Power Cycles and Energy Storage

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Outline

How to meet our daily cycle of electrical power consumption

Today's scenario: Base Load Power Plants (24/7) + Dispatchable Power Plants (evening only)

Possible future scenario: Base Load Plants + Massive Energy Storage

Candidates for Massive Energy:

- Pumped Storage Hydro
- Hydrogen Fuel Cells
- Flywheel Energy Storage
- Compressed Air Energy Storage (CAES)
- Capacitor / Super Capacitor Energy Storage
- Battery Energy Storage
- Molten Salt Heat Energy Storage

How much of each is required for Base Load + Massive Energy Storage scenario?

More ambitious scenario of ALSO eliminating ALL non-green power sources

(Written / Revised: March 2020)

Power Cycles and Energy Storage

I talk about the **puzzle** of designing future power systems

"Puzzle," because so many factors must be balanced to:

Provide **enough** affordable power

While sustaining a high quality biosphere

We've also seen that renewables are **not silver bullets**

If only because they demand **huge** natural resource commitments

Meaning that future power systems will have to combine **different technologies**

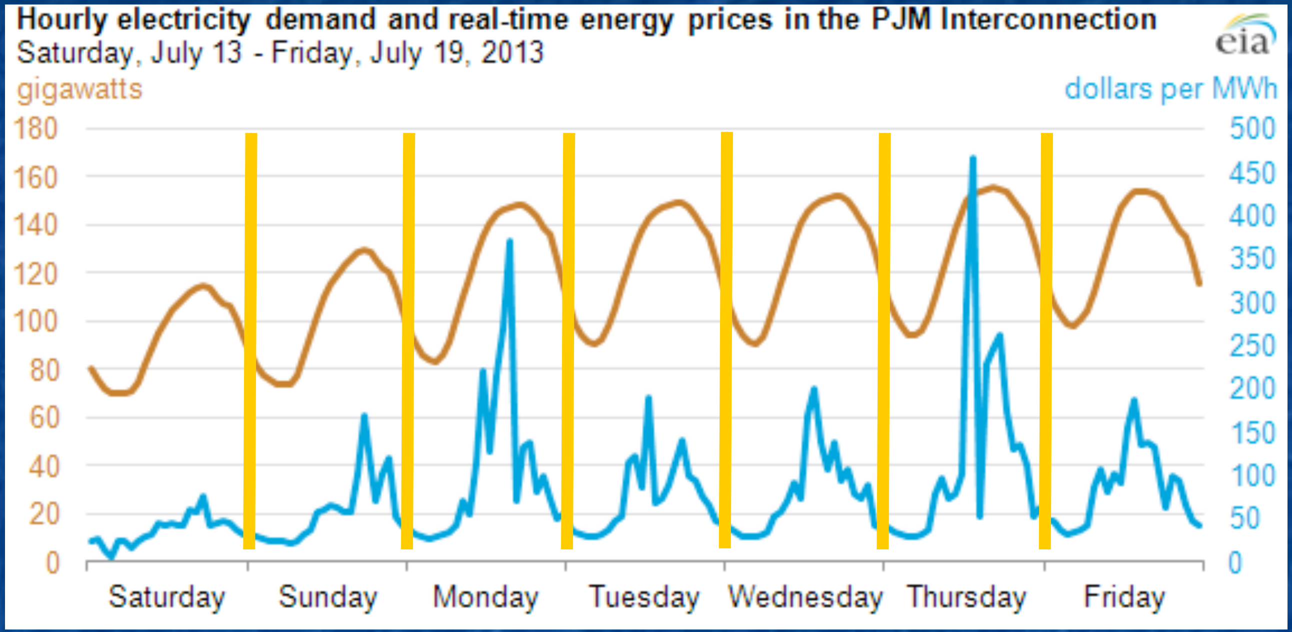
Today you will see how the natural cycles of power consumption and production

ALSO drive the use of different technologies

And how **energy storage** will become critical

It all starts with this:

The cycles in our consumption of electrical power (and its real time cost):



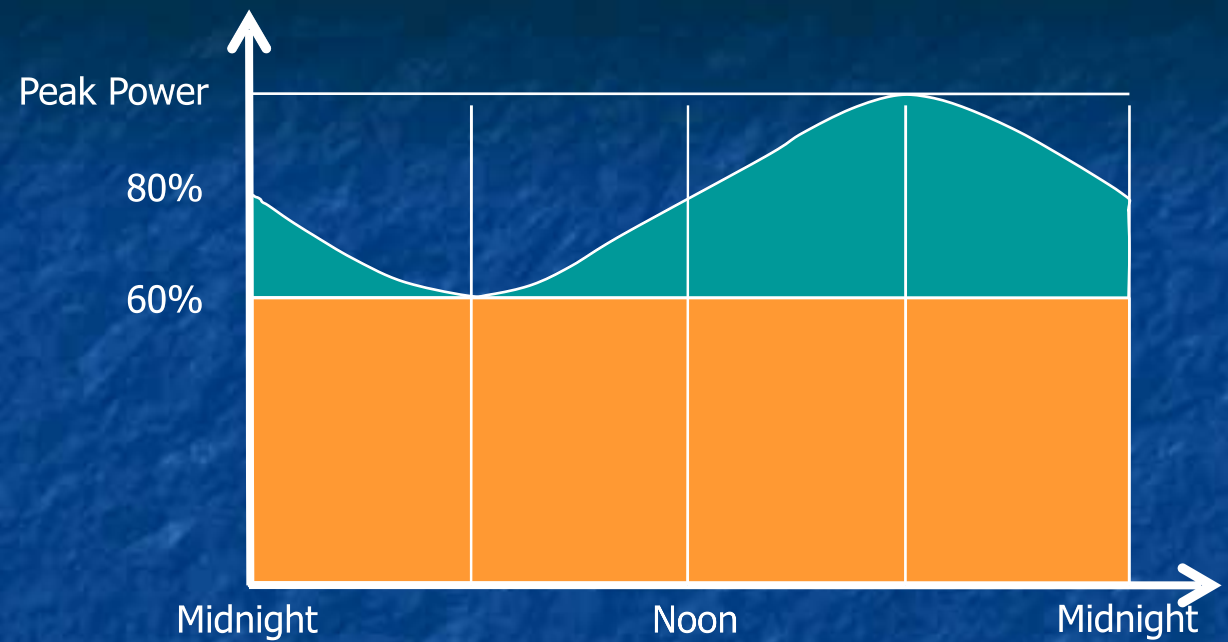
www.eia.gov/todayinenergy/detail.cfm?id=12711 *YELLOW midnight lines added*

Note the almost sinusoidal cycles:

Peaking at 6pm (cook dinner, cool down/heat up house, do laundry . . .)

With amplitude of the oscillation equaling ~ 40% of peak value

Simplifying a little bit, over one day:



We have a constant component at about 60% of the peak

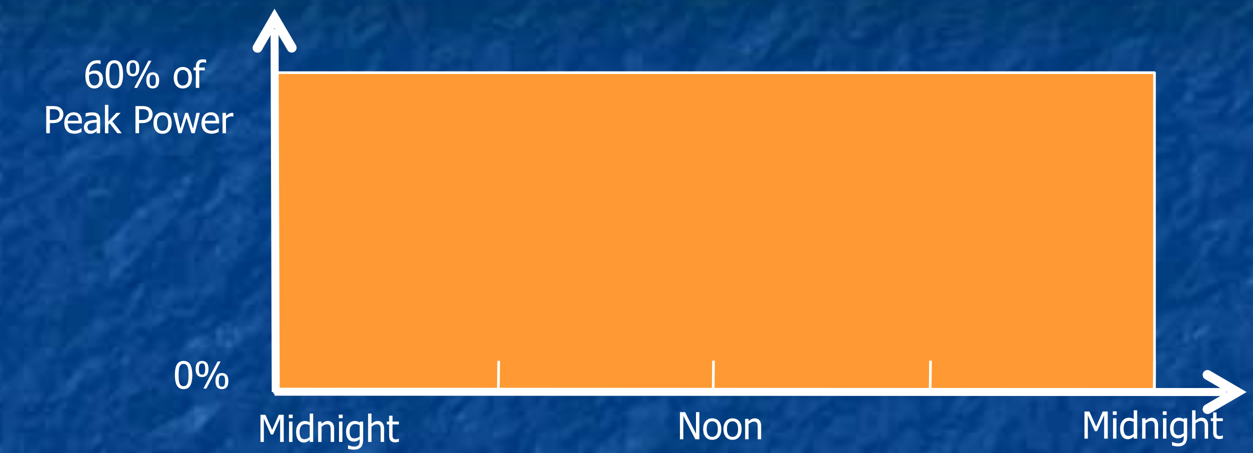
Plus an oscillating component moving from there up to 100% at about 6 pm

With oscillating component's **average** at 80% (from its symmetry)

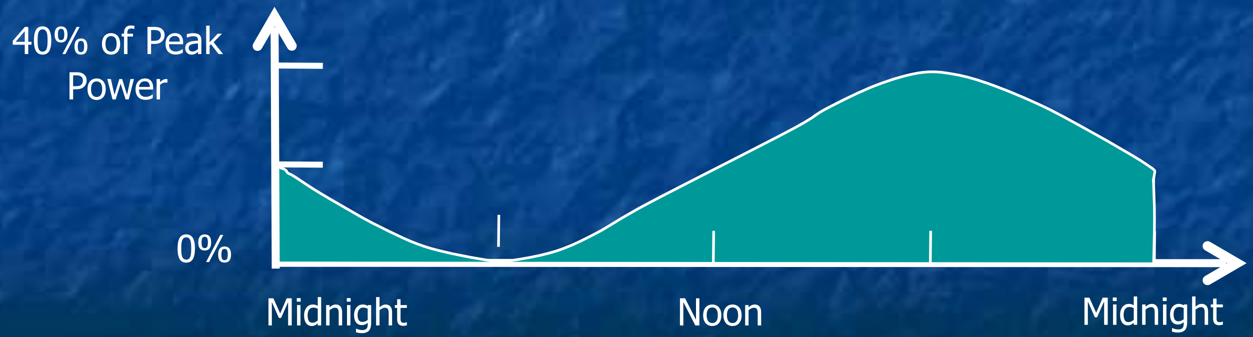
Meaning that **time averaged total power** is also about 80% of the **peak power**

Or dividing these two up:

The constant "**base**" electrical load:



Plus a variable "**dispatchable**" component (so called because a dispatcher controls it?)



So we could also call Scenario #1: "Base + Dispatchable"

Scenario #1) Base Power Plants + Dispatchable Power Plants + no storage:

This is TODAY's scenario, now in almost universal use

But, of course, power companies want to minimize costs (theirs and yours)

Costs come in two principal flavors: FIXED COSTS and VARIABLE COSTS

A **fixed cost** is just that, something you're going to have to pay no matter what

For power plants, the biggest are most often construction (**capital**) costs

Which are then translated into **ongoing** mortgage / bond payments

Which have to be paid, whatever power you are now producing

A **variable cost** is instead a cost that varies with the plant's power output

Which includes the labor cost of the operators as well as fuel costs

The contrast between Base and Dispatchable Plants:

FIXED COSTS: For **both** base **and** dispachable plants are ~ mortgage payments

Which depend upon building cost, mortgage interest and duration

VARIABLE COSTS:

Base Plant = Labor & Fuel costs while power is being produced (= all the time)

Dispatchable Plant =

Labor & Fuel costs while power is being produced +

Labor & Fuel costs while plant is **warming up** (**NOT** producing power) +

Labor costs while plant is shutting down (**NOT** producing power) +

Some labor costs 24/7, for security, maintenance, deliveries . . .

But for all but open-cycle-gas-turbine dispatchable plants (which don't use steam):

Warm up time + Shut down time can easily exceed power production time!

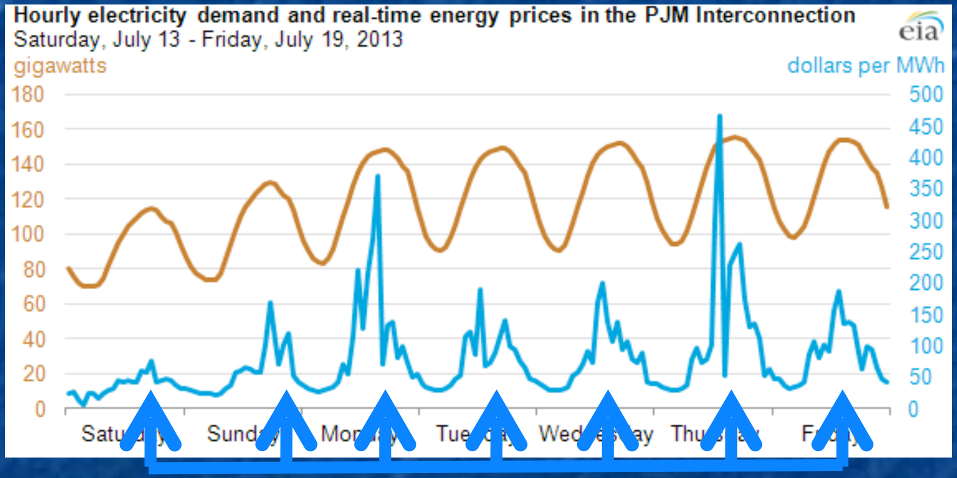
The LCOE is still going to be hugely inflated, because it still equals:

LCOE = Levelized Cost / Energy Produced

With numerator still depending on FULL purchase/construction cost (via mortgage)

But denominator now hugely reduced: E.G., for plant operating 3 hours per day:

Denominator reduced by (3/24) = 1/8 => **LCOE increases by 8X**



Which is indeed seen in the blue cost of power time variation above!

Which is WHY our gas "peaking" power is ~ 4X cost of base power

*Scenario #2) Add **storage** in place of dispatchable plants*

Why pay for dispatchable power plants that sit idle almost all of the day!

