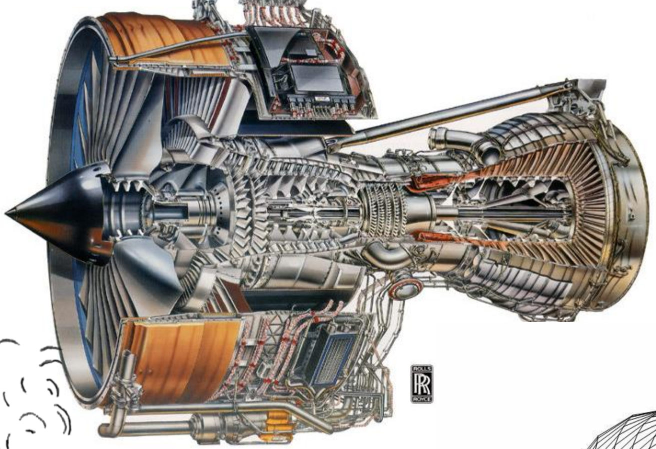
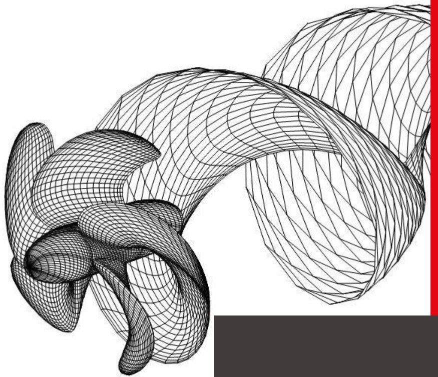
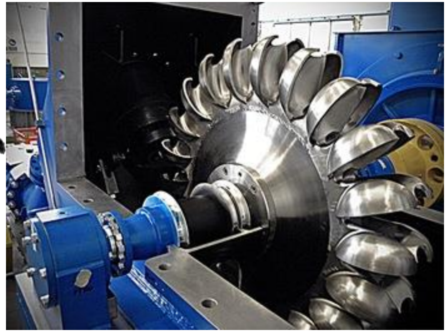




ME-342 Introduction to Turbomachinery

Prof. Eunok Yim
HEAD Lab. IGM



Chapter 1. Introduction

École polytechnique fédérale de Lausanne

About the course

- Prof. Eunok Yim (eunok.yim@epfl.ch)
  - (2024~) Hydro Energy and Applied fluid Dynamics Lab. (HEAD)

  - B.Sc. (2010) and M.Sc. (2012) degrees in Mechanical Engineering from KAIST, Korea
  - Ph.D (2015) in fluid dynamics at LadHyX, Ecole Polytechnique, Palaiseau, France
  - PostDocs (2016), M2P2, Aix-Marseille University, EPFL (2020) LFMI.
  - GE Renewable Energy, Hydropower (2024)

About the course

- The contents are adopted from the previous years by **Prof. Farhat** and **Prof. Ott**
- Slides in PDF
- Lecture recordings (*Kaltura*)
- Exercise sessions
- A popup quiz – not included in grading
- Language: English
- TAs for exercise sessions
  - Antoine Sache (antoine.sache@epfl.ch)
  - Thomas Antoine Nicolas Berger (thomasantoinenicolas.berger@epfl.ch)
- Exam
  - Written exam at the end of the semester

About the course

- Main topics covered in the present course:
  - Basic fluid mechanics required for turbomachinery
  - Pumps and Turbines: Working principle, characteristic curves
  - Centrifugal Pumps
  - Hydraulic machines
  - Similarity rules
  - Brief introduction to thermal turbomachines (steam, gas turbine and compressors)

- Not included
  - Wind turbines, tidal turbines, etc..

Learning Objectives

- Learn and remind basic fluid mechanical concepts required for turbomachinery principles (reminder of ME-280 and some new ones)
- Explain how and why a turbomachine works
- Describe the basic differences between a turbine and a pump
- Discuss the importance of minimizing loss in a turbomachine
- Select an appropriate class of turbomachines for a particular application
- Determine the operating point for a turbomachine installed in a system
- Sketch typical turbomachine blades and velocity diagrams
- Apply similarity laws to predict the effects of size and/or speed on a family of turbomachines
- Perform engineering work or undertake advanced study involving the fluid mechanics for turbomachinery
- Able to explain working principals of the two models of turbomachinery at the entrances of MEB and MED buildings

Introduction to turbomachinery

Definition

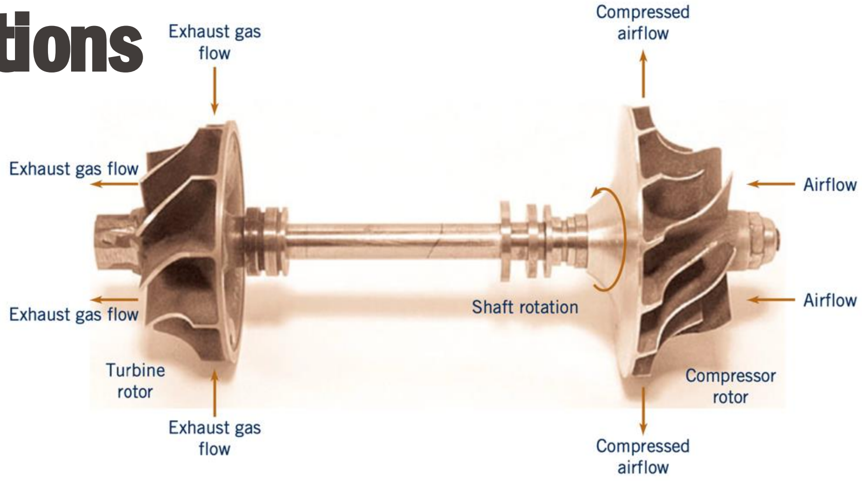
- A turbomachine designates any device, consisting of a **rotating element** (rotor), which extracts or transfers **energy** from a fluid in motion
- The working fluid may be liquid or gas

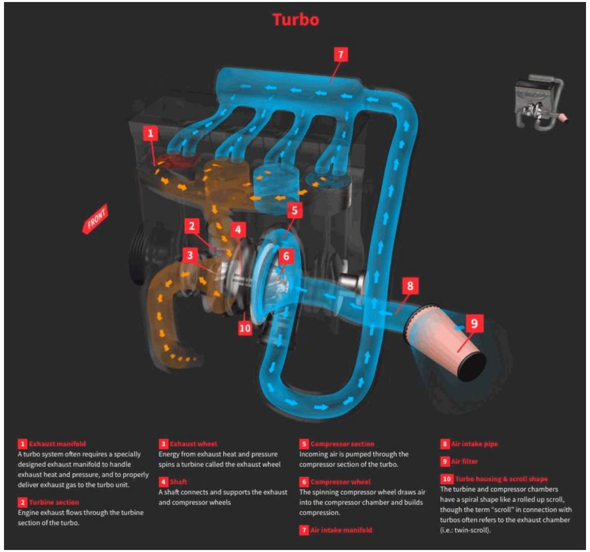
- Examples:
  - Water as working fluid:
    - Hydraulic turbines or hydro-turbines (electricity generation)
    - Hydraulic pumps (water supply, water treatment, cooling, …)
    - Marine propellers (marine transportation)
  - Gas as working fluid:
    - Compressors, fans, wind turbines, gas turbines, steam turbines, …
  - Gas & Liquid mixture as working fluid:
    - Multiphase pumps in oil industry: Oil, water and gas are pumped together from the production site to the processing facility

Turbomachines - applications

- Power generation
  - **Hydroelectric**
  - Steam turbines
  - Gas turbines
  - Windmills
- Marine
  - Steam turbine
  - Gas turbine
  - Water jet
- Automobile
  - Turbochargers
  - Superchargers
  - Gear transmission
- General
  - **Pumps**
  - Air compressors
  - Fans
- Aerospace
  - Gas turbine
  - Turbopumps
  - Turbojet
  - Helicopter
  - Rocket fuel tank
- ……

All are governed by one most important equation





Historical facts

- 1^{st} steam turbine in history: Aeolipile (or Hero's engine)

Invented by Hero of Alexandria

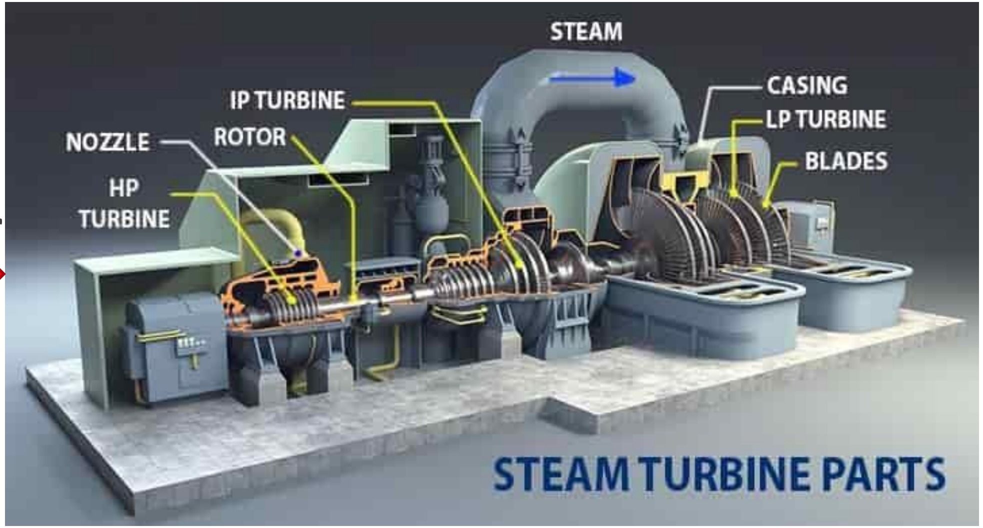
Date: 120 BC or 62 AD

Principle: The bowl held a supply of water and served as a boiler. Two hollow tubes extended from the boiler are connected to the sphere. The hot steam escapes from two small pipes, forming two opposite tangential jets, which generate a torque and cause the sphere to spin.

