Hydro energy

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Seminar Energy Supply, Climate Change and Nuclear Fusion Research

WS 19-20

Photo: International Energy Agency

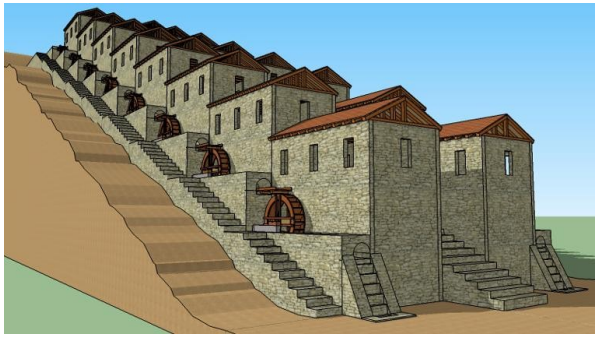
Contents

Introduction

Photo: John Gibbons
https://unsplash.com/photos/E2TVn-NpCU4

Hydropower

- Hydropower is the power derived from **flowing water**
- It has been used by humans for thousands of years (Persian Empire, Egypt, Roman Empire…)
- First electric generators around 1880s in UK, US and Canada



Model of the Roman watermill complex at Barbegal (France)

Source: Prof. Dr. Stephen ressler personal website
https://stephenjressler.com/portfolio/roman-mill-complex-at-barbegal/

Photo of the old Schoelkopf power station (US) in 1900

Source: Wikipedia “Schoellkopf Power Station” (visited on 6.12.2019)
https://en.wikipedia.org/wiki/Schoellkopf_Power_Station

Las Médulas (Spain), the most important gold mine, as well as the largest open-pit gold mine, in the entire Roman Empire.

Source: Newspaper “La Vanguardia” (20.09.2019)
http://tiny.cc/l7tlhz

Hydroelectricity (I)

The Three Gorges Dam (China) is the biggest hydroelectric power station with a capacity of 22.5 GW

Source: Nikkei Asian Review (visited on 6.12.2019)
https://asia.nikkei.com/Business/Companies/China-s-Three-Gorges-rules-out-new-domestic-hydro-projects

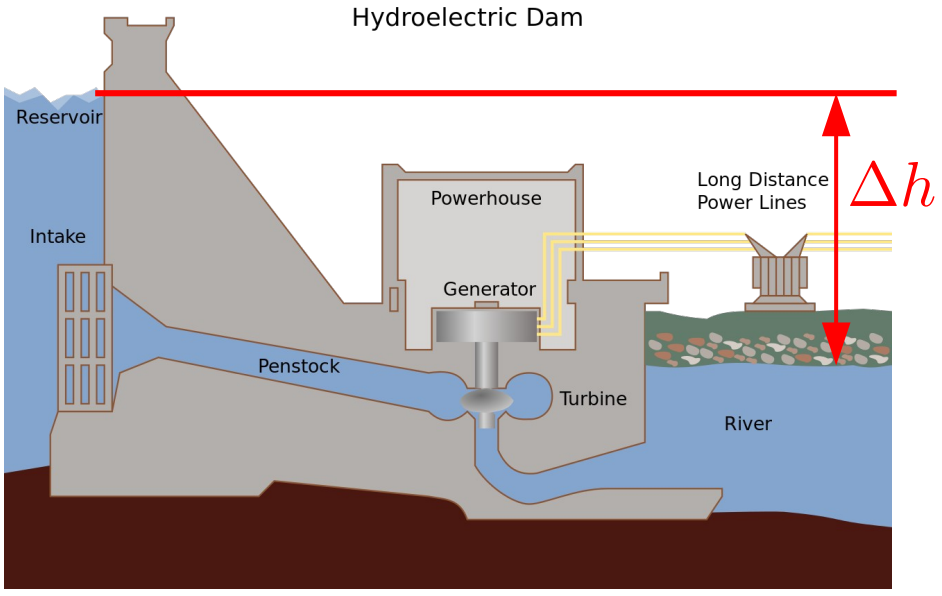
- Many small hydroelectric stations constructed at the beginning of 20th century
- Large stations from second half of 20th century
- There is no official classification but we can divide facilities into: large (>100 MW), small (~10 MW), micro (<100 kW) and pico (<5 kW)
- Different methods to generate electricity
  - → Conventional
  - → Run-of-the-river (ROR)
  - → Tide/Wave (talk 9.1.2020)
  - → Pumped-storage (next talk)

Hydroelectricity (II): Conventional (dam + reservoir)

- Conventional hydroelectric power stations use the potential energy of **dammed water driving a water turbine and generator**
- The capacity depends on the the **volume flow rate** and the **height difference** between the source and the water's outflow (usually the term *head* from fluid dynamics is used for this)

$$C = \eta \dot{m} g \Delta h = \eta \rho \dot{V} g \Delta h$$

  - Efficiency is often higher (~1) in stations with larger and modern turbines
  - Volume flow rate can be regulated using the reservoir

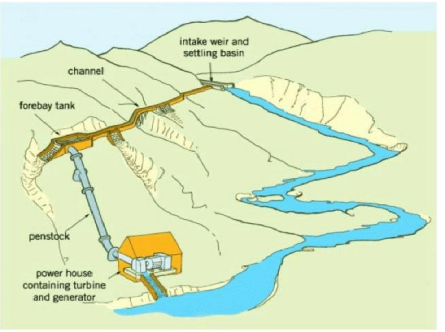


Cross section of a conventional hydroelectric dam

Source: Wikipedia “Hydroelectricity” (visited on 10.12.2019)
https://en.wikipedia.org/wiki/Hydroelectricity

Hydroelectricity (III): Run-of-the-river (ROR)