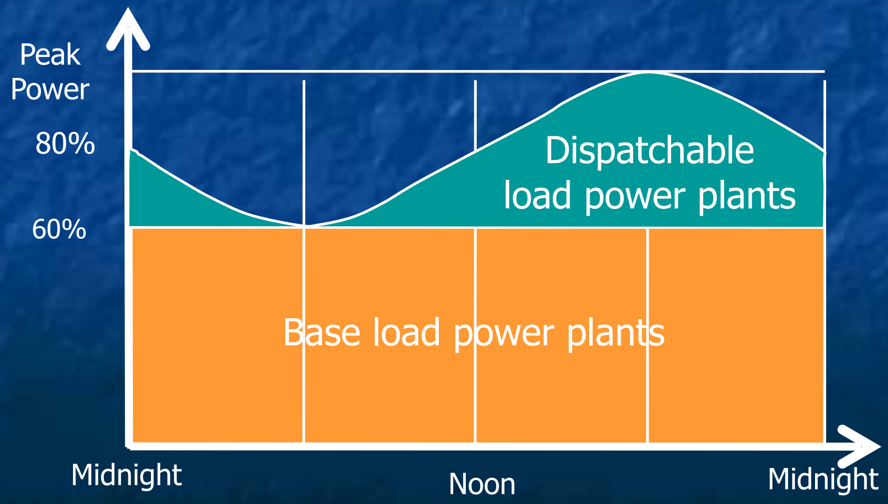
INSTEAD: Choose the CHEAPEST CLEANEST TYPE(S) OF POWER PLANTS

Let them run ALL DAY AT FULL POWER (maximizing their bang / capital buck)

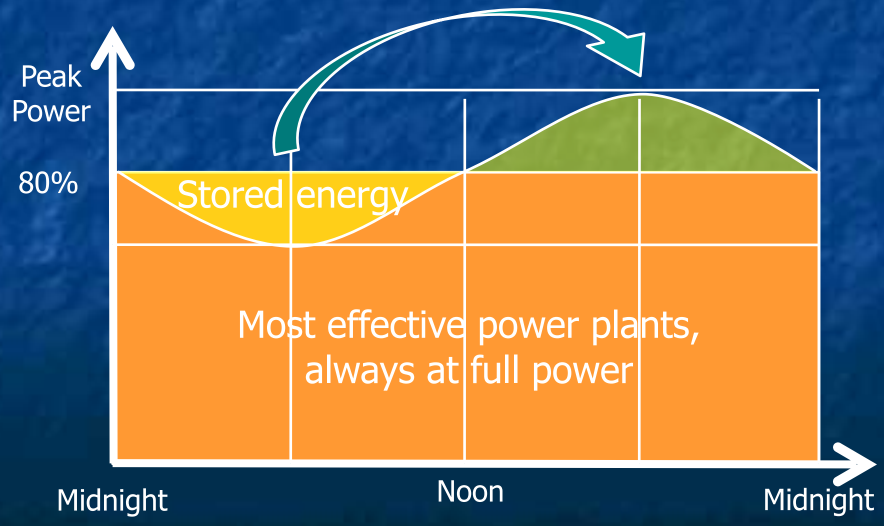
Size them so their power = 80% of peak power = average daily power

And **STORE** EXCESS POWER produced early in the day for use later in the day

Old Scenario #1:



New Scenario #2:



But how MUCH energy do we have to store early in the day?

From earlier discussion, average power per day = 80% of peak power

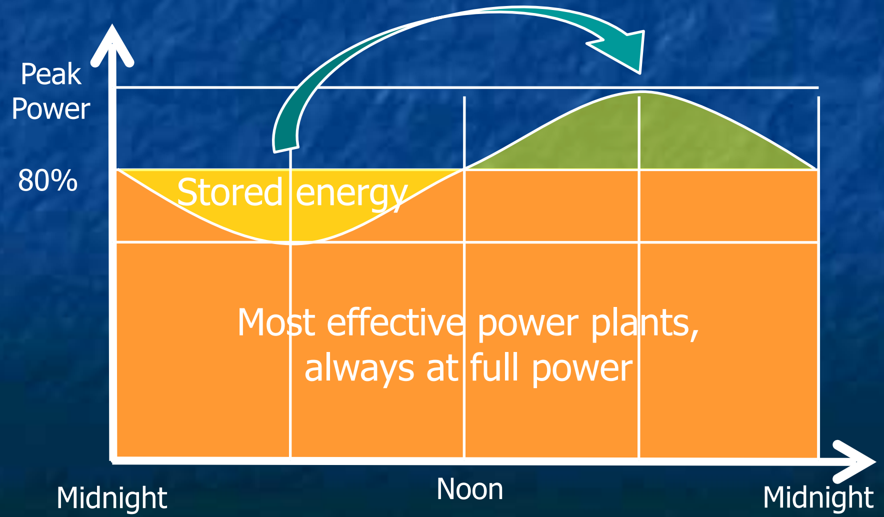
So daily energy = E_{daily} = 0.8 P_{peak} x 1 day

Assuming shape of energy stored & moved curve below is indeed sinusoidal:

From the diagram, amplitude of the sine = (0.2 x peak power)

Then, stored early day energy = integral (from 0 to day/2) of 0.2 P_{peak} Sin

= 0.2 P_{peak} x day / Pi = 0.064 P_{peak} x day = (0.064)(E_{daily}/0.8) = **8% of E_{daily}**



So we could also call Scenario #2:

"Conventional Power

+

8% Storage"

U.S. energy per day value:

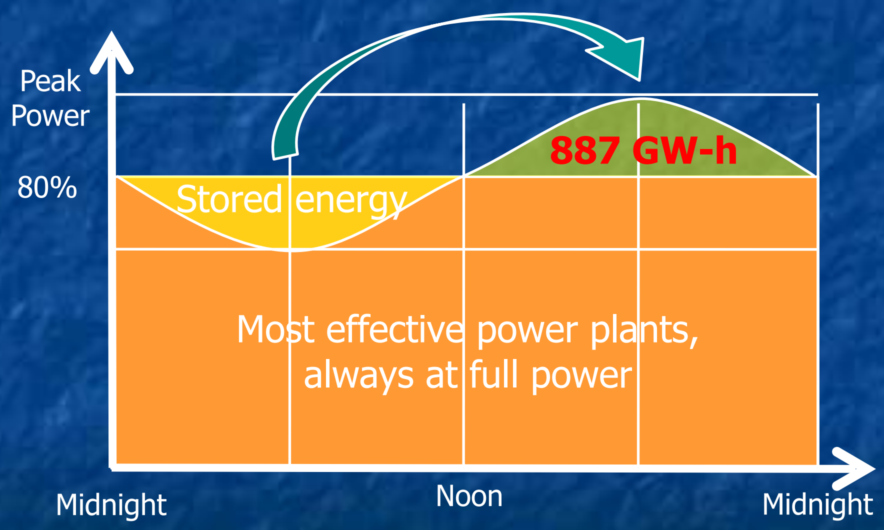
From the Power Plant Land and Water Requirements lecture:

Total US energy production (2012) = 4,047,765 GW-h [1] per year

Which translates into US energy production = 11,089 GW-h per day

So we'd need to store 8% of that early in the morning (for use later in that day):

Scenario #2 US energy storage required per day = 887 GW-h



So with that target figure in mind, what are the alternatives?

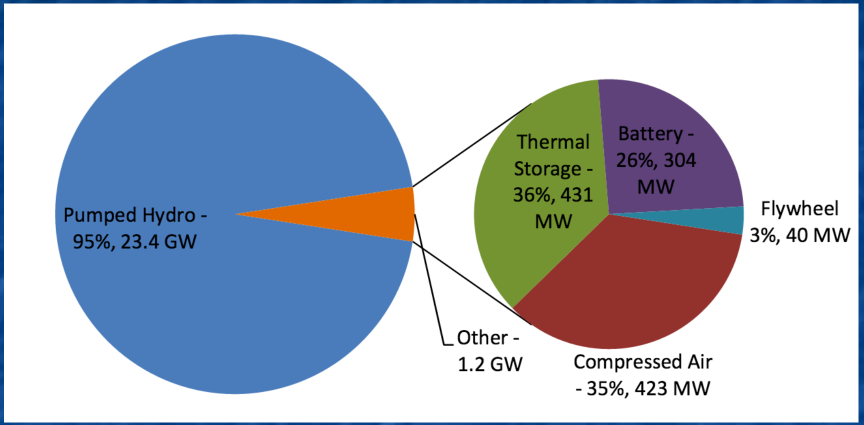
1) www.eia.gov/tools/faqs/faq.cfm?id=65&t=2

Candidate energy storage technologies:

From the U.S. Department of Energy (DOE) 2013:

Current U.S. energy storage capacity:

(ALMOST ALL of it is pumped hydro!)



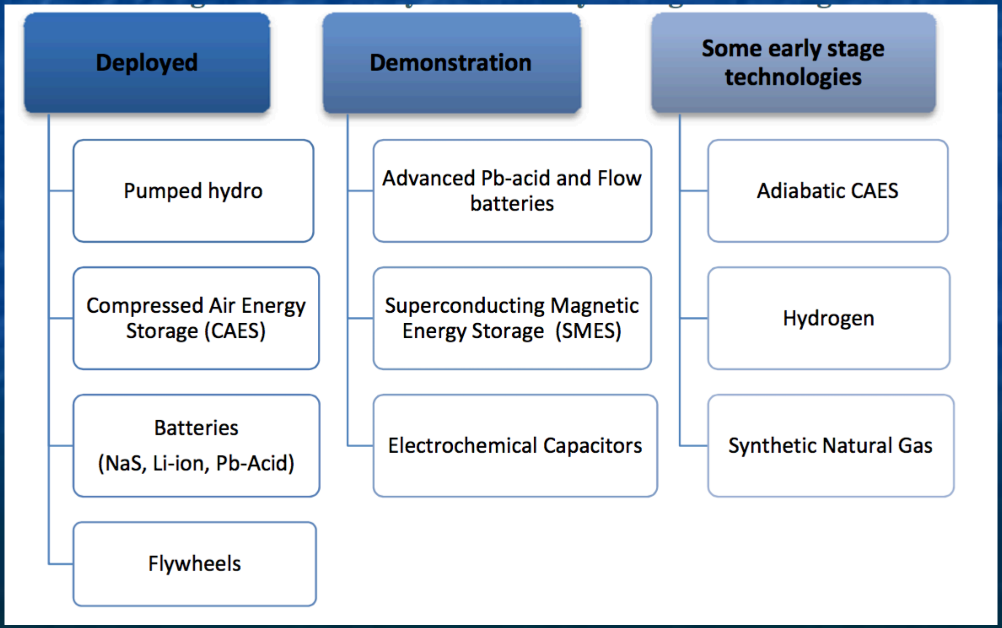
Maturity of storage technologies:

NOTE WILD EXAGGERATION!

Net U.S. Hydro storage is still tiny

And it **dwarfs** other 3 "Deployed"

(which at **BEST** = 1-2 test plants)



http://www.sandia.gov/ess/docs/other/Grid_Energy_Storage_Dec_2013.pdf

Nevertheless, sorting the more plausible/mature candidates:

Which fall into two categories based on naturally different figures of merit

Energy storage SYSTEMS = Multi-component plants, spread over hectares:

a) Pumped Hydro Energy Storage

b) Hydrogen Fuel Cell Energy Storage

c) Flywheel Energy Storage

d) Compressed Air Energy Storage (CAES)

Energy storage THINGS = Components that would just be massively warehoused:

e) Capacitor / Super Capacitor Energy Storage

f) Battery Energy Storage

g) Molten Salt Heat Energy Storage

For each of these candidates, we need to know:

How much is required for our #2 energy storage scenario?

That is, storing 8% of early day energy for later use => 887 GW-h

For **all** candidates, this involves their **"round trip return efficiency"**

Because energy returned = energy put in x return efficiency

For energy storage **SYSTEMS,** we need their plant **footprint** & **storage capacity**

In order to work out total number of plants and size required

For energy storage **THINGS** we need their **energy storage density** (kW-h / m^3)

We could then assume, say, that they'd be warehoused ~1 meter high

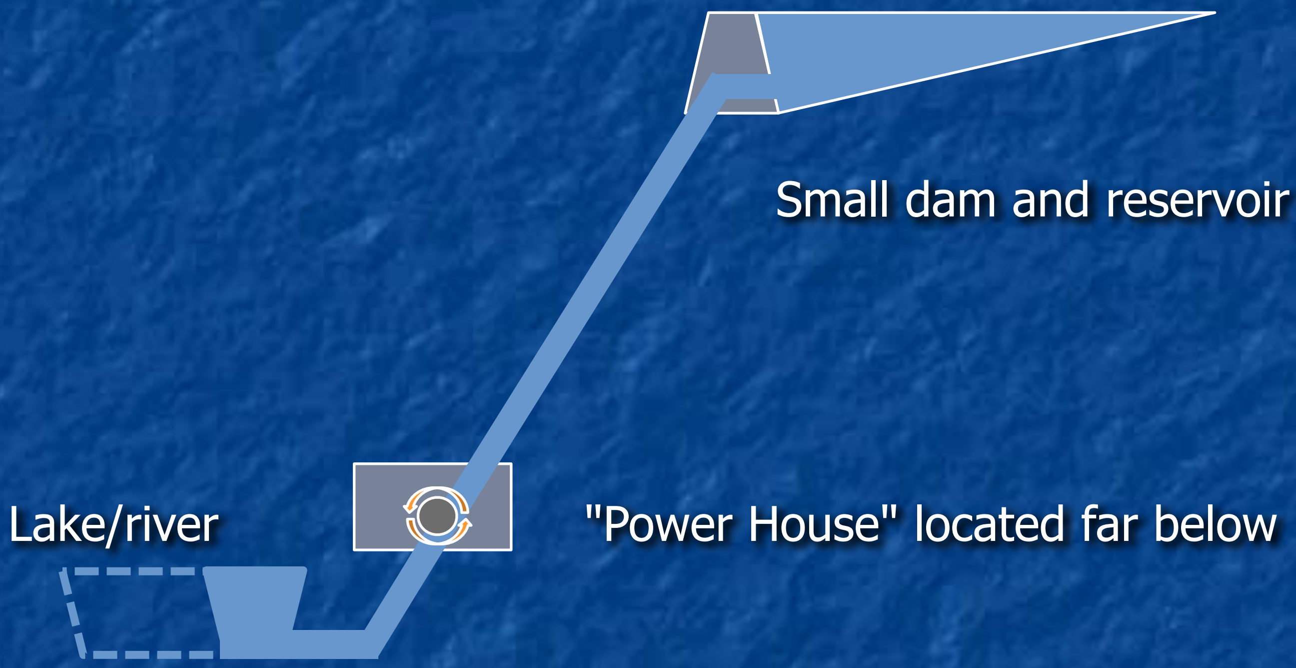
Combining => Net national size of such energy storage warehouses

And for **all** candidates, we need their **projected levelized cost**

a) Energy storage via Pumped Storage Hydro (PSH)

The best **current** way to store power

Which, in my Hydropower / Windpower lecture I represented thusly:



But data from previous lecture was incomplete, so we must slow down:

The Bath County Virginia pumped hydro storage plant:

From Dominion Power's website:[1]

"The World's Biggest Battery" – but no numbers!

