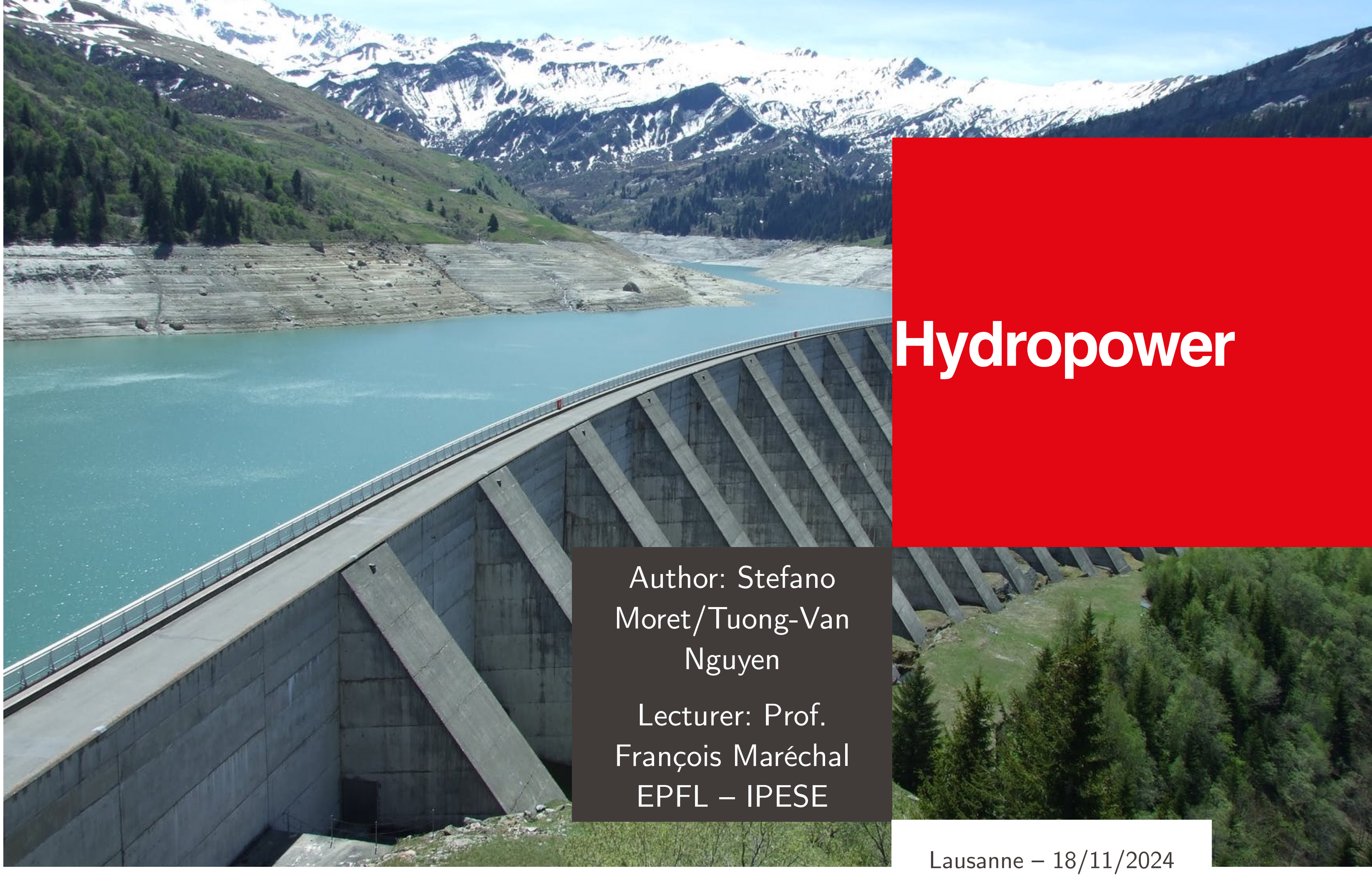

Hydropower

Author: Stefano Moret/Tuong-Van Nguyen

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EPFL – IPESE

Lausanne – 18/11/2024

École polytechnique fédérale de Lausanne

Outline

- Introduction
  - Hydro today and future potential
  - Types of power stations
- Physics of hydro
  - Key equations: energy balance
  - Buckingham π theorem: similarity
- Hydraulic turbines
  - Hydraulic turbines: Pelton, Francis, Kaplan
  - New developments: microturbines
- Hydro & energy systems
  - Integration in the energy system
- Take home message

