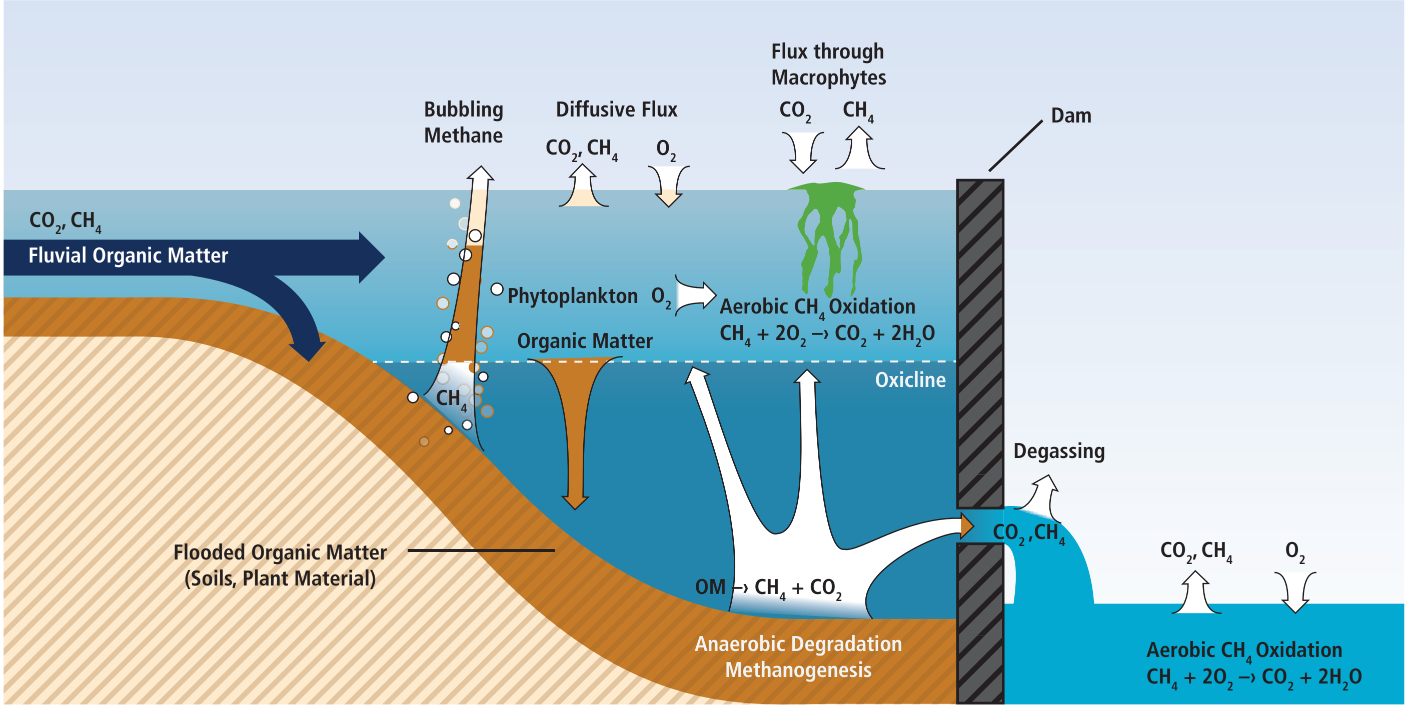


Figure 5.16 | Carbon dioxide and methane pathways in a freshwater reservoir with an anoxic hypolimnion (adapted from Guerin, 2006).

Table 5.6 | Range of gross CO_2 and CH_4 emissions from hydropower freshwater reservoirs; numbers of studied reservoirs are given in parentheses (UNESCO-RED, 2008).

GHG pathway	Boreal and temperate		Tropical	
	CO_2 (mmol/m²/d)	CH_4 (mmol/m²/d)	CO_2 (mmol/m²/d)	CH_4 (mmol/m²/d)
Diffusive fluxes	-23 to 145 (107)	-0.3 to 8 (56)	-19 to 432 (15)	0.3 to 51 (14)
Bubbling	0	0 to 18 (4)	0	0 to 88 (12)
Degassing[1]	~0.2 (2) to 0.1 (2)	n.a.	4 to 23 (1)	4 to 30 (2)
River below the dam	n.a.	n.a.	500 to 2500 (3)	2 to 350 (3)

Note: 1. The degassing (generally in mg/d) is attributed to the surface of the reservoir and is expressed in the same units as the other fluxes (mmol/m²/d).

1993; Tremblay et al., 2005), temperate (Casper et al., 2000; Soumis et al., 2004; Therrien et al., 2005) and tropical/subtropical (e.g., Guerin et al., 2008) regions. Gross emissions measurements are summarized in Table 5.6.

Gross emissions measurements in boreal and temperate regions from Canada, Finland, Iceland, Norway, Sweden and the USA imply that highly variable results can be obtained for CO_2 emissions, so that reservoirs can act as sinks, but also can present significant CO_2 emissions. In some cases, small CH_4 emissions were observed in these studies. Under boreal and temperate conditions, significant CH_4 emissions are expected only for reservoirs with large drawdown zones and high organic and nutrient inflows.

In tropical regions, high temperatures coupled with important demand for oxygen due to the degradation of substantial organic matter (OM) amounts favour the production of CO_2, the establishment of anoxic conditions, and thus the production of CH_4. In new reservoirs, OM mainly comes from submerged biomass and soil organic carbon with different absolute and relative contents of OM (Galy-Lacaux et al., 1999; Blais et al., 2005; Descloux et al., 2010). Later, OM may also come from primary production or other biological processes within the reservoir.

According to the UN Educational, Scientific and Cultural Organization (UNESCO) and the IHA (UNESCO/IHA, 2008), measurements of gross emissions have been taken in the tropics at four Amazonian locations and 16 additional sites in central and southern Brazil. They have shown, in some cases, significant gross GHG emissions. Measurements are not available from reservoirs in other regions of the tropics or subtropics except for Gatum in Panama, Petit-Saut in French Guyana and Nam Theun 2, Nam Ngum and Nam Leuk in Lao People's Democratic Republic (UNESCO/IHA, 2009). Preliminary studies of Nam Ngum and Nam Leuk indicate that an old reservoir might act as a carbon sink under certain conditions (Harby et al., 2009). This underlines the necessity to also monitor old reservoirs. The age of the reservoir has proven to be an important issue as well as the organic carbon standing stock, water residence time, type of vegetation, season, temperature, oxygen and local primary production, themselves dependent on the geographic area (Fearnside, 2002). According to the IPCC (2006), evidence suggests that CO_2 emissions for approximately the first 10 years after flooding are the results of decay of some of the organic matter on the land prior to flooding, but, beyond this time period, these emissions are sustained by the input of inorganic and organic carbon material transferred into the flooded area from the watershed or by internal processes in the reservoir. In boreal and temperate conditions, GHG emissions have been observed to return to the levels found in neighbouring natural lakes after the two to four years following impoundment (Tremblay et al., 2005). Further measurements could resolve this question for tropical conditions. Comparisons of these results are not easy to achieve, as different methodologies and data (e.g., concerning equipment, procedures, units of measurement) were applied for each study. Few measurements of material transported into or out of the reservoir have been reported, and few studies have measured carbon accumulation in reservoir sediments (UNESCO-RED, 2008).

Since 2008, UNESCO and IHA have been hosting an international research project, with the aim of establishing a robust methodology to accurately estimate the net effect on GHG emissions caused by the creation of a reservoir, and to identify gaps in knowledge. The project published *GHG Measurement Guidelines for Freshwater Reservoirs* in 2010 (UNESCO/IHA, 2010) to enable standardized measurements and calculations worldwide, and aims at delivering a database of results and characteristics of the measurement specification guidance being applied to a representative set of reservoirs worldwide. The final outcome will be building predictive modelling tools to assess the GHG status of unmonitored reservoirs and new reservoir sites, and guidance on mitigation for vulnerable sites. Recently, the IEA has set up a program called IEA Hydropower Agreement Annex XII that will work in parallel with IHA and UNESCO to solve the GHG issue regarding reservoirs.

5.7 Prospects for technology improvement and innovation[25]

Though hydropower is a proven and well-advanced technology, there is still room for further improvement, for example, through optimization of operation, mitigating or reducing environmental impacts, adapting to new social and environmental requirements and more robust and cost-effective technological solutions.

Large hydropower turbines are now close to the theoretical limit for efficiency, with up to 96% efficiency when operated at the best efficiency point, but this is not always possible and continued research is needed to make more efficient operation possible over a broader range of flows. Older turbines can have lower efficiency by design or reduced efficiency due to corrosion and cavitation damage.

Potential therefore exists to increase energy output by retrofitting new equipment with improved efficiency and usually also with increased capacity. Most of the existing hydropower equipment in operation today will need to be modernized during the next three decades, allowing for improved efficiency and higher power and energy output (UNWWAP, 2006) but also for improved environmental solutions by utilizing environmental design principles.

The structural elements of a hydropower project, which tend to take up to 70% of the initial investment cost for large hydropower projects, have a projected life of up to 100 years or more. On the equipment side, some refurbishment can be an attractive option after 30 years. Advances in technology can justify the replacement of key components or even complete generating sets. Typically, generating equipment can be upgraded or replaced with more technologically advanced electromechanical equipment two or three times during the life of the project, making more effective use of the same flow of water (UNWWAP, 2006).

The US Department of Energy reported that a 6.3% generation increase could be achieved in the USA from efficiency improvements if plant units fabricated in 1970 or prior years, having a total capacity of 30,965 MW, are replaced. Based on work done for the Tennessee Valley Authority and other hydroelectric plant operators, a generation improvement of 2 to 5.2% has also been estimated for conventional hydropower in the USA (75,000 MW) from installing new equipment and technology, and optimizing water use (Hall et al., 2003). In Norway it has been estimated that an increase in energy output from existing hydropower of 5 to 10% is possible with a combination of improved efficiency in new equipment, increased capacity, reduced head loss and reduced water losses and improved operation.

There is much ongoing research aiming to extend the operational range in terms of head and discharge, and also to improve environmental performance and reliability and reduce costs. Some of the promising technologies under development are described briefly in the following section. Most of the new technologies under development aim at utilizing low (<15 m) or very low (<5 m) head, opening up many sites for hydropower that have not been possible to use with conventional technology. Use of computational fluid dynamics (CFD) is an important tool, making it possible to design turbines with high efficiency over a broad range of discharges. Other techniques like artificial intelligence, neural networks, fuzzy logic and genetic algorithms are increasingly used to improve operation and reduce the cost of maintenance of hydropower equipment.