Supplies "over ½ million customers with (peak) power"

At rate "exceeding Hoover Dam"

One reservoir 1262 feet (385 m) above other reservoir

Max rate of flow back down =

13.5 million gallons / minute (852 m^3 / sec)

Area of upper reservoir = 265 acres (1.07 x 10^6 m^2)

Its "water level fluctuates 105 feet (32 meters) during operation"

OK, now we have finally got enough information to calculate energy stored!

1) Link to webpage: www.dom.com/about/stations/hydro/bath-county-pumped-storage-station.jsp

Energy stored in Bath pumped storage energy plant:

Water's energy as it falls down into lower reservoir:

$\Delta E = M\ g\ h = \rho_{water}$ x (volume of water moved) x g x (height difference)

$\rho_{water} = 1000$ kg / m^3 $\quad\quad$ g = 9.8 m / sec^2

height difference = 385 meters

volume of water moved = (1.07 x 10^6 m^2) (32 meters)

ΔE = (1000 kg / m^3) (1.07 x 10^6 m^2) (32 meters) (9.8 m / sec^2) (385 m)

= 1.29 x 10^{14} kg m / s^2 = 1.29 x 10^{14} Joules

= 1.29 x 10^{14} / (3,600,000,000) MW-h = **35.8 MW-h**

Bath upper reservoir = 265 acres = 1.07 km^2

If lower reservoir were reduced to same size => **~ 2 km^2 reservoir area**

Round trip energy efficiency of pumped storage hydro?

Its largely limited by the HUGE electrical motor/generators/turbines required

Motors drive the turbines driving the water UP the hill, then:

Water turns turbines driving generators as it falls back DOWN

But some power may also be lost by turbulence-induced heating of the water itself

Overall power recovery, after accounting for all possible losses?

Various sources give efficiencies from 70% [1] to 85% [2]

I'll go with the NREL study [3] number: **80% efficiency**

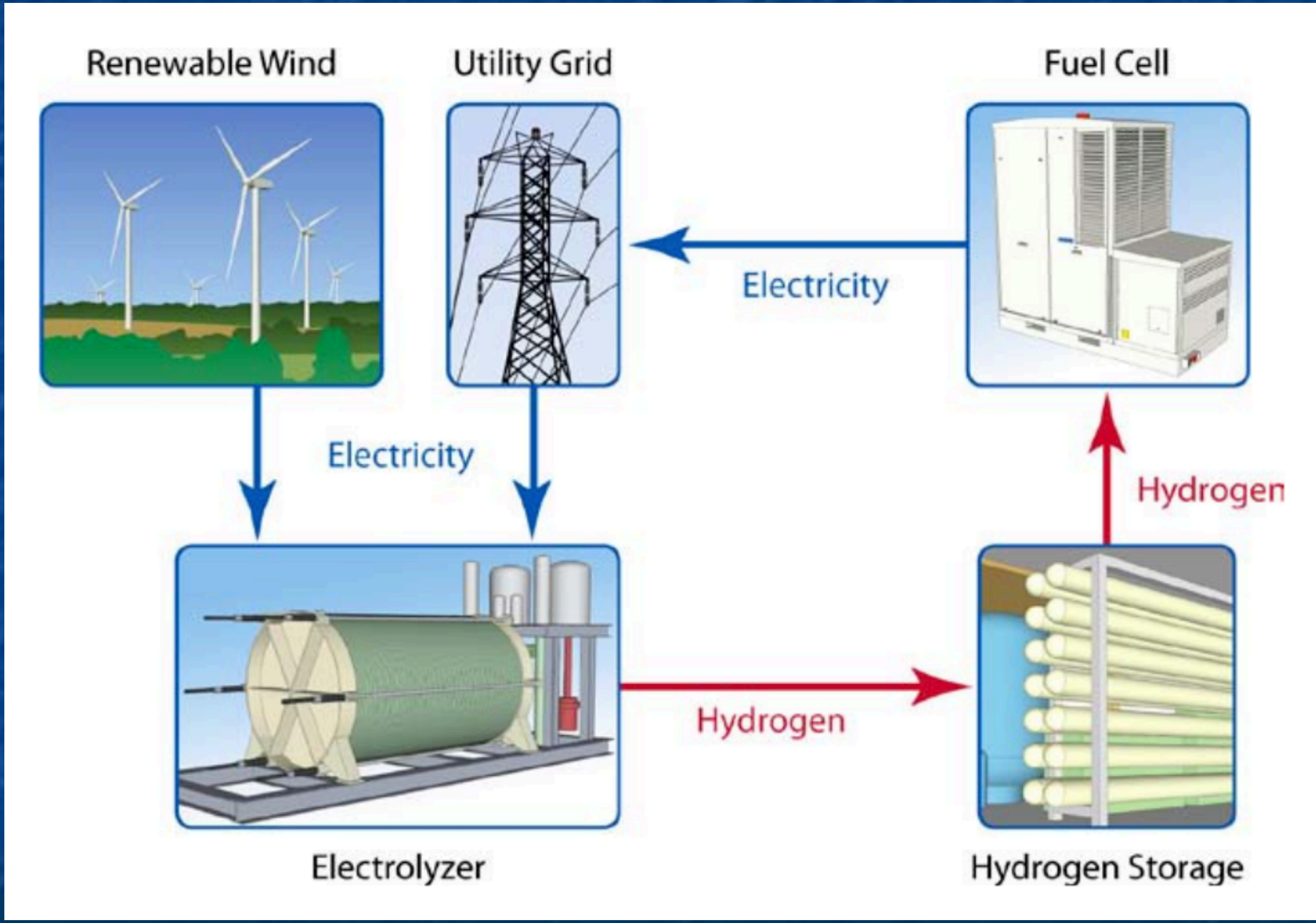
1) The Economist: www.economist.com/node/21548495?frsc=dg|a)

2) European Commission: etis.ec.europa.eu/publications/jrc-setis-reports/pumped-hydro-energy-storage-potential-transformation-single-dams

3) NREL: www.nrel.gov/docs/fy14osti/60806.pdf

b) Fuel cell based energy storage:

Idea as depicted in an NREL presentation: [1]



U.S. National Renewable Energy Lab: "Analysis of Hydrogen and Competing Technologies for Utility-Scale Energy Storage"
http://www.nrel.gov/docs/fy10osti/47547.pdf

Fuel cell based storage has three stages:

- **Electrochemical cell # 1** uses electrical energy to electrolyze water:

  H_2O + electrical energy => $H_2 + ½ O_2$

- Gaseous H_2 (and possibly O_2) are then stored in **pressurized tanks**

- When energy is needed, gases are sent into **Electrochemical cell #2**:

  $H_2 + ½ O_2$ => H_2O + electrical energy

ONE electrochemical cell COULD do both things (~ charging/discharging of battery)

But, apparently to optimize designs, input & output cells are separate

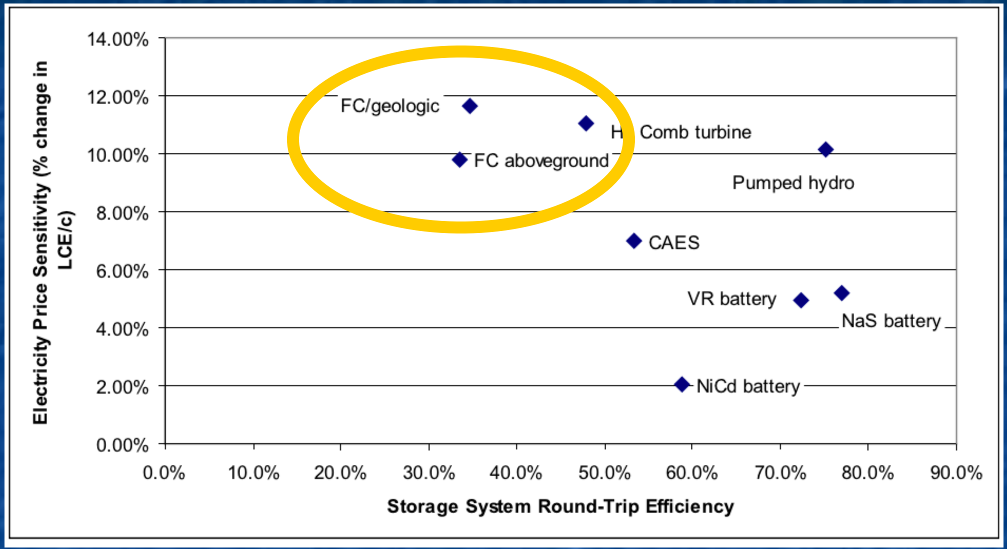
ALTERNATIVE: Stored H_2 is instead sent to a **gas turbine generator**

Eliminating fuel cell #2

Likely less efficient but also likely reducing capital cost

Fuel cell energy storage numbers?

From earlier Batteries and Fuel cell lecture:



Poor round trip efficiencies:

Only 30-35% !

U.S. National Renewable Energy Lab: "Hydrogen for Energy Storage Analysis Overview"
http://www.nrel.gov/hydrogen/pdfs/48360.pdf

What about **energy storage density**? It's very complicated:

"Storage" is in tanks, but **RATE** of energy storage and release

Will depend on size of input and output electrochemical cells

NREL's **design studies** are for **300 MW-h** storage plants

But are **now** storing energy from **single** 10 kW wind turbine (i.e. ~ **50 kW-h**)

c) Flywheel based energy storage:

Maximum possible energy stored:

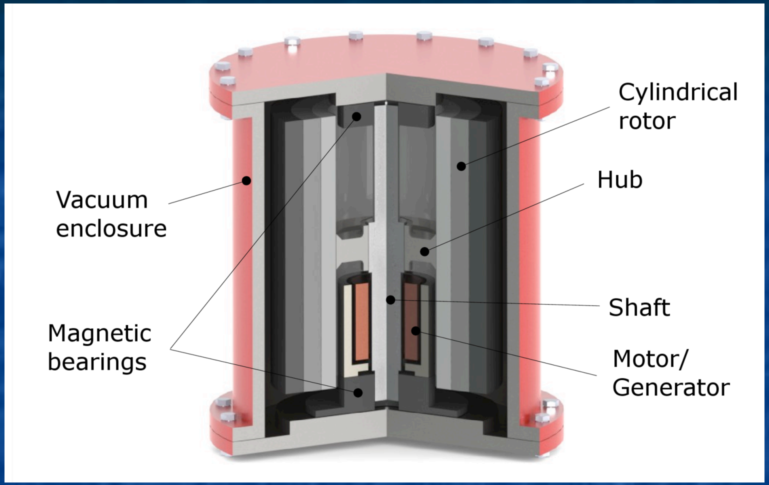
$$E_{max} = K \times M \times \sigma / \rho$$

K = "flywheel shape factor"

M = flywheel mass

σ = tensile strength of material

ρ = density of material



https://en.wikipedia.org/wiki/Flywheel_energy_storage

Why doesn't formula contain rotation speed? And why include tensile strength?

Because strategy is to run flywheel so fast it almost tears itself apart!

Thus almost-destructive-speed is what formula seemingly assumes

Round trip energy recovery efficiency? Energy is lost to heat in rotation bearings

Conventional bearings: "20-50% energy loss in two hours"

Magnetic levitation bearings: **85% round trip energy efficiency**

Flywheel energy storage numbers?

Web search produced information on only two experimental grid storage projects:

Beacon Power in Hazle Township, Pennsylvania – completion 2015 (?) [1]

Rhode, County Offalay, Ireland – completion 2017 [2-4]

Data: Storage targets: Beacon **25 kW-h** / Rhode **2 MW-h**

Pennsylvania: 200 flywheels (as depicted at right)

Ireland: Projected efficiency: **85-90%**

Carbon fibers / magnetic bearings / vacuum

The flywheels are buried in the ground to reduce visual impact and run silently

Size? / Power storage density? Found no direct data

But from this picture is of Irish site [3]

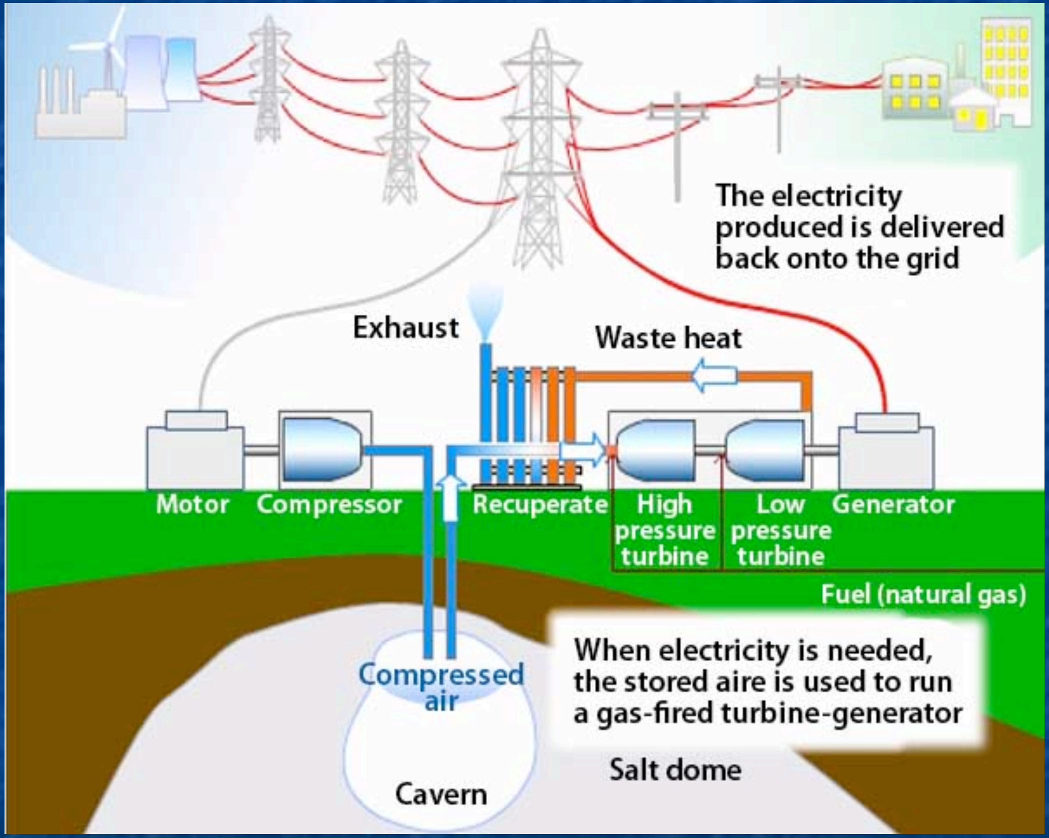
Footprint: **~ 2 hectares = 0.02 km²**

1) http://energy.gov/sites/prod/files/2015/05/f22/Beacon-Power-Flywheel-Aug2013.pdf
2) http://www.theguardian.com/environment/2015/apr/08/new-energy-storage-plant-could-revolutionise-renewable-sector
3) http://www.rte.ie/news/business/2015/0326/689945-renewable-energy-storage/
http://schwungrad-energie.com/projects/rhode-hybrid-test-facility/

d) Compressed air energy storage (CAES):

Idea is potentially **large scale**:

Compress air into tank or reservoir / Release air to drive turbine generator



<= Natural Gas in ?