- Same idea but **ROR power stations have no reservoir**
- The volume flow rate is subject to seasonal river flows
- Previous formula still valid, but what is the head now?
- Alternative (but equivalent) derivation (analogous to Wind power)



Example of a ROR power station where a part of the river flow is deviated to a turbine

Source: Mbaka, John & Mwaniki, Mercy. (2017). Small Hydro-power Plants in Kenya: A Review of Status, Challenges and Future Prospects. Journal of Renewable Energy and Environment. 3. 20-26.

$$C = \frac{1}{2}\eta\rho\dot{V}v^2 = \frac{1}{2}\eta\rho A v^3$$

Hint to proof equivalency: Bernoulli's equation (conservation of energy for incompressible fluids)

$$P = \frac{1}{2}\rho v^2 + \rho g \Delta h = \text{cte}$$

Beauharnois ROR hydroelectric power station in Quebec (Canada)

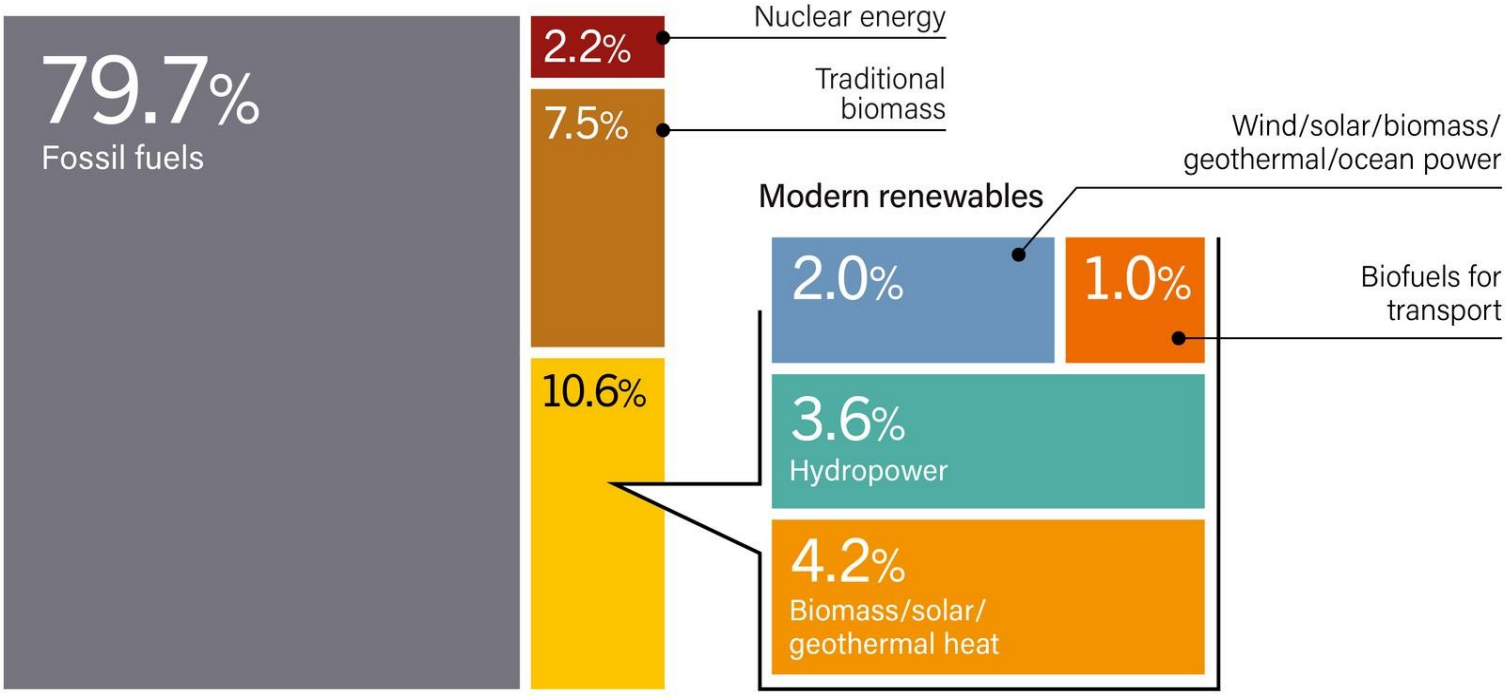
Source: Wikipedia “Beauharnois generating station” (visited on 13.12.2019)

Some numbers

Photo: Anthony Da Cruz
https://unsplash.com/photos/SGOm1cy4O5Q

The big picture (I)

Estimation of the renewable share of the **total final energy consumption** (TFEC) in the **world** in **2017**

