Data Science for Energy System Modelling
Lecture 4: Storage and Hydropower

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Hybrid Format Information: Zoom and Recordings

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Today’s Mentimeter

Instructions

Go to

www.menti.com

Enter the code

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Or use QR code

Balancing wind and solar generation with demand

How much wind and solar do we need?

We have three time series:

- $\{d_t\}, d_t \in \mathbb{R}$ the load (in GW)
- $\{w_t\}, w_t \in [0,1]$ the wind capacity factor
- $\{s_t\}, s_t \in [0,1]$ the solar capacity factor

Assume α GW of wind and β GW of solar.
Now the effective **residual load** or **mismatch** is

$$m_t = d_t - \alpha w_t - \beta s_t$$

Choose α, β such that on **average** load is covered

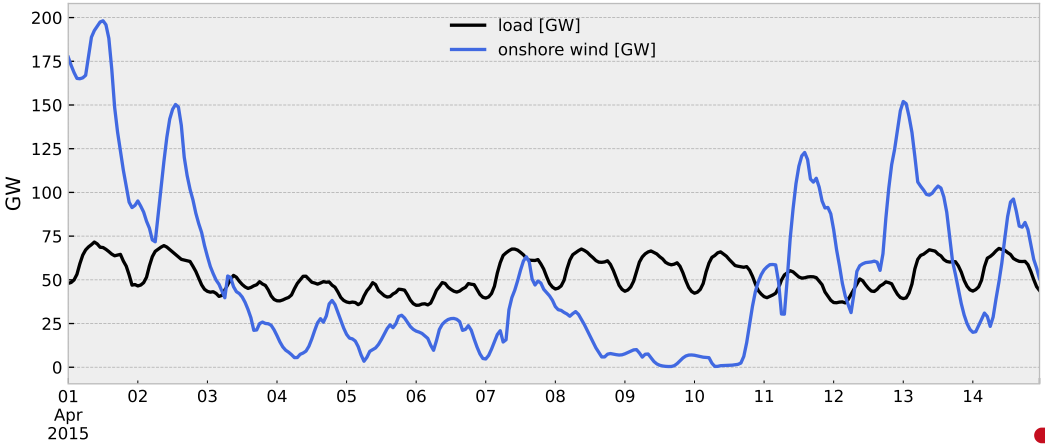
$$\langle m_t \rangle = 0$$

	load [GW]	onwind [pu]	solar [pu]
⋮	⋮	⋮	⋮
2015-01-05 04:00:00	43.93	0.29	0.00
2015-01-05 05:00:00	50.07	0.30	0.00
2015-01-05 06:00:00	56.24	0.32	0.00
2015-01-05 07:00:00	59.86	0.33	0.00
2015-01-05 08:00:00	61.18	0.33	0.06
2015-01-05 09:00:00	62.10	0.33	0.13
2015-01-05 10:00:00	63.02	0.31	0.16
2015-01-05 11:00:00	62.95	0.29	0.18
2015-01-05 12:00:00	62.11	0.25	0.18
2015-01-05 13:00:00	61.18	0.20	0.15
2015-01-05 14:00:00	60.45	0.18	0.09
2015-01-05 15:00:00	61.34	0.16	0.01
⋮	⋮	⋮	⋮

Source: Load: Open Power System Data Platform; Renewables: renewables.ninja

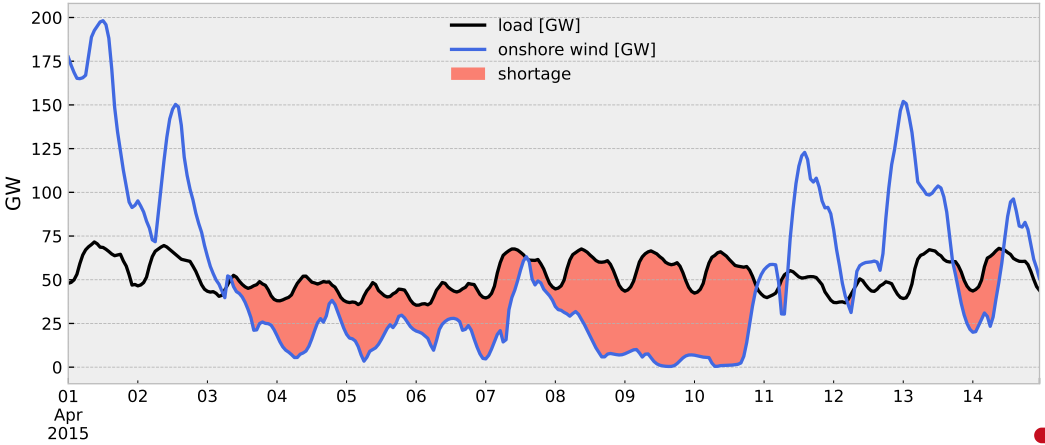
Balancing **wind** generation with demand (one month example)

Balancing on average is **not enough**: need matching generation and demand in **every hour**!