Most of the data available on hydropower technical potential are based on field work produced several decades ago, when low-head

25 Section 10.5 offers a complementary perspective on drivers and trends of technological progress across RE technologies.

hydropower was not a high priority. Thus, existing data on low-head hydropower technical potential may not be complete. As an example, in Canada, a market potential of 5,000 MW has recently been identified for low-head hydropower (in Canada, low head is defined as below 5 m) alone (Natural Resources Canada, 2009). As another example, in Norway, the environmentally feasible small-scale hydropower (<10 MW) market potential was previously assumed to be 7 TWh (25.2 PJ). A study conducted from 2002 to 2004, however, revealed this market potential to be nearly 25 TWh (90 PJ) at a cost below 6 US cents per kWh, and 32 TWh (115 PJ) at a cost below 9 US cents per kWh (Jensen, 2009).

5.7.1 Variable-speed technology

Usually, hydropower turbines are optimized for an operating point defined by speed, head and discharge. At fixed-speed operation, any head or discharge deviation involves some decrease in efficiency. The application of variable-speed generation in hydroelectric power plants offers a series of advantages, based essentially on the greater flexibility of the turbine operation in situations where the flow or the head deviate substantially from their nominal values. In addition to improved efficiency, the abrasion from silt in the water will also be reduced. Substantial increases in production in comparison to a fixed-speed plant have been found in simulation studies (Terens and Schafer, 1993; Fraile et al., 2006).

5.7.2 Matrix technology

A number of small identical units comprising turbine and generator can be inserted in a frame in the shape of a matrix where the number of (small) units is adapted to the available flow. During operation, it is possible to start and stop any number of units so those in operation can always run under optimal flow conditions. This technology can be installed at existing structures, for example, irrigation dams, low-head weirs, ship locks etc where water is released at low heads (Schneeberger and Schmid, 2004).

5.7.3 Fish-friendly turbines

Fish-friendly turbine technology is an emerging technology that provides a safe approach for fish passing though low-head hydraulic turbines by minimizing the risk of injury or death (Cada, 2001). While conventional hydropower turbine technologies focus solely on electrical power generation, a fish-friendly turbine brings about benefits for both power generation and protection of fish species.[26] Alden Laboratory (USA) predicts that their fish-friendly turbine will have a maximum efficiency of 90.5% with a survival rate for fish of between 94 and 100% (Amaral et al., 2009). One turbine manufacturer predicts approximately 98% fish survival through fish-friendly improvements on their Kaplan turbines.[27]

5.7.4 Hydrokinetic turbines

Generally, projects with a head under 1.5 or 2 m are not viable with traditional technology. New technologies are being developed to take advantage of these small water elevation changes, but they generally rely on the kinetic energy in the stream flow as opposed to the potential energy due to hydraulic head. These technologies are often referred to as kinetic hydropower or hydrokinetic (see Section 6.3 for more details on this technology). Hydrokinetic devices being developed to capture energy from tides and currents may also be deployed inland in both free-flowing rivers and in engineered waterways such as canals, conduits, cooling water discharge pipes or tailraces of existing dams. One type of these systems relies on underwater turbines, either horizontal or vertical. Large turbine blades would be driven by the moving water, just as windmill blades are moved by the wind; these blades would turn the generators and capture the energy of the water flow (Wellinghoff et al., 2008).

'Free flow' or 'hydrokinetic' generation captures energy from moving water without requiring a dam or diversion. While hydrokinetic technology includes generation from ocean tides, currents and waves, it is believed that its most practical application in the near term is likely to be in rivers and streams (see Section 6.3.4). Hydrokinetic turbines have low energy density.

A study from 2007 concluded that the current generating capacity of hydropower of 75,000 MW in the USA (excluding pumped storage) could be nearly doubled, including a contribution from hydrokinetic generation in rivers and constructed waterways of 12,800 MW (EPRI, 2007).

In a 'Policy Statement' issued on 30 November 2007 by the US Federal Energy Regulatory Commission (FERC, 2007) it is stated that:

> *"Estimates suggest that new hydrokinetic technologies, if fully developed, could double the amount of hydropower production in the United States, bringing it from just under 10 percent to close to 20 percent of the national electric energy supply. Given the potential benefits of this new, clean power source, the Commission has taken steps to lower regulatory barriers to its development."*

The potential contributions from very low head projects and hydrokinetic projects are usually not included in existing resource assessments for hydropower (see Section 5.2). The assessments are also usually based on rather old data and lower energy prices than today and future values. It is therefore highly probable that the hydropower resource potential

26 See: canmetenergy-canmetenergie.nrcan-rncan.gc.ca/eng/renewables/small_hydropower/fishfriendly_turbine.html.

27 Fish friendliness, Voith Hydro, June 2009, pp 18-21; www.voithhydro.com/media/Hypower_18_18.pdf.

will increase significantly as these new sources are more closely investigated and technology is improved.

5.7.5 New materials

Corrosion, cavitation damages and abrasion are major wearing effects on hydropower equipment. An intensified use of suitable proven materials such as stainless steel and the invention of new materials for coatings limit the wear on equipment and extend lifespan. Improvements in material development have been performed for almost every plant component. Examples include: a) penstocks made of fibreglass; b) better corrosion protection systems for hydro-mechanical equipment; c) better understanding of electrochemical corrosion leading to a suitable material combination; and d) trash rack systems with plastic slide rails.

Water in rivers often contains large amounts of sediments, especially during flood events when soil erosion creates high sediment loads. In reservoirs the sediments may have time to settle, but in run-of-the-river projects most of the sediments may follow the water flow up to the turbines. If the sediments contain hard minerals like quartz, the abrasive erosion of guide vanes, runners and other steel parts may become very high and quickly reduce efficiency or destroy turbines completely within a very short time (Lysne et al., 2003; Gummer, 2009). Erosive wear of hydropower turbine runners is a complex phenomenon, depending on different parameters such as particle size, density and hardness, concentration, velocity of water and base material properties. The efficiency of the turbine decreases with the increase in the erosive wear. The traditional solution to the problem has been to build de-silting chambers to trap the silt and flush it out in bypass outlets, but it is very difficult to trap all particles, especially the fines. New solutions are being developed by coating steel surfaces with a very hard ceramic coating, protecting against erosive wear or delaying the process.

The problem of abrasive particles in hydropower plants is not new, but is becoming more acute with increasing hydropower development in developing countries with sediment-rich rivers. For example, many new projects in India, China and South America are planned in rivers with high sediment concentrations (Gummer, 2009). The problem may also become more important in cases of increased use of hydropower plants in peaking applications.

Modern turbine design using three-dimensional flow simulation provides not only better efficiencies in energy conversion by improved shape of turbine runners and guide/stay vanes, but also leads to a decrease in cavitation damages at high-head power plants and to reduced abrasion effects when dealing with heavy sediment-loaded propulsion water. Other inventions concern, for example, improved self-lubricating bearings with lower damage potential and the use of electrical servo motors instead of hydraulic ones.

5.7.6 Tunnelling technology

Recently, new equipment for very small tunnels (0.7 to 1.3 m diameter) based on oil-drilling technology has been developed and tested in hard rock in Norway, opening up the possibility of directional drilling of 'penstocks' for small hydropower directly from the power station up to intakes, up to 1 km or more from the power station (Jensen, 2009). This could lower cost and reduce the environmental and visual impacts from above-ground penstocks for small hydropower, and open up even more sites for small hydropower.

5.7.7 Dam technology

The International Commission on Large Dams (ICOLD) recently decided to focus on better planning of existing and new (planned) hydropower dams. It is believed that the annual worldwide investment in dams will be about USD 30 billion during the next decade, and the cost can be reduced by 10 to 20% by more cost-effective solutions. ICOLD also wants to promote multipurpose dams and better planning tools for multipurpose water projects (Berga, 2008). Another main issue ICOLD is focusing on is that of small-scale dams between 5 and 15 m high.

The roller-compacted concrete dam is relatively new dam type, originating in Canada in the 1970s. This dam type is built using much drier concrete than in other gravity dams, and it allows a quicker and more economical dam construction (as compared to conventional concrete placing methods). It is assumed that this type of dams will be much more used in the future, lowering the construction cost and thereby also the cost of energy for hydropower projects.

5.7.8 Optimization of operation

Hydropower generation can be increased at a given plant by optimizing a number of different aspects of plant operations, including the settings of individual units, the coordination of multiple unit operations, and release patterns from multiple reservoirs. Based on the experience of federal agencies such as the Tennessee Valley Authority and on strategic planning workshops with the hydropower industry, it is clear that substantial operational improvements can be made in hydropower systems, given new investments in R&D and technology transfer (Sale et al., 2006b). In the future, improved hydrological forecasts combined with optimization models are likely to improve operation and water use, increasing the energy output from existing power plants significantly.

5.8 Cost trends[28]

Hydropower generation is a mature RE technology and can provide electricity as well as a variety of other services at low cost compared to many other power technologies. A variety of prospects for improvement of currently available technology as outlined in the above section exist, but these are unlikely to result in a clear and sustained cost trend due to other counterbalancing factors.

This section describes the fundamental factors affecting the levelized cost of electricity (LCOE) of hydropower plants: a) upfront investment costs; b) operation and maintenance (O&M) costs; c) decommissioning costs; d) the capacity factor; e) the economic lifetime of the investment; and f) the cost of project financing (discount rate).

Discussion of costs in this section is largely limited to the perspective of private investors. Chapters 1, 8, 10 and 11 offer complementary perspectives on cost issues covering, for example, costs of integration, external costs and benefits, economy-wide costs and costs of policies.

Historic and probable future cost trends are presented throughout this section drawing mainly on a number of studies that were published from 2003 up to 2010 by the IEA and other organizations. Box 5.3 contains brief descriptions of each of those studies to provide an overview of the material assessed for this section. The LCOEs provided in the studies themselves are not readily comparable, but have to be considered in conjunction with the underlying cost parameters that affect them. The parameters and resulting study-specific LCOE estimates range are summarized in Table 5.7a for recent conditions and Table 5.7b with a view to future costs.

Later in this section, some of the underlying cost and performance parameters that impact the delivered cost of hydroelectricity are used to estimate recent LCOE figures for hydropower plants across a range of input assumptions. The methodology used in these calculations is described in Annex II, while the input parameters and the resulting range of LCOEs are also listed in Annex III to this report and are reported in Chapters 1 and 10.

It is important to recognize, however, that the LCOE is not the sole determinant of the economic value or profitability of hydropower projects. Hydropower plants designed to meet peak electricity demands, for instance, may have relatively high LCOEs. However, in these instances, not only is the cost per unit of power usually higher, but also average power prices during periods of peak demand and thus revenues per unit of power sold to the market.

Since hydropower projects may provide multiple services in addition to the supply of electric power, the allocation of total cost to individual purposes also matters for the resulting LCOE. Accounting for costs of multipurpose projects is dealt with in Section 5.8.5.

5.8.1 Investment cost of hydropower projects and factors that affect it

Basically, there are two major cost groups for hydropower projects: a) the civil construction costs, which normally are the major costs of the hydropower project, and b) the cost related to electromechanical equipment for energy transformation. Additionally, investment costs include the costs of planning, environmental impact analysis, licensing, fish and wildlife mitigation, recreation mitigation, historical and archaeological mitigation and water quality monitoring and mitigation.