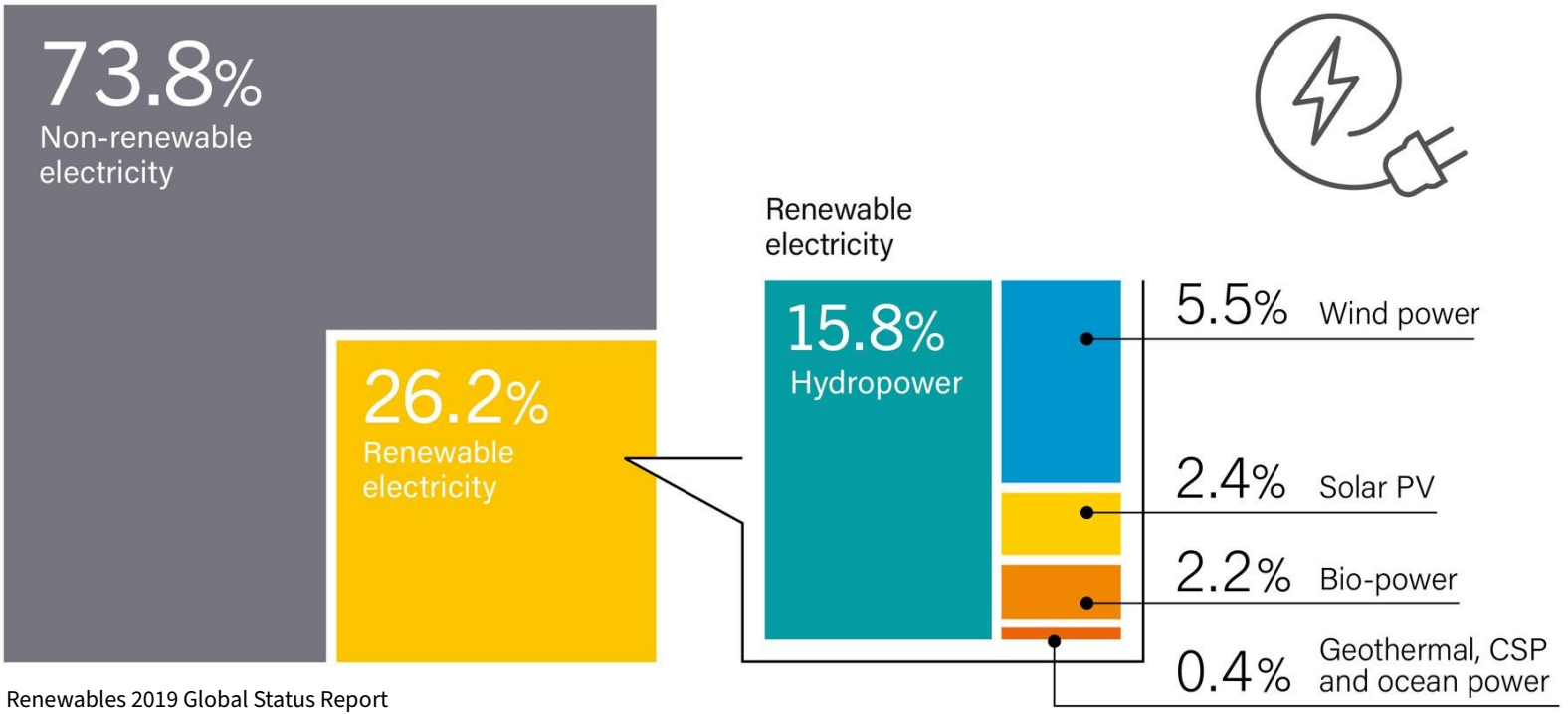


Renewables 2019 Global Status Report
https://ren21.net

Based on OECD/IEA, World Energy Balances and Statistics, 2018 edition (Paris, 2018)
https://www.iea.org/statistics/balances/

The big picture (I)

Estimated Renewable Energy Share of Global Electricity Production, End-2018



Renewables 2019 Global Status Report
https://ren21.net

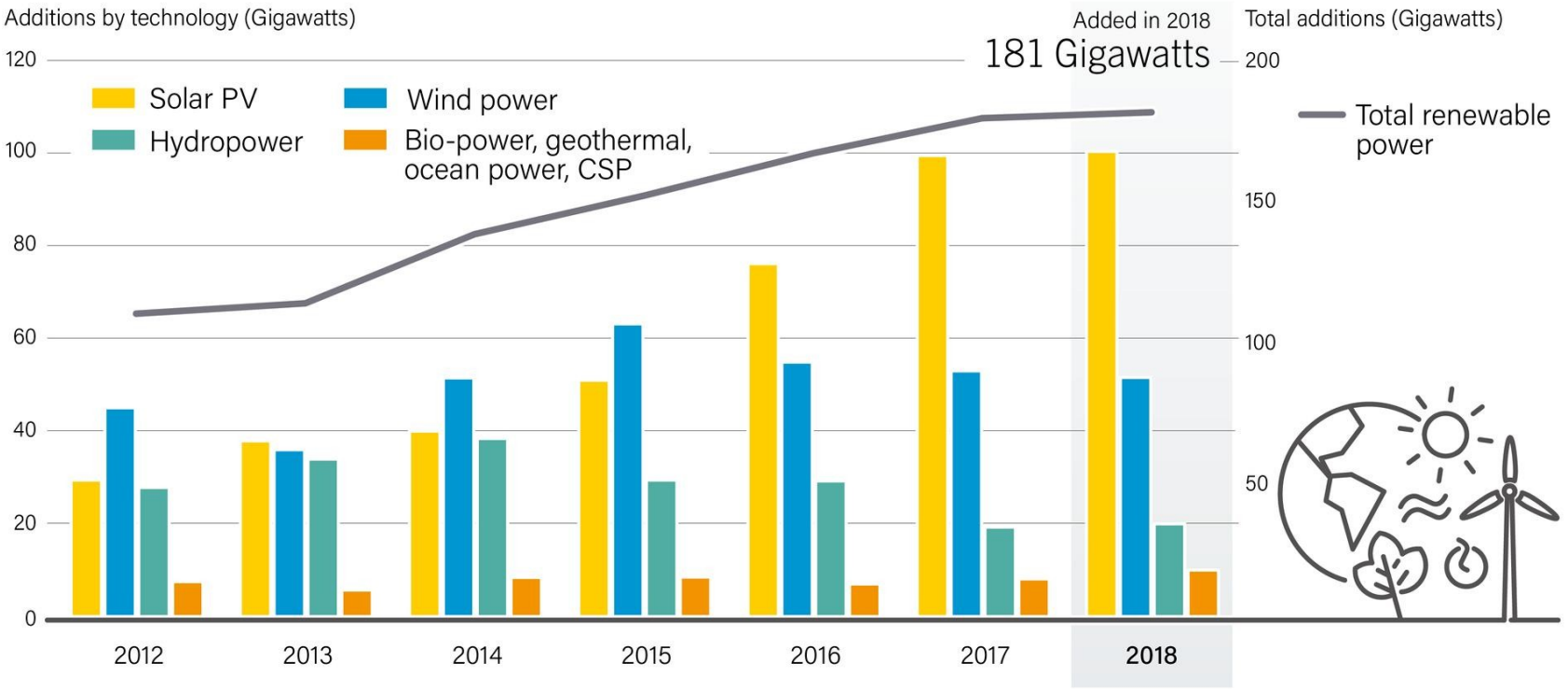
60% of renewable electricity comes from hydropower