Balancing **wind** generation with demand (one month example)

Question: What to do in periods of shortage?



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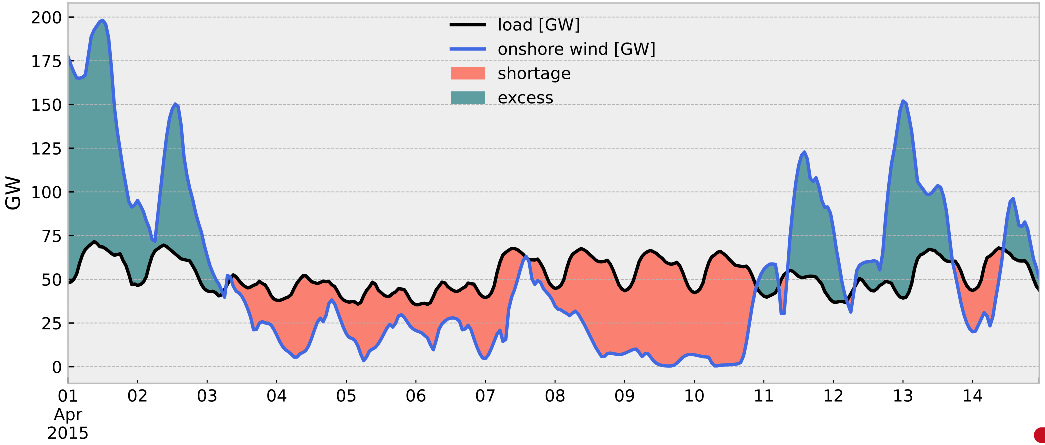
Balancing **wind** generation with demand (one month example)

Question: What to do in periods of excess?



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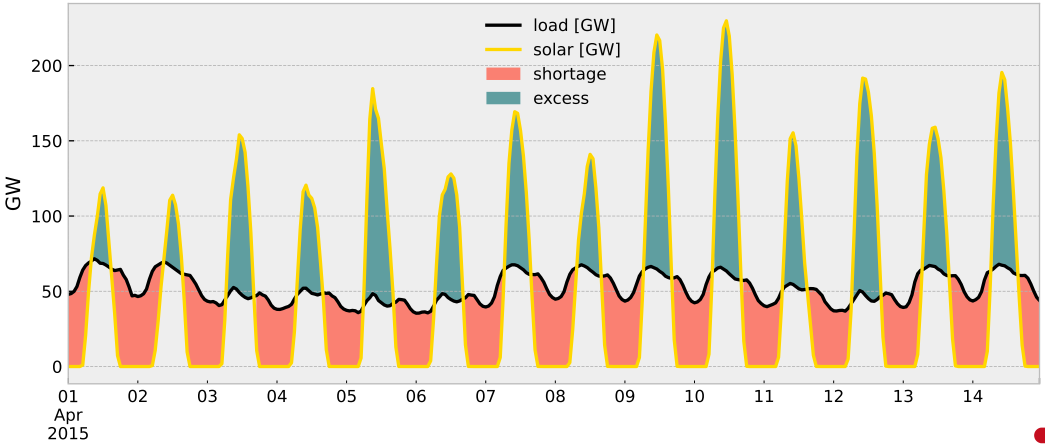
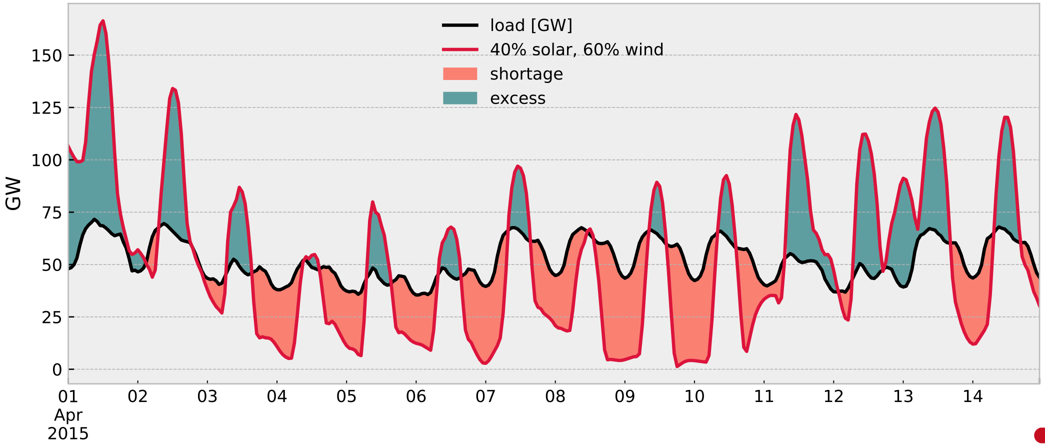
Balancing **solar** generation with demand (one month example)