Historical facts

- 1st steam turbine in history: Aeolipile (or Hero's engine)

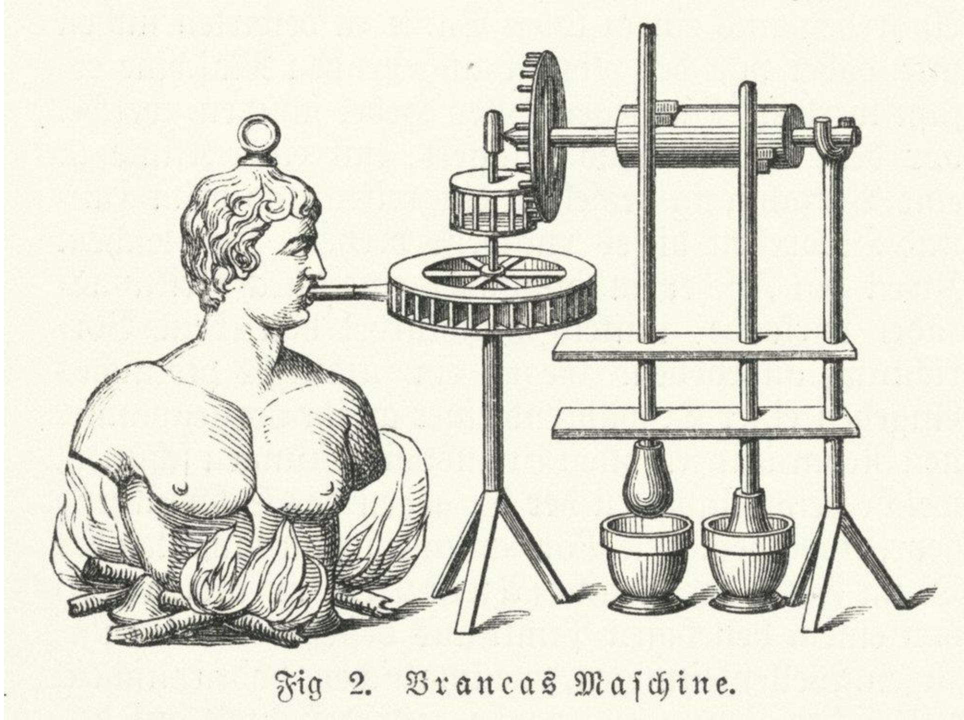
2000 years later



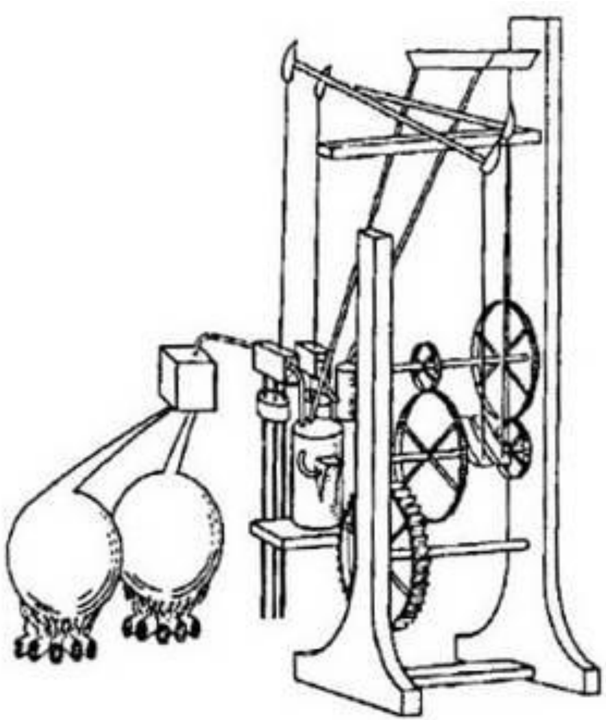
Reference: C. B. Meher-Homj, The Historical Evolution of Turbomachinery, Proc. Of 29th Turbomachinery Symposium

Historical facts

- The first patent for gas turbines were filed in 1791 by John Barber. Practical hydroelectric water turbines and steam turbines did not appear until the 1880s.



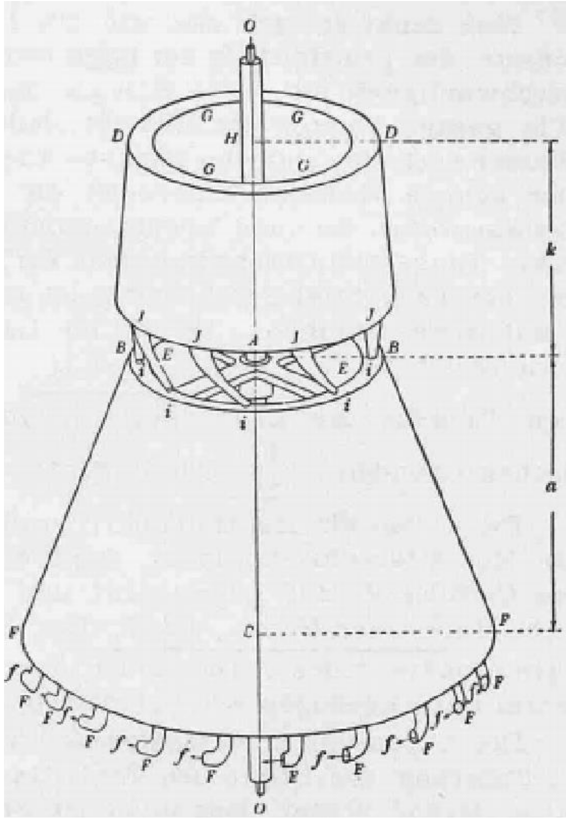
Branca's steam stamping mill (1629)



Barber's steam turbine (1791)

Historical facts

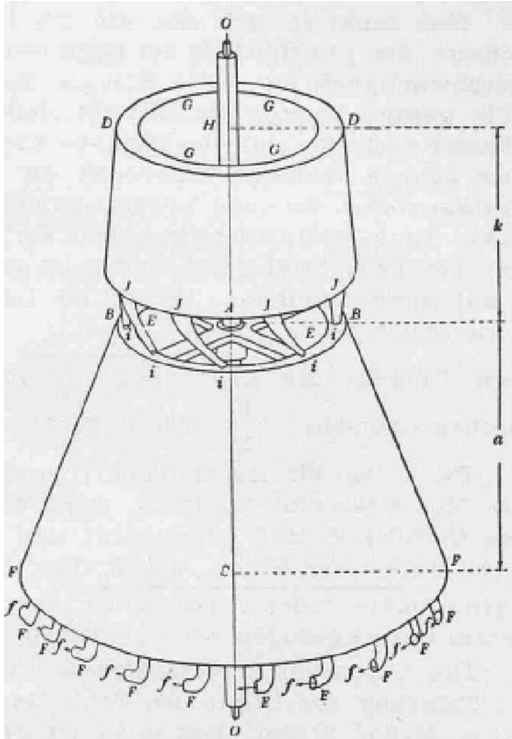
- 1st hydraulic reaction turbine:
  - Invented by Euler in 1754
  - Principle: Water, supplied by the upper reservoir, falls inside a rotating wheel and flows outside through several nozzles. The resulting jets generate a torque on the shaft, and the wheel rotates.
  - It was designed for a head of 1 m, a water discharge of 19.7 l/s, and a rotation speed of 300 RPM. The mean diameter at the inlet of the impeller was 200 mm (300 mm at the exit).
  - Euler was the author of the 1st general theory of rotating machines: “Théorie plus complète des machines qui sont mises en mouvement par la réaction de l’eau”, 1756.



E. Yim

Historical facts

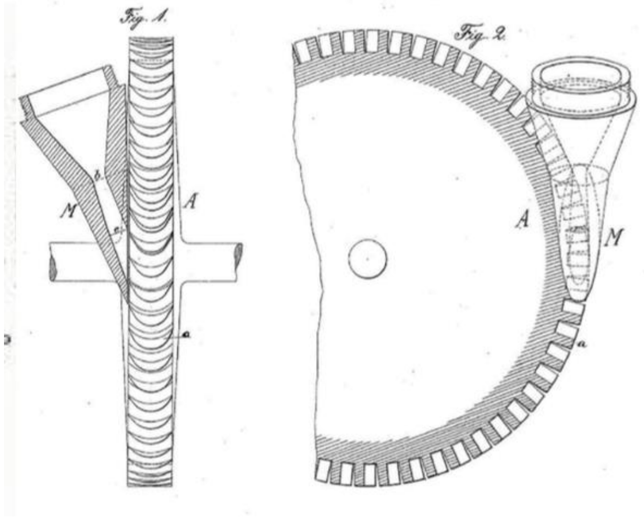
- 1st hydraulic reaction turbine: Invented by Euler in 1754

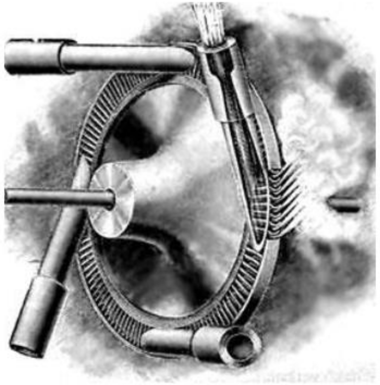


Prototype @ EPFL (LMH)