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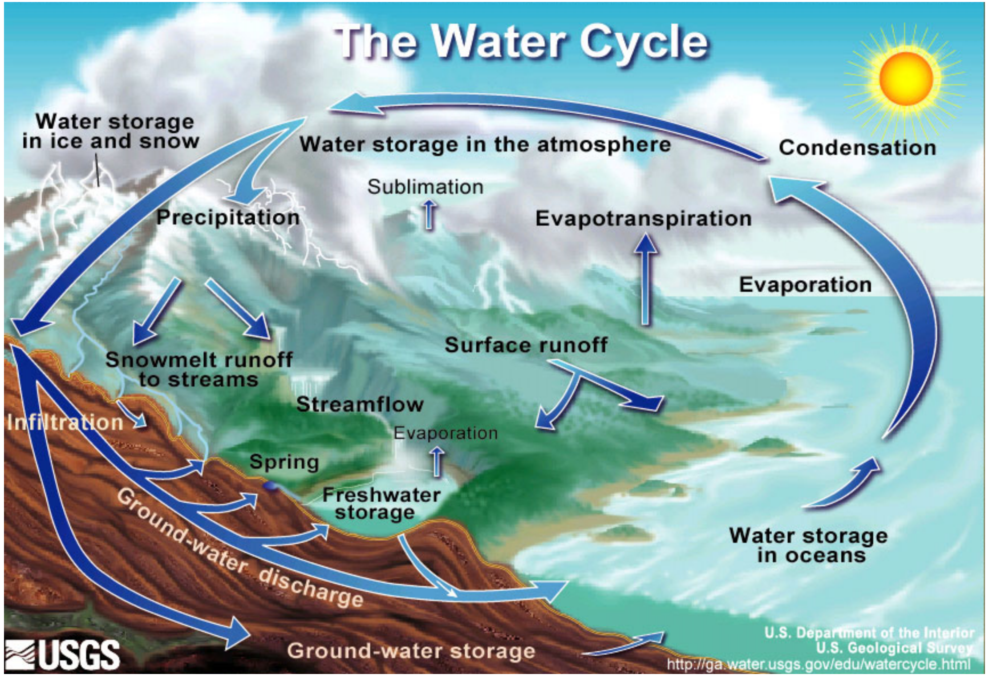
Introduction

What is hydropower?

- Water covers 71% of the Earth surface, mostly (>95%) concentrated in oceans. → the water cycle is driven by the sun.

- Used since early history:
  - Water wheels for irrigation
  - Water mills
  - Barbegal (Arles, F), 260 AD:
    - 10km long aqueduct
    - 18m head
    - 53 kW for flour production



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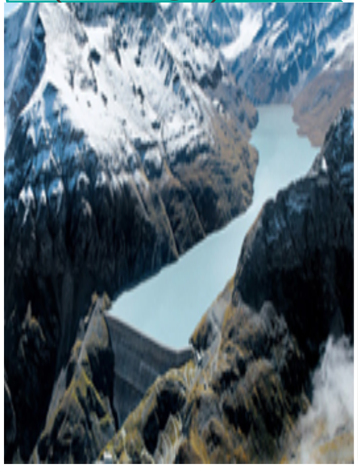
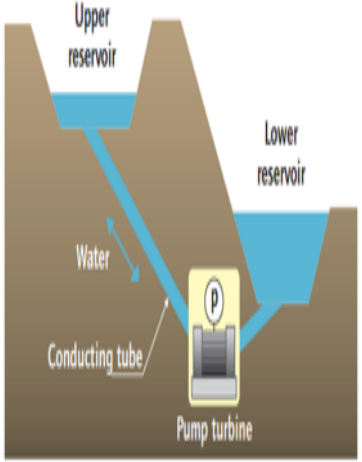
Types of hydro power plants