Generation and demand patterns determine requirements for storage technology.

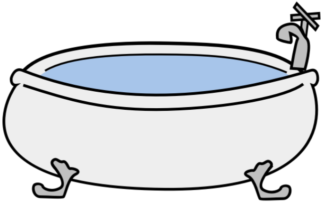


Balancing **mixed** renewable generation with demand (one month example)

Question: How to determine the storage capacity required?



Bathtub analogy for energy storage

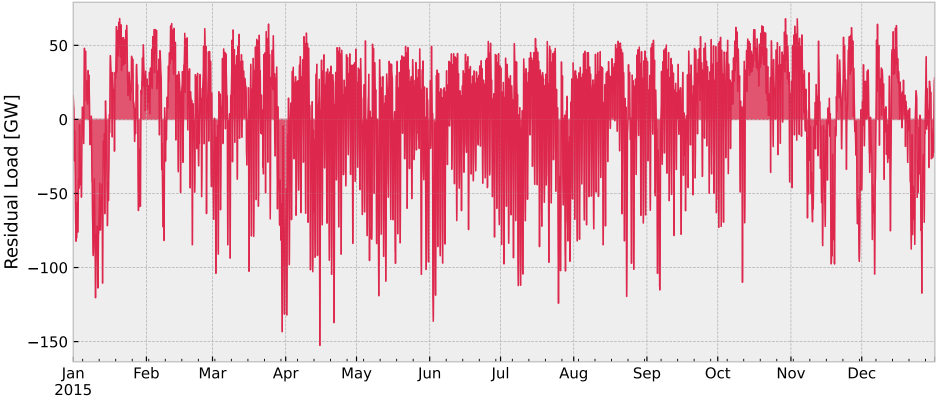


There are three different storage capacities to consider: the **energy capacity** (MWh), the **charging power capacity** (MW), and the **discharging power capacity** (MW).

Bathtub	Energy Storage
inflow	charging (in excess supply)
outflow	discharging (in supply shortage)
water level	state of charge (SOC)
bathtub volume	energy capacity
max inflow rate	charging power capacity
max outflow rate	discharging power capacity

Residual load from **mixed** generation (one year example)

Residual load = demand - variable renewable generation



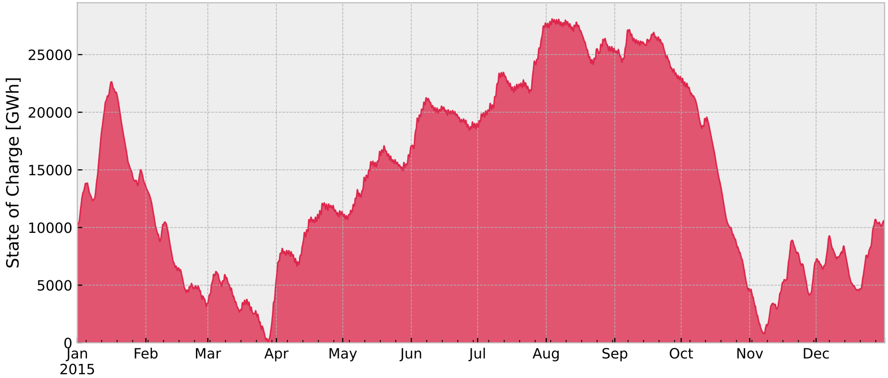
Positive residual load = **shortage**

Negative residual load = **excess**

Calculating energy storage state of charge (SOC) (one year example)

The SOC can be calculated from the **cumulative sum** of the residual load time series *(assuming lossless storage)*.