(I'll return to this!)

http://www.powermag.com/revived-energy-storage-technology-offers-major-grid-benefits/

Most sources make CAES sound simple - It isn't!

It sounds like you just need to invoke the Ideal Gas Law:

P V = n R T where R = the ideal gas constant

But rework this and you can spot a problem: **P = n R (T/V)**

So if you increase the pressure of a gas (P), what happens?

Does temperature (T) **increase**? Does volume (V) **decrease?** OR **both?**

REALITY CHECK: Try touching an air compressor, or even a bicycle tire pump

Actually don't, you'll burn your hand because compressing gas => heat

Refrigerators, **air conditioners**, and **heat pumps** are ALL partially based on:

- **Fact** that pressurizing gases HEATS them

- **Fact** that depressurizing gases COOLS them

Faced by this reality, Wikipedia et al. ignore it

They pretend temperature stays constant, allowing them to use only Ideal Gas Law

But this also makes calculation of CAES efficiency impossible!

RIGHT thing to do is instead add a 2nd relationship: $P V^{m}$ = constant

This squirrely relationship describes a "Polytropic Process"

In it, the exponent m depends on the "heat capacity" of the gas

= Δ Energy that must be added to raise gas temperature by one degree

If heating is "reversible" (Δ Entropy = 0), heat capacity is constant => m is constant

THEN polytropic equation can be substituted into ideal gas law to produce:

Description of how pressurization changes **BOTH** V and T

=> Efficiency limits of Compressed Air Storage (CAES) [1-3]

1) https://www.princeton.edu/pei/energy/publications/texts/SuccarWilliams_PEI_CAES_2008April8.pdf
2) http://content.lib.utah.edu/utils/getfile/collection/etd2/id/86/filename/1430.pdf
3) https://www.eeh.ee.ethz.ch/uploads/tx_ethpublications/Samaniego_2010.pdf

Challenge of heat loss => Multiple CAES versions:

The main ones are: **DIABATIC CAES** and **ADIABATIC CAES**

But what the heck do diabatic and adiabatic mean?

A quick Google search on "adiabatic" (= non-diabatic):

> ad·i·a·bat·ic
>
> /ˌādīəˈbatik, ˌadēə-/
>
> PHYSICS
>
> *adjective*
>
> 1. relating to or denoting a process or condition in which heat does not enter or leave the system concerned.

But Heat = Energy

So heat leaving a Compressed Air Energy Storage System = Energy lost

Nevertheless, only **diabatic** (heat-loosing) CAES has been tried to date!

Contrasting the two main CAES approaches:

DIABATIC CAES (simple CAES) **releases heat of compression to atmosphere**

Which means that heat for **re-expansion** must come from other sources

If you've got plenty of time to wait, atmosphere can resupply the heat

But you DON'T have time to wait with grid energy storage thus:

Heat for re-expansion is instead supplied by burning natural gas

=> LOW NET EFFICIENCY (total energy out / total energy put in)

THIS is scheme shown in preceding (and almost all other) CAES figures

ADIABATIC CAES **traps both air and heat** (as it is released)

This requires tanks/cavities that are BOTH pressure-tight AND heat-tight

So that stored heat can later be applied to re-heating & expanding air

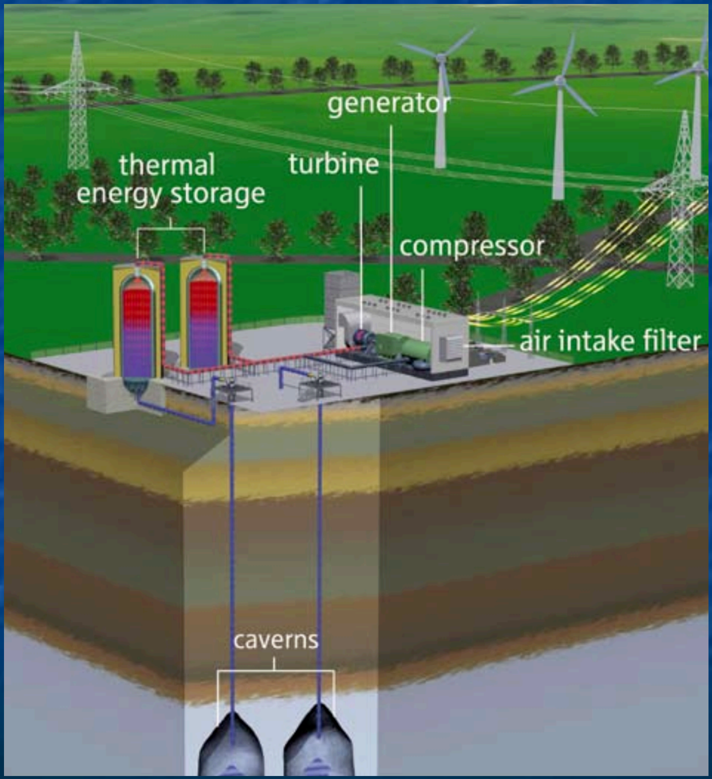
=> MUCH higher energy storage efficiencies, theoretically, up to ~ 100%

Compressed air energy storage numbers?

There are only two existing CAES plants worldwide, both **diabatic** (= heat wasting)

Huntorf Germany (**42%** efficient), McIntosh Alabama (**54%** efficient)

But a large new **adiabatic** (heat trapping) plant is being built: German "ADELE"



Liberated heat is stored in above-ground tanks

By warming the liquids they contain

While compressed gas goes to buried caverns

These are recombined to expand gas

Design goals (upon planned completion in 2018):

- Round trip energy efficiency: **70%**
- Energy Storage: **1000 MW-h**
- Footprint: **~ 1 hectare = 0.01 km²**

https://www.rwe.com/web/cms/mediablob/en/391748/data/364260/1/rwe-power-ag/innovations/Brochure-ADELE.pdf

Did the ADELE CAES project achieve its 70% efficiency goal?

In December of 2019, I searched the web for an answer

To my surprise, post 2017 information about ADELE was virtually non-existent

A few CAES review articles suggested that ADELE had achieved its 70% efficiency

Their apparent source was a single 2017 conference paper about ADELE

which stated in its abstract: [1]

"After its completion in summer 2017 main achievements include the confirmation of a round-trip efficiency of about 70%"

But **within** that paper, the relevant section discussed **only** modeled results, about **alternate** technologies, none even identified as being relevant to ADELE:

"Thermodynamic calculations for different plant calculations and TES technology options confirm a substantial cost reduction potential and improved operation flexibility, albeit with an acceptable decrease in efficiency compared to the adiabatic process. Depending on the specific system configuration and the level of permissible costs the round-trip efficiency ranges from 60 to 70% and somewhat above, with CAPEX below 280 €/kWh"

1) "Electricity storage with adiabatic compressed air energy storage: Results of the BMWi-project ADELE-ING"
https://ieeexplore.ieee.org/document/8278771

Another 2017 paper stated ADELE was on hold (possibly not even complete)

As published in the journal **Energies** (and posted by the University of Warwick) [1]

That article's (complete) discussion of ADELE reads:

"In Germany, as shown in Figure 15, the world's first large-scale AA-CAES project - ADELE - with 70% cycle efficiency cycle efficiency has been designed by RWE Power, General Electric and other partners. The aim of this project is to optimize the co-existence and smooth interaction of the individual energy sources, especially for wind power. It is planned to have 1 GWh storage capacity and be capable of generating up to 200 MW, said the RWE power. The ADELE project could provide backup capacity within a very short time and replace forty state-of-the-art wind turbines for a period of 5 h. The project is now on hold due to uncertain business conditions [61]."

Note that paragraph's recurrent use of future tense AND its final sentence

If that did not confuse matters enough, when I clicked on the link provided in reference [61], I was taken to a U.S. EIA webpage which not only contained **zero** information about CAES, much less about ADELE. Further, that webpage was dated "June 29, 2012" (i.e., **years** before ADELE's construction even **began**).

Actual status of ADELE (or Adiabatic CAES in general)? Heck if I can figure it out!

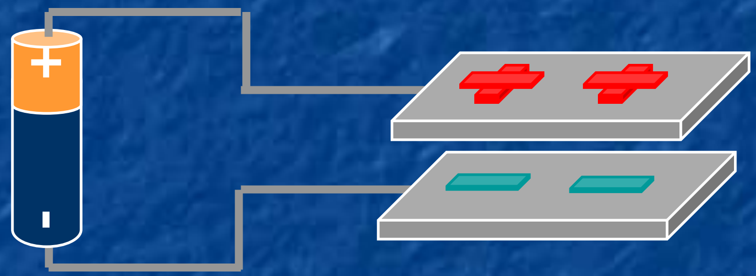
1) "Overview of Compressed Air Energy Storage and Technology Development"
http://wrap.warwick.ac.uk/91858/7/WRAP-overview-compressed-air-energy-storage-technology-development-Wang-2017.pdf
2) https://www.eia.gov/todayinenergy/detail.php?id=6910

e) Energy storage via Capacitors or Super-Capacitors

As mentioned in an earlier lecture, capacitors sidestep Maxwell's 1st equation:

Trying to push more charge into an object doesn't really work:

Unless you fold the two plates over on top of one another:



No longer need charge balance on **each** plate

Excess +'s on top plate don't like one another

But repulsion's balanced by attraction to -'s below

Amount of charge stored is proportional to the pushing voltage: **$Q = C\,V$ (1)**

Constant (C) = "Capacitance" of the capacitor - It increases the closer the plates are:

Capacitance = Area x (dielectric constant of material in gap) / (gap thickness)

$$C = \varepsilon \text{ Area} / d \qquad (2)$$

But how much energy can a capacitor store?

Power of any type = Energy flow => $P = \Delta E / \Delta t$ (3)

But electrical power = voltage x current = voltage x (charge flow)

Charge flow into a capacitor = $\Delta Q / \Delta t$ (change in charge stored per time)

So power into a capacitor is: $P_{capacitor} = V \times (\Delta Q / \Delta T)$ (4)

Equations (3) and (4) BOTH give the power and are thus equal:

$\Delta E / \Delta t = V \times (\Delta Q / \Delta T)$ Or in calculus terms: $dE/dt = V\, dQ/dT$

But from equation (1), Q = CV, substituting this in: $dE/dt = C\, V\, dV/dT$

Integrating over the capacitor's charging time: $\mathbf{Energy_{capacitor} = \frac{1}{2}\, C\, V^2}$

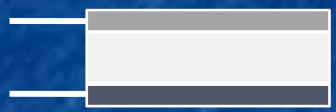
Doubled voltage applied to a capacitor => Quadrupled energy stored

Design of a SUPER CAPACITOR:

Here we want huge energy storage **per volume** = energy storage density

$$\textbf{Volume}_{\text{capactior}} = \textbf{Area}_{\text{capacitor}} \times \textbf{Thickness}_{\text{capacitor}}$$

Simple capacitor:



Gray = metal plates **White = insulator**

$$\textbf{Thickness}_{\text{capacitor}} = 2\,T_{\text{plate}} + T_{\text{insulator}}$$

Then Energy stored in this stacked capacitor per volume is

$$\textbf{Capacitor energy density} = C\,V^2 / [2 \times A \times (2\,T_{\text{plate}} + T_{\text{insulator}})]$$