The civil construction costs follow the price trend of the country where the project is going to be developed. In the case of countries with economies in transition, the civil construction costs are usually lower than in developed countries due to the use of local labour and local construction materials.

Civil construction costs are always site specific, mainly due to the inherent characteristics of the topography, geological conditions and the construction design of the project. This could lead to different investment cost and LCOE even for projects of the same capacity.

The costs of electromechanical equipment—in contrast to civil construction cost—follow world market prices for these components. Alvarado-Ancieta (2009) presents the typical cost of electromechanical equipment from various hydropower projects in Figure 5.17.

Figure 5.18 shows the investment cost trend for a large number of investigated projects of different sizes in the USA. The figure is from a study by Hall et al. (2003) that presents typical plant investment costs for new sites.

Figure 5.18 shows that while there is a general tendency of increasing investment cost as the capacity increases, there is also a wide range of cost for projects of the same capacity, given by the spread from the general (blue) trend line. For example, a project of 100 MW in size has an average investment cost of USD_{2002} 200 million (USD_{2002} 2,000/kW) but the range of costs is from less than USD_{2002} 100 million (USD_{2002} 1,000/kW) and up to more than USD_{2002} 400 million (USD_{2002} 4,000/kW). (There could of course also be projects with higher costs, but these have already been excluded from analysis in the selection process).

In hydropower projects where the installed capacity is less than 5 MW, the electromechanical equipment costs tend to dominate. As the capacity increases, the costs are increasingly influenced by the cost of civil structures. The components of the construction project that impact the civil construction costs most are dams, intakes, hydraulic pressure conduits (tunnels and penstocks) and power stations; therefore,

28 Chapter 10.5 offers a complementary perspective on drivers and trends of technological progress across RE technologies.

Box 5.3 | Brief description of some important hydropower cost studies.

Hall et al. (2003) published a study for the USA where 2,155 sites with a total potential capacity of 43,036 MW were examined and classified according to investment cost. The distribution curve shows investment costs that vary from less than USD 500/kW up to over USD 6000/kW (Figure 5.18). Except for a few projects with very high cost, the distribution curve is nearly linear for up to 95% of the projects. The investment cost of hydropower as defined in the study included the cost of licensing, plant construction, fish and wildlife mitigation, recreation mitigation, historical and archaeological mitigation and water quality monitoring cost.

VLEEM-2003 (Very Long Term Energy-Environment Model) was an EU-funded project executed by a number of research institutions in France, Germany, Austria and the Netherlands. One of the reports contains detailed information, including cost estimates, for 250 hydropower projects worldwide with a total capacity of 202,000 MW, with the most in-depth focus on Asia and Western Europe (Lako et al., 2003). The projects were planned for commissioning between 2002 and 2020.

WEA-2004. The World Energy Assessment (WEA) was first published in 2000 by the United Nations Development Programme (UNDP), the United Nations Department of Economic and Social Affairs (UNDESA) and the World Energy Council (WEC). An update to the original report (UNDP/UNDESA/WEC, 2000) was issued in 2004 (UNDP/UNDESA/WEC, 2004), and data from this version are used here. The report gives cost estimates for both current and future hydropower development. The cost estimates are given both as turnkey investment cost in USD per kW and as energy cost in US cents per kWh. Both cost estimates and capacity factors are given as a range with separate values for small and large hydropower.

IEA has published several reports, including *World Energy Outlook 2008* (IEA, 2008a), *Energy Technology Perspectives 2008* (IEA, 2008b) and *Projected Costs of Generating Electricity 2010 Edition* (IEA, 2010b) where cost data can be found both for existing and future hydropower projects.

EREC/Greenpeace. The European Renewable Energy Council (EREC) and Greenpeace presented a study in 2008 called *Energy [R] evolution: A Sustainable World Energy Outlook* (Teske et al., 2010). The report presents a global energy scenario with increasing use of renewable energy, in particular wind and solar energy. It contains a detailed analysis up to 2050 and perspectives for beyond, up to 2100. Hydropower is included and future scenarios for cost are given from 2008 up to 2050.

BMU Lead Study 2008. *Further development of the strategy to increase the use of renewable energies within the context of the current climate protection goals of Germany and Europe* (BMU, 2008) was commissioned by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and published in October 2008. It contains estimated cost for hydropower development up to 2050.

Krewitt et al. (2009) reviewed and summarized findings from a number of studies from 2000 through 2008. The main sources of data for future cost estimates were UNDP/UNDESA/WEC (2000), Lako et al. (2003), UNDP/UNDESA/WEC (2004) and IEA (2008).

REN21. The global status reports by the Renewable Energy Policy Network for the 21st Century (REN21) are published regularly, with the last update in 2010 (REN21, 2010).

ECOFYS 2008. In the background paper *Global Potential of Renewable Energy sources: A Literature Assessment*, provided by Ecofys for REN21, data can be found both for assumed hydropower resource potential and cost of development for undeveloped technical potential (Hoogwijk and Graus, 2008).

these elements have to be optimized carefully during the engineering design stage.

The same overall generating capacity can be achieved with a few large or several smaller generating units. Plants using many small generating units have higher costs per kW than plants using fewer, but larger units. Higher costs per kW installed capacity associated with a higher number of generating units are justified by greater efficiency and flexibility of the hydroelectric plants' integration into the electric grid.

Table 5.7a | Cost ranges for hydropower: Summary of main cost parameters from 10 studies.

Source	Investment cost (IC) (USD_{2005}/kW)	O&M cost (% of IC)	Capacity Factor (%)	Lifetime (years)	Discount rate (%)	LCOE (cents/kWh)	Comments
Hall et al. 2003 *Ref: Hall et al. (2003)*	<500 – 6,200 Median 1,650 90% below 3,250		41 – 61				2,155 Projects in USA 43,000 MW in total Annual Capacity factor (except Rhode Island)
VLEEM-2003 *Ref: Lako et al. (2003)*	<500 – 4,500 Median 1,000 90% below 1,700		55 – 60				250 Projects for commissioning 2002–2020 Total Capacity 202,000 MW Worldwide but mostly Asia and Europe
WEA 2004 *Ref: UNDP/UNDESA/WEC (2004)*	1,000 – 3,500 700 – 8,000		35 – 60 20 – 90			2 – 10 2 – 12	Large Hydro Small Hydro (<10 MW) (Not explicitly stated as levelized cost in report)
IEA-WEO 2008 *Ref: IEA (2008a)*	2,184	2.5	45	40	10	7.1	
IEA-ETP 2008 *Ref: IEA (2008b)*	1,000 – 5,500 2,500 – 7,000	2.2 – 3			10 10	3 – 12 5.6 – 14	Large Hydro Small Hydro
EREC/Greenpeace *Ref: Teske et al. (2010)*	2,880 in 2010	4	45	40	10	10.4	
BMU Lead Study 2008 *Ref: BMU (2008)*	2,440				6	7.3	Study applies to Germany only
Krewitt et al 2009 *Ref: Krewitt et al. (2009)*	1,000 – 5,500	4	33	30		9,8	Indicative average LCOE year 2000
IEA-2010 *Ref: IEA (2010b)*	750 – 19,000 in 2010 (1,278 average)		51	80 80		2.3 – 45.9 4.8	Range for 13 projects from 0.3 to 18,000 MW Weighted average for all projects
REN21 *Ref: REN21 (2010)*						5 – 12 3 – 5 5 – 40	Small Hydro (<10 MW) Large Hydro (>10 MW) Off-Grid (<1 MW)

Table 5.7b | Future cost of hydropower: Summary of main cost parameters from five studies.

Source	Investment cost (IC) (USD_{2005}/kW)	O&M cost (% of IC)	Capacity Factor (%)	Lifetime (years)	Discount rate (%)	LCOE (cents/kWh)	Comments
WEA 2004 *Ref: UNDP/UNDESA/WEC (2004)*						2 – 10	No trend—Future cost same as in 2004 Same for small and large hydro
IEA-WEO 2008 *Ref: IEA (2008a)*	2,194 in 2030 2,202 in 2050	2.5 2.5	45 45	40 40	10 10	7.1 7.1	
IEA-ETP 2008 *Ref: IEA (2008b)*	1,000 – 5,400 in 2030 1,000 – 5,100 in 2050 2,500 – 7,000 in 2030 2,000 – 6,000 in 2050	2.2 – 3			10 10 10 10	3 – 11.5 3 – 11 5.2 – 13 4.9 – 12	Large Hydro Large Hydro Small Hydro Small Hydro
EREC/Greenpeace *Ref: Teske et al. (2010)*	3,200 in 2030 3,420 in 2050	4 4	45 45	40 40	10 10	11.5 12.3	
Krewitt et al 2009 *Ref: Krewitt et al. (2009)*	1,000 – 5,400 in 2030 1,000 – 5,100 in 2050	4 4	33 33	30 30		10.8 11.9	Indicative average LCOE in 2030 Indicative average LCOE in 2050

Specific investment costs (per installed kW) tend to be reduced for a higher head and higher installed capacity of the project. With higher head, the hydropower project can be set up to use less volume flow, and therefore smaller hydraulic conduits or passages. The size of the equipment is also smaller and related costs are lower.