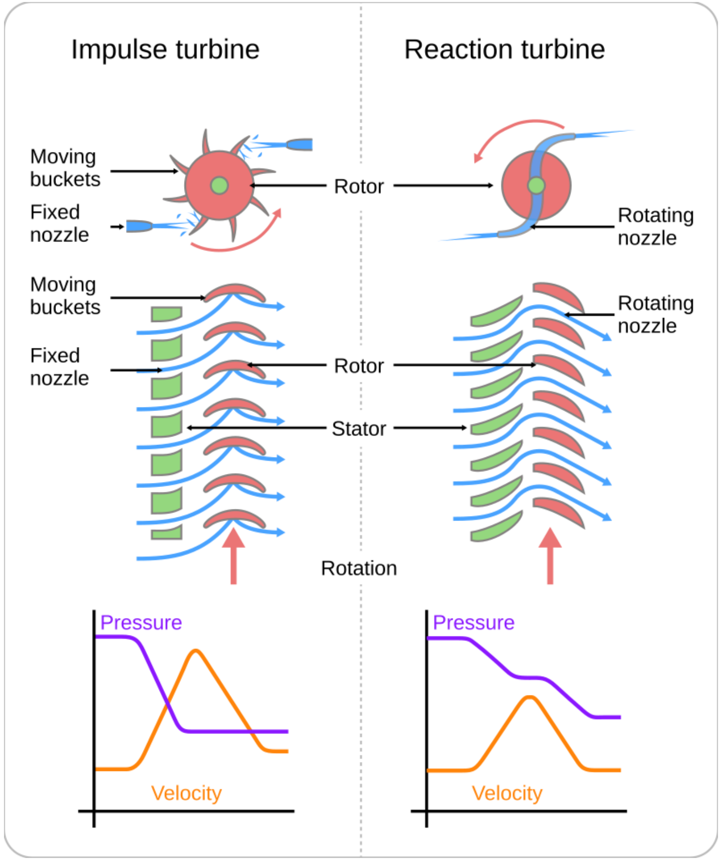
10 CHF banknote
(1979 – 2000)

Historical facts



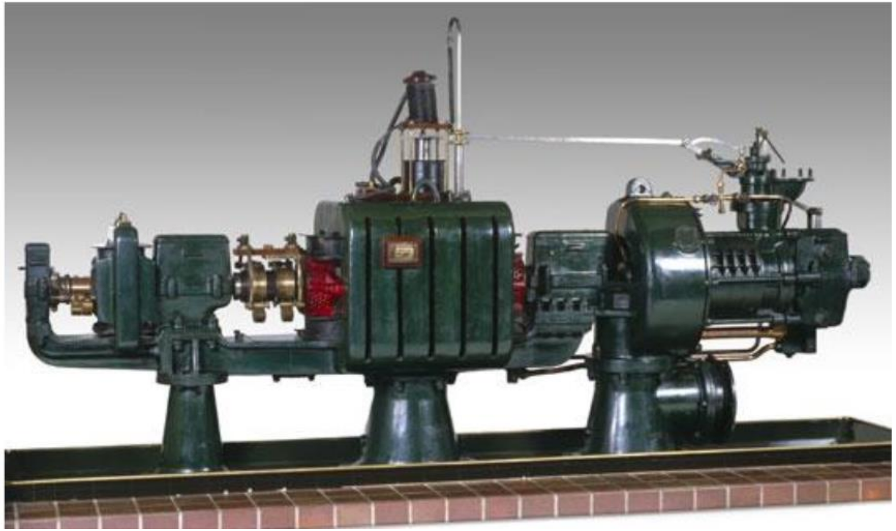


Laval turbine (1882)



Historical facts

Parsons' radial flow steam turbine-generator (1891), Science Museum, London



- Until the invention of the steam turbine by Charles Parsons (1854-1931) in 1884, steam engines could not turn fast enough to produce electricity efficiently on a large scale. Used at the Cambridge Electric Light Station, this radial flow turbine-generator was the first to prove that turbines could be run as economically as the best steam engines. It used the energy of high-pressure steam at 200 degrees centigrade to run the turbine. Turning at 4,800 revolutions per minute, it had a power output of 100 kilowatts and operated for 30 years. Steam turbines still drive most generators today.

https://www.diomedia.com/stock-photo-parsons-radial-flow-steam-turbine-generator-1891-image5531342.html

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World's largest power generation facility (in terms of capacity) is

ⓘ Start presenting to display the poll results on this slide.

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

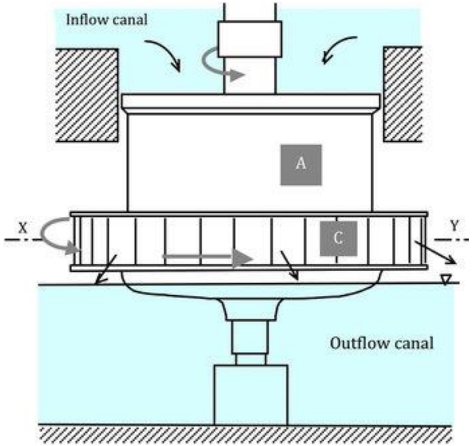
Turbomachinery has a lot of applications, but as hydropower is one of the most relevant ones for Switzerland and the current world's needs for clean energy, let's discuss more about it.

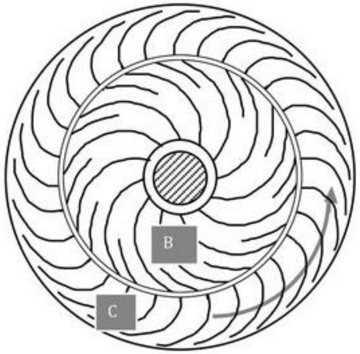
Top 20 largest power producing facilities [edit]

Rank	Station	Country	Location	Capacity (MW)	Annual generation (TWh)	Type	Notes	Refs
1.	Three Gorges Dam	China	30°49′15″N 111°00′08″E	22,500	78.79 (2022)[8]	Hydro		[1]
2.	Baihetan Dam	China	27°13′07″N 102°54′22″E	16,000	40.06 (2022)[8]	Hydro		[9][10]
4.	Itaipu Dam	Brazil Paraguay	25°24′31″S 54°35′21″W	14,000	83.88 (2023) [11]	Hydro		[12][13] [unreliable source?] [14][15]
5.	Xiluodu	China	28°15′52″N 103°38′47″E	13,860	57.8 (2022)[8]	Hydro		[16][17]
6.	Belo Monte	Brazil	03°07′27″S 51°42′01″W	11,233	39.5 (average)	Hydro	Installation of the 18th and final turbine was completed in November 2019.	[18][19]
7.	Guri	Venezuela	07°45′59″N 62°59′57″W	10,235	47 (average)	Hydro		[20] [unreliable source?]
8.	Wudongde Dam	China	26°19′29.4″N 102°38′2.2″E	10,200	36.61 (2022)[8]	Hydro		[21]
9.	Jebel Ali	United Arab Emirates	25°03′35″N 55°07′02″E	8,695		Natural gas		[22]
10.	Tucuruí	Brazil	03°49′53″S 49°38′36″W	8,370	21.4 (average)	Hydro		[12][16]
-	Kashiwazaki-Kariwa	Japan	37°25′45″N 138°35′43″E	7,965	60.3 (1999) 0 (2012–Present)	Nuclear	Suspended in 2011. Restart date scheduled to April 2025.	[23][24] [unreliable source?] [25][26]

Historical facts

- Fourneyron turbine (1832)
  - Benoit Fourneyron developed a small turbine model (4.5 kW) derived from the Euler model
  - The major characteristic of the Fourneyron turbine is that water was flowing from the inside (stator) to the outside (rotor).
  - 1832: Patent + 1st industrial turbine (37 kW) installed in Dampiere (Jura)
  - 1843: A total of 129 Fourneyron turbines running across Europe
  - 1895: 3 Fourneyron turbines (3.7 MW) installed in Niagara Falls hydropower plant.

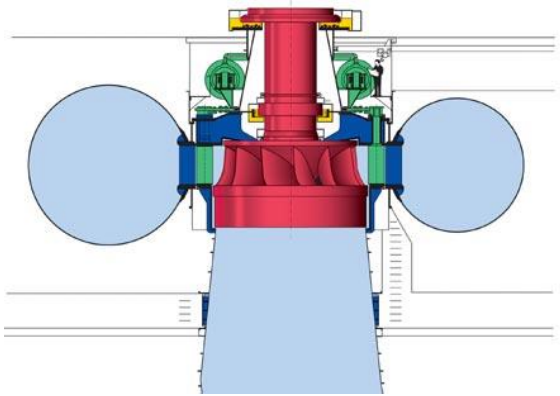


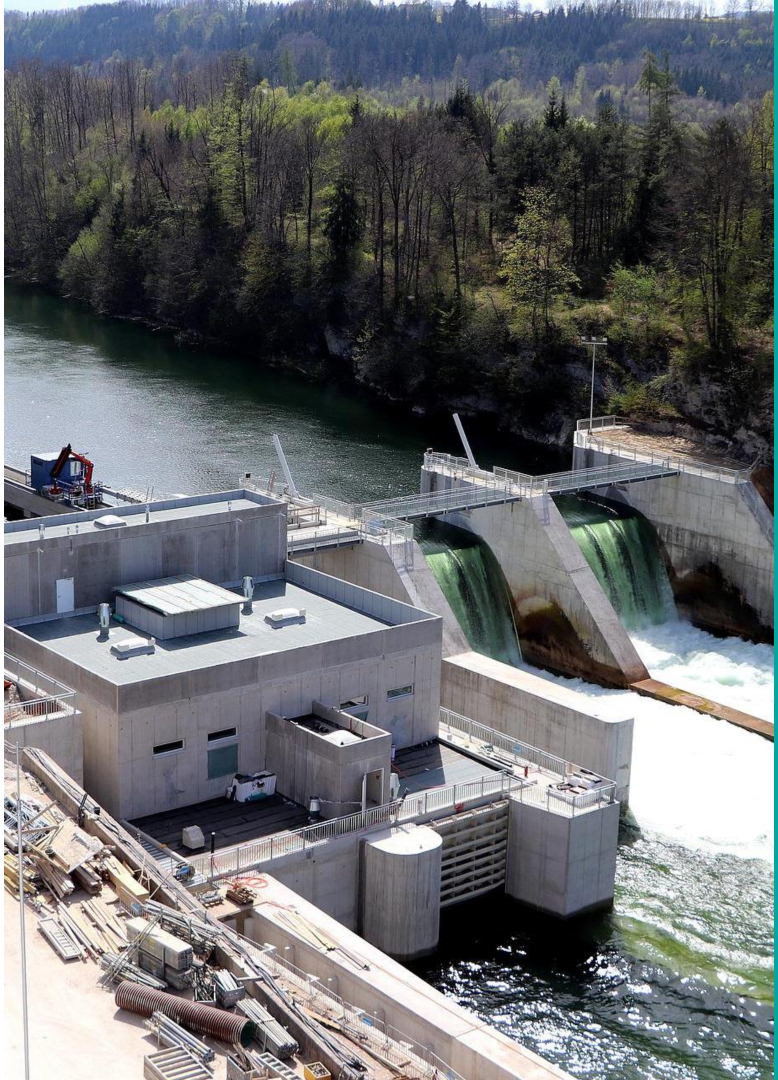


Horizontal cut XY

Historical facts

- Francis turbine
  - Improvement of Fourneyron turbine
  - 1855: 1st publication of the result of his design
    - used a principle adverse to the Fourneyron turbine’s one, with the rotor inside and the distributor outside, and a flow strictly radial in the turbine.
    - Later, the concept of the Francis turbine moved in such a way that the flow would no longer be strictly radial but progressively change its direction downward, which is still the principle of today’s Francis turbines
    - Today, 700-MW Francis turbines are operating on the largest hydropower plants such as Grand Coolee (USA), Itaipu (Bresil), Three Gorges (China)