The big picture (II)

- The **total hydropower capacity** install worldwide is about **1132 GW**
- Worldwide generation from hydropower in 2018 is estimated 4210 TWh (enough to supply “1.1 Germanies”) → ~**2 kWh/d/p**
- Global renewable power capacity grew to around **2378 GW** in 2018
- After PV (~55%) and wind (~28%), **hydropower** accounts for **~11%** of the total renewable power generation growth (new ~ 20 GW added)
- China leads the investment raking in new hydropower facilities followed by Brazil, Pakistan and Turkey
- Hydropower accounted for **~60% of renewable electricity production** in 2018, followed by wind power (~21%), solar PV (~9%) and bio-power (~8%)

The big picture (III)

Annual Additions of Renewable Power Capacity, by Technology and Total, 2012-2018



Renewables 2019 Global Status Report
https://ren21.net

The small picture (Germany)

- The installed hydropower capacity in Germany is **11.258 MW** (including 6.806 MW of pumped storage), this is **~1%** of world hydropower capacity (in 2018)
- Hydropower generation produced **16.290 GWh** in 2018 → **~0.5 kWh/d/p**
- **Due to drought**, hydropower generation dropped almost 15%, and contributed 2.6% of total power production, accounting for just over 7% of total generation from renewables
- The majority of the country's hydropower resources are located in the mountainous southern provinces, with 50% of all projects located in Bayern and **20% in Baden-Württemberg**
- These two states account for over **80%** of annual German hydropower production

My estimation for Germany

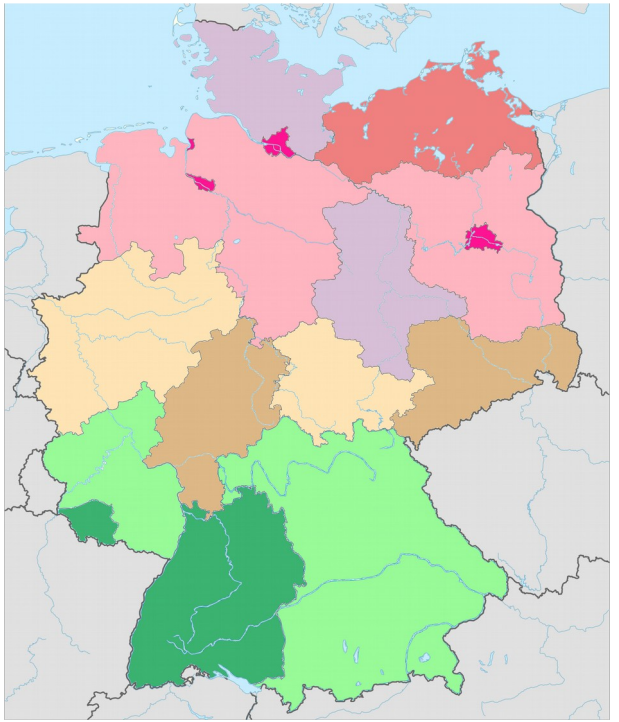
Photo: Steve Halama
https://unsplash.com/photos/JHaFjDuri2A

Method

$$\frac{P_{\max}}{m^2} = \langle \text{rainfall} \rangle_{\text{yr}} \times \rho \times g \times \langle \text{altitude} \rangle$$

1) Divide Germany in three regions: southern, central and northern states
2) Calculate annual rainfall averages for each region
3) Calculate average altitude of each region
4) Plug numbers into formula above to get the theoretical upper bound for hydropower per unit area in each region
5) Estimate plausible practical limit from the upper bound