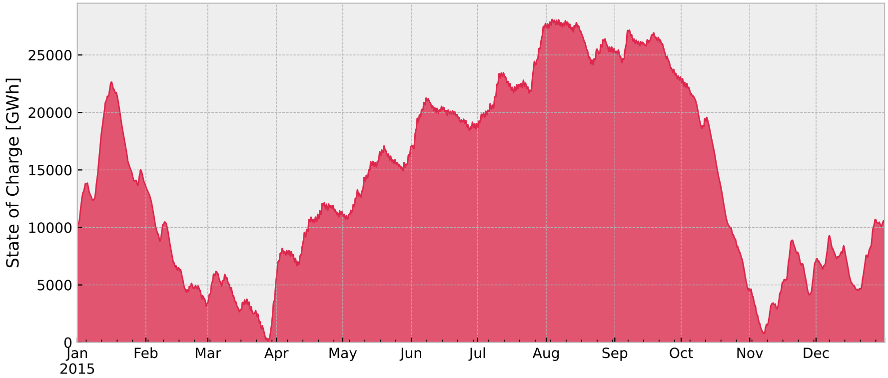
Negative residual load **increases** SOC, positive residual load **decreases** SOC.



Calculating energy storage state of charge (SOC) (one year example)

The SOC must be a **non-negative** quantity. Since we look at only one year of data, we need to set the **initial SOC** such that the SOC never goes negative.

We can do this by **shifting** the entire SOC time series by the minimum value *(negative)*.



Actions to deal with shortages and excess supply

Periods of Excess

- curtail / spill
- charge storage
- export
- increase demand

Periods of Shortage

- backup generation
- discharge storage
- import
- reduce demand

Which of these options are good?

Backup generation may cause additional CO_2 emissions.

Curtailment is also a waste of energy if it can be avoided.

Better to options:

1. Using **electricity storage** to shift energy from times of surplus to times of deficit.
2. **Demand-side management** to shift demand to times when renewables are abundant.
3. Balancing in space with **transmission grids** over large areas.

Storage equations in math at time *t*

Discharging power d_t within **discharging capacity** D (in MW):

$$0 \leq d_t \leq D$$

Charging power c_t within **charging capacity** C (in MW):

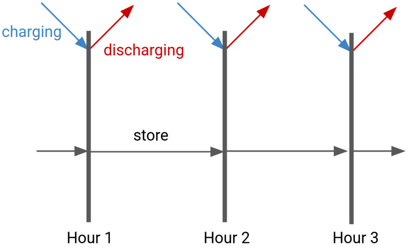
$$0 \leq c_t \leq C$$

There is also a **limit** E (in MWh) on the SOC e_t:

$$0 \leq e_t \leq E$$

The state-of-charge e_t evolves in relation to c_t and d_t:

$$e_t = e_{t-1} + c_t - d_t$$



Factoring in efficiency & losses in conversion & storage

Because energy lost in the process of storing power, the storage consistency equation

$$e_t = e_{t-1} + c_t - d_t$$

needs to be amended for **efficiencies** $\eta_* \in [0,1]$, corresponding to **losses** $1 - \eta_*$

$$e_t = \eta_{\text{self}}\, e_{t-1} + \eta_{\text{charge}}\, c_t - \frac{1}{\eta_{\text{discharge}}}\, d_t$$

η_{charge} corresponds to the **charging efficiency**,

$\eta_{\text{discharge}}$ to the **discharging efficiency**, and

η_{self} to the efficiency after **standing losses / self-discharge**.

Hydro reservoirs can also **spill** water to reduce stored potential energy; they can also have a **natural inflow** increasing the storage filling level ($\rightarrow$ later).

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Simple Example

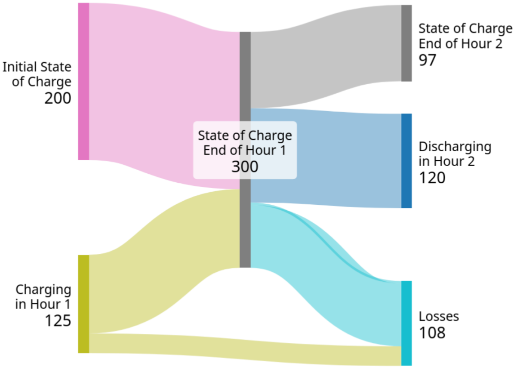
Suppose the initial SOC of a storage unit is 200 MWh at the start of hour 1.

In hour 1, we charge the storage with a rate of 125 MW with an efficiency of 80%.

In hour 2, we discharge the storage to supply 120 MW of electricity with an efficiency of 60%.

In hour 2, the ambient conditions make the storage unit loose 1% of its energy per hour.

What is the SOC at the end of hour 2?