Results from two of the studies listed in Box 5.3 and Table 5.7a can be used to illustrate the characteristic distribution of investment costs within certain geographic areas. The detailed investment cost surveys provide an assessment of how much of the technical potential can be exploited at or below specific investment costs. Such studies are not readily available in the published literature for many regions. The results of two studies on cumulative investment costs are presented in Figure 5.19. A summary from a study of investment cost typical of the USA by Hall et al. (2003) shows a range of investment costs for 2,155 hydropower projects with a total capacity of 43,000 MW from less than USD_{2005} 500/kW up to more than USD_{2005} 6,000/kW. Twenty-five percent of the assessed technical potential can be developed at an investment cost of up to USD_{2005} 960/kW, an

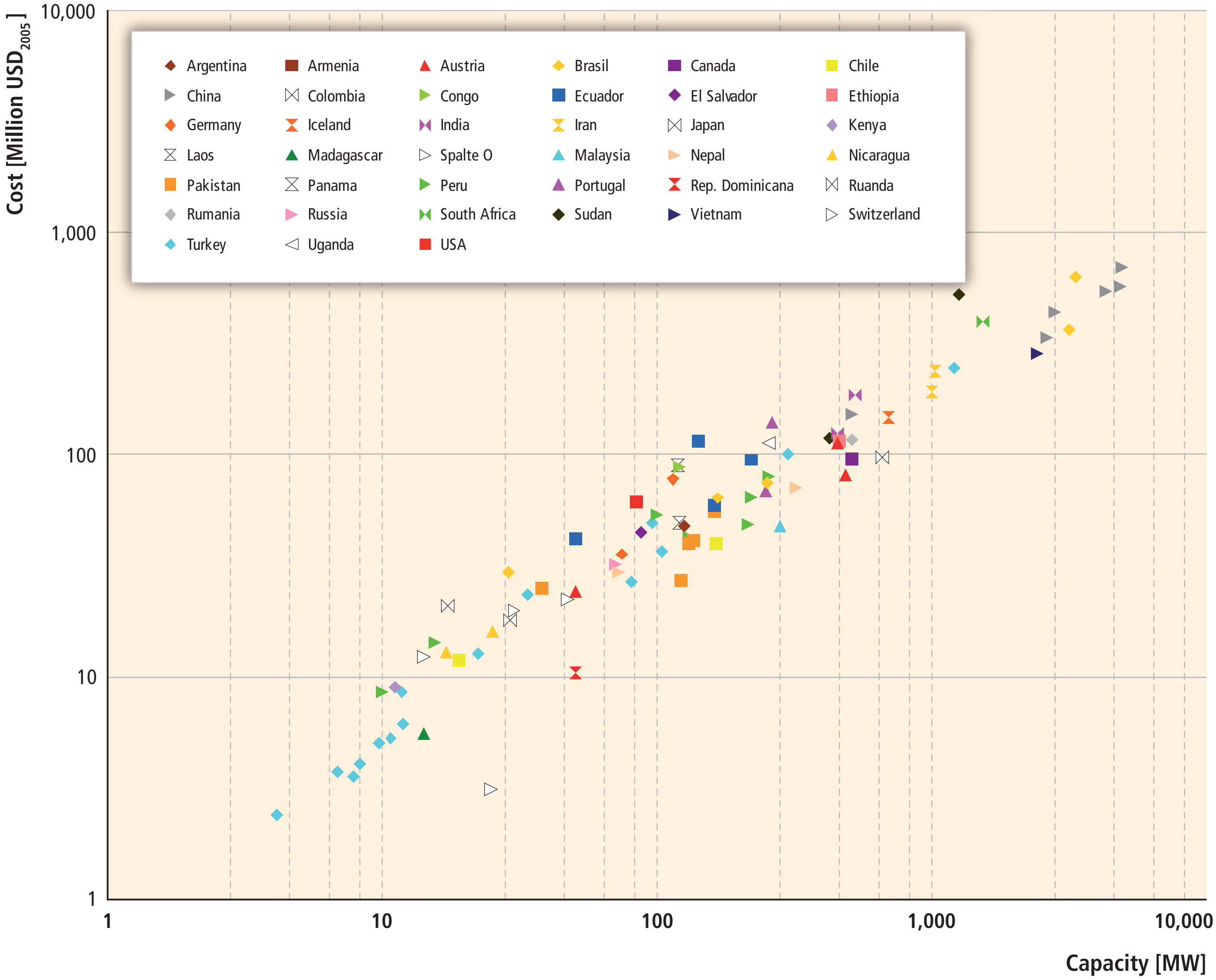


Figure 5.17 | Costs of electrical and mechanical equipment as a function of installed capacity in 81 hydropower plants in America, Asia, Europe and Africa in USD_{2008}. Source: Alvarado-Ancieta (2009).

additional 25% at costs between USD_{2005} 960 and 1,650/kW, and another 25% at costs between USD_{2005} 1,650 and 2,700/kW.

A similar summary of cost estimates for 250 projects worldwide with a total capacity of 202,000 MW has been compiled in the VLEEM-2003 study (Lako et al., 2003). Here, the range of investment costs are from USD_{2005} 450/kW up to more than USD_{2005} 4500/kW. Weighted costs (percentiles) are: 25% can be developed at costs up to USD_{2005} 660/kW, 50% (median) at costs up to USD_{2005} 1,090/kW, and 75% at costs up to USD_{2005} 1,260/kW. In general, these and other studies suggest average recent investment cost figures for storage hydropower projects of USD_{2005} 1,000 to 3,000/kW. Small projects in certain areas may sometimes have investment costs that exceed these figures, while lower investment costs are also sometimes feasible. For the purpose of the LCOE calculations that follow, however, a range of USD_{2005} 1,000 to 3,000/kW is considered representative of most hydropower projects.

5.8.2 Other costs occurring during the lifetime of hydropower projects

Operation and maintenance (O&M) costs: Once built and put in operation, hydropower plants usually require very little maintenance and operation costs can be kept low, since hydropower plants do not have recurring fuel costs. O&M costs are usually given as a percentage of investment cost per kW. The EREC/Greenpeace study (Teske et al., 2010) and Krewitt et al. (2009) used 4%, which may be appropriate for small-scale hydropower but is too high for large-scale hydropower plants.

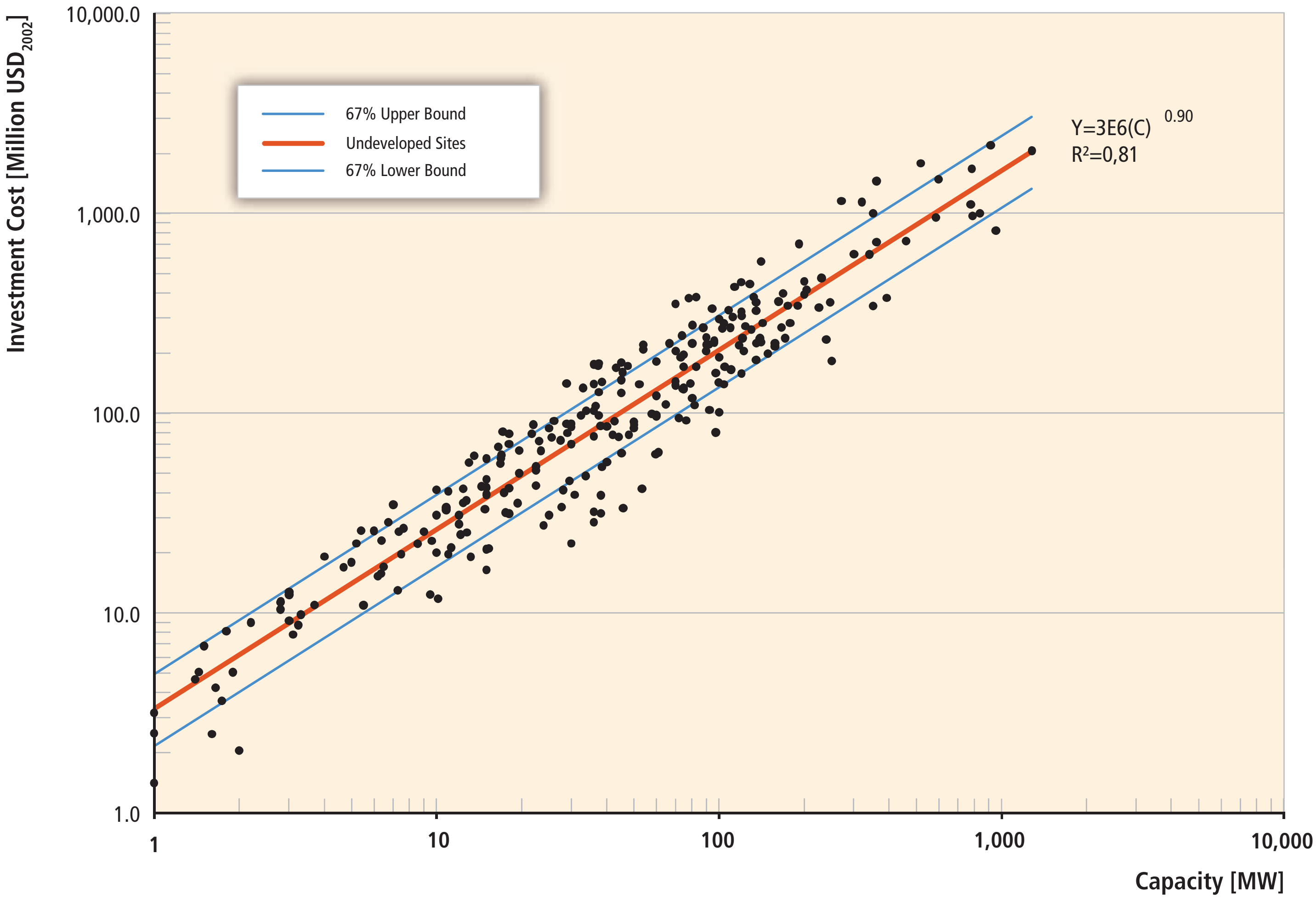


Figure 5.18 | Hydropower plant investment cost as a function of plant capacity for undeveloped sites. Adapted from Hall et al. (2003) (Note: both axes have a logarithmic scale).

The IEA WEO used 2.5% (IEA, 2008a) and 2.2% for large hydropower increasing to 3% for smaller and more expensive projects in IEA-ETP (IEA, 2008b). A typical average O&M cost for hydropower is 2.5%, and this figure is used in the LCOE calculations that follow.

Decommissioning cost: Hydropower plants are rarely decommissioned and it is therefore very difficult to find information about decommissioning costs in the literature. An alternative to decommissioning is project re-licensing and continued operation. A few cases of dam decommissioning are reported in the literature, but these dams are usually not hydropower dams. Due to the long lifetime of hydropower projects (see Section 5.8.3), the decommissioning costs occurring 40 to 80 years into the future are unlikely to contribute significantly to the LCOE. Therefore, decommissioning costs are usually not included in LCOE analyses for hydropower.

5.8.3 Performance parameters affecting the levelized cost of hydropower

Capacity factor: For variable energy sources like solar, wind and waves, the statistical distribution of the energy resource will largely determine the capacity factor. For hydropower, however, the capacity factor is usually designed in the planning and optimization of the project, by considering both the statistical distribution of flow and the market demand characteristics for power. A peaking power plant will be designed to have a low capacity factor, for example 10 to 20%, in order to supply peaking power to the grid only during peak hours. On the other hand, a power plant designed for supplying energy to aluminium plants may be designed to have a capacity factor of 80% or more, in order to supply a nearly constant base load. Reservoirs may be built in order to increase the stability of flow for base-load production, but could also be designed for supplying highly variable (but reliable) flow to a peaking power plant.