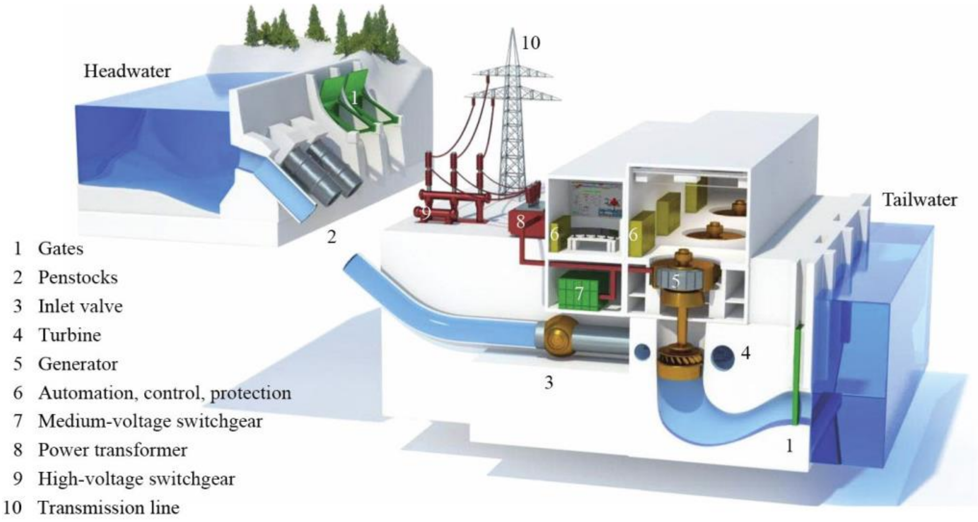


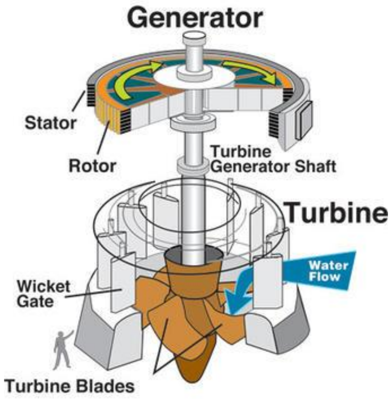


Hydropower

Hydropower Generation

- Types of hydropower plants
  - Storage powerplants:
    - Made of a large reservoir and exploit the water elevation (gravity)
    - The water flows through a large pipe (also called penstock or tunnel) from the reservoir to the power station to drive the turbines.
    - The water returns back to the river through a downstream reservoir





Hydropower Generation

- Types of hydropower plants
  - Storage powerplants:

Three Gorges


April 17, 1987

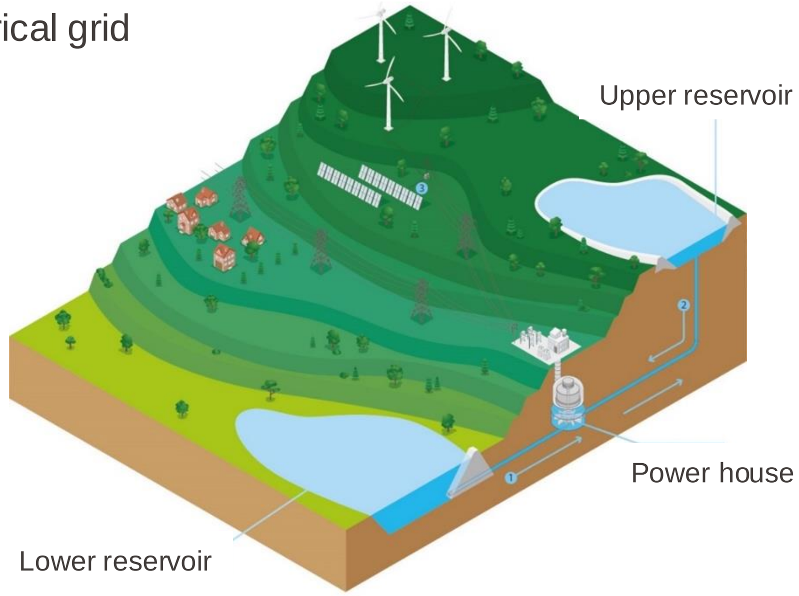
November 7, 2006

- Water reservoir 40 km3 → 200 km2 (underwater 0.2 km)
- Large impacts in every nature…

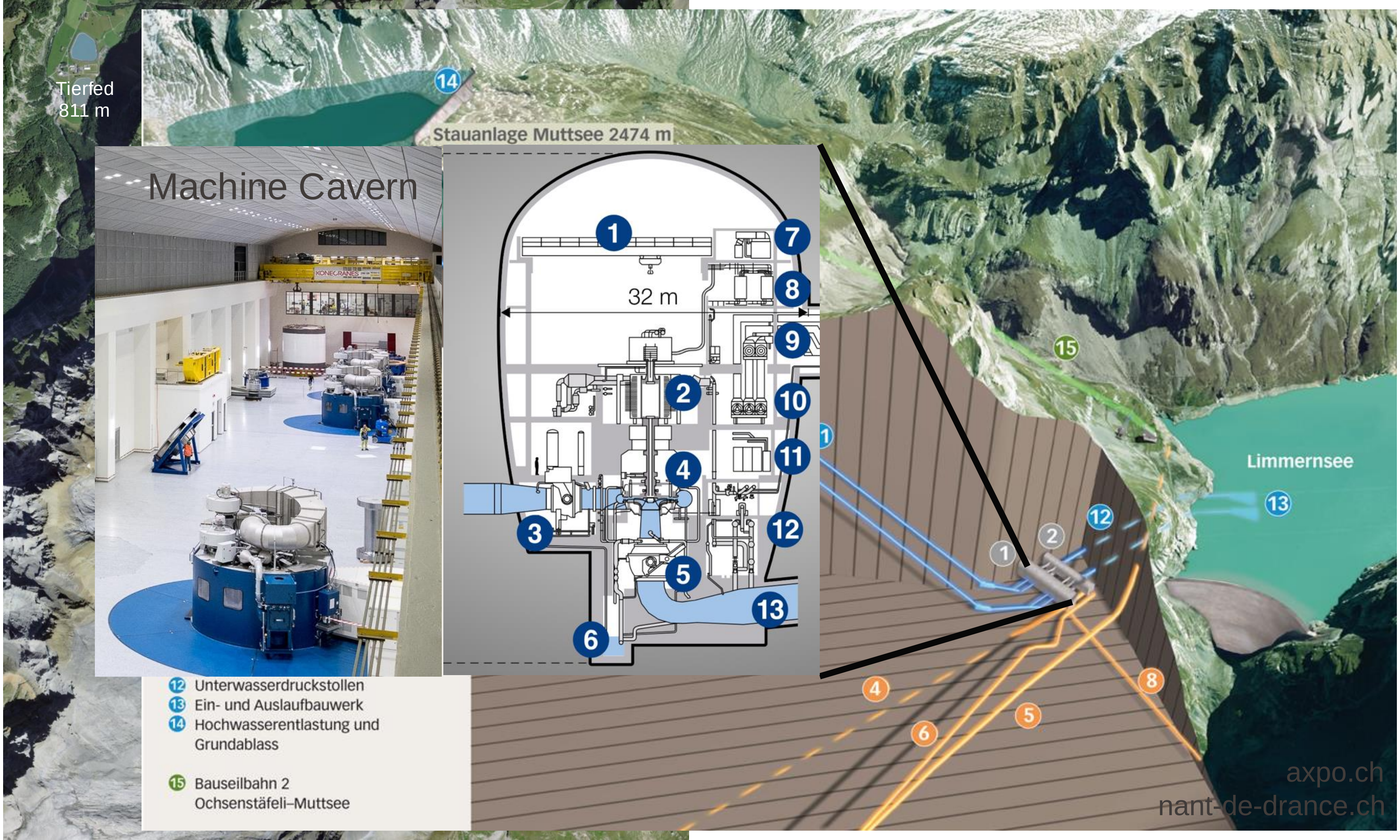
- Types of hydropower plants
  - Run-of-river powerplants:
    - Built on rivers and exploit energy of flowing water.
    - Characterized by a low head and a large flow rate.