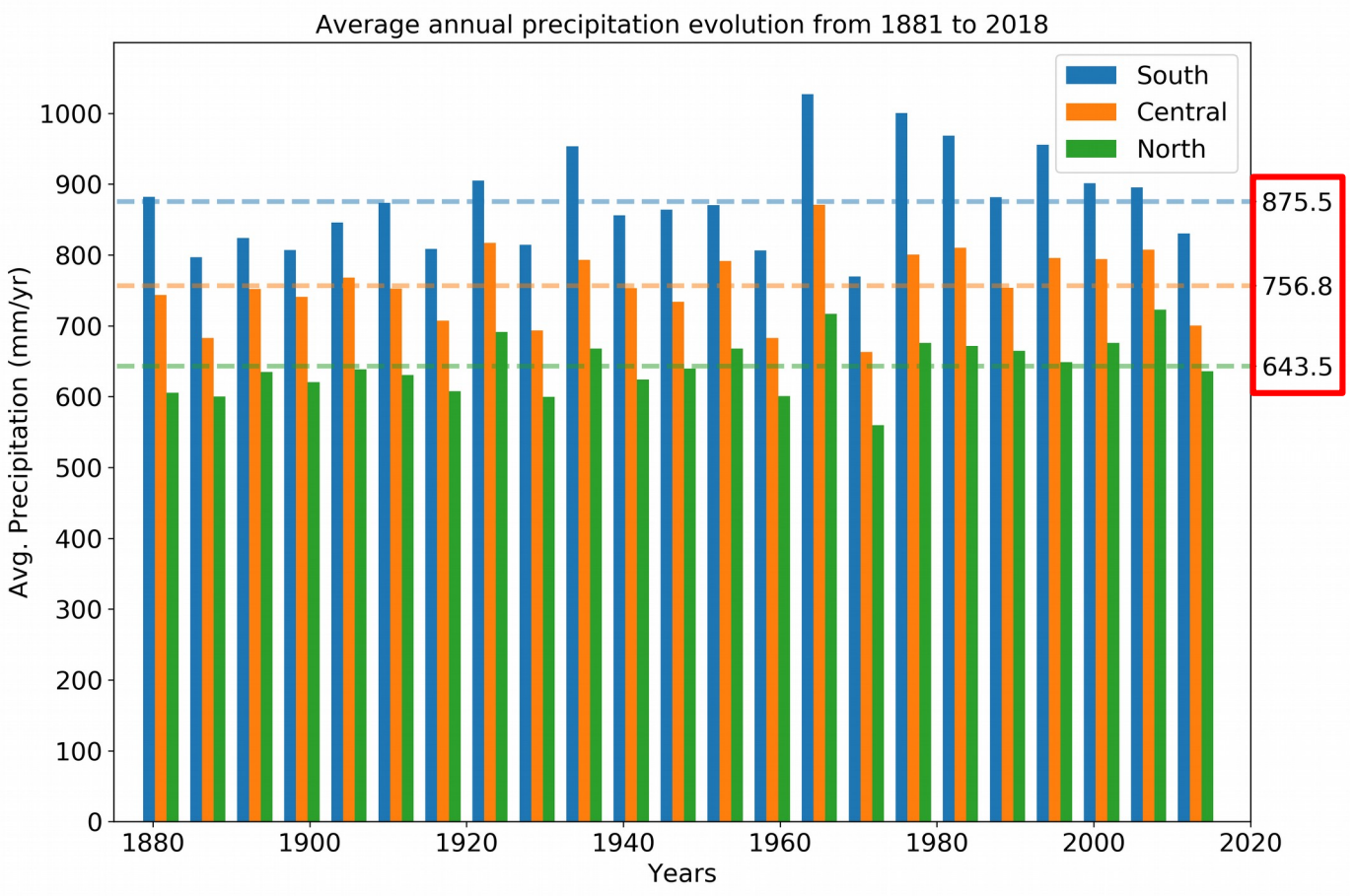
Reference: David JC MacKay, *"Sustainable Energy – without the hot air"* (p.55)
https://www.withouthotair.com/c8/page_55.shtml



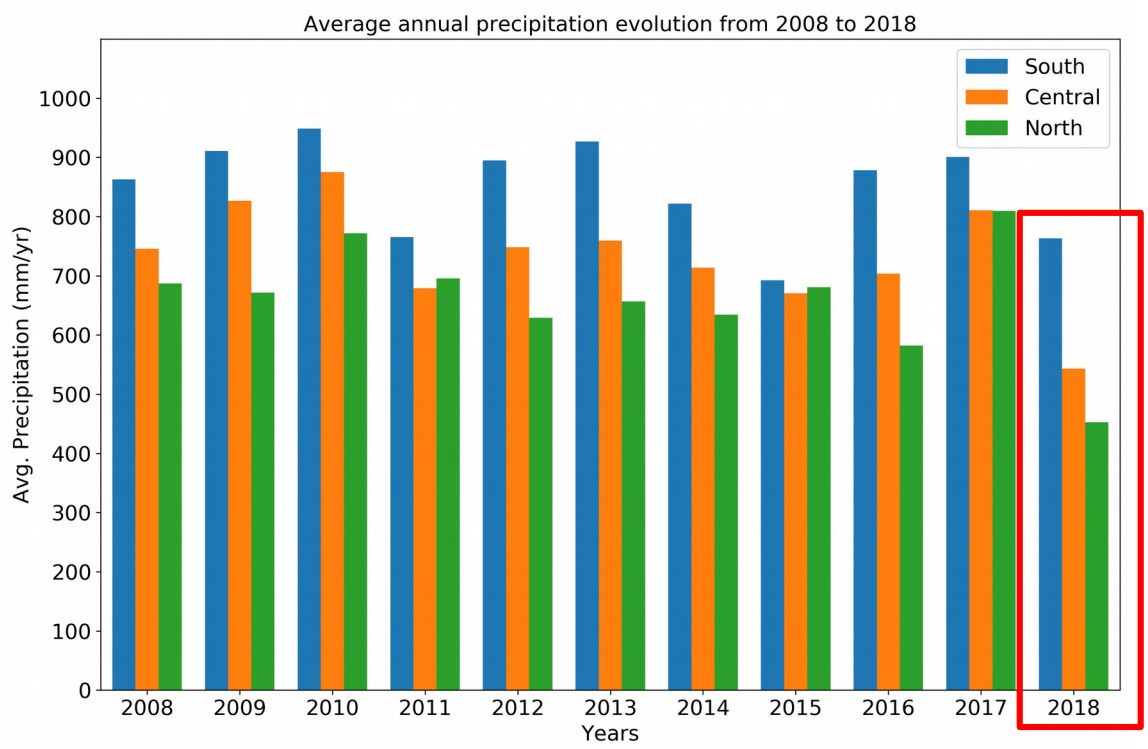
Original file: Wikimedia "Germany adm location map.svg"
https://commons.wikimedia.org/wiki/File:Germany_adm_location_map.svg