Storage Technologies

Different types of storage vary in their parameters

We can relate the power capacities (C or D) to the energy capacity (E) with the maximum number of hours the storage unit can be dis-/charged at full power before the energy capacity is empty/full, e.g. $E = \text{max-hours} \cdot D$.

Example numbers for 2030	Battery	Hydrogen	Pumped-Hydro
η_{self} (small)	$1-\varepsilon$	$1-\varepsilon$	$1-\varepsilon$
η_{charge}	$\geq 95\%$	60-70%	$\approx$90%
$\eta_{\text{discharge}}$	$\geq 95\%$	30-50%	$\approx$90%
max-hours	1-8	weeks to months	4-10
€ per kW [C and D]	170	1500 (electrolyser) + 1100 (H_2 turbine)	depends
€ per kWh [E]	150	2 (underground) or 45 (steel tank)	depends

Hydrogen storage systems would include three main components: **Electrolyser** to produce hydrogen, **turbine** to re-electrify hydrogen, **steel tank** or **salt cavern** to store hydrogen.

Source: `https://github.com/PyPSA/technology-data/blob/master/outputs/costs_2030.csv`

Different storage units have different use cases

Consider the cost of a storage with 1 kW of power capacity, and different energy capacities.

The total losses are given by the **round-trip losses** in and out of the storage $1 - \eta_{\text{charge}} \cdot \eta_{\text{discharge}}$.

	Battery		Hydrogen	
round-trip losses	$1 - 0.95^2$	$= 0.0975$	$1 - 0.5 \cdot 0.7$	$= 0.65$
€ for 4 kWh	$170 + 4 \cdot 150$	$= 770$	$2600 + 2 \cdot 4$	$= 2608$
€ for 100 kWh	$170 + 100 \cdot 150$	$= 15170$	$2600 + 100 \cdot 2$	$= 2800$

Battery has lower losses and is cheaper for short storage periods.

Hydrogen has higher losses but is much cheaper for longer storage periods.

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Different storage units are useful for different applications

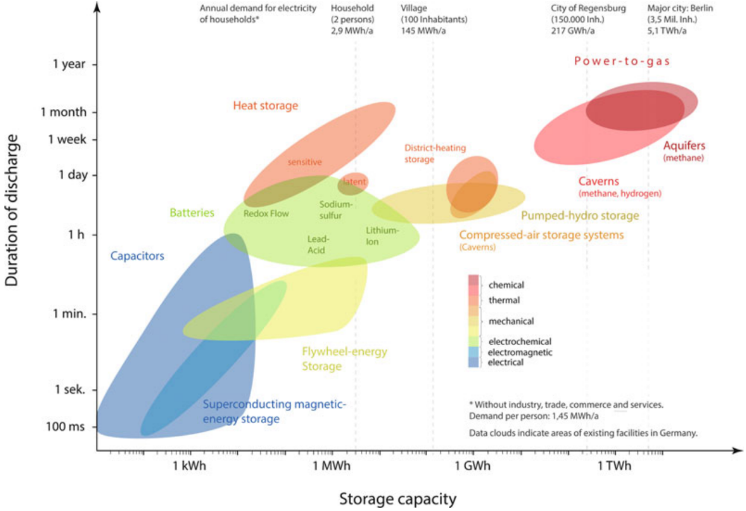
Daily variations:

- pumped-hydro
- batteries
- small thermal storage (e.g. in households)
- demand-side management (e.g. electric vehicles, households, industry)

Weekly and seasonal variations:

- hydrogen (electrolysis + fuel cell / turbine)
- carbonaceous fuel (methane, methanol with turbine)
- thermal energy storage
- hydro reservoirs

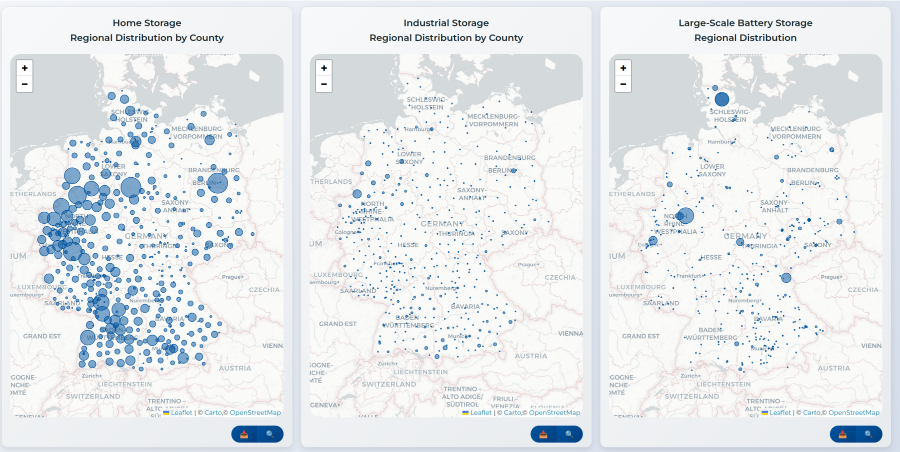
Overview of storage applications and technologies



Common to categorise storage by energy / power ratings and discharge times (i.e. how long they can discharge at full capacity from full to empty).