Hydro run-of-river

Hydro dam (storage)

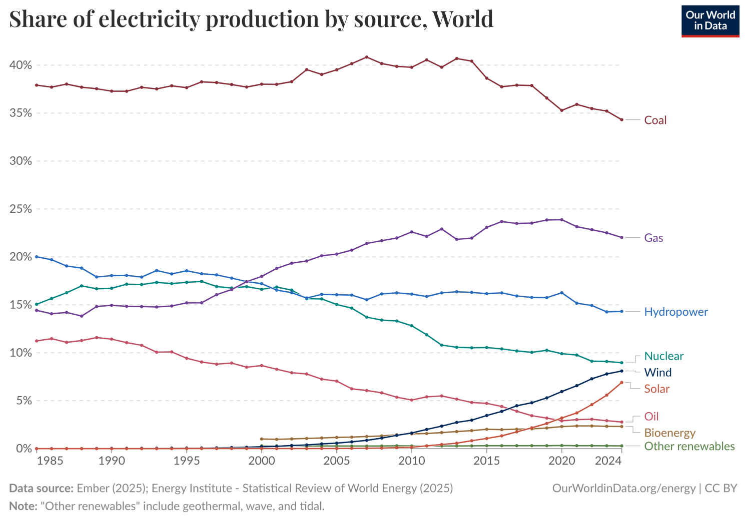


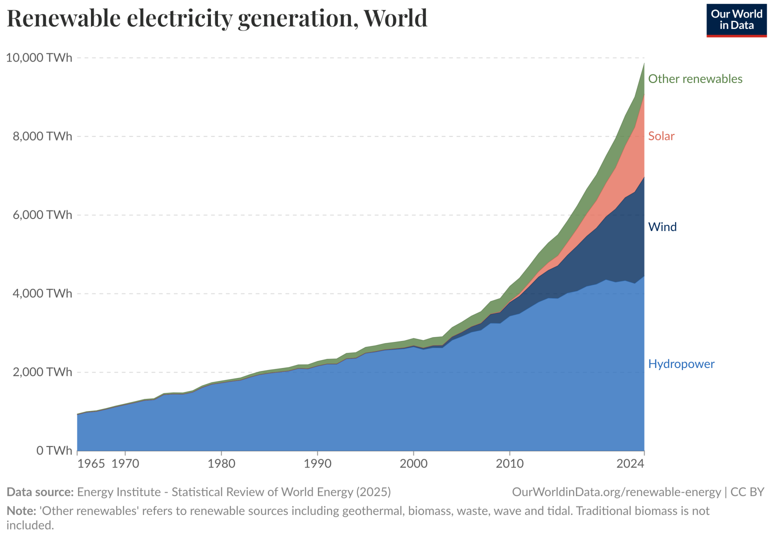
Pumped storage



Hydro Power in the energy mix?

- World final energy consumption: 123800 TWh/y (2023)
- World electricity production: 28066 TWhe/y (2023)
- Hydro electricity production: 4210 TWhe/y (2023) (14.5%)
- IEA technical potential: 15000 TWhe/y
- Most developed and mature renewable technology





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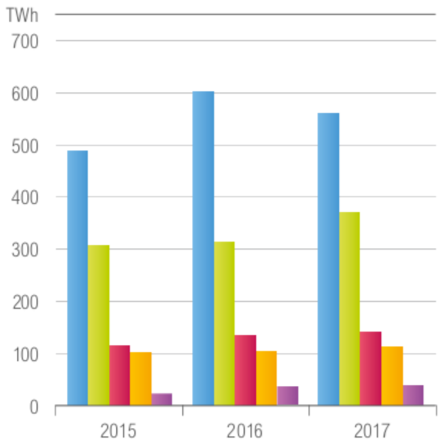
Hydro today : Europe