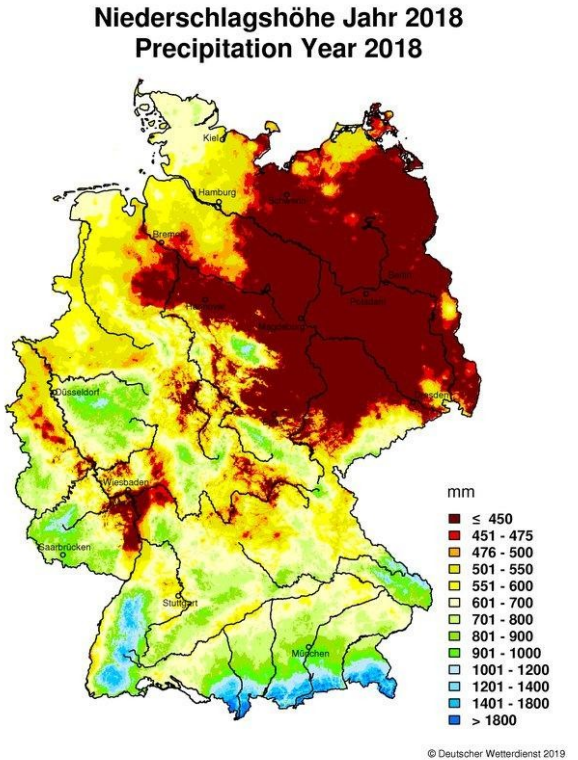
Annual rainfall averages

Raw data from the Deutscher Wetterdienst (DWD)
http://tiny.cc/eg5lhz



Drought in 2018 (and 2019)





A decrease in precipitations has affected the amount of hydroelectricity produced in Germany

Average altitudes

- Average altitude for each state obtained from topographic-map.com
- Average altitude for each region computed as the weighted (with areas) average

$$\langle \text{altitude region} \rangle = \sum_{s \in \text{region}} \langle \text{altitude state s} \rangle \times \frac{\text{Area state s}}{\text{Total area region}}$$

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Average altitude of southern states = 562 m
Average altitude of central states  = 255 m
Average altitude of northern states =  89 m
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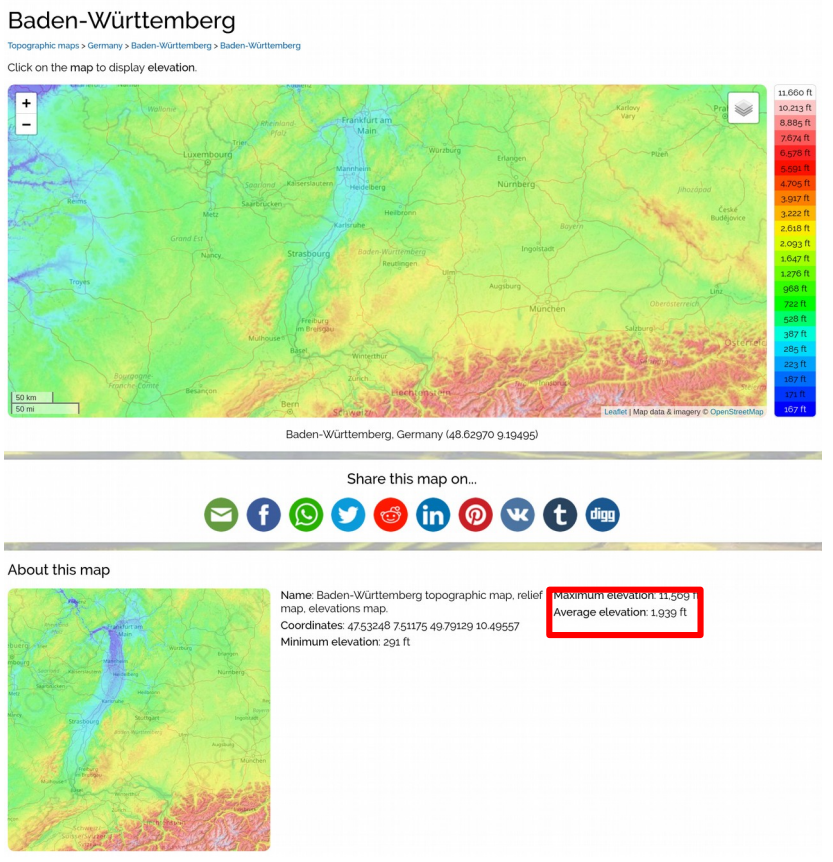


Example for Baden-Württemberg state

Source: https://en-gb.topographic-map.com/maps/lpy6/Baden-W%C3%BCrttemberg/

Theoretical upper bound power per unit area

$$\frac{P_{\max}}{m^2} = \langle \text{rainfall} \rangle_{\text{yr}} \times \rho \times g \times \langle \text{altitude} \rangle$$

$$\rho = 1000\,\text{kg/m}^3$$

$$g = 10\,\text{m/s}^2$$

$$\text{Population} = 82 \times 10^6$$

Region	Rainfall (mm/yr)	Altitude (m)	Upper bound (W/m²)	Upper bound (kWh/d/p)
Southern	876	562	0.16	5.9
Central	757	255	0.06	1.6
Northern	643	89	0.02	0.7

Estimation

Region	Upper bound (kWh/d/p)	Estimation (kWh/d/p)	Actual real number (kWh/d/p)
Southern	5.9	1.2	?
Central	1.6	0.3	?
Northern	0.7	0.1	?
Germany	**8.2**	**1.6**	**0.5**

Discussion and conclusions

Photo: Hanbyul Jeong
https://unsplash.com/photos/7kwODn2_b2o

Advantages & Disadvantages

Advantages

- It is a renewable energy source
- Flexibility (~1 min from cold start-up to full load)
- Low cost and high value
- Low CO_2 emissions
- It can support the use of intermittent sources of renewable energy (PV, Wind...)