A low capacity factor gives low production and higher LCOE. Krewitt et al. (2009) used a low value for hydropower, 2,900 hours or 33%, while, for example, IEA (2010b) used an average of 4,470 hours or 51%. An analysis of energy statistics from the IEA shows that typical capacity factors for existing hydropower systems are in the range from below 40 to nearly 60% (USA 37%, China 42%, India 41%, Russia 43%, Norway 49%, Brazil 56%, Canada 56%). In Figure 5.3, average capacity factors are given for each region, with 32% in Australasia/Oceania, 35% in

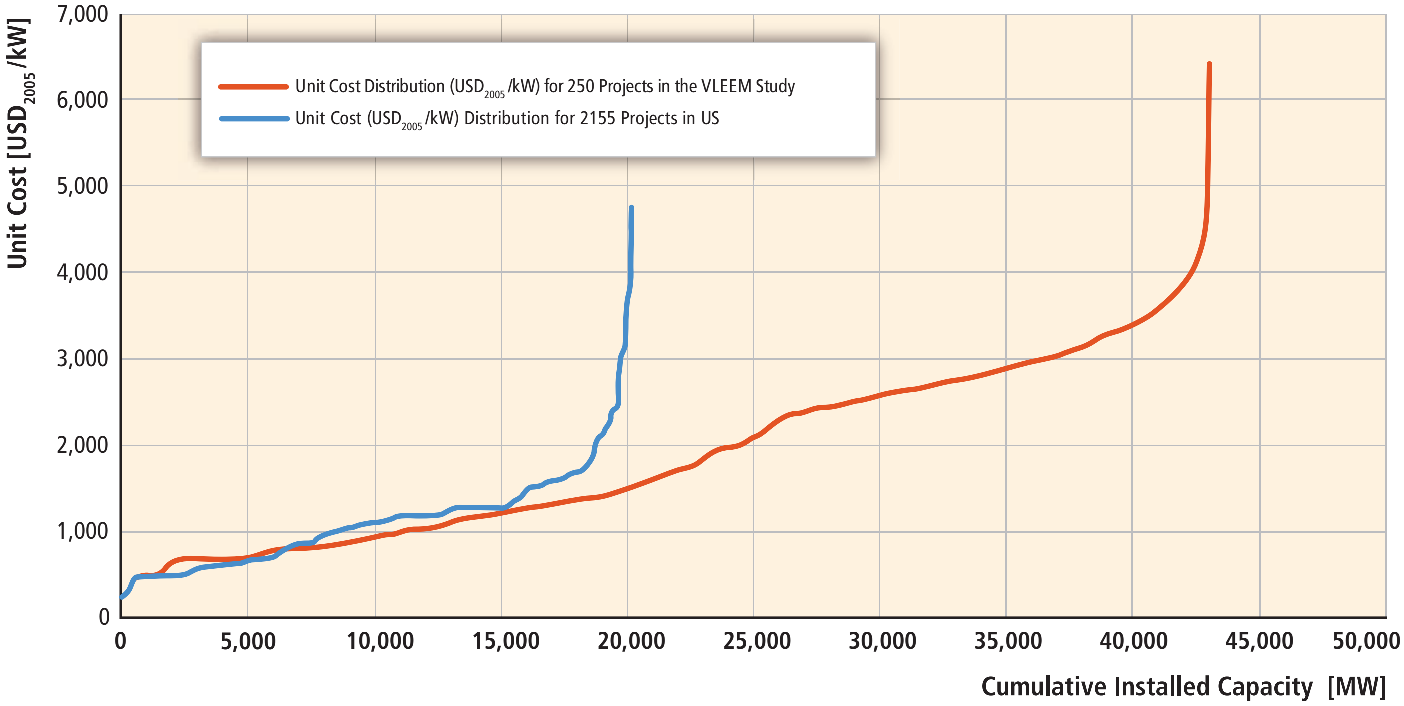


Figure 5.19 | Distribution of investment cost (USD_{2005}/kW) for 2,155 hydropower project sites studied in the USA (Hall et al., 2003), and for 250 hydropower project sites worldwide studied in the VLEEM project (Lako et al., 2003). This graph is also called a cumulative capacity curve.

Europe, 43% in Asia, 47% in North America, 47% in Africa and 54% in Latin America. The weighted world average in 2009 was roughly 44%.

Based on the parameters listed in Annex III and methods described in Annex II, Figure 5.20 (upper) illustrates the effect of capacity factors in the range of 30 to 60% on the LCOE of hydropower under three different investment cost scenarios: USD_{2005} 1,000/kW, 2,000/kW and 3,000/kW; other parameter assumptions include a 2.5%/yr O&M cost as a proportion of investment cost, a 60-year economic design lifetime, and a 7% discount rate. Average regional hydropower capacity factors from Figure 5.3 are also shown in the graph.

Lifetime: For hydropower, and in particular large hydropower, the largest cost components are civil structures with very long lifetimes, like dams, tunnels, canals, powerhouses etc. Electrical and mechanical equipment, with much shorter lifetimes, usually contribute less to the cost. It is therefore common to use a longer lifetime for hydropower than for other electricity generation sources. Krewitt et al. (2009) used 30 years, IEA-WEO 2008 (IEA, 2008a) and Teske et al. (2010) used 40 years and the IEA (2010b) used 80 years as the lifetime for hydropower projects. A range of 40 to 80 years is used in the LCOE calculations presented in Annex III as well as in Chapters 1 and 10.

Discount rate:[29] The discount rate is not strictly a performance parameter. Nonetheless, it can have a critical influence on the LCOE depending on the patterns of expenditures and revenues that typically occur over the lifetime of the investment. Private investors usually choose discount rates according to the risk-return characteristics of available investment alternatives. A high discount rate will be beneficial for technologies with low initial investment and high running costs. A low discount rate will generally favour RE sources, as many of these, including hydropower, have relatively high upfront investment cost and low recurring costs. This effect will be even more pronounced for technologies with long lifetimes like hydropower. In some of the studies, it is not stated clearly what discount rate was used to calculate the LCOE. The BMU Lead Study 2008 (BMU, 2008) used 6%. In IEA (2010b) energy costs were computed for both 5 and 10% discount rates. For hydropower, an increase from 5 to 10% gives an increase in the LCOE of nearly 100%. The relationship between the discount rate and resulting LCOE is illustrated in Figure 5.20 (lower) for discount rates of 3, 7 and 10% as used in this report over a range of capacity factors, and using other input assumptions as follows: investment costs of USD_{2005} 2,000/kW, O&M cost of 2.5%/yr of investment cost, and an economic design lifetime of 60 years.

5.8.4 Past and future cost trends for hydropower projects

There is relatively little information on historical trends of hydropower cost in the literature. Such information could be compiled by studying a large number of already-implemented projects, but because hydropower projects are so site-specific it would be difficult to identify trends in project component costs unless a very detailed and time-consuming analysis was completed for a large sample of projects. It is therefore difficult to present historical trends in investment costs and LCOE.

29 For a general discussion of the effect of the choice of the discount rate on LCOE, see Section 10.5.1.

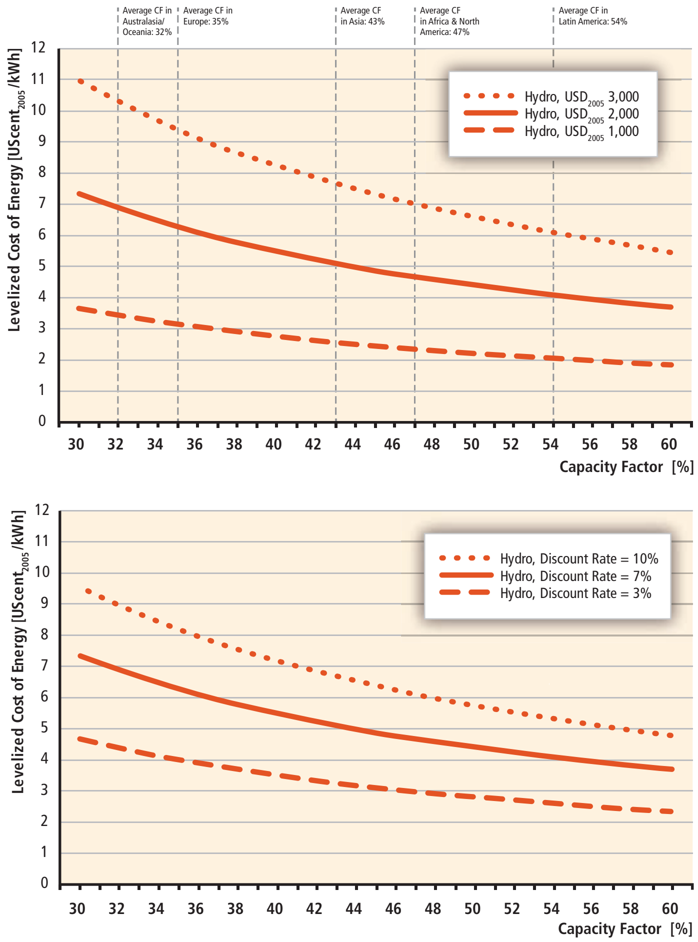


Figure 5.20 | Recent estimated levelized cost of hydropower. Upper panel: Cost of hydropower as a function of capacity factor and investment cost. Lower panel: Cost of hydropower as a function of capacity factor and discount rate. Source: Annex III.

Note: In the upper panel the discount rate is assumed to equal 7%, in the lower panel the investment cost is assumed to be USD 2,000/kW, and in both panels the annual O&M cost is assumed at 2.5%/yr of investment cost and plant lifetime as 60 years.

As a general trend, it can be assumed that projects with low cost will tend to be developed first, and once the best projects have been developed, increasingly costly projects will be developed. (There are, however, many barriers and the selection of the 'cheapest projects first' may not always be possible. Some of these barriers are discussed in Section 5.4.5.) Overall, this general trend could lead to a gradually increasing cost for new projects.

On the other hand, technological innovation and improvements (as discussed in Section 5.7) could lower the cost in the future. Empirical evidence for reductions in the cost of specific components of hydropower systems is provided for tunnelling costs in Figure 5.10. However, evidence for an overall trend with respect to the specific investment cost of hydropower projects or the levelized cost of hydropower cannot be deduced from such information and is very limited. Kahouli-Brahmi (2008) found historical learning rates in the range from 0.5 to 2% for the investment cost of hydropower (for different types of hydropower with varying regional scope and time periods).

In the studies included in Box 5.3 and Table 5.7b, there is no consensus on the future cost trend. Some studies predict a gradually lowering cost (IEA, 2008b; Krewitt et al., 2009), some a gradually increasing cost and one no trend (UNDP/UNDESA/WEC, 2004).

A reason for this may be the complex cost structure of hydropower plants, where some components may have decreasing cost trends (for example tunnelling costs), while other may have increasing cost trends (for example social and environmental mitigation costs). This is discussed, for example, in WEA-2004 (see Box 5.3) where the conclusion is that these factors probably balance each other.

There is significant technical potential for increased hydropower development, as discussed in other sections of this chapter. Since hydropower projects are site-specific, this technical potential necessarily includes projects with widely varying costs, likely ranging from under USD_{2005} 500/kW up to and over USD_{2005} 5,000/kW.

Investment costs based on studies in Table 5.7a (recent) and Table 5.7b (future) are typically in the range from USD_{2005} 1,000 to 3,000/kW, though higher and lower cost possibilities exist, as discussed earlier. Since different studies do not agree on trends in future cost, the present cost range is assumed as typical for the near-term future up to 2020. With investment costs ranging from USD_{2005} 1,000 to 3,000/kW and capacity factor and O&M costs as discussed earlier, typical values for the LCOE of hydropower can be computed for different discount rates (3, 7, 10) and lifetimes (40 and 80 years). The results are shown in Table 5.8, giving an indication of the typical LCOE for hydropower in the near-term future up to 2020. The O&M cost was fixed at 2.5% per year and capacity factor at 45% for the purpose of the results presented in the table.