Source: https://link.springer.com/content/pdf/10.1007/978-3-662-55504-0.pdf

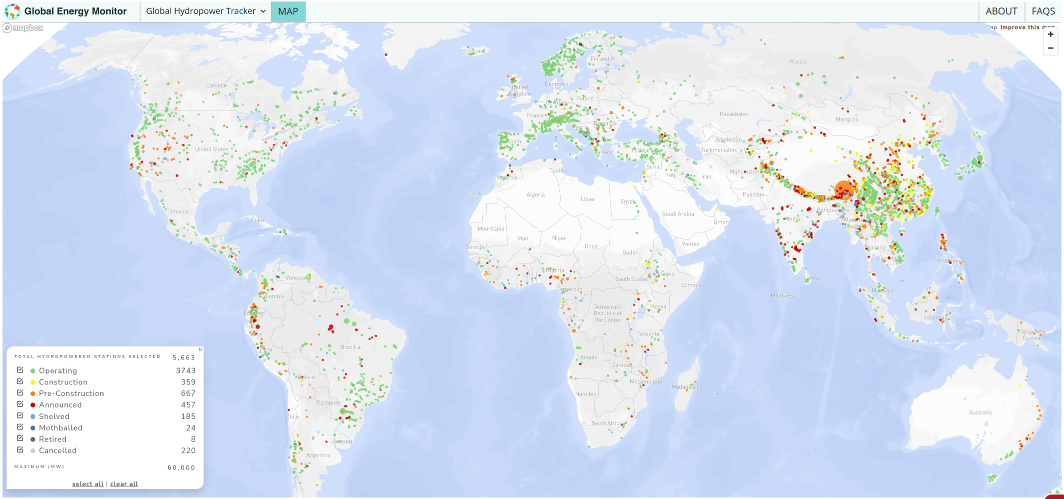
Current status of battery storage in Germany



Almost **16 GW and 24 GWh** of battery storage, mostly Li-ion and 2 GW utility-scale.

Source: `https://battery-charts.de/battery-charts`

Hydropower in the World



Source: Global Energy Monitor (https://globalenergymonitor.org/projects/global-hydropower-tracker/tracker-map/)

Largest hydro plant in the world: The Three Gorges Dam

Yangtze River, China, construction began 1994, opened in 2003-2012, 181m high, 2.3km wide, hydraulic head 80m, 32 x 700 MW turbines, rated capacity 22.5 GW.

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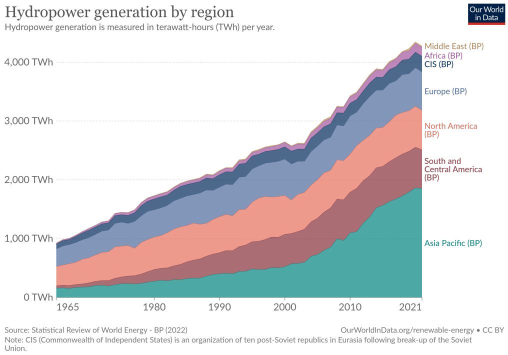
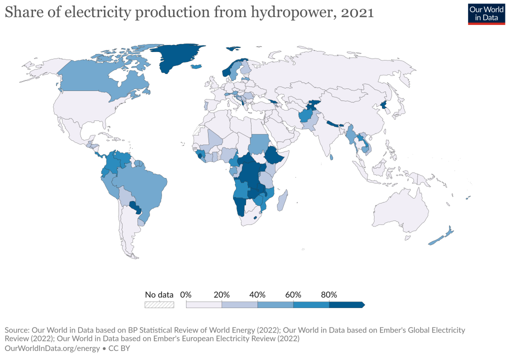
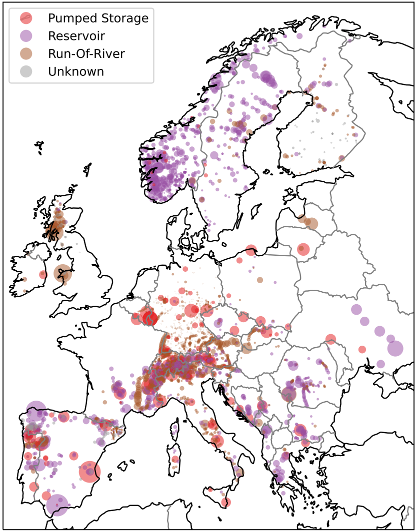
Development and significance of hydroelectricity around the world