- Hydro capacity relatively stable
- ENTSO-E hydro electricity: 600 TWh/y (2023) → 15.3%
- ENTSO-E hydro capacity: 230 GW (2023) → 18.4%

ENTSO-E renewable generation[1]

	year	TWh	%
Renewable net generation	2015	1 042.4	
	2016	1 200.0	
	2017	**1 228.1**	
of which hydro	2015	489.2	47
	2016	604.6	50
	2017	**562.8**	**46**
of which wind	2015	310.6	30
	2016	316.1	26
	2017	**370.8**	**30**
of which biomass	2015	116.2	11
	2016	136.1	11
	2017	**141.1**	**11**
of which solar	2015	102.0	10
	2016	105.0	9
	2017	**114.3**	**9**
of which other renewable	2015	24.5	2
	2016	38.3	3
	2017	**39.3**	**3**



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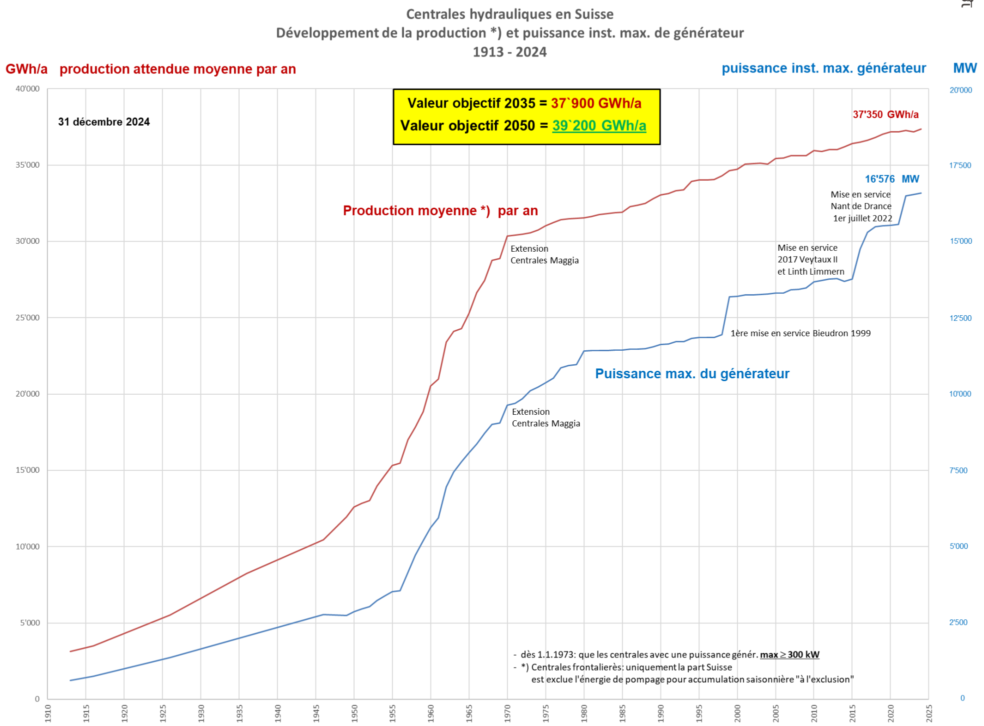
Hydro today : CH

- Swiss electricity hydro production: 35 TWh_e/y
  - → ~60% of Swiss gross electricity production
- Of which hydro: (2024)
  - Dams (47.5%): 16.6 TWh/y
  - Rivers (48.4%): 17 TWh/y
  - Pumped Hydro(4.1%): 1.4 TWh/y



Environ **48,4 %** sont générés par des centrales au fil de l'eau, **47,5 %** par des centrales à accumulation, et **4,1 %** par des centrales à pompage-turbinage.