The LCOE values in Table 5.8 are well within the typical range of cost estimates given in Table 5.7a, (UNDP/UNDESA/WEC, 2004; BMU, 2008; IEA, 2008b; IEA, 2010b; REN21, 2010) but somewhat lower than the values found by Teske et al. (2010) and Krewitt et al. (2009). The results demonstrate that LCOE is very sensitive to investment costs and interest rates, but less sensitive to lifetime, within the lifetime range typical for hydropower (40 to 80 years). Particularly small projects would be expected to have higher investment costs on a dollar per kW basis, and therefore may tend towards the higher end of the range presented in Table 5.8, and may in some instances fall above that range.

5.8.5 Cost allocation for other purposes

Hydropower stations can be installed along with multiple purposes such as irrigation, flood control, navigation, provision of roads,

Table 5.8 | LCOE estimation for parameters typical of current and near-term future hydropower projects in US cents$_{2005}$ (2010 up to 2020).

Investment cost (USD$_{2005}$/kW)	Discount rate (%)	O&M cost (%/yr)	Capacity factor (%)	Lifetime (years)	LCOE (cents/kWh)	Lifetime (years)	LCOE (cents/kWh)
1,000	3	2.5	45	40	1.7	80	1.5
1,000	7	2.5	45	40	2.5	80	2.4
1,000	10	2.5	45	40	3.2	80	3.2
2,000	3	2.5	45	40	3.5	80	2.9
2,000	7	2.5	45	40	5.1	80	4.8
2,000	10	2.5	45	40	6.5	80	6.3
3,000	3	2.5	45	40	5.2	80	4.4
3,000	7	2.5	45	40	7.6	80	7.3
3,000	10	2.5	45	40	9.7	80	9.5

drinking water supply, fish supply and recreation. Many of the purposes cannot be served alone as they have consumptive use of water and may have different priority of use. There are different methods of allocating the cost to individual purposes, each of which has advantages and drawbacks. The basic rules for cost allocation are that the allocated cost to any purpose does not exceed the benefit of that purpose and each purpose will carry its separable cost. Separable cost for any purpose is obtained by subtracting the cost of a multipurpose project without that purpose from the total cost of the project with the purpose included (Dzurik, 2003). Three commonly used cost allocation methods are: the separable cost-remaining benefits method (US Inter-Agency Committee on Water Resources, 1958), the alternative justifiable expenditure method (Petersen, 1984) and the proportionate use-of-facilities method (Hutchens, 1999).

Historically, reservoirs were mostly funded and owned by the public sector, thus project profitability was not the highest consideration or priority in the decision. Today, the liberalization of the electricity market has set new economic standards for the funding and management of dam-based projects. The investment decision is based on an evaluation of viability and profitability over the full lifecycle of the project. The merging of economic elements (energy and water selling prices) with social benefits (flood protection, supplying water to farmers in case of lack of water) and the value of the environment (to preserve a minimum environmental flow) are becoming tools for consideration of cost sharing for multipurpose reservoirs (Skoulikaris, 2008).

Votruba et al. (1988) reported the practice in Czechoslovakia for cost allocation in proportion to benefits and side effects expressed in monetary units. In the case of the Hirakund project in India, the principle of the alternative justifiable expenditure method was followed, with the allocation of the costs of storage capacities between flood control, irrigation and power in the ratio of 38:20:42 (Jain, 2007). The Government of India later adopted the use-of-facilities method for allocation of joint costs of multipurpose river valley projects (Jain, 2007).

5.9 Potential deployment[30]

Hydropower offers significant potential for near- and long-term carbon emissions reductions. The hydropower capacity installed by the end of 2008 delivered roughly 16% of worldwide electricity supply: hydropower is by far the largest current source of RE in the electricity sector (representing 86% of RE electricity in 2008). On a global basis, the hydropower resource is unlikely to constrain further development in the near to medium term (Section 5.2), though environmental and social concerns may limit deployment opportunities if not carefully managed (Section 5.6). Hydropower technology is already being deployed at a rapid pace (see Sections 5.3 and 5.4), therefore offering an immediate option for reducing carbon emissions from the electricity sector. With good conditions, the LCOE can be around 3 to 5 cents/kWh (see Section 5.8). Hydropower is a mature technology and is at the crossroads of two major issues for development: water and energy. This section begins by highlighting near-term forecasts (2015) for hydropower deployment (Section 5.9.1). It then discusses the prospects for and potential barriers to hydropower deployment in the longer term (up to 2050) and the potential role of that deployment in reaching various GHG concentration stabilization levels (Section 5.9.2). Both sections are largely based on energy market forecasts and carbon and energy scenarios literature published in the 2006 to 2010 time period.

5.9.1 Near-term forecasts

The rapid increase in hydropower capacity over the last 10 years is expected by several studies, among them EIA (2010) and IEA (2010c), to continue in the near term (see Table 5.9). Much of the recent global increase in renewable electricity supply has been fuelled by hydropower and wind power. From the 945 GW of hydropower capacity, including pumped storage power plants, installed at the end of 2008, the IEA (2010c) and US Energy Information Administration (EIA, 2010) reference-case forecasts predict growth to 1,119 and 1,047 GW, respectively, by 2015 (e.g., and additional 25 and 30 GW/yr, respectively, by 2015).

30 Complementary perspectives on potential deployment based on a comprehensive assessment of numerous model based scenarios of the energy system are presented in Sections 10.2 and 10.3 of this report.

Table 5.9 | Near-term (2015) hydropower energy forecasts.

Study	Hydropower situation				Hydropower forecast for 2015		
	Reference year	Installed capacity (GW)	Electricity generation (TWh/EJ)	Percent of global electricity supply (%)	Installed capacity (GW)	Electricity generation (TWh/EJ)	Percent of global electricity supply (%)
IEA (2010c)	2008	945[1]	3 208/11.6	16	1,119	3,844/13.9	16%
EIA (2010)	2006	776	2 997/10.8	17	1,047	3,887/14	17%

Note: 1. Including pumped storage hydropower plants.

Non-OECD countries, and in particular Asia (China and India) and Latin America, are projected to lead in hydropower additions over this period.

5.9.2 Long-term deployment in the context of carbon mitigation

The IPCC's Fourth Assessment Report (AR4) assumed that hydropower could contribute 17% of global electricity supply by 2030, or 5,382 TWh/yr (~19.4 EJ/yr) (Sims et al., 2007). This figure is not much higher than some commonly cited business-as-usual cases. The IEA's World Energy Outlook 2010 reference scenario, for example, projects 5,232 TWh/yr (18.9 EJ/yr) of hydropower by 2030, or 16% of global electricity supply (IEA, 2010c). The EIA forecasts 4,780 TWh/yr (17.2 EJ/yr) of hydropower in its 2030 reference case projection, or 15% of net electricity production (EIA, 2010).

Beyond the reference scenario, the IEA's World Energy Outlook 2010 presents three additional GHG mitigation scenarios (IEA, 2010c). In the most stringent 450 ppm stabilization scenarios in 2030, installed capacity of new hydropower increases by 689 GW compared to 2008 or 236 GW compared to the Existing Policies scenario in 2030. The report highlights that there is an increase in hydropower supply with increasingly low GHG concentration stabilization levels. Hydropower is estimated to increase annually by roughly 31 GW in the most ambitious mitigation scenario (i.e., 450 ppm) until 2030.

A summary of the literature on the possible future contribution of RE supplies in meeting global energy needs under a range of GHG concentration stabilization scenarios is provided in Chapter 10. Focusing specifically on hydro energy, Figures 5.21 and 5.22 present modelling results on the global supply of hydro energy in EJ/yr and as a percent of global electricity demand, respectively. About 160 different long-term scenarios underlie Figures 5.21 and 5.22. Those scenario results derive from a diversity of modelling teams, and span a wide range of assumptions for—among other variables—energy demand growth, the cost and availability of competing low-carbon technologies and the cost and availability of RE technologies (including hydro energy). Chapter 10 discusses how changes in some of these variables impact RE deployment outcomes, with Section 10.2.2 providing a description of the literature from which the scenarios have been taken. In Figures 5.21 and 5.22, the hydro energy deployment results under these scenarios for 2020, 2030 and 2050 are presented for three GHG concentration stabilization ranges, based on the AR4: Baselines (>600 ppm CO_2), Categories III and IV (440 to 600 ppm CO_2) and Categories I and II (<440 ppm CO_2), all by 2100. Results are presented for the median scenario, the 25th to 75th percentile range among the scenarios, and the minimum and maximum scenario results.[31]

The baseline projections of hydropower's role in global energy supply span a broad range, with medians of roughly 13 EJ in 2020,[32] 15 EJ in 2030 and 18 EJ in 2050 (Figure 5.21). Some growth of hydropower is therefore projected to occur even in the absence of GHG mitigation policies, but with hydropower's median contribution to global electricity supply dropping from about 16% today to less than 10% by 2050. The decreasing share of hydroelectricity despite considerable absolute growth in hydropower supply is a result of expected energy demand growth and continuing electrification. The contribution of hydropower grows to some extent as GHG mitigation policies are assumed to become more stringent: by 2030, hydropower's median contribution equals roughly 16.5 EJ in the 440 to 600 and <440 ppm CO_2 stabilization ranges (compared to the median of 15 EJ in the baseline cases), increasing to about 19 EJ by 2050 (compared to the median of 18 EJ in the baseline cases).

The large diversity of approaches and assumptions used to generate these scenarios results in a wide range of findings. Baseline results for hydropower supply in 2050 range from 14 to 21 EJ at the 25th and 75th percentiles (median 18 EJ), or 7 to 11% (median 9%) of global electricity supply. In the most stringent <440 ppm stabilization scenarios, hydropower supply in 2050 ranges from 16 to 24 EJ at the 25th and 75th percentiles (median 19 EJ), equivalent to 8 to 12% (median 10%) of global electricity supply.

31 In scenario ensemble analyses such as the review underlying the figures, there is a constant tension between the fact that the scenarios are not truly a random sample and the sense that the variation in the scenarios does still provide real and often clear insights into collective knowledge or lack of knowledge about the future (see Section 10.2.1.2 for a more detailed discussion).

32 12.78 EJ was reached already in 2009 and thus the average estimates of 13 EJ for 2020 will be exceeded soon, probably already in 2010. Also, some scenario results provide lower values than the current installed capacity for 2020, 2030 and 2050, which is counterintuitive given, for example, hydropower's long lifetimes, its significant market potential and other important services. These results could maybe be explained by model/scenario weaknesses (see discussions in Section 10.2.1.2 of this report).