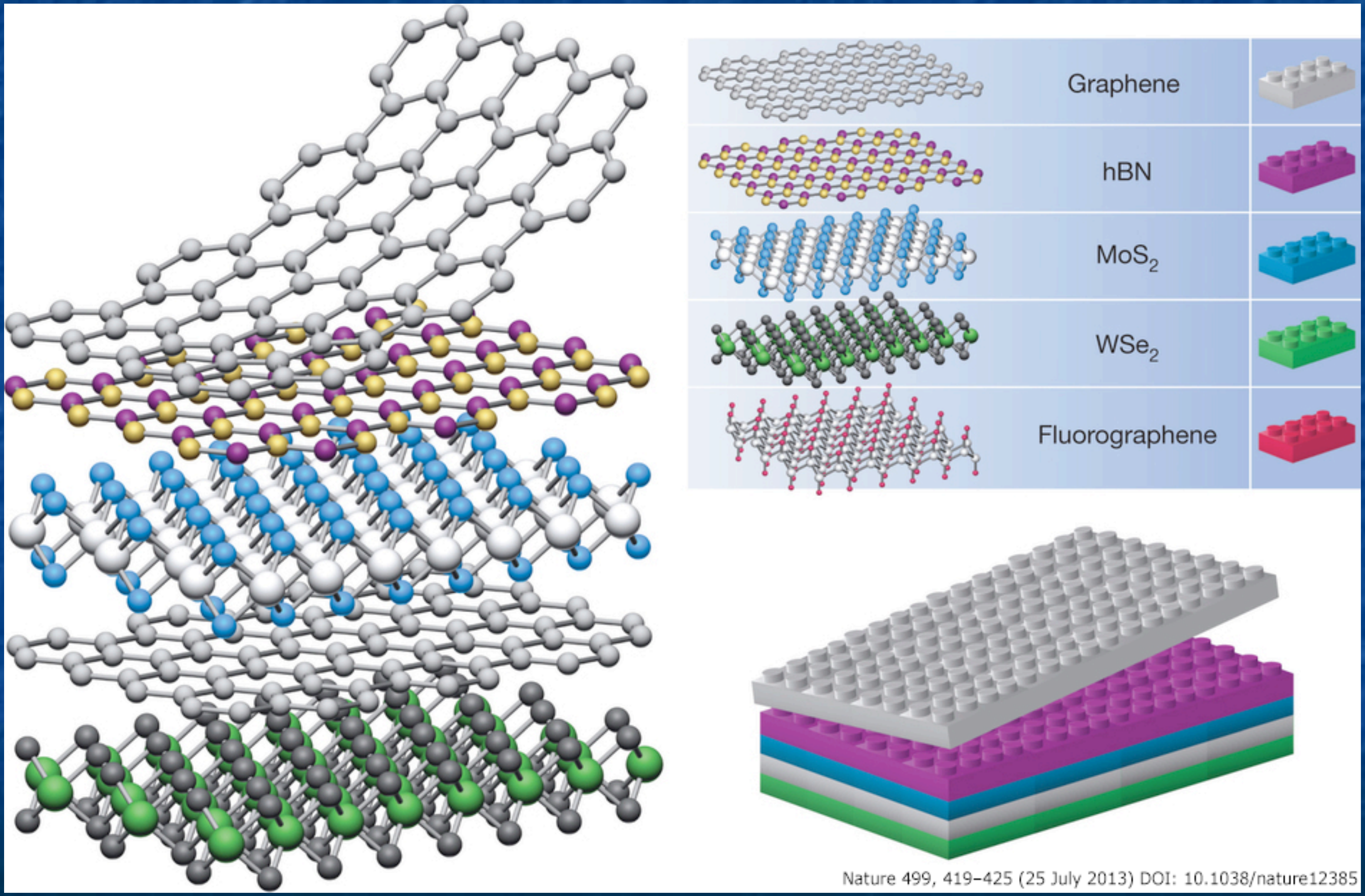
So thinning down both the plates and insulators is a good idea, however:

Plates have to be thick enough that electron flow won't overheat them

Insulator has to be thick enough that electrons cannot jump through it

This all suggests use of ultrathin **nano materials**

Which might allow for capacitors using single atom thick plates and insulators



http://graphene.nus.edu.sg/barbaros/

But while there are extraordinarily good nano metals for the plates

Nano insulators are NOT exceptionally good at blocking electron flow

Key phenomenon is called **dielectric breakdown**

Which occurs when the electric field across insulator exceeds $\xi_{\mathbf{breakdown}}$

Electrons then arc through, irreversibly damaging the insulator!

But electric field in insulator = Capacitor voltage / Thickness $_{\mathbf{insulator}}$ = V / T $_{\mathbf{insulator}}$

To avoid breakdown, T $_{\mathbf{insulator}}$ must thus increase in proportion to voltage used

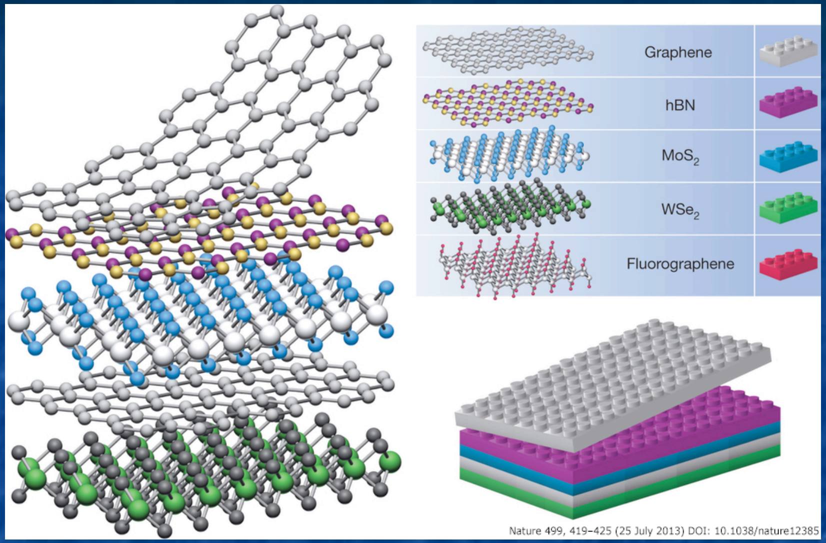
But from earlier formula, energy stored in a capacitor increases as voltage squared

So despite need for thicker insulators

It still makes sense to use higher voltages in these capacitors

As a conveniently "high" voltage, let's choose 110 volts (DC)

Calculating required insulator thickness:



Choosing a nano insulator from the above figure: hexagonal boron nitride:

For **h-BN**, $\xi_{\mathbf{breakdown}}$ is **700-900 MV / meter** [1,2]

For our voltage choice of 110 volts (DC) if we use h-BN for insulator then:

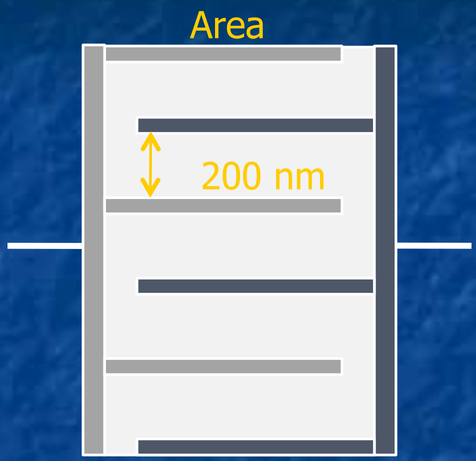
For no sparks, need $T_{h\text{-}BN}$ > 110 Volts / (700 MV/m) ~ 160 nanometers

For a safety margin, choose $T_{h\text{-}BN\ insulator}$ = **200 nanometers**

1) Nano Research, August 2013, Volume 6, Issue 8, pp 602-610
*2) Journal of Physics: Conference Series **471** (2013)*

Then calculating this "nano" capacitor's energy density:

$\text{Capacitor}_{\text{energy density}} = C\,V^2 / [2 \times \text{Area} \times (T_{\text{plate}} + T_{\text{insulator}})]$



Where: $C = \varepsilon\,\text{Area} / T_{\text{insulator}}$

And for our choice of h-BN insulator using 110 VDC:

$T_{\text{h-BN insulator}} = 200 \text{ micron} = 10^{-6}\text{ m}$

$T_{\text{insulator}} >> T_{\text{plate}}$

$\varepsilon_{\text{h-BN}} = (3 \text{ to } 4) \times \varepsilon_o{}^{(1)} \sim 30 \times 10^{-12}\ s^4\,\text{Amp}^2 / \text{kg m}^3$

Capacitor $_{\textbf{energy density}} \sim (\varepsilon\,A / T_{\text{insulator}})\,V^2 / (2\,A\,T_{\text{insulator}}) = \varepsilon\,\mathbf{V^2 / 2\,T_{insulator}^2}$

$= (3\text{x}10^{-11}\ s^4\,\text{Amp}^2 / \text{kg m}^3)\,(110 \text{ volts})^2 / 2\,(0.2\text{x}10^{-6}\text{ m})^2$

$= (3\text{x}10^{-11})(1.2\text{x}10^{4})(0.5)(2.5\text{x}10^{13})(s^2\,J^2/\text{kg-m}^5) = 4.5\text{ MJ/m}^3 =$ **1.25 kW-h/m³**

Likely efficiencies: **~ 100%**

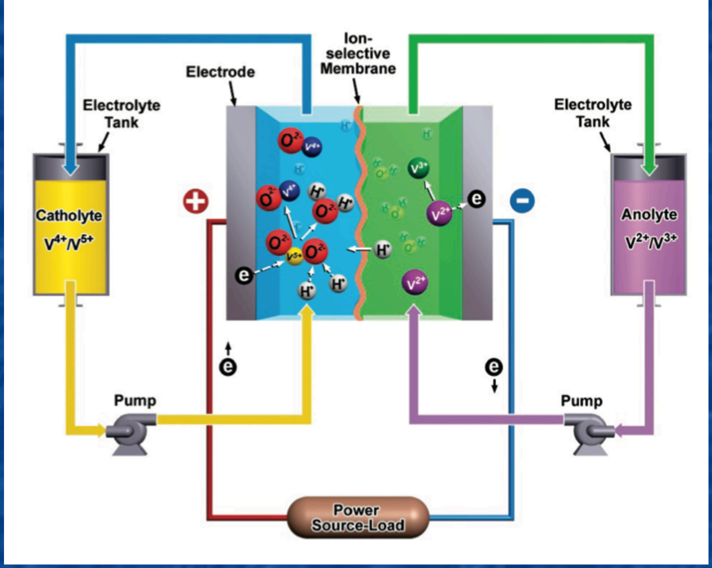
1) *Journal of Physics: Conference Series* ***471*** *(2013)*

f) Energy storage via Super-Batteries

From note set on **Batteries and Fuel Cells** (pptx / pdf / key),

the top candidate might be **flow batteries**:

Which, recall, have this strange and complex configuration:



With two different electrolytes circulated in (via pumps) from external tanks

To a central cell with an "ion selective membrane"

Plus simple metal electrodes to either side

Molten sodium beta alumina batteries were a second candidate

With overall structure:

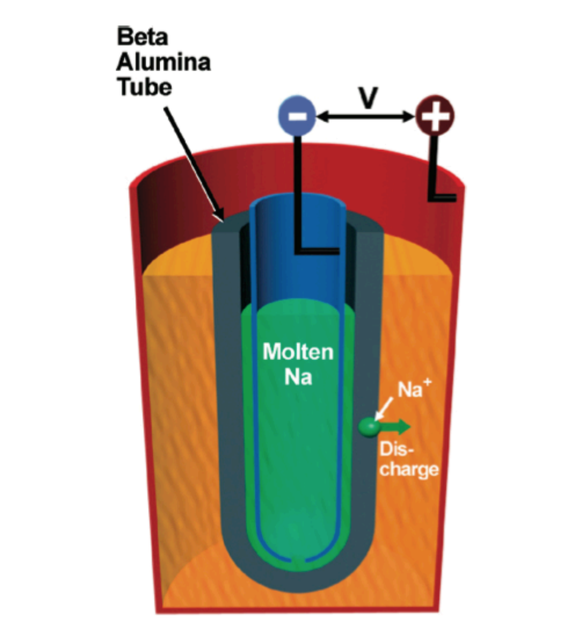
- Central (anode) reservoir of molten sodium (green)

- Membrane capable of passing Na^+ ions (gray)

  Typically: Al_2O_3 "beta alumina" ceramic

- Surrounding (cathode) outer cylinder (orange)

  Typically: Sulfur / Sodium Sulfide (Na_2S_x)



In the central anode:

$2\ Na \Rightarrow 2\ Na^+ + 2\ e^-$

At the outer cathode:

$x\ S + 2\ Na^+ + 2\ e^- \Rightarrow Na_2S_x$

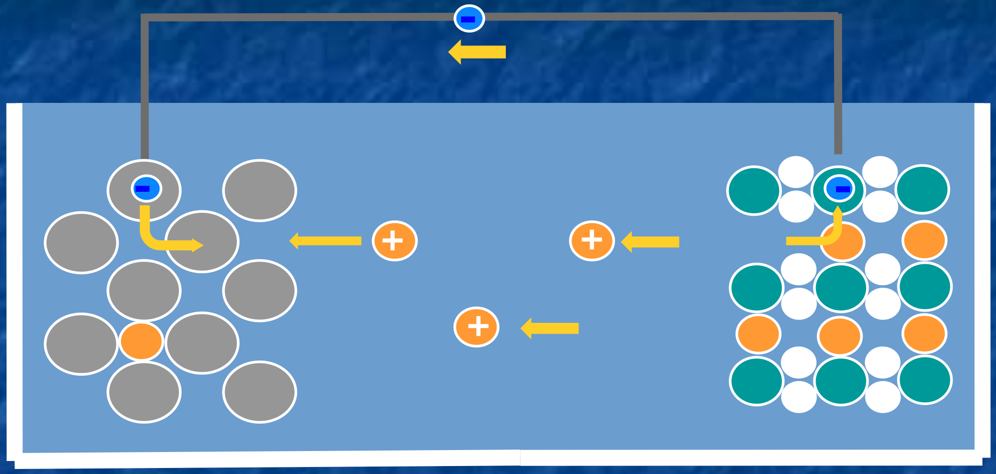
With Na^+ ions formed in anode migrating through beta alumina toward cathode

Figure: Electrochemical Energy Storage for Green Grid, Yang et al., Chemical Reviews 111, 3577–3613 (2011)
1) http://en.wikipedia.org/wiki/Molten_salt_battery

Lithium ion batteries were a third candidate:

During CHARGING, **Li** is actually transferred from **inside** cathode to **inside** anode