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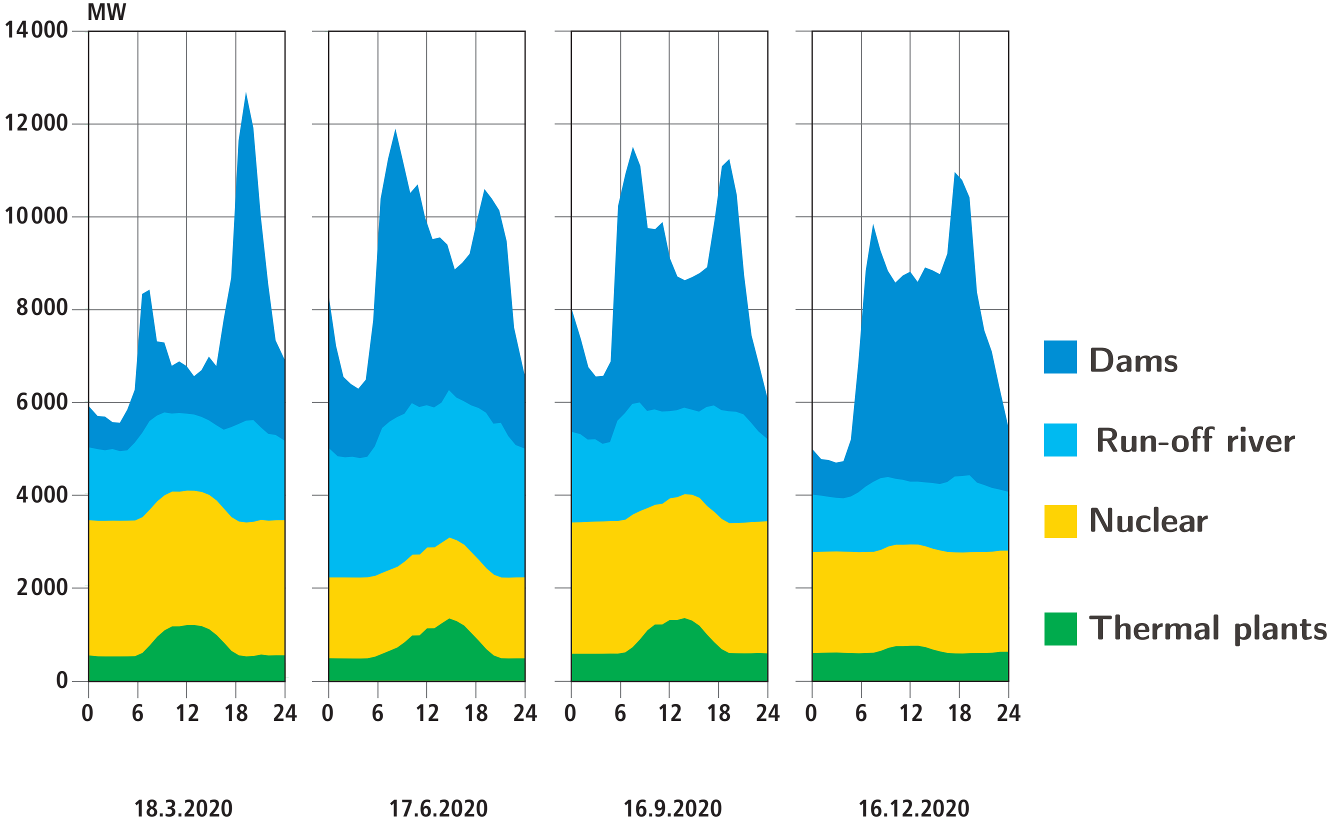