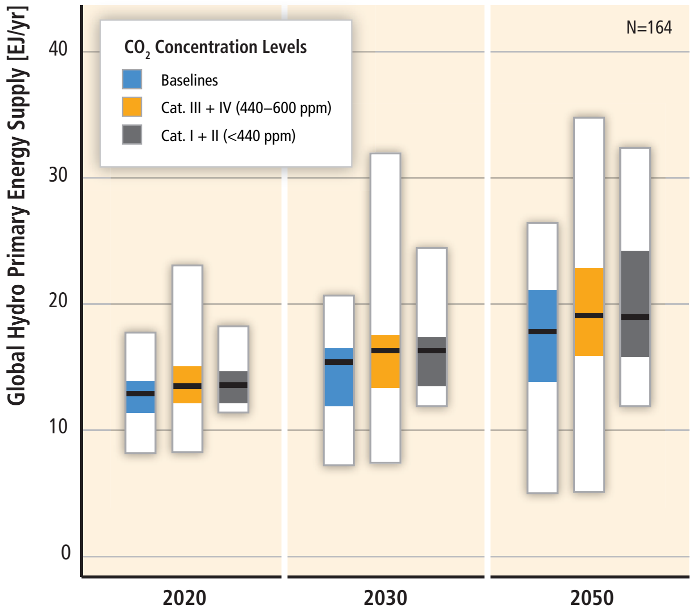


Figure 5.21 | Global primary energy supply from hydro energy in long-term scenarios (median, 25th to 75th percentile range, and full range of scenario results; colour coding is based on categories of atmospheric CO_2 concentration level in 2100; the specific number of scenarios underlying the figure is indicated in the right upper corner) (adapted from Krey and Clarke, 2011; see also Chapter 10).

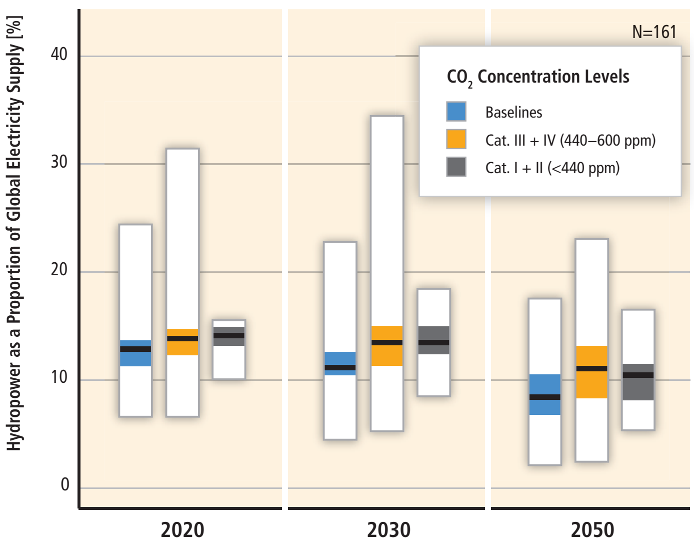


Figure 5.22 | Hydropower electricity share of total global electricity supply in the long-term scenarios (median, 25th to 75th percentile range, and full range of scenario results; colour coding is based on categories of atmospheric CO_2 concentration level in 2100; the specific number of scenarios underlying the figure is indicated in the right upper corner) (adapted from Krey and Clarke, 2011; see also Chapter 10).

Despite this wide range, hydropower has the lowest range compared to other renewable energy sources (see Chapter 10). Moreover, the AR4 estimate for potential hydropower supply of 19.4 EJ by 2030 appears somewhat conservative compared to the more recent scenarios literature presented above, which reaches 24 EJ in 2030 for the IEA's 450 ppm scenario (IEA, 2010c).

Although the literature summarized in Figure 5.21 shows an increase in hydropower supply for scenarios aiming at lower GHG concentration stabilization levels, that impact is smaller than for bioenergy, geothermal, wind and solar energy, where increasingly stringent GHG concentration stabilization ranges lead to more substantial increases in technology deployment (Section 10.2.2.5). One explanation for this result is that hydropower is already mature and economically competitive; as a result, deployment is projected to proceed steadily even in the absence of ambitious efforts to reduce GHG emissions.

The scenarios literature also shows that hydropower could play an important continuing role in reducing global carbon emissions: by 2050, the median contribution of hydropower in the two stabilization categories is around 19 EJ, increasing to 23 EJ at the 75th percentile, and to 35 EJ in the highest scenario. To achieve this contribution requires hydropower to deliver around 11% of global electricity supply in the medium case, or 14% at the 75th percentile. Though this implies a decline in hydropower's contribution to the global electricity supply on a percentage basis, it would still require significant absolute growth in hydropower generation.

Assuming that lower hydropower costs prevail and that growth continues based on the current trend (e.g., the same used in the IEA (2010c) 450 ppm scenario), the hydropower industry forecasts a hydropower market potential of more than 8,700 TWh/yr or 32.2 EJ/yr (IJHD, 2010) to be reached in 2050. The long lifetime of HPPs (in many cases more than 100 years, no/or very few decommissioning cases), along with hydropower's significant market potential, the ability of storage hydropower as a controllable RE source to be used to balance variable RE, and the multipurpose aspects of hydropower, could be taken as support for this view. However, to achieve these levels of deployment, a variety of possible challenges to the growth of hydropower deserve discussion.

Resource Potential: Even the highest estimates for long-term hydropower production are within the global technical potential presented in Section 5.2, suggesting that—on a global basis, at least—technical potential is unlikely to be a limiting factor to hydropower deployment. Moreover, ample market potential exists in most regions of the world to enable significant hydro energy development on an economic basis. In certain countries or regions, however, higher deployment levels will begin to constrain the most economical resource supply, and hydro energy will therefore not contribute equally to meeting the needs of every country (see Section 10.3).

Regional Deployment: Hydropower would need to expand beyond its current status, where most of the resource potential developed so far has been in Europe and North America. The IEA reference case forecast projects the majority (57%) of hydropower deployment by 2035 to come from non-OECD Asia countries (e.g., 33% in China and 13% in India), 16% from non-OECD Latin America (e.g., 7% in Brazil) and only 11% in OECD countries (see Table 5.10). Regional collaboration would be required to combine power systems development with sound

Table 5.10 | Regional distribution of global hydropower generation in 2008 and projection for 2035 in TWh and EJ (percentage of hydropower generation in regional electricity generation, CAAGR: 'compounded average annual growth rate' from 2008 to 2035) for the IEA New Policies Scenario[1] (IEA, 2010c).

Hydropower generation by region		2008			2035			CAAGR 2008–2035 (%)
		TWh/yr	EJ/yr	% of global electricity supply	TWh/yr	EJ/yr	% of global electricity supply	
World		**3,208**	**11.58**	**16**	**5,533**	**19.97**	**16**	**2.0**
OECD	**OECD total**	**1,312**	**4.74**	**12**	**1,576**	**5.69**	**12**	**0.7**
	North America	**678**	**2.45**	**13**	**771**	**2.78**	**12**	**0.5**
	USA	257	0.93	6	310	1.12	6	0.7
	OECD Europe	**521**	**1.88**	**14**	**653**	**2.36**	**15**	**0.8**
	EU	327	1.18	10	402	1.45	10	0.8
	OECD Pacific	**114**	**0.41**	**6**	**152**	**0.55**	**7**	**1.1**
Non-OECD	**Non-OECD Total**	**1,895**	**6.84**	**20**	**3,958**	**14.29**	**18**	**2.8**
	Eastern Europe/Eurasia	**284**	**1.03**	**17**	**409**	**1.48**	**17**	**1.4**
	Russia	165	0.60	16	251	0.91	18	1.6
	Non-OECD Asia Total	**834**	**3.01**	**16**	**2,168**	**7.83**	**14**	**3.6**
	China	585	2.11	17	1,348	4.87	14	3.1
	India	114	0.41	14	408	1.47	13	4.8
	Africa	**95**	**0.34**	**15**	**274**	**0.99**	**23**	**4.0**
	Latin America Total	**673**	**2.43**	**63**	**1,054**	**3.81**	**59**	**1.7**
	Brazil	370	1.34	80	528	1.91	64	1.3

Note: 1. The 'new policy scenario' reflects conditions set forth by the UNFCCC's Copenhagen accord, and is considered a reference scenario by the IEA.

integrated water resources management, as was observed, for example, in the Nile Basin Initiative and the Greater Mekong Subregion program (see Section 5.10.3).

Supply chain issues: 40 GW of new hydropower capacity was added globally in 2008, which is equivalent to the highest annual long-term IEA forecast scenario in its 450 ppm scenario (IEA, 2010c). As such, though some efforts may be required to ensure an adequate supply of labour and materials in the long term, no fundamental long-term constraints to materials supply, labour availability or manufacturing capacity are envisioned if policy frameworks for hydropower are sufficiently attractive.

Technology and Economics: Hydropower is a mature technology that under many circumstances is already cost-competitive compared to market energy prices. Though additional technical advances are anticipated, they are not central to achieving the lower ranges of GHG concentration stabilization levels described earlier. Hydropower also comes in a broad range of types and size, and can meet both large centralized needs and small decentralized consumption, ensuring that hydropower might be used to meet the electricity needs of many countries and in many different contexts.

Integration and Transmission: Hydropower development occurs in synergy with other RE deployment. Indeed hydropower with reservoirs and/or pumped storage power plants (PSPP) provide a storage capacity that can help transmission system operators to operate their networks in a safe and flexible way by providing balancing generation for variable RE (e.g., wind and solar PV). Hydropower is useful for ancillary services and for balancing unstable transmission networks, as hydropower is the most responsive energy source for meeting peak demand (see Chapter 8). PSPPs and storage hydropower can therefore ensure transmission, and also distribution, security and quality of services.

Social and Environmental Concerns: Social and environmental impacts of hydropower projects vary depending on type, size and local conditions. The most prominent impacts include barriers to fish migration, GHG emissions and water quality degradation in some tropical reservoirs, loss of biological diversity, and population displacement (Section 5.6.1). Impoundments and the existence of reservoirs stand out as the source of the most severe concerns, but can also provides multiple beneficial services beyond energy supply. Efforts to better understand the nature and magnitude of these impacts, together with efforts to mitigate any remaining concerns, will need to be pursued in concert with increasing hydropower deployment. This work has been initiated by the WCD (2000), and has been endorsed and improved by the IHA (2006), providing guidelines and best practice examples.

5.9.3 Conclusions regarding deployment

Overall, evidence suggests that relatively high levels of deployment in the next 20 years are feasible. Even if hydropower's share of the global electricity supply decreases by 2050 (from 16% in 2008 to about 10 to 14% according to different long-term scenarios), hydropower remains an attractive RE source within the context of global carbon mitigation scenarios. Furthermore, increased development of storage hydropower may enable investment into water management infrastructure, which is needed in response to growing problems related to water resources, including climate change adaptation (see Section 5.10).