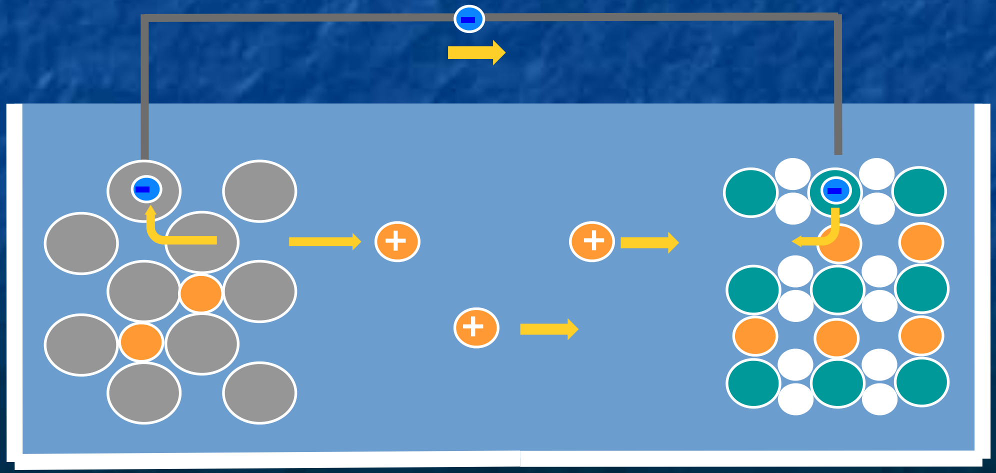
Anode:
Li absorbing
and deionizing



Cathode:
Li dissolving and
ionizing

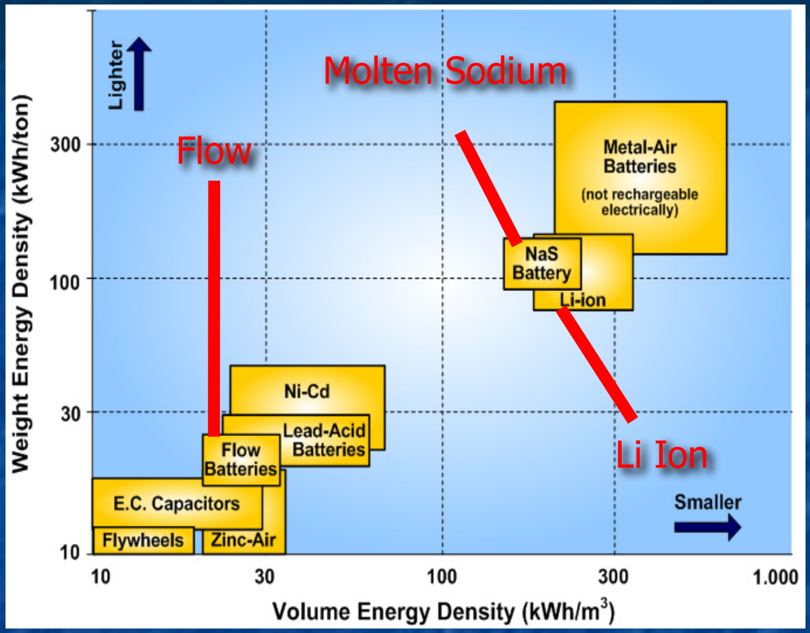
DISCHARGE reverses this: Li transferred from **inside** the anode to **inside** cathode:

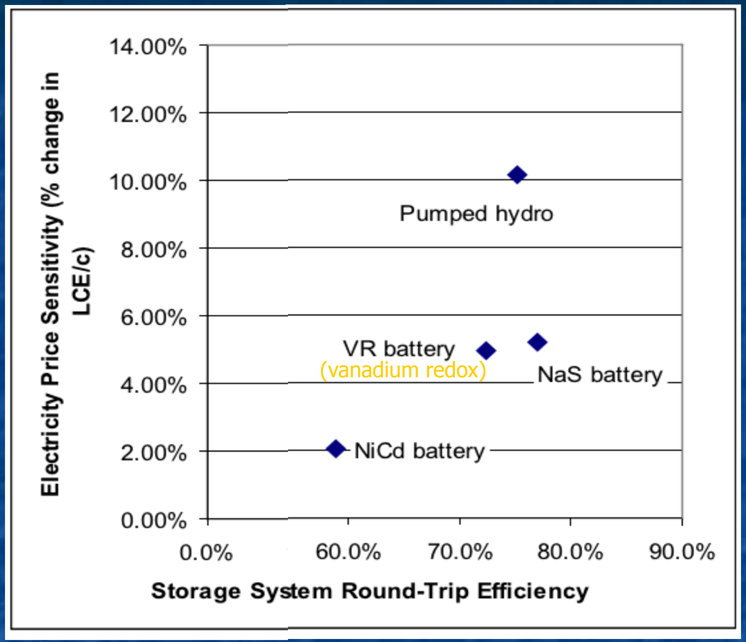
Anode:
Li desorbing
and ionizing



Cathode:
Li absorbing
and deionizing

Comparative battery energy density data on all of these:





Ion flow $_{\text{energy density}}$ = Up to 30 kW-h / m³ at ~ 73% efficiency

Molten Na $_{\text{energy density}}$ = Up to 270 kW-h / m³ at ~ 77% efficiency

Li Ion battery $_{\text{density}}$ = Up to 350 kW-h / m³

Left) http://www.sc.ehu.es/sbweb/energias-renovables/temas/almacenamiento/almacenamiento.html
Right (compacted version of): http://www.nrel.gov/hydrogen/pdfs/48360.pdf

g) Heat energy storage via Molten Salts

Best batteries returned ~ 80% of **electrical** energy

Using electrical power in => electrical storage => electrical power out

Molten salts return only about **70%** of **heat** energy

A 10% drop (compared to batteries) sounds significant

But while batteries are expensive, salt is cheap!

We might even mine AND store heat in the original SALT MINES!

NREL - Halotechnics Molten Salt Energy Storage Test Project, Emeryville CA:

35.45 kW-h stored in 0.19 m^3 of salt, returning 25.1 kw-h (71%) [1]

Which gives:

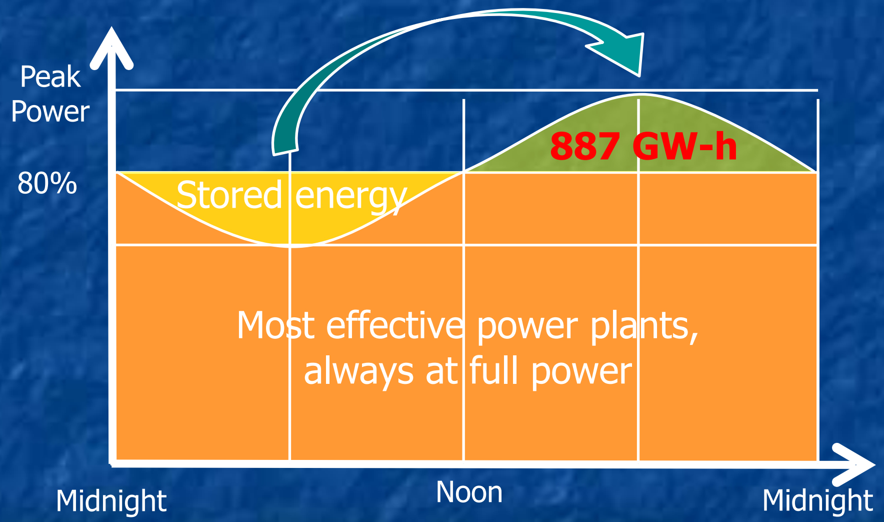
$\textbf{Salt}_{\textbf{energy storage density}}$ = 25.1 kW-h/0.19 m^3 = **132 kW-h/m^3**

1) http://www.nrel.gov/docs/fy13osti/58595.pdf

FINALLY (!): Using ALL of the data from above:

To compute the impact of the most promising storage technologies when used in:

Scenario #2 = Conventional Power + 8% Storage:



Projected numbers for nation-wide energy storage SYSTEMS:

Pumped Storage Hydro based energy storage SYSTEMS: **80% efficiency**

Bath PSH = 35.8 MW-h occupying ~ 2 km^2

Number of plants: 887 GW-h / 35.8 MW-h **= 24,781 plants**

Cumulative national footprint: (~ 25,000) x (~ 2 km^2) => **~ 50,000 km^2**

Fuel Cell based energy storage SYSTEMS: **30-35% efficiency**

"Planned" (future) plant capacity = 300 MW-h:

Number of plants: 887 GW-h / 300 MW => **2,956 plants**

Current test plant = 50 MW-h, no info given on plant sizes

Number of plants: 887 GW-h / 50 MW => **17,740 plants**

Cumulative national footprint: Not enough information given = **? km^2**

Projected numbers for nation-wide energy storage SYSTEMS (cont'd):

Flywheel based energy storage SYSTEMS: **85-90% efficeint**

Current projects = 2 MW-h occupying ~ about 2 hectares

Number of plants: 887 GW-h / (2 MW-h) => **443,500 plants**

Cumulative national footprint: ~ 90,000 hectares => **9000 km^2**

Adiabatic compressed air based energy storage SYSTEMS: **70% efficient**

Adiabatic plant (under construction) = 1000 MW occupying ~ 1 hectare

Number of plants: : 887 GW-h / (1 GW-h) => **886 plants**

Cumulative national footprint: ~ 900 hectares => **9 km^2**

Now moving onto energy storage THINGS:

Projected numbers for nation-wide energy storage THINGS:

Based on assumptions: Volume = 887 GW-h / (energy storage density)

Converted to a footprint by assuming these are piled ~ 1 m high in warehouses

Battery based energy storage THINGS: **70-80% efficient**

Energy Storage Density – **Flow Batteries**: 30 kW-h/m^3

Cumulative volume => footprint: 29×10^6 m^3 => **29 km^2**

Energy Storage Density – **Molten Sodium Batteries**: 270 kW-h/m^3

Cumulative volume => footprint: 3.3×10^6 m^3 => **3.3 km^2**

Energy Storage Density - **Lithium Ion Batteries**: 350 kW-h/m^3

Cumulative footprint: 2.5×10^6 m^3 = **2.5 km^2**

Projected numbers for nation-wide energy storage THINGS (cont'd):

Capacitor based energy storage THINGS: **likely nearly 100% efficient**

Energy Storage Density – **h-BN insulator** : 1.25 kW-h/m^3

Cumulative volume => footprint: 1.26 x 10^8 m^3 => **126 km^2**

Molten Salt based heat energy storage THINGS: **70% efficient**

Energy Storage Density: 132 kW-h/m^3

Cumulative volume => footprint: 6.7 x10^6 m^3 => **6.7 km^2**

However, if you could get them to efficiently store heat,

Salt Caverns might be a much better idea for cheap/large-scale storage

Leading to the somewhat surprising result:

In contrast to note set **Power Plants Requirements: Land & Water** (pptx / pdf / key)

For this **Scenario #2 = Conventional Power + 8% Storage**

Land requirements of essentially all storage technologies are NOT excessive!

Indeed, especially for the technologies located primarily underground:

Surface ground use and overall environmental impact might be small

So WHY don't we already make extensive use of energy storage?

The answers must lie in:

The Cost of Grid Scale Energy Storage

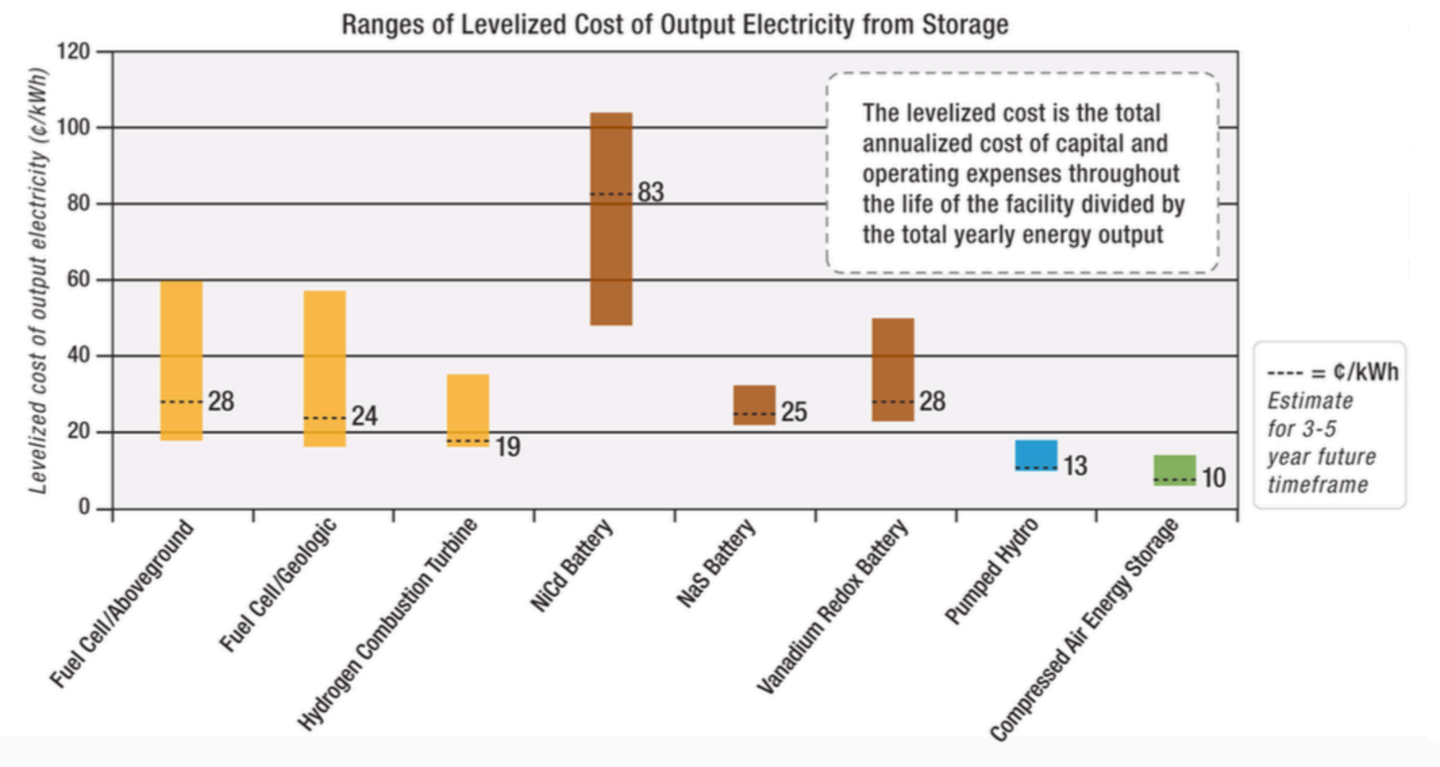
NREL estimates of energy storage LCOEs:

From a 2010 NREL presentation (with dashed lines giving anticipated 2015 costs):

Figure uses units of ¢/kW-hr rather than more common units of $/MW-h:

1¢/kW-hr => $10/MW-h (i.e. multiply by ten and change units)

100$/MW-h →



U.S. National Renewable Energy Lab: "Hydrogen Energy Storage Overview"
http://www.nrel.gov/hydrogen/pdfs/48360.pdf

An independent corporate study:

"Projections of the Levelized Cost Benefit of Grid Scale Energy Storage Options"

From a 2010 conference paper presented by **Doty Energy Corp.**

Final column gives levelized cost due to storage using the indicated technology

Table 1. Projected Incremental Energy Delivery Cost at 7% Discount Rate in $90M facilities (ignoring input energy cost) for 2015 Technology