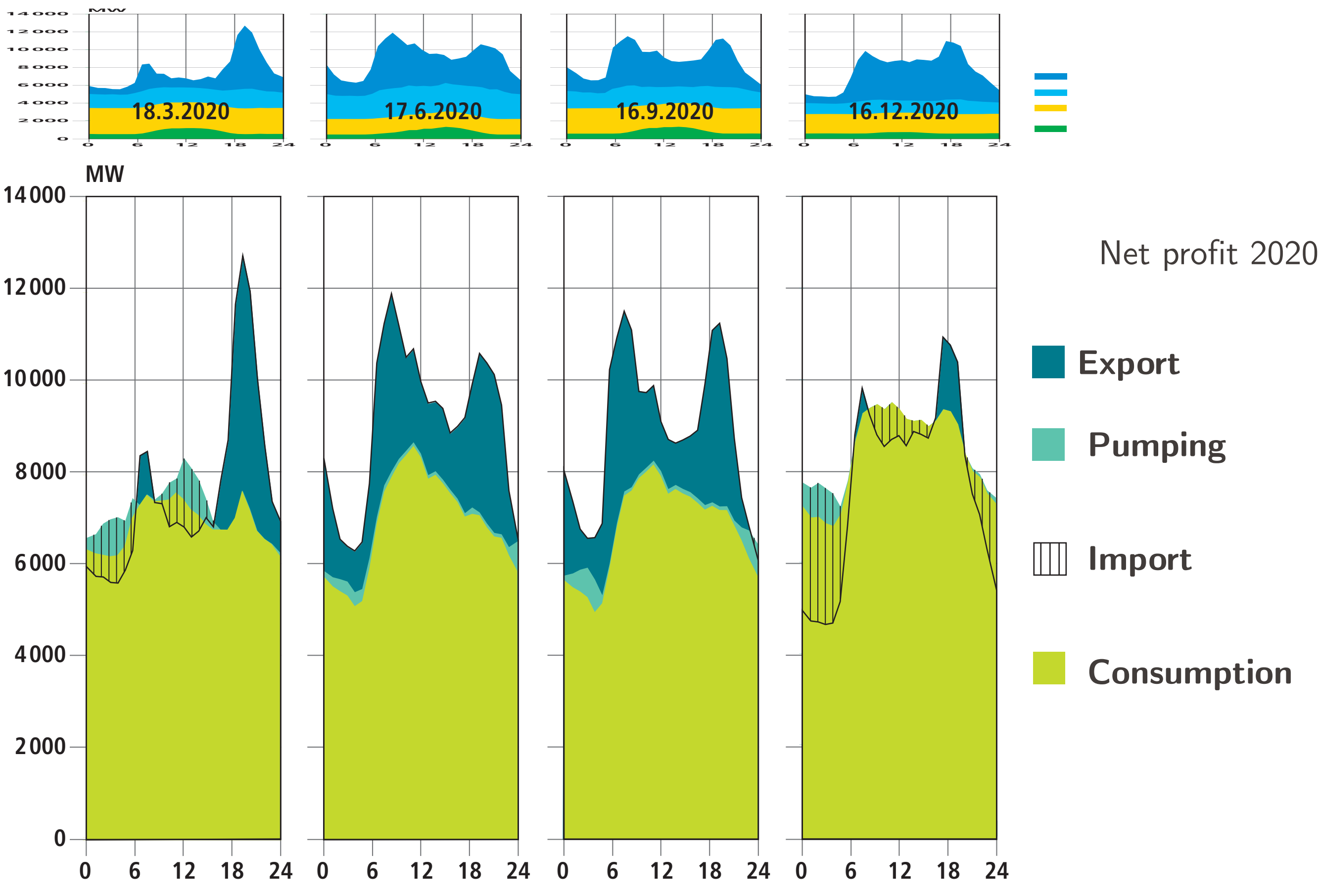
Role of Hydro Power in the electricity in CH : following the demand