- Example: Iron Gates powerplant at Romanian-Serbian border (on the Danube river)

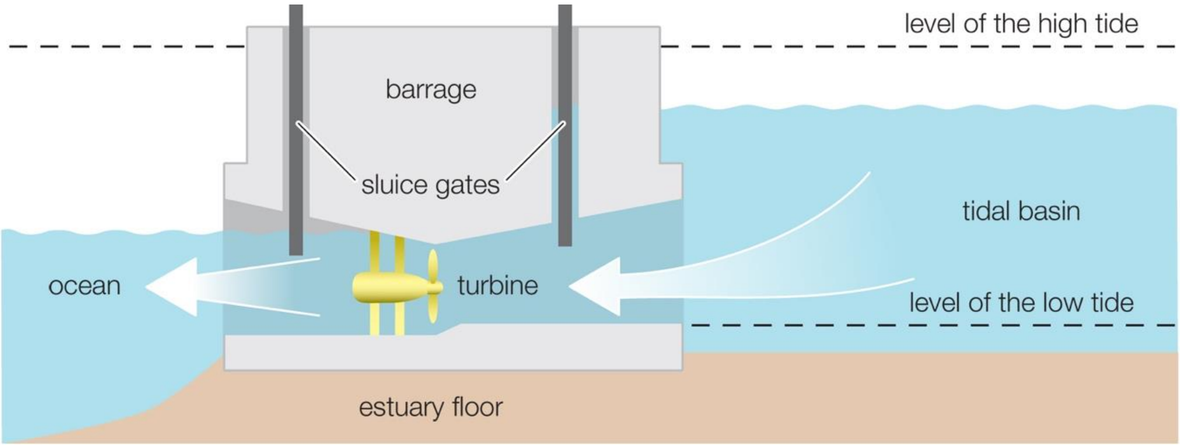
- Types of hydropower plants
  - Pumped storage powerplants:
    - Use reversible machines (pump-turbines) to move water back and forth between lower and upper reservoirs
    - They can store extra electricity through water pumping and switch to generating mode when it is needed.
    - They play a growing role in the stability of electrical grid



Machine Cavern



- Other types of hydropower plants (Ocean energy harvesting)
  - Tidal power plants:
    - Convert energy from tides into electricity.
    - Advantage: Tides are more predictable than the wind and the sun.
    - Disadvantage: High cost and limited availability of sites with sufficiently high tidal ranges or flow velocities.

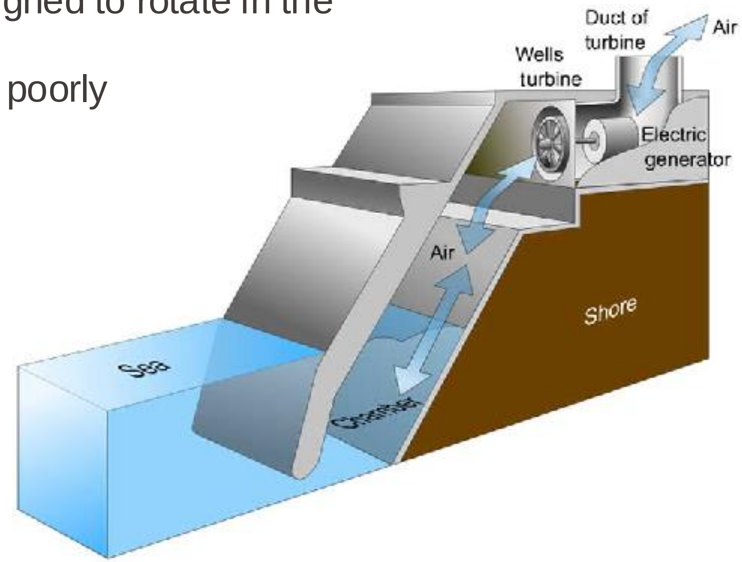


- Other types of hydropower plants (Ocean energy harvesting)
  - Tidal power plants:
    - Example: “L’usine marémotrice de La Rance, France”

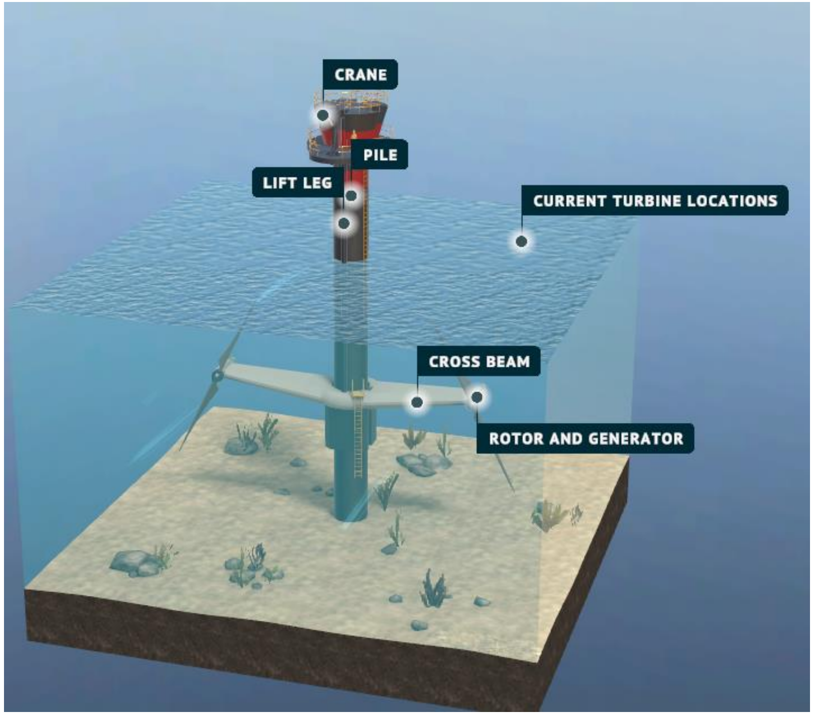
- Other types of hydropower plants (Ocean energy harvesting)

Sebastian Steudtner, surfing 26 m high wave in Portugal (2023)

- Other types of hydropower plants (Ocean energy harvesting)
  - Wave energy converters (Oscillating water column):
    - Use the power of ocean waves to generate electricity
    - Made of a large submerged chamber connected to the atmosphere through a pipe where a “wells turbine” is installed. The periodic passage of the waves moves the free surface up and down leading to periodic air compression and expansion through the turbine. OWC runners are designed to rotate in the same direction regardless of the direction of the flow.
    - Several pilot sites were built but the technology is still poorly developed. Mainly because of its low power density.



- Other types of hydropower plants (Ocean energy harvesting)
  - Current power plant
    - A marine turbine is similar to a wind turbine - the force of flowing water turns the composite blades, which turns a rotor connected via a shaft and gears with an electric generator which produces electricity. These turbines have a patented feature by which the rotor blades can be pitched through 180 degrees, allowing them to operate in both flow directions - on ebb and flood tides. They start to rotate when the current is faster than 1m/s , and at maximum speed, the tips move at approximately 12 m/s



3d.energyencyclopedia.com

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How much electricity in % generated in world by hydropower?

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How much electricity in % generated in Switzerland by hydropower?

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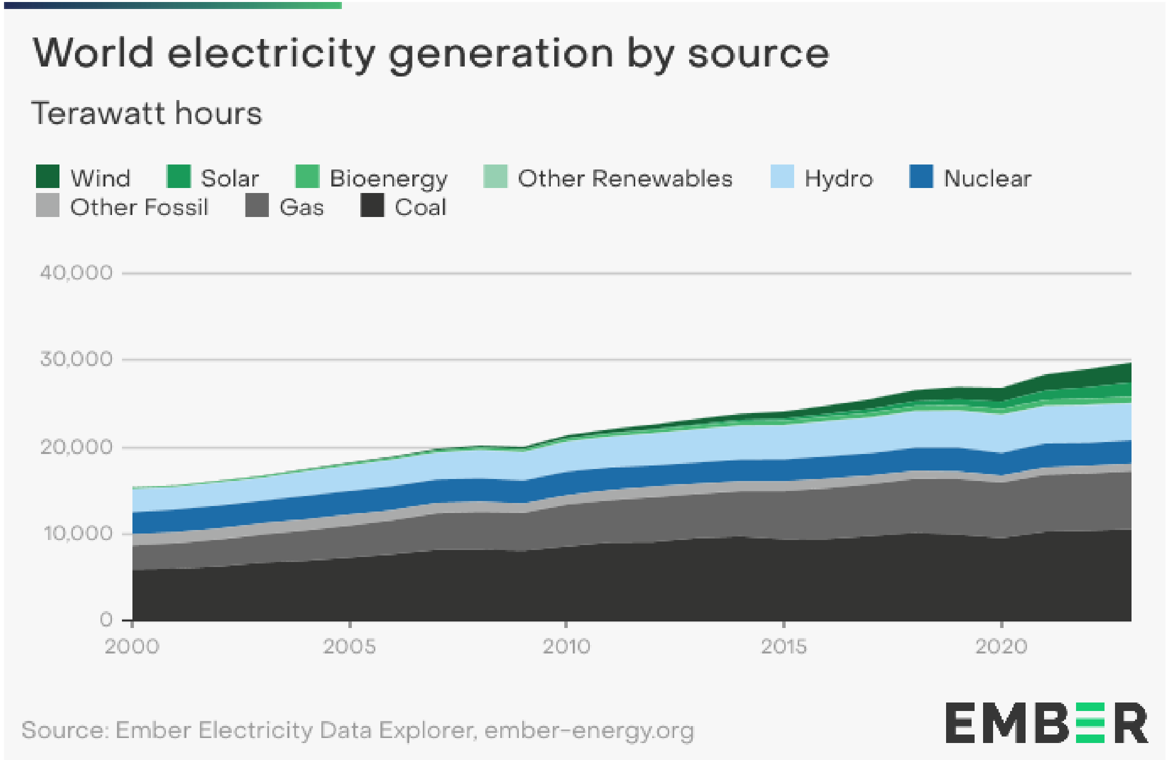
- The contribution of Hydropower in world electricity production