Device	Storage Capacity	Peak Power	Storage Cost	Power Cost	Cycle Effic.	Mean Cycle Depth	Cycle Rate	Power Duty Cycle	Life Time	Incremental Cost of Energy
units	MWh	**MW**	$/kWh	**$/kW**	%		cycle/yr		years	**$/MWh**
Windfuels	2000	**100**	0.05	**900**	0.52	**0.5**	320	**0.5**	30	**38**
H2 fuel cell	2800	**120**	10	**540**	0.7	**0.4**	320	**0.4**	10	**51**
pumped hydro storage	600	**50**	120	**300**	0.8	**0.7**	330	**0.4**	50	**56**
UPHS	550	**40**	120	**500**	0.75	**0.7**	320	**0.4**	50	**68**
carbon-lead-acid battery	750	**70**	100	**250**	0.75	**0.4**	500	**0.3**	10	**102**
AA-CAES	350	**30**	150	**1200**	0.61	**0.55**	320	**0.3**	30	**162**
lithium-ion battery	160	**40**	500	**250**	0.8	**0.6**	600	**0.2**	20	**167**
lead-acid battery	1100	**100**	60	**250**	0.75	**0.5**	250	**0.2**	5	**181**
flywheel	30	**20**	2800	**500**	0.85	**0.7**	800	**0.1**	30	**532**
NaS battery	75	**9**	1200	**300**	0.74	**0.7**	280	**0.25**	15	**774**
ultra-capacitors	5	**5**	20K	**400**	0.7	**0.7**	1000	**0.1**	30	**2910**
SMES	0.6	**0.2**	150K	**700**	0.5	**0.6**	300	**0.1**	30	**94,000**

http://dotyenergy.com/PDFs/Doty-90377-Storage-ASME-ES10.pdf

A comparison of those data (all in $/MW-h):

Storage Technology	NREL LCOE 2010	Doty LCOE 2010	NREL LCOE ~ 2015
Pumped Storage Hydro	130-180	56	130
Fuel Cell	100-600	51	240-280
V redox battery	220-500		280
Adiabatic CAES	100-165	162	100
Li ion battery		167	
Flywheel		532	
Lead Acid battery		181	
NaS battery	220-320	774	250
NiCd battery	480-1030		830
Ultra Capacitors		2910	

Quick analysis of storage LCOE's:

Pumped storage hydro (PSH / UPSH) is cheapest: ~ $50 / MW-h

Fuel cell storage: Doty: Comparable to PSH NREL: 4-5 X PSH

Adiabatic CAES & best battery storage ~ 2-3 X PSH = $100-150 / MW-h

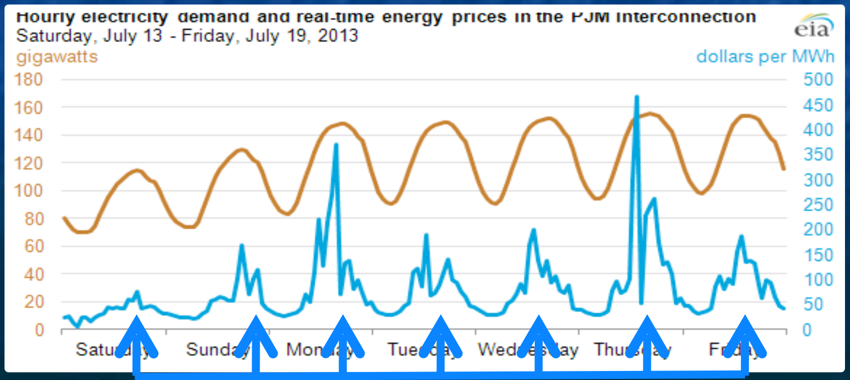
Storage LCOE would be ADDED to energy's production LCOE = $70-150 / MW-h

Seemingly at least doubling or tripling the total cost of energy!

But not really, because under Scenario #2:

Storage cost is added to **only** to the ~ 8% of power we need to store

And competition = Scenario #1 evening power, already 2-4X more expensive!



Thus some experts say storage could be competitive within five years

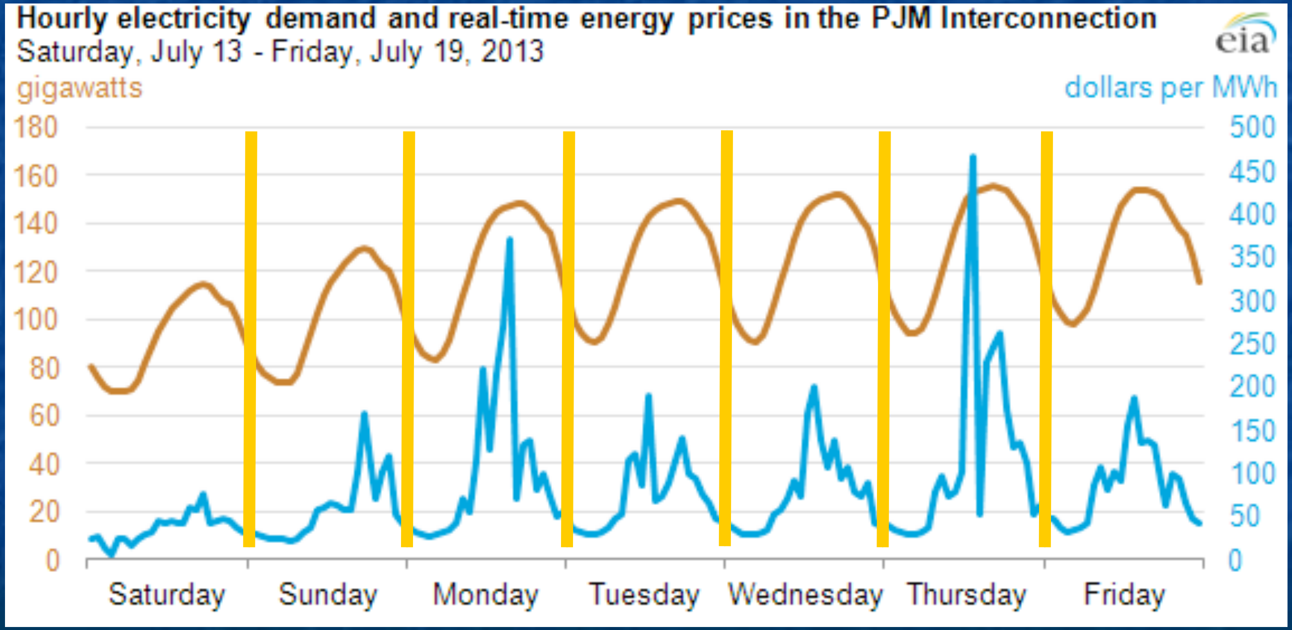
NEW Scenario 3: Use of ONLY "green" sustainable power sources

"Greenest" of renewable energy sources don't produce energy all of the time:

Examples include solar power, wind power, tidal power

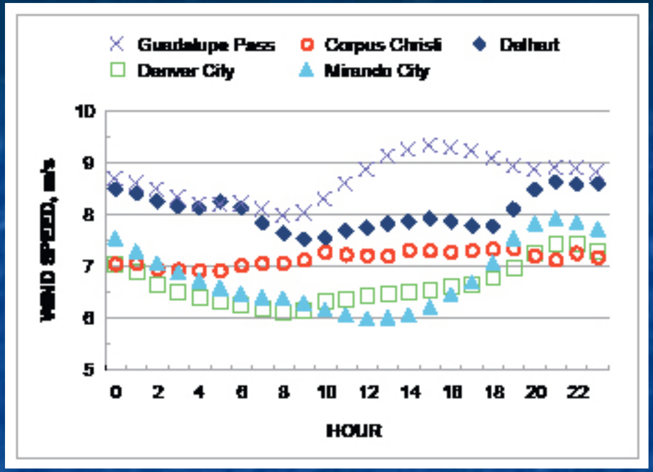
And when they DO produce, it's not when we most need their production!

This, again, is how we LIKE to consume energy:

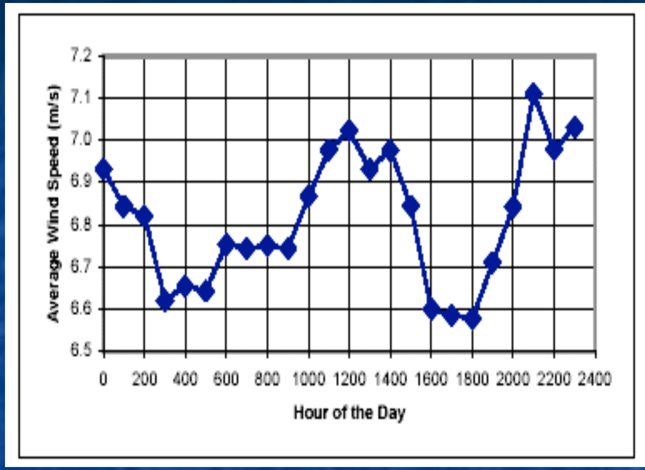


www.eia.gov/todayinenergy/detail.cfm?id=12711 *YELLOW midnight lines added*

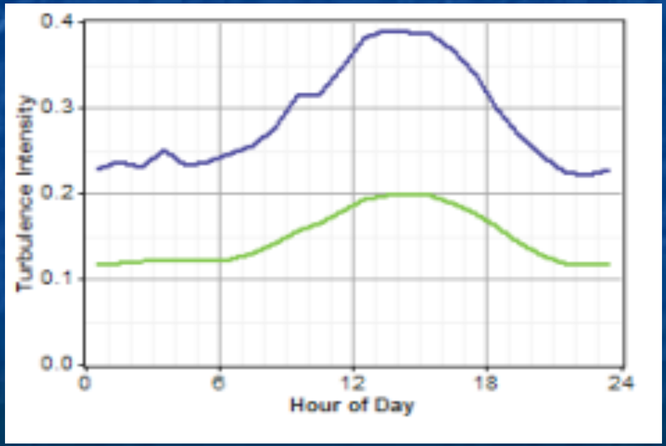
These are data on actual wind speeds vs. time of day



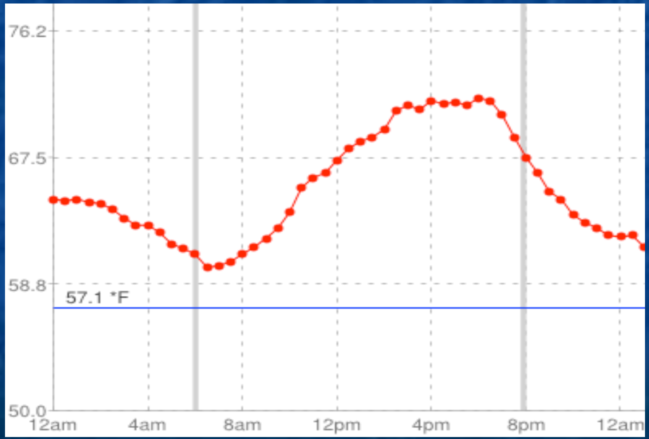
TEXAS: www.seco.cpa.state.tx.us/publications/renewenergy/windenergy.php



ONTARIO CANADA: www.omafra.gov.on.ca/english/engineer/facts/03-047.htm



NETHERLANDS: www.ekopower.nl/wind-energy-monitoring-data-logger-data-processing.htm



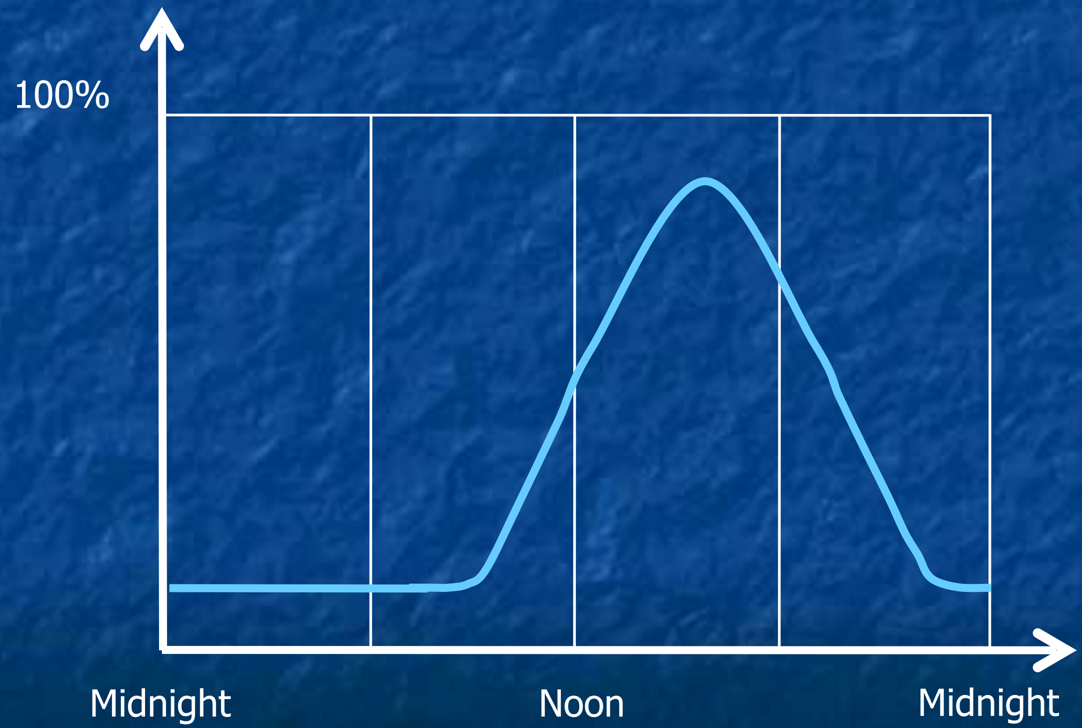
WISCONSIN: www.windpowerweather.com/history?date=last2days

Which, recalling that wind energy goes as wind velocity cubed:

Would lead to a typical wind **energy** versus time of day plot something like this:

(~ doubled afternoon wind speed => ~ 2^3 X wind power)