Fig. 17 Belastungsverlauf am 3. Mittwoch des Monats: Erzeugung (oben), Verbrauch (unten)
Diagramme de la puissance/charge le 3e mercredi du mois: production (en haut), conso



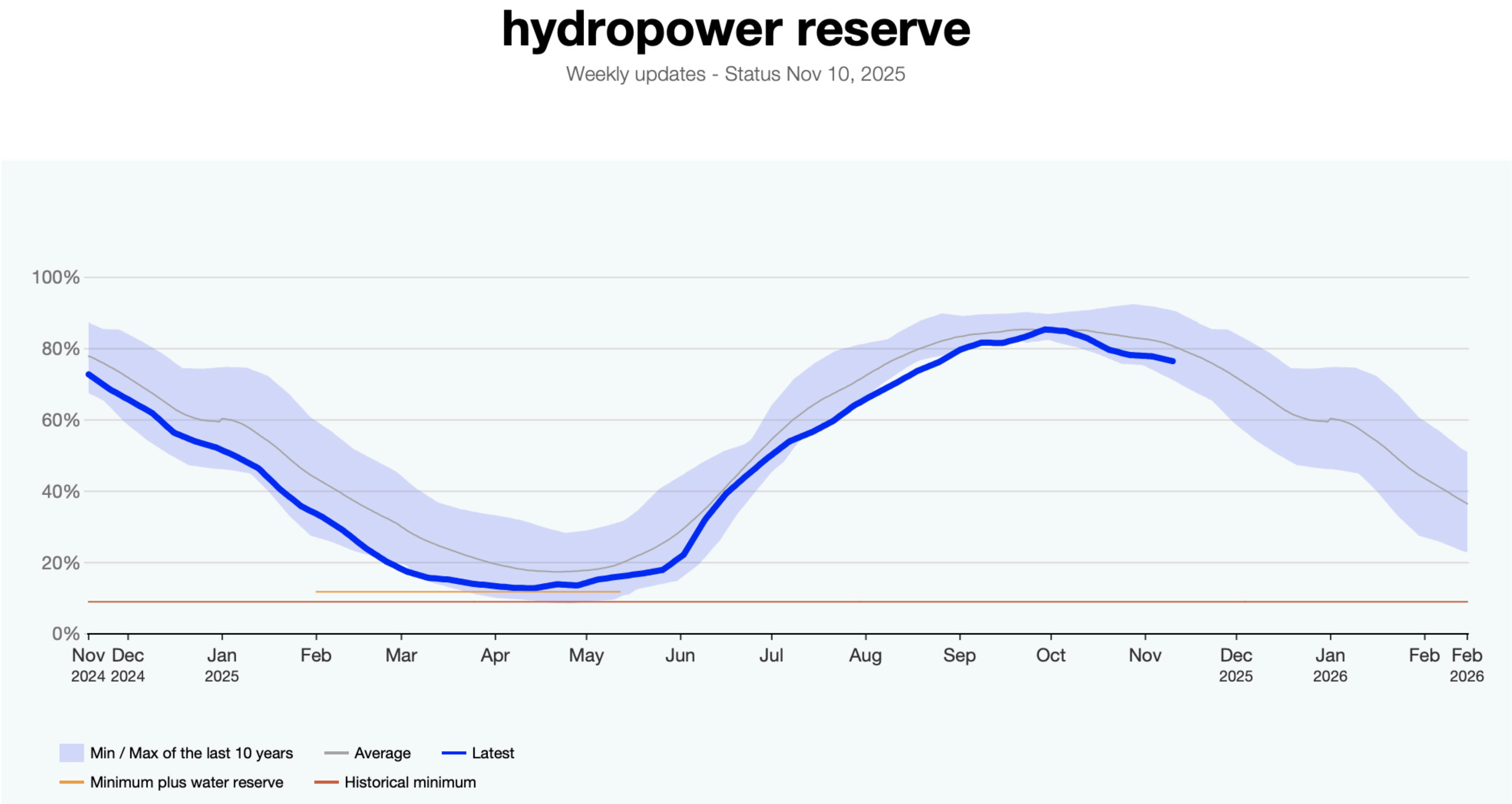
Role of Hydro Power in the electricity in CH : following the market