- mostly stagnating & exhausted potentials in Europe
- high shares/dependency in many African and South American countries
- growing capacities in mainly in China and Rest of Asia

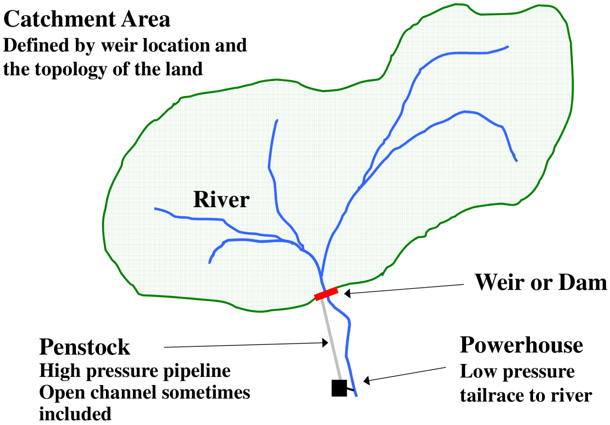
Hydropower in Europe and Types of Hydro Plants

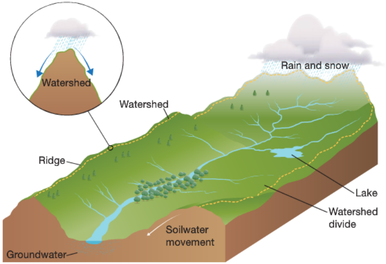


- ≈ 105 GW **hydro reservoirs**
- ≈ 55 GW **pumped-hydro storage**
- ≈ 49 GW **run-of-river plants**
- in particular in Norway and Alps
- sustainable potential considered to be largely exhausted, few new large projects, also given environmental impact

Source: powerplantmatching

Foundation: Catchment areas for water flow estimation



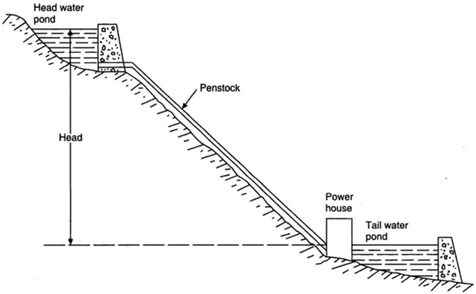


Source: University of Edinburgh,
https://sncyear7geography.weebly.com/catchment.html

Hydropower: Using head and flow to estimate power & energy

Power available is proportional to head × flow

$$P = \eta \cdot \rho \cdot g \cdot H \cdot \dot{Q}$$



$H =$ net head (m)

$\dot{Q} =$ flow (m^3/s)

$g =$ gravitational acceleration, 9.81 (m/s^2)

$\rho =$ density (kg/m^3)

$\eta =$ efficiency of turbine-generator (%)

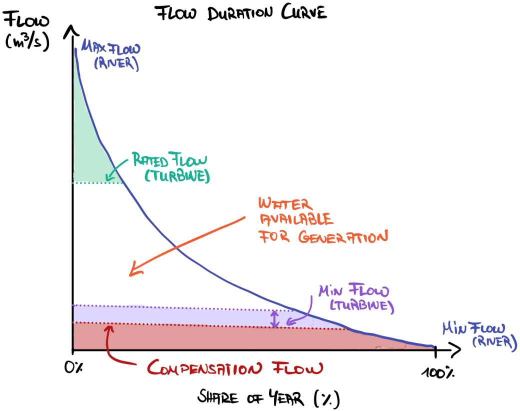
Estimate of annual **energy** production from total flow Q (m^3) with head & efficiency

$$E = \bar{\eta} \cdot \rho \cdot g \cdot \bar{H} \cdot Q$$

Robust estimates consider **changing heads**, **friction** losses in pipes, and **timing** of flow.