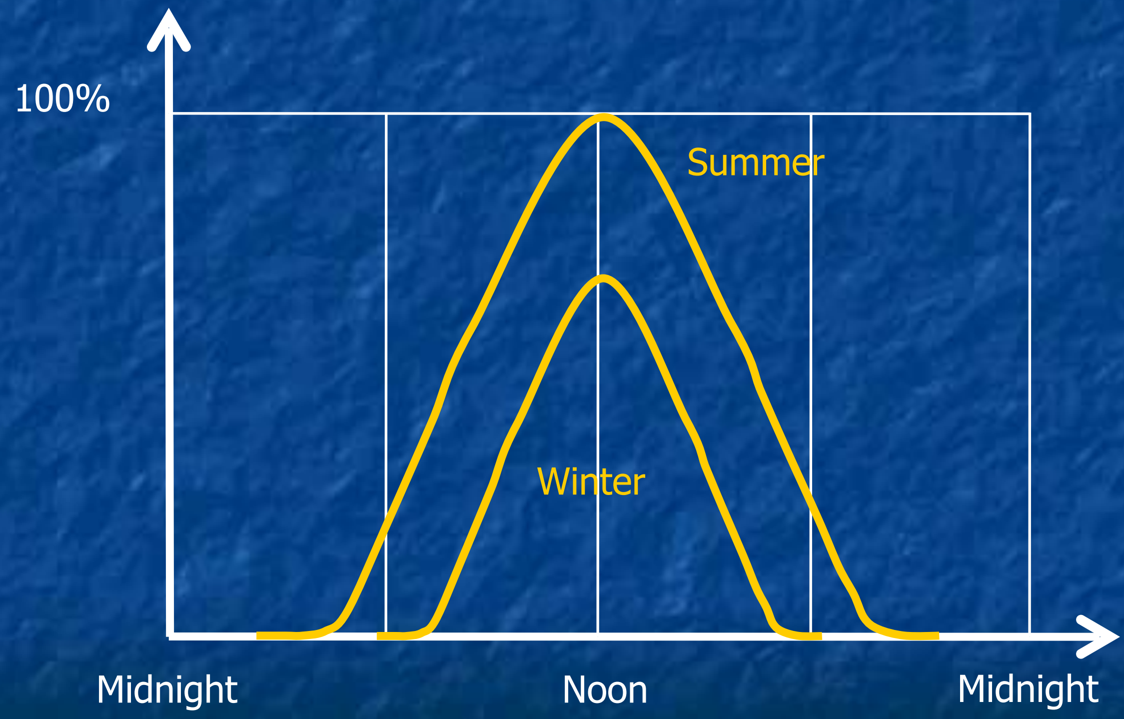
Thus, with wind energy peaking sharply in the late afternoon, we'd get power like:



Solar energy peaks midday, but also varies by season:

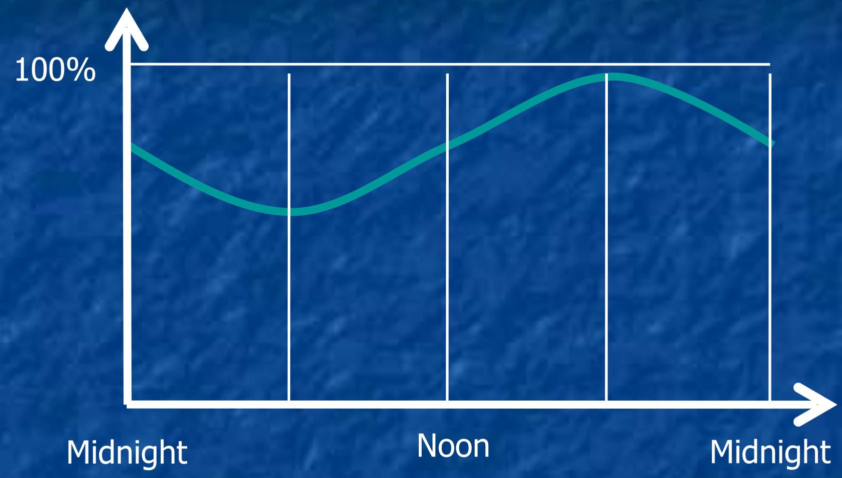
Starts at sunrise, peaks at about noon, ends at sunset

And lasts longer and is more intense in the summer:

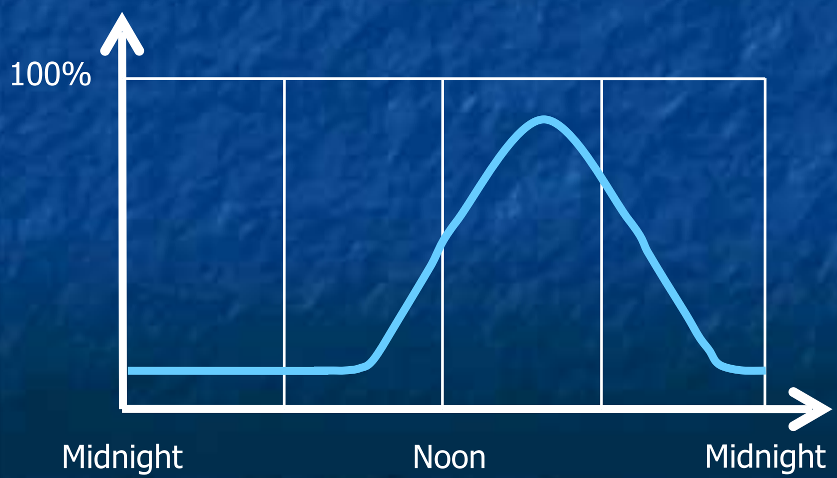


Wholesale use of renewables => HUGE NEED for storage!

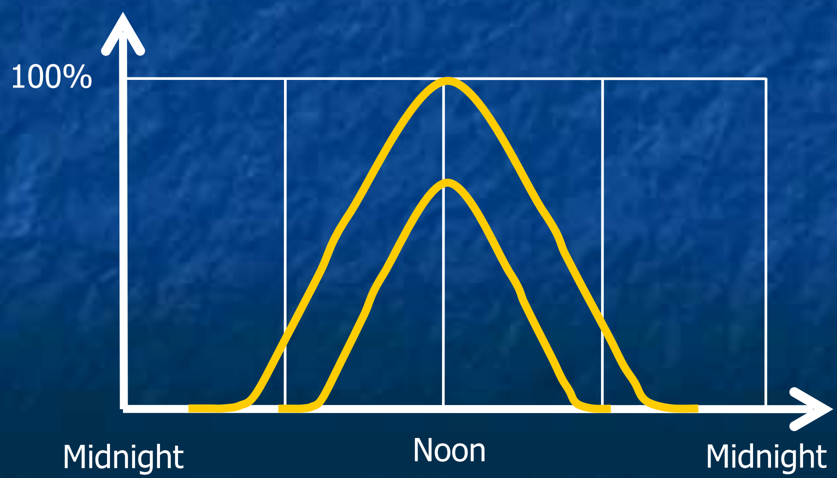
What we now need/want in the way of daily power:



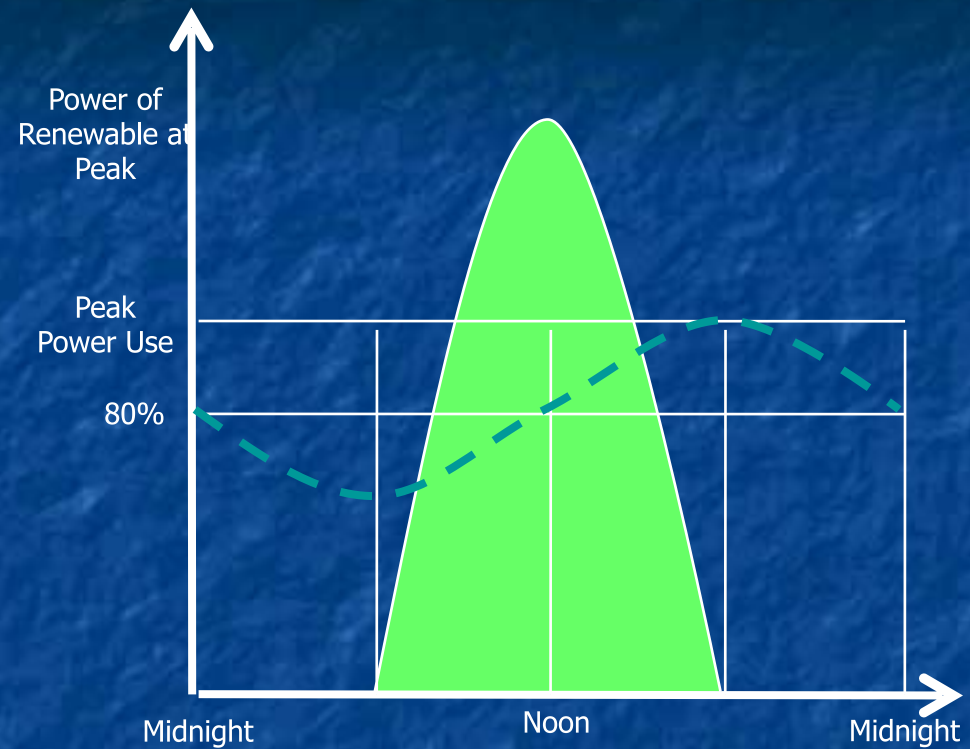
What we'd get from a **wind** plant:



What we'd get from a **solar** plant:



*Let me (somewhat crudely) approximate **either** as half sine wave:*

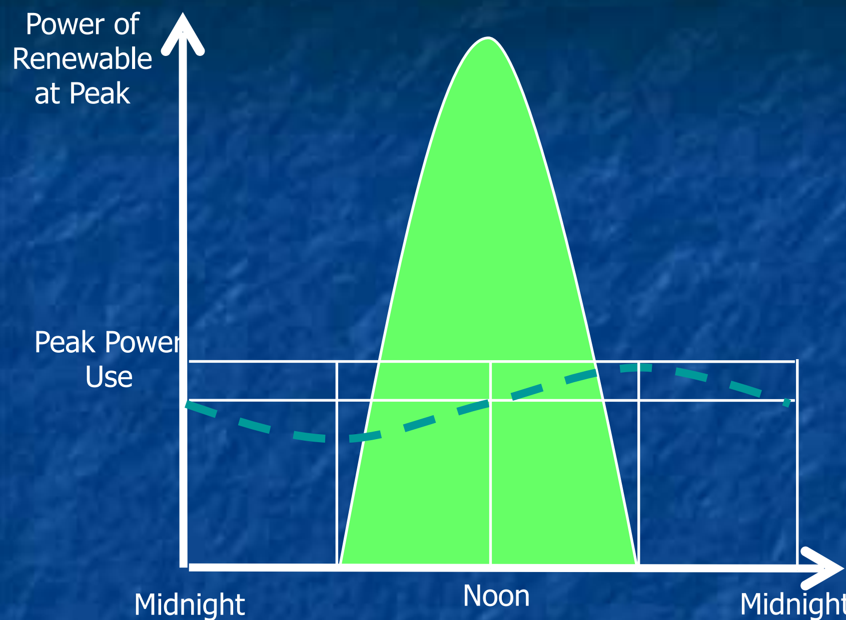


Area under half sinusoid = Amplitude x day / Pi = $P_{peak\_renewable}$ x day / Pi

But if this to be **all** our power, this must = 80% P_{peak_use} x day

Implying $P_{peak\_renewable}$ = 0.8 Pi P_{peak_use} = 2.5 P_{peak_use}

Whoops, so wind energy production would have to be more like:



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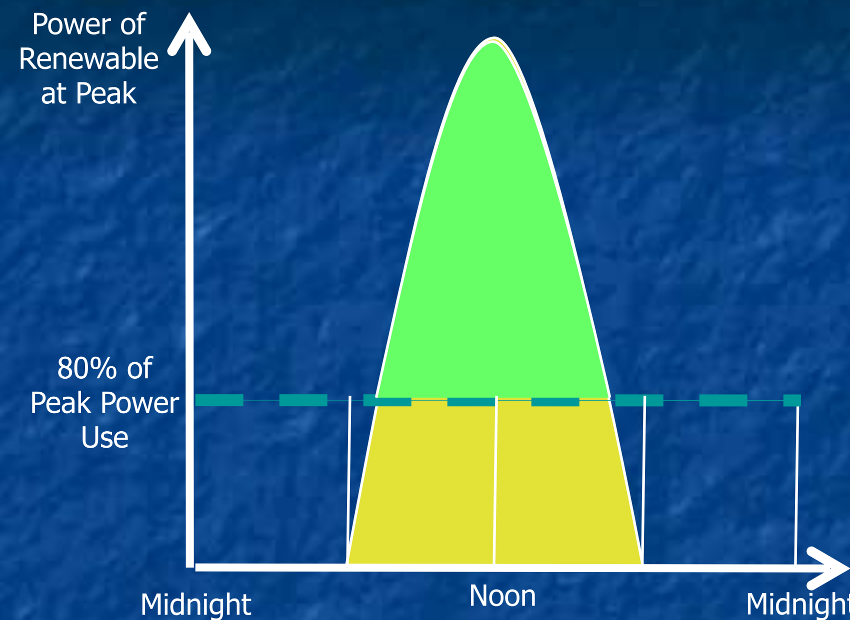

But I now need to store and shift ALL energy above green "use" line!

Yellow Base ~ $(0.8\ P_{peak\_use})(d/2) = (0.4\ d)(P_{peak\_renewable}/2.5) = 0.16\ P_{peak\_renewable}\ d$

Fraction that must be stored and shifted = 1 - Yellow base / All

$= 1 - (0.16\ P_{peak\_renewable}\ d) / (P_{peak\_renewable}\ d\ \text{day} / \text{Pi}) = 1 - 0.16\ \text{Pi} =$ **50%**

Making this the **"Green (only) Sustainables + 50% Storage"** scenario

Whoops squared!

From previously having to store **8%** of energy to accommodate our power use curve

If we use single "green" renewable (i.e. neither hydro or nuclear), we would have to:

Store and shift **50%** of energy to accommodate our power use curve

Switch to renewables => Need to increase storage by ~ 6X

(vs. storage Scenario #2 which just eliminated evening "peaking" power plants)

Two renewables, peaking at different times (e.g. solar and wind) help a little

Two renewables, coming from different time zones, help a little more

But this strongly suggests that **we will have to retain some 24/7 power sources**

Producing a good fraction of the present day (Scenario #1) base load

It's going to be really hard to abandon hydro & nuclear power!

Credits / Acknowledgements

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This set of notes was authored by John C. Bean who also created all figures not explicitly credited above.