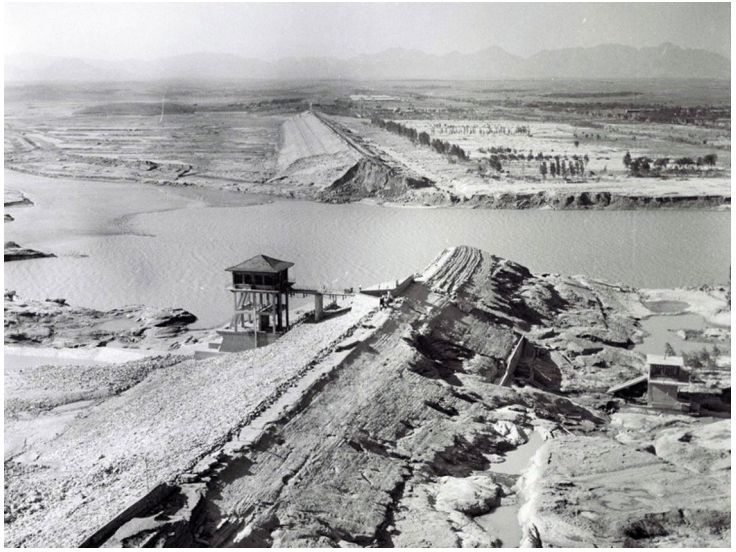
Disadvantages

- Damage ecosystem
- Loss of land
- Water loss
- Methane emissions
- Relocation of people
- Failures and disasters

Most (if not all) of the disadvantages and negative effects arise from the use of dams and reservoirs, not from the hydroelectric stations

Accidents

- Almost all accidents related to the failure of the dam
- Natural disasters or sabotage can be catastrophic to downriver settlements and infrastructure



Banqiao Dam was the world's deadliest infrastructure failure ever

Source: https://www.ozy.com/flashback/230000-died-in-a-dam-collapse-that-china-kept-secret-for-years/

Longarone (Italy), before and after 50 million cubic metres of water overtopped the dam in a wave of 250 metres

Source: Wikipedia "Vajont Dam"
https://en.wikipedia.org/wiki/Vajont_Dam

Future accidents?

Aerial photos of the Three Gorges Dam (China) in 2009 and 2018

Source: http://www.visiontimes.com/2019/08/16/satellite-photos-raise-fears-about-condition-of-three-gorges-dam.html

Role of hydro energy in the balance sheet

- (As of 2017) it has an important role within the renewables
- In Germany (and many other countries) **it will not be relevant in terms of kWh/d/p**
- It may have a role as **integration element** of other renewables (PV, wind) and to deal with intermittency
- 160 GW (6806 MW in Germany) of pumped storage capacity worldwide. Is this enough/relevant? (maybe next talk?)

Summary

- Hydropower is the power derived from flowing water
- We saw two methods to generate electricity: conventional and ROR
- Hydropower generation in **Germany** produced around **0.5 kWh/d/p**
- My **estimation** (20% of theoretical upper bound) was about **1.6 kWh/d/p**
- Not relevant (~1%) for Germany with a consuption of 126 kWh/d/p
- It may help integrating other renewables and dealing with intermittency