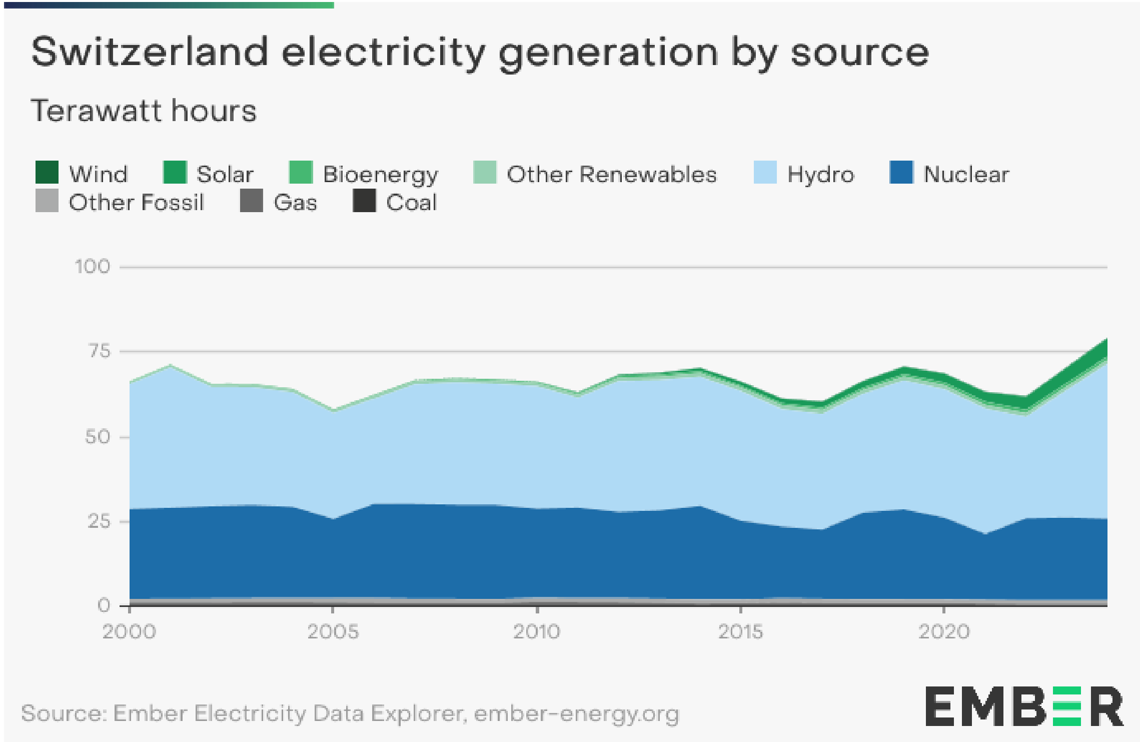
Electricity generation share 2023

Fossil (~ 60%)	Coal	35.21
	Gas	22.53
	Other Fossil	2.91
Clean (~40 %)	Nuclear	9.1
	Hydro	14.29
	Wind	7.79
	Solar	5.54
	Bioenergy	2.32
	Other Renewables	0.3

https://ember-energy.org/data/electricity-data-explorer/

Hydropower Generation

- The contribution of Hydropower in Switzerland electricity production



Electricity generation share in Switzerland 2024

Fossil (~ 2%)	Gas	0.48
	Other Fossil	1.54
Clean (~98 %)	Nuclear	30.41
	Hydro	57.84
	Wind	0.18
	Solar	6.92
	Bioenergy	1.25
	Other Renewables	1.38

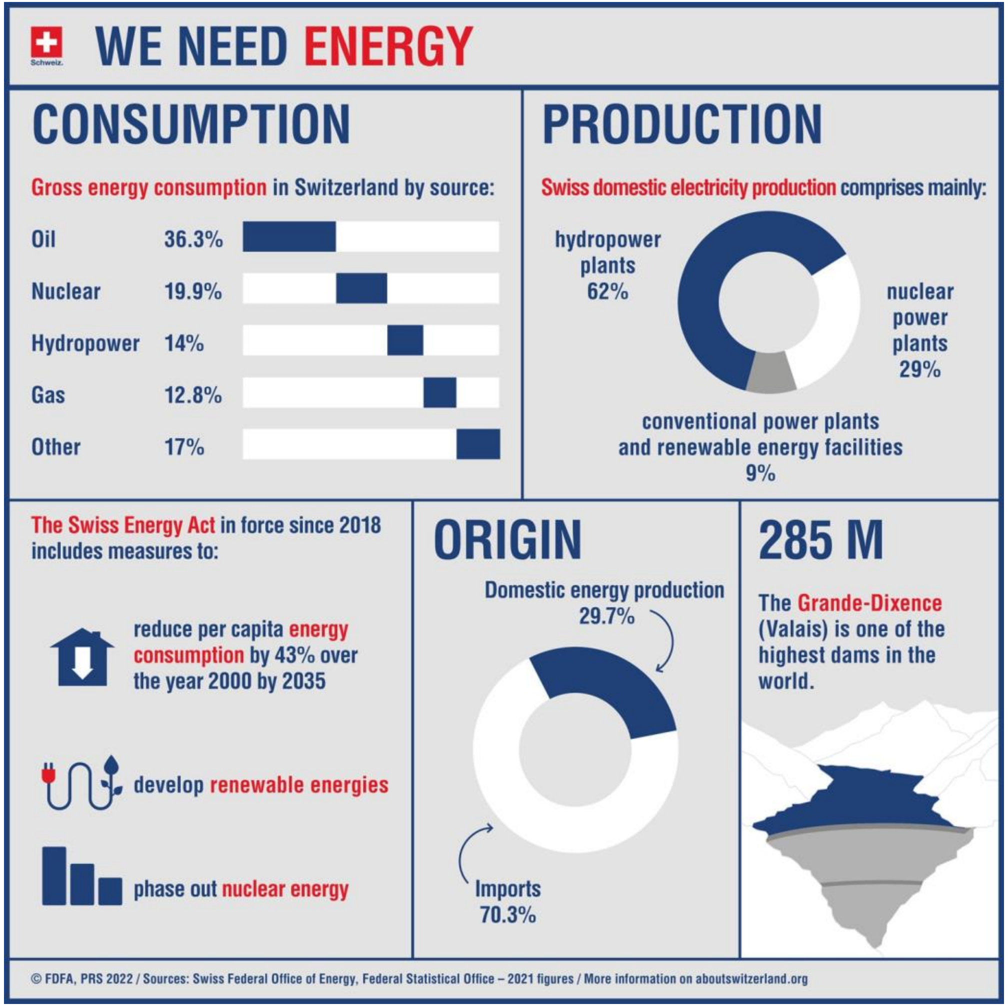
https://ember-energy.org/data/electricity-data-explorer/

Achtung!

Electricity is not the only Energy

Over the last 5 years, **Switzerland** has consumed an annual average of around 225 terawatt-hours (TWh) and is dependent on imports for around 70% of this.

In 2023, 70 TWh of electricity was produced



Source: Swiss Federal office of Energy

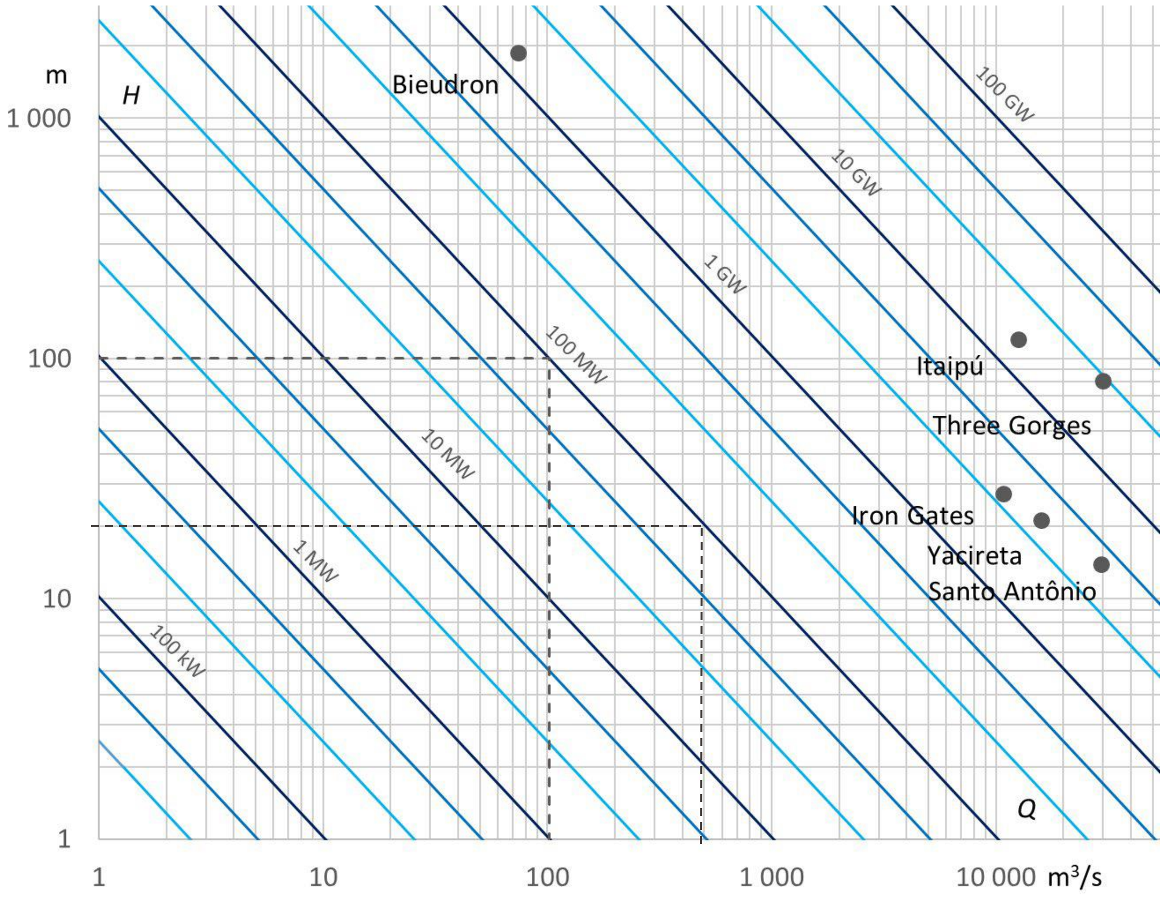
Typical hydropower plant

$$P = \rho g \Delta H . Q$$

Where:

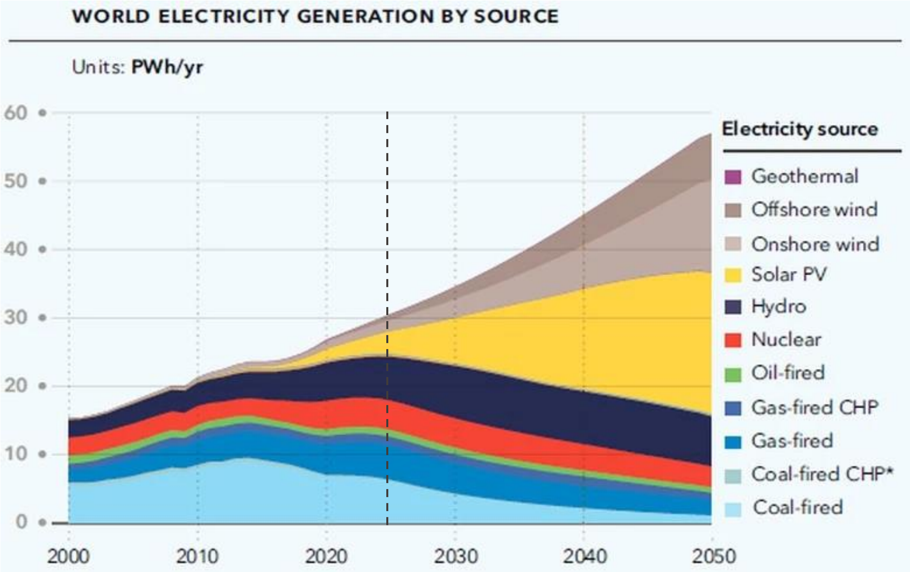
- P is the power [W]
- ΔH is the water head [m]
- Q is the flowrate [m³/s]

World record: 1 GW single turbine (Baihetan in China 16 of them)



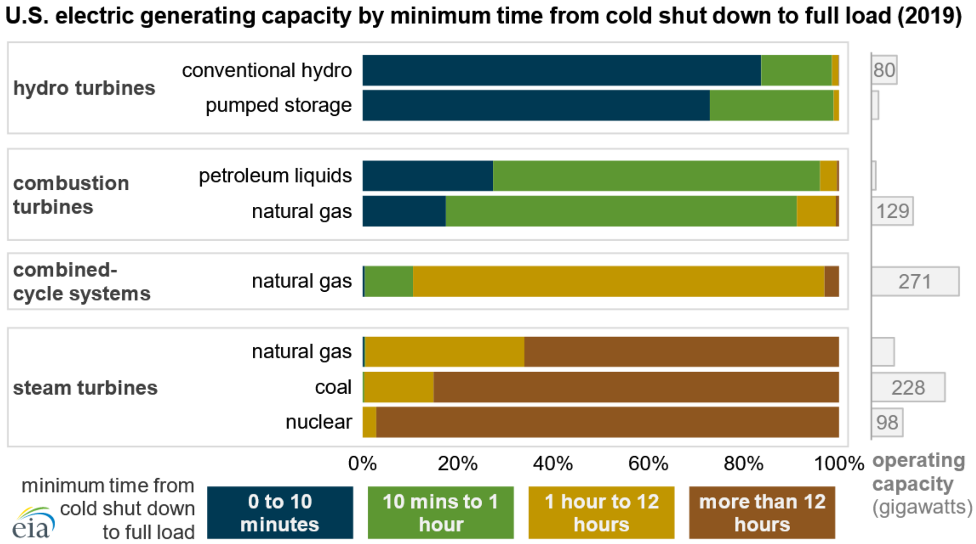
Hydropower Generation and its future

- Relevance for Switzerland: 60 % of electricity production is provided by hydropower
- Fast evolving environment of energy market:
    - Deregulation of European energy market → Strong increase in short-term trading
    - A booming development of new renewable CO_2 free primary energies
    - Shutdown of nuclear power plants, planned in a near future



Hydropower Generation and its future

- Incidence on hydropower plants:
  - Hydropower is suitable to follow the market trend (flexibility, short response time)
  - Hydropower is suitable for energy storage and power grid stability
  - Modern power plants are expected to operate at variable load in a wider range of power with improved efficiency, flexibility and safety
    → Nowadays, hydraulic turbines are operated far from optimal conditions with frequent starts & stops due to the volatile peak energy demand → Increase of mechanical stress



- PSH accounts for more than 99% of bulk storage capacity worldwide: around 127,000MW, according to the Electric Power Research Institute (EPRI)

- Energy supply and global warming → 2 majors problematics & 2 conflicting objectives

    1. A strong need to increase energy production to satisfy the growing demand around the globe.
    2. A strong pressure to reduce significantly the CO_2 emission to “save the planet” from global warming.

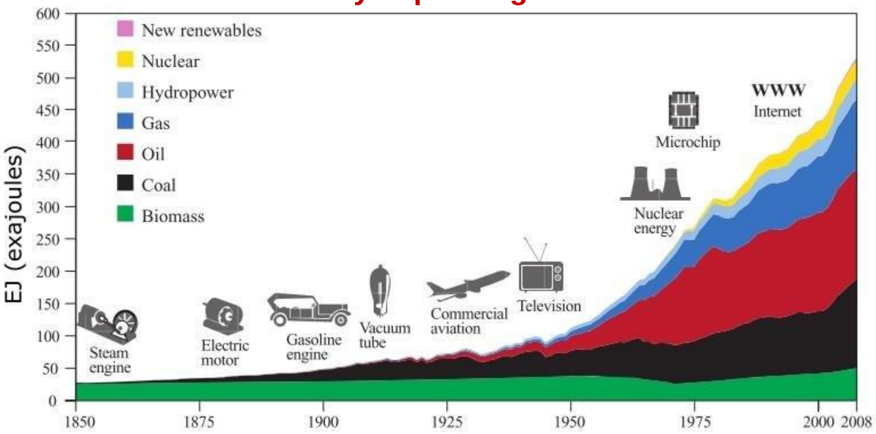
⇒ Energy Transition (Solution for a decarbonized energy consumption)

- Main idea: Replace fossil energies with renewables
- Popular idea, promoted by most of the governments and large companies
    - Wood → coal → oil → natural gas → nuclear → solar & wind
- But … unfortunately unrealistic !
    - Wood + coal + oil + natural gas + nuclear + solar & wind
      (the different forms of energy rather piled up and did not replace each other)

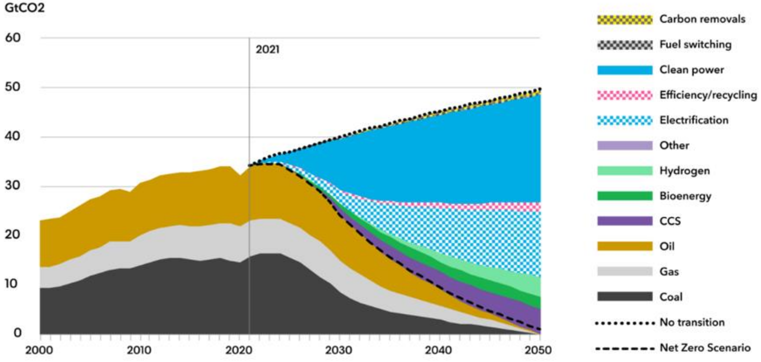
Hydropower Generation and its future

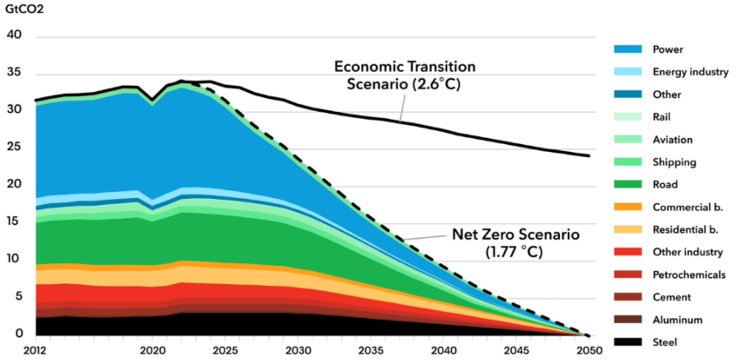
- Energy supply and global warming → 2 majors problematics & 2 conflicting objectives

History of power generation



Future of energy mix: different scenarios





Source: Bloomberg, 2022

- In the past, the different forms of energy piled up and did not replace each other
- → The Net Zero Scenario seems very hard to achieve !

Hydropower Generation and its future

- Today:
  - Extreme fragility of energy supply
  - Climate change (growing faster !)

    → More pressure on energy sector in general and hydropower in particular

- What is the future of Hydropower and what is the role of university in shaping this future ?
  - Research must be re-invented to take into account the new Hydropower environment :

    → Refurbishment of old power plants (Lighter turbines, more efficient, more flexible)

    → Smart monitoring of hydropower plants, using innovative technologies:

      → Sensing network for the entire power plant, artificial intelligence.