5.10 Integration into water management systems

Water, energy and climate change are inextricably linked. On the one hand, water availability is crucial for many energy technologies, including hydropower (see Section 9.3.4.4), and on the other hand, energy is needed to secure water supply for agriculture, industries and households, particularly in water-scarce areas in developing countries (Sinha et al., 2006; Mukherji, 2007; Kahrl and Roland-Holst, 2008). This mutual dependence has lead to the understanding that the water-energy nexus must be addressed in a holistic way, especially regarding climate change and sustainable development (Davidson et al., 2003; UNESCO-RED, 2008; WBCSD, 2009). Providing energy and water for sustainable development will require improved regional and global water governance, and since hydroelectric facilities are often associated with the creation of water storage facilities, hydropower is at the crossroads of these issues and can play an important role in enhancing both energy and water security.

Therefore, hydropower development is part of water management systems as much as energy management systems, both of which are increasingly becoming climate driven.

5.10.1 The need for climate-driven water management

As described in Section 5.2.2, climate change will probably lead to changes in the hydrological regime in many countries, including increased variability and more frequent hydrological extremes (floods and droughts). This will introduce additional uncertainty into water resource management. For poor countries that have always faced hydrologic variability and have not yet achieved water security, climate change will make water security even more difficult and costly to achieve. Climate change may also reintroduce water security challenges in countries that for 100 years have enjoyed water security. Today, about 700 million people live in countries experiencing water stress or scarcity. By 2035, it is projected that three billion people will be living in conditions of severe water stress (World Bank, 2011). Many countries with limited water availability depend on shared water resources, increasing the risk of conflict. Therefore, adaptation to climate change impacts on often scarce resources will become very important in water management (World Bank, 2009). Major international financial institutions are aware of the growing need for water storage. For example, the World Bank recognizes the need for better security against climate variability by investing in major hydraulic infrastructure (e.g., dams, canals, dykes and inter-basin transfer schemes). In the Bank's Resource Sector Strategy it is mentioned that developing countries have as little as 1% of the hydraulic infrastructure of developed countries with comparable climatic variability. It was suggested that developing countries construct well-performing hydraulic infrastructures to be used for hydropower generation and water management that also meet environmental and social standards (World Bank, 2004).

Climate change affects the function and operation of existing water infrastructure as well as water management practices. Adverse climate effects on freshwater systems aggravate the impacts of other stresses, such as population growth, changing economic activity, land use change and urbanization. Globally, water demand will grow in the coming decades, primarily due to population growth and increased affluence; regionally, climate change may lead to large changes in irrigation water demand. Current water management practices may be inadequate to reduce the negative impacts of climate change on water supply reliability, flood risk, health, energy and aquatic ecosystems. Improved incorporation of current climate variability into water-related management would make adaptation to future climate change easier.

The need for climate-driven water management positions hydropower systems as key components of future multipurpose water infrastructure projects.

5.10.2 Multipurpose use of reservoirs and regulated rivers

Creating reservoirs is often the only way to adjust the uneven distribution of water in space and time that occurs in the unmanaged environment. Reservoirs add great benefit to hydropower projects, because of the possibility to store water (and energy) during periods of water surplus, and release the water during periods of deficit, making it possible to produce energy according to the demand profile. This is necessary because of large seasonal and year-to-year variability in the inflow. Such hydrological variability is found in most regions in the world, caused by climatic variability in rainfall and/or air temperature. Most reservoirs are built for supplying seasonal storage, but some also have capacity for multi-year regulation, where water from two or more wet years can be stored and released during a later sequence of dry years. The need for water storage also exists for many other types of water use, such as irrigation, water supply and navigation and for flood control. In addition to these primary objectives, reservoirs can provide a number of other uses like recreation and aquaculture. Reservoirs that are created to serve more than one purpose are known as multipurpose reservoirs. Harmonious and economically optimal operation of such multipurpose schemes may involve trade-offs between the various uses, including hydropower generation.

According to the WCD, about 75% of the existing 45,000 large dams in the world were built for the purpose of irrigation, flood control, navigation and urban water supply schemes (WCD, 2000). About 25% of large reservoirs are used for hydropower alone or in combination with other uses, as multipurpose reservoirs (WCD, 2000).

For instance, China is constructing more than 90,000 MW of new hydropower capacity and much of this development is designed for multipurpose utilization of water resources. For the Three Gorges Project (22,400 MW of installed capacity) the primary purpose of the project is flood control (Zhu et al., 2007). In Brazil, it has been recommended that hydropower generation be sustained and expanded, given the uncertainties of the current climate models when predicting future rainfall patterns in the Brazilian and its trans-boundary drainage basins (Freitas, 2009; Freitas and Soito, 2009). On the other hand, significant potential exists for increased hydropower deployment by upgrading existing dams, or using low-head waterways at irrigation dams and conveyance systems (see Sections 5.3.5 and 5.7).

In a context where multipurpose hydropower can be a tool to mitigate both climate change and water scarcity, multipurpose hydropower projects may play an enabling role beyond the electricity sector as a financing instrument for reservoirs, thereby helping to secure freshwater availability. However, multiple uses may increase the potential for conflicts and reduce energy production in times of low water levels. As many watersheds are shared by several nations, regional and international cooperation is crucial to reach consensus on dam and river management.

5.10.3 Regional cooperation and sustainable watershed management

The availability and movement of water may cross political or administrative boundaries. There are 263 trans-boundary river basins and 33 nations have over 95% of their territory within international river basins. While most trans-boundary river basins are shared between two countries, this number is much higher in some river basins. Worldwide, 13 river basins are shared between five to eight countries. Five river basins, namely the Congo, Niger, Nile, Rhine and Zambezi, are shared between 9 to 11 countries. The Danube River flows through the territory of 18 countries, which is the highest number of states for any basin (CWC, 2009). Management of trans-boundary waters poses a difficult and delicate problem, but the vital nature of freshwater also provides a powerful natural incentive for cooperation. Fears have been expressed that conflicts over water might be inevitable as water scarcity increases. International cooperation is required to ensure that the mutual benefits of a shared watercourse are maximized and optimal utilization of the water resources is achieved. This cooperation will be key to facilitate economic development and maintain peaceful relations in the face of water scarcity.

Hamner and Wolf (1998) studied the details of 145 water treaties and found that 124 (86%) are bilateral and the remaining multilateral. Twenty-one (14%) are multilateral; two of the multilateral treaties are unsigned agreements or drafts (Hamner and Wolf, 1998). Most treaties focus on hydropower and water supplies: 57 (39%) treaties discuss hydroelectric generation and 53 (37%) water distribution for consumption. Nine (6%) mention industrial uses, six (4%) navigation, and six (4%) primarily discuss pollution. Thirteen of the 145 (9%) focus on flood control (Hamner and Wolf, 1998). Mountainous nations at the headwaters of the world's rivers are signatories to the bulk of the hydropower agreements. Disputes regarding treaties are resolved through technical commissions, basin commissions or via government officials.

International treaties may be a tool for establishing cooperation in trans-boundary water management. The 1997 UN Convention on the Non-Navigational Uses of International Watercourses (UN IWC, 1997) is the only universal treaty dealing with the use of freshwater resources. Of bilateral treaties, Nepal alone has four with India (the Kosi River agreements, 1954, 1966 and 1978 and the Gandak Power Project, 1959) to exploit the huge power potential in the region. Itaipu Hydropower on the river Parana in Brazil and Paraguay and Victoria Lake hydropower in Uganda, Tanzania and Kenya are other instances of regional cooperation for hydropower development.

The inter-governmental agreements signed between Laos and its neighbouring countries (Thailand, Vietnam, Cambodia) create the necessary institutional framework for the development of major trans-boundary projects such as the 1,088 MW Nam Theun 2 project developed under a public-private partnership model (Viravong, 2008). The support of the World Bank and other international financial institutions has greatly helped in mobilizing private loans and equity. The sales of electricity to Thailand started in March 2010. Over the 25-year concession period, the revenues for the Government of Laos will amount to USD 2 billion, which will be used to serve the country's development objectives through a Poverty Reduction Fund and environmental programmes (Fozzard, 2005).

Several initiatives by international institutions, or intergovernmental agreements, focus on the development of hydropower in a broader context of sustainable development, for example:

- The UN 'Beijing Declaration on Hydropower and Sustainable Development' (UN, 2004) underscores the strategic importance of hydropower for sustainable development, calling on governments and the hydropower industry to disseminate good practices, policies, frameworks and guidelines and build on those to mainstream hydropower development in an economically, socially and environmentally sustainable way, and in a river basin context. The Declaration also calls for tangible action to assist developing countries with financing sustainable hydropower.[33]

33 See: www.un.org/esa/sustdev/sdissues/energy/hydropower_sd_beijingdeclaration.pdf.

- The Action Plan elaborated during the *African Ministerial Conference on Hydropower* held in Johannesburg in 2006 aimed, inter alia, at strengthening regional collaboration, fostering the preparation of feasibility studies, strengthening legal and regulatory frameworks and human capacity, promoting synergies between hydropower and other renewable technologies, ensuring proper benefit sharing, and expanding the use of the CDM for financing hydropower projects in Africa (ADB, 2006).

- In 2009, the World Bank Group (WBG) released its *Directions in Hydropower* that outlines the rationale for hydropower sector expansion and describes the WBG portfolio and renewed policy framework for tackling the challenges and risks associated with scaling up hydropower development. WBG's lending to hydropower increased from less than USD 250 million per year during the period 2002 to 2004 to over USD 1 billion in 2008 (World Bank, 2009).

- The Nile basin initiative,[34] comprised of nine African countries (Uganda, Sudan, Egypt, Ethiopia, Zaire, Kenya, Tanzanian, Rwanda and Burundi), aims at developing the Nile River in a cooperative manner, sharing substantial socioeconomic benefits, and promoting regional peace and security in a region that is characterized by water scarcity, poverty, a long history of dispute and insecurity, and rapidly growing populations and demand for water.

- The Greater Mekong sub-region (GMS), comprised of Cambodia, the People's Republic of China, Lao People's Democratic Republic, Myanmar, Thailand and Viet Nam, established a program of sub-regional economic cooperation[35] in 1992 to enhance their economic relations, building on their shared histories and cultures. The program covers nine priority sectors: agriculture, energy, environment, human resource development, investment, telecommunications, tourism, transport infrastructure, and transport and trade facilitation.

- In India, following the announcement of a 50,000 MW hydropower initiative by the Prime Minister in 2003, the Federal Government has taken a number of legislative and policy initiatives, including preparation of a shelf of well-investigated projects and streamlining of statutory clearances and approval, establishment of independent regulatory commissions, provision for long-term financing, increased flexibility in sale of power, etc. India is also cooperating with Bhutan and Nepal for the development of their hydropower resource potential (Ramanathan and Abeygunawardena, 2007).

34 See: www.nilebasin.org/.

35 See: www.adb.org/gms/.

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