References

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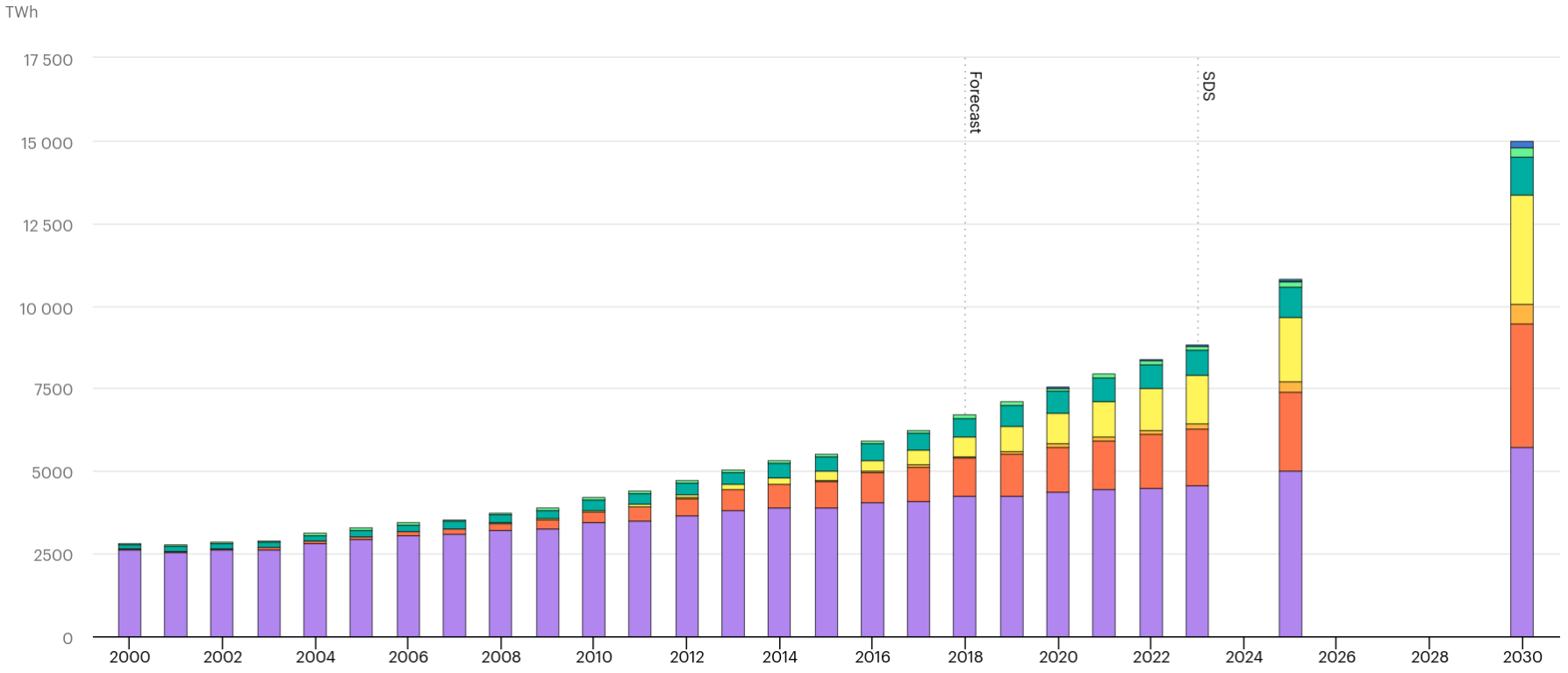
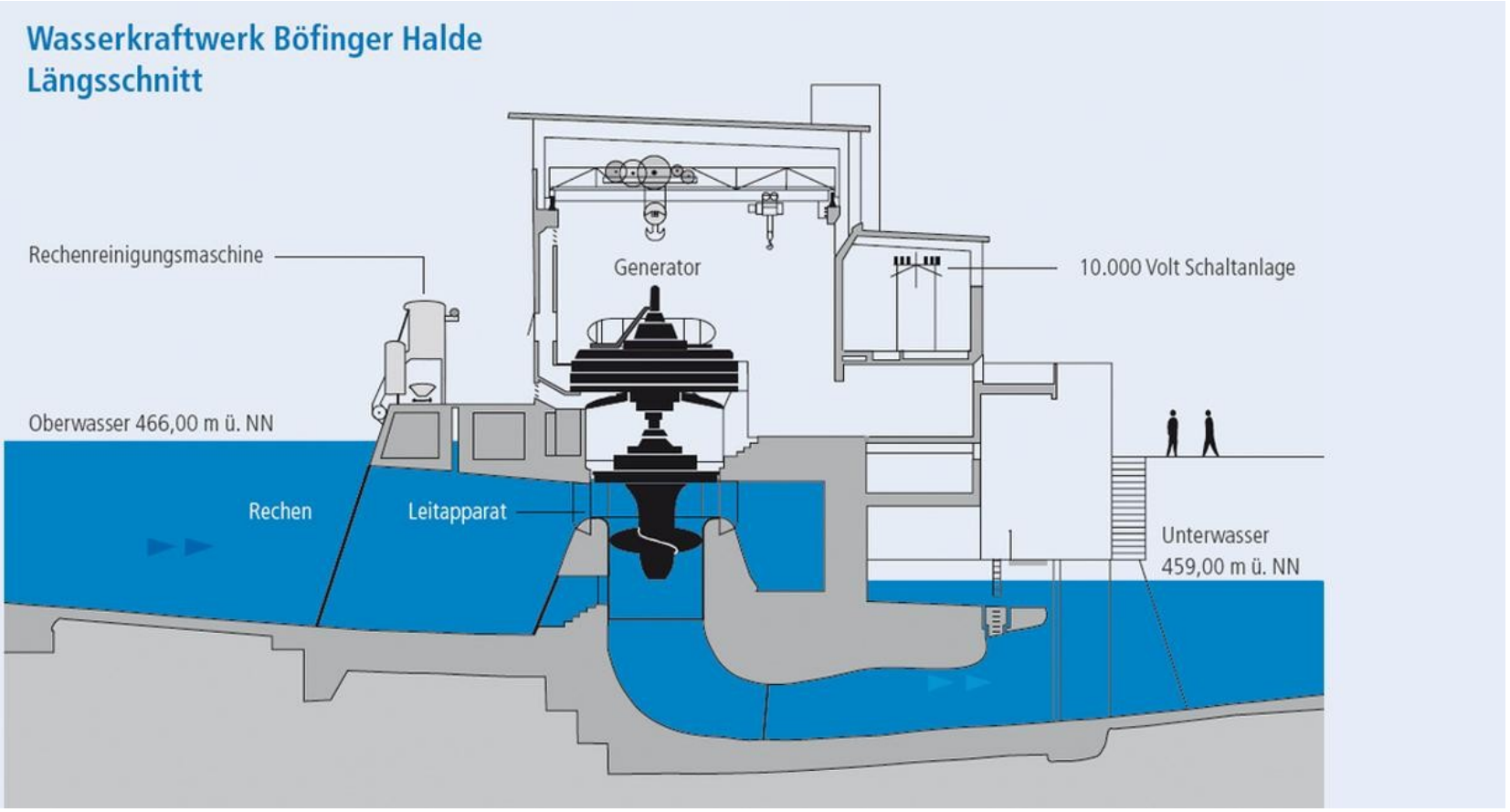
- *"Hydropower"* article from Wikipedia (https://en.wikipedia.org/wiki/Hydropower)
- *"Hydroelectricity"* article from Wikipedia (https://en.wikipedia.org/wiki/Hydroelectricity)
- International Energy Agency (https://www.iea.org/reports/tracking-power-2019/hydropower)
- Yang, Xiankun & Lu, X.X.. (2013). *Ten years of the Three Gorges Dam: A call for policy overhaul.* Environmental Research Letters. 8. 1006-. 10.1088/1748-9326/8/4/041006.

Renewable power generation by technology



Tracking power from IEA

Source: https://www.iea.org/data-and-statistics/charts/renewable-power-generation-by-technology-in-the-sustainable-development-scenario-2000-2030



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