      → Preventive operation (e.g. forecast of silt concentration to avoid sand erosion)

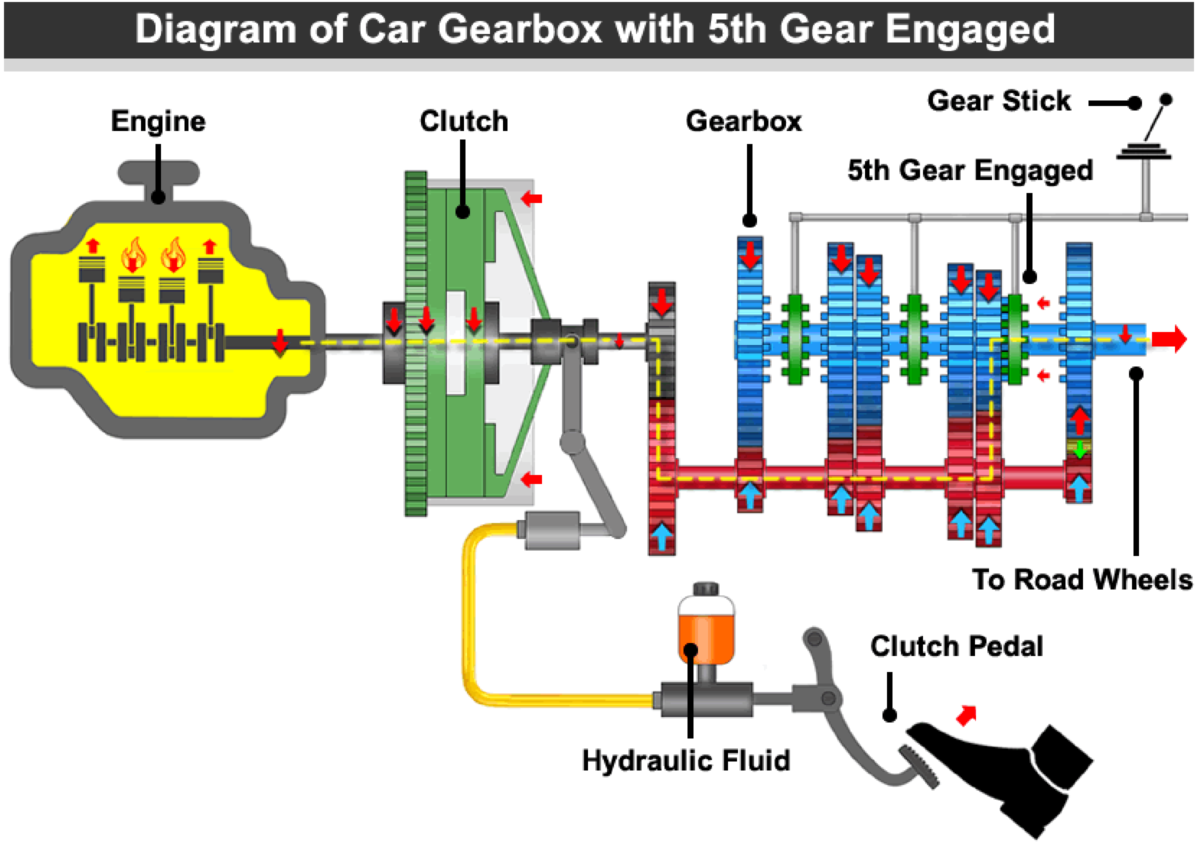
    → Environmental impact

      → Fish-friendly, Sediment transport between reservoirs, Control of oxygen content, …
- A tremendous challenge for new generation of engineers and researchers

Some examples to other type s of turbomachinery which will not be covered in the course….

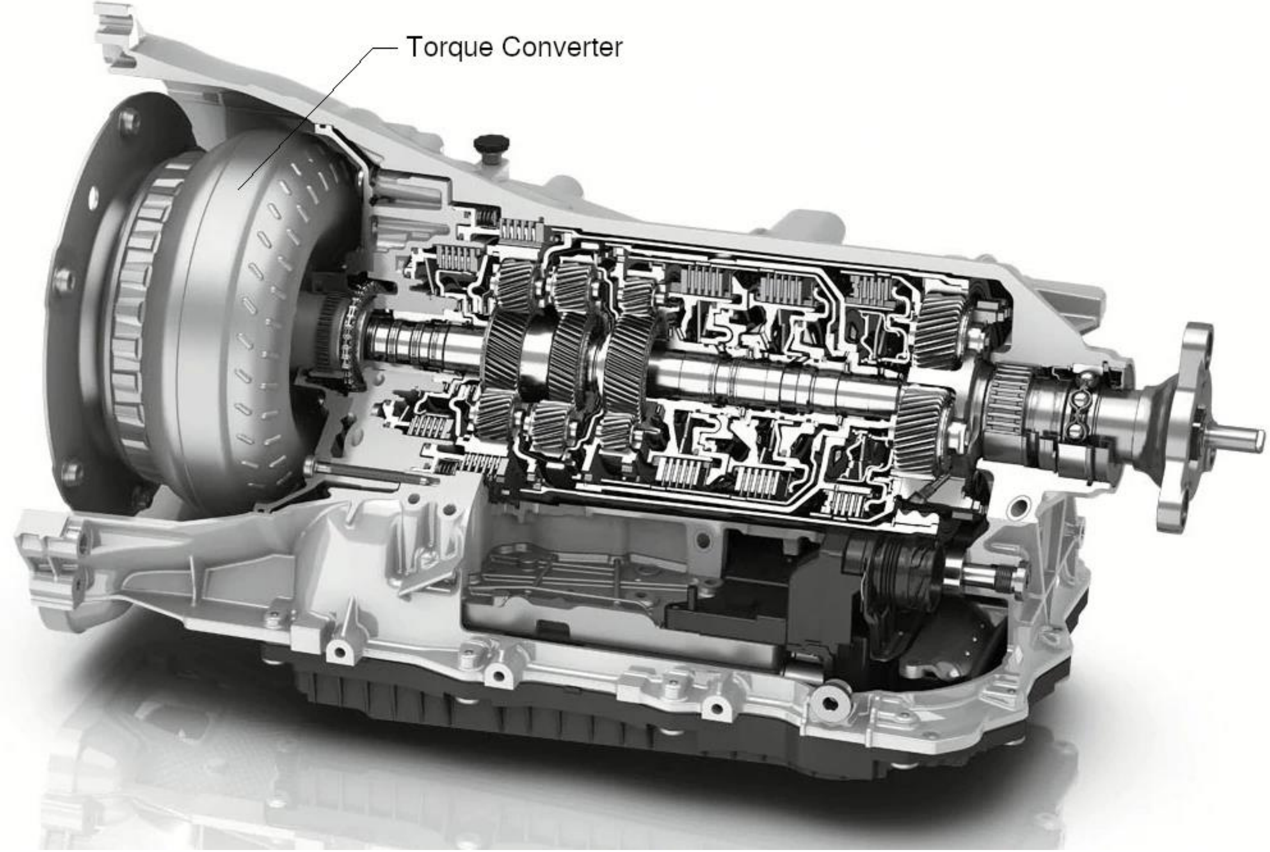
Automobile transmission system with turbomachinery

- Manual transmission



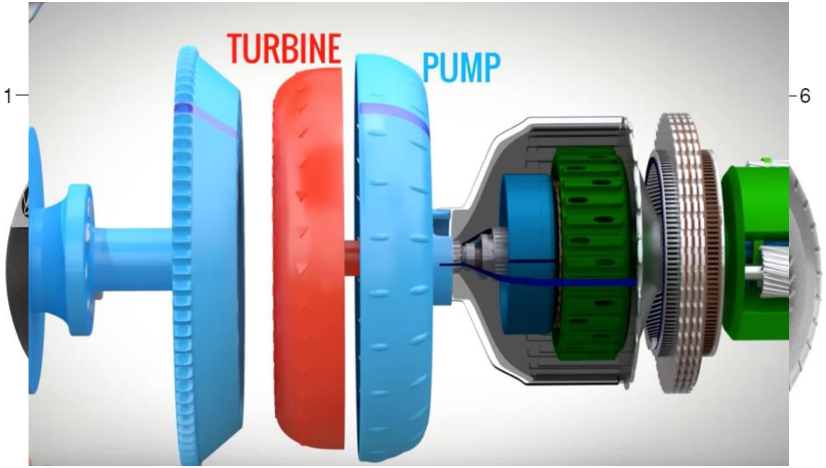
Automobile transmission system with turbomachinery

- Automatic transmission



https://x-engineer.org/

Automobile transmission system with turbomachinery



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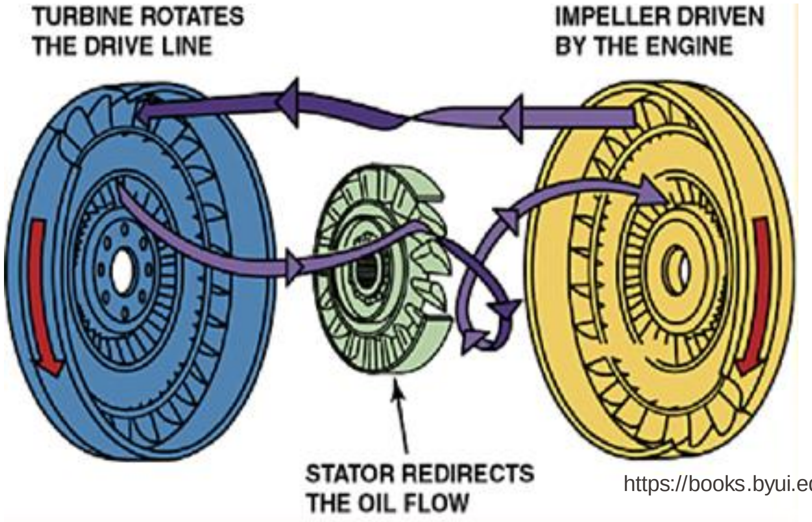
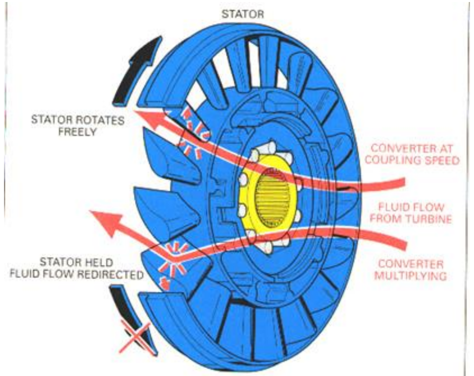


https://books.byui.edu

1.torque converter front cover
2.clutch friction discs
3.clutch pressure disc with torsional damper
4.turbine
5.stator mounted on a one-way mechanism
6.impeller housing



Wind turbine