Source: University of Edinburgh

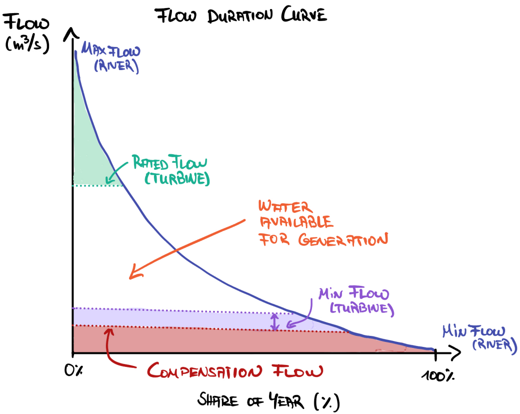
Design approach for a run-of-river hydro scheme

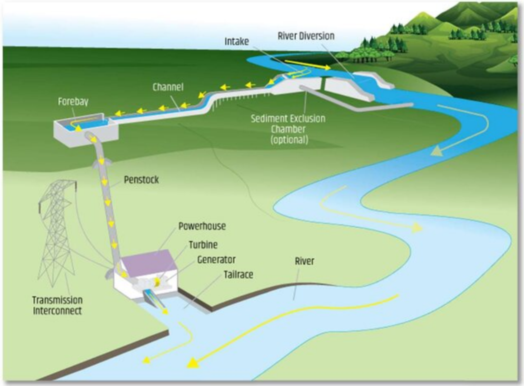


- River flows vary across **seasons** (e.g. snow melt) and **weeks** (e.g. rainfall)
- Calculation of 'useful' water flow makes use of **flow duration curve**
- A **compensation flow** must remain in river to preserve wildlife (e.g. 95% quantile)
- A **rated flow** is chosen to maximise economic return (e.g. 30% quantile)
- A **minimum flow** that the turbine requires technically to operate may also be specified

Source: University of Edinburgh

Flow duration curve in run-of-river scheme illustration

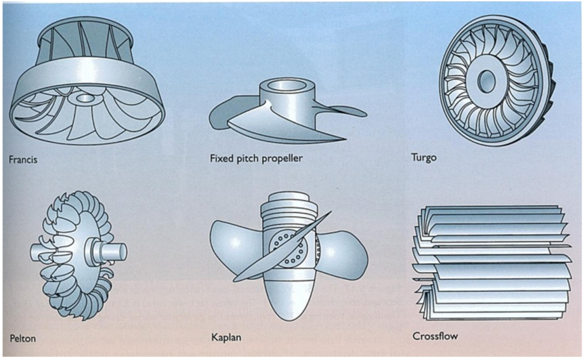




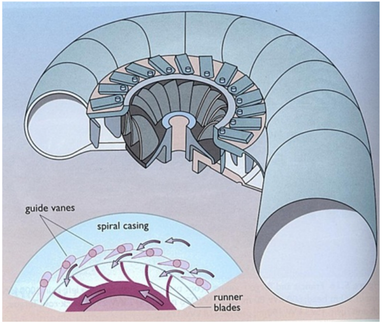
Source: University of Edinburgh

Types of turbines

There are various different types of turbines, which are employed for a specific application depending mainly upon the **head** and **flow rate**.



Types of turbine runner
Source: Boyle, 2004



Francis turbine: cut-away diagram and flow across guide vanes and runner
Source: Boyle, 2004

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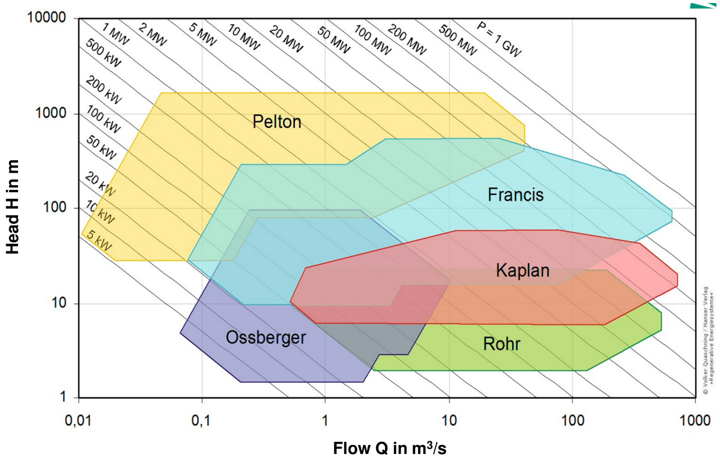
Gudelines for choosing the right turbine type



Example:

- head: 100m
- flow: 10 m^3/s
- efficiency: 90%

What is the right turbine for this hydro reservoir?