Net profit 2020 : 230 MCHF/y

Hydro power reserve : CH

https://energiedashboard.admin.ch/strom/fuellstaende-speicherseen



Physics of hydro

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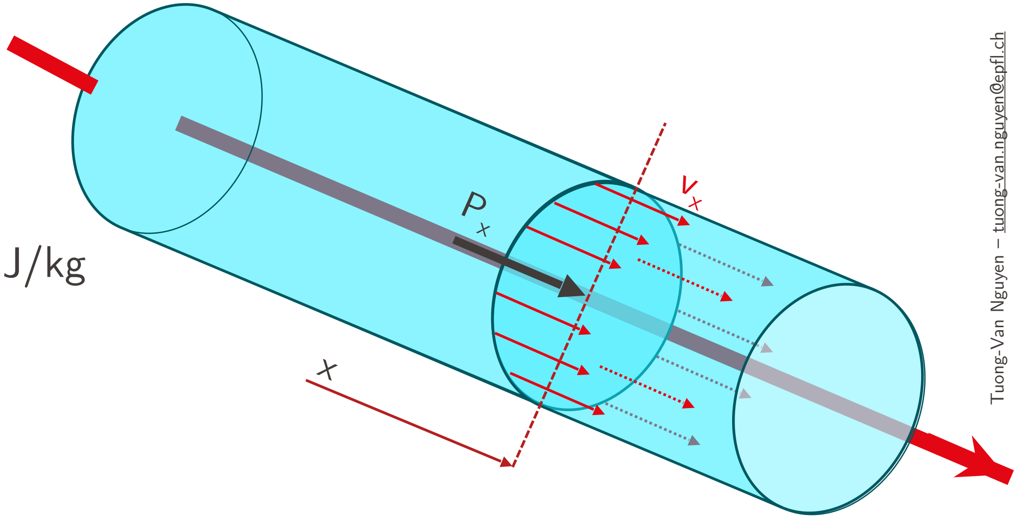
Physics of hydro

Key equations



- Low energy density resource:
  - Water @ 100m height: 0.001 MJ/kg
  - Natural gas: 45-50 MJ/kg

- Basic equations for a water flow:
  - Bernoulli at x → specific enthalpy [J/kg] $gH_x = gz_x + \frac{P_x}{\rho} + \frac{v_x^2}{2}$
  - Discharge (flow rate) [m^3/s]: $Q = \int_A \vec{v} \cdot \vec{n} \mathrm{d}A = v_x A$
  - Power [W]: $\dot{E} = \rho v_x A g H_x$

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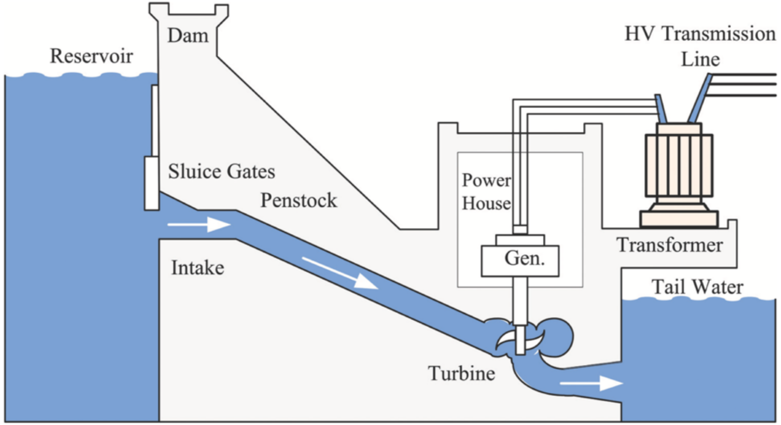
Physics of hydro
Energy balance

- Schematics of a power station:
  - z_U: level of the upper reservoir [m]
  - z_L: level of the lower reservoir [m]
  - 1: entry of the turbine
  - 2: exit of the turbine



1. High energy side (head water):

$$gH_U = \frac{P_{atm}}{\rho} + gz_U + 0 = gH_1 + \sum_{Head\ side} gH_r$$

2. Low energy side (tail water):

$$gH_L = \frac{P_{atm}}{\rho} + gz_L + 0 = gH_2 + \sum_{Tail\ side} gH_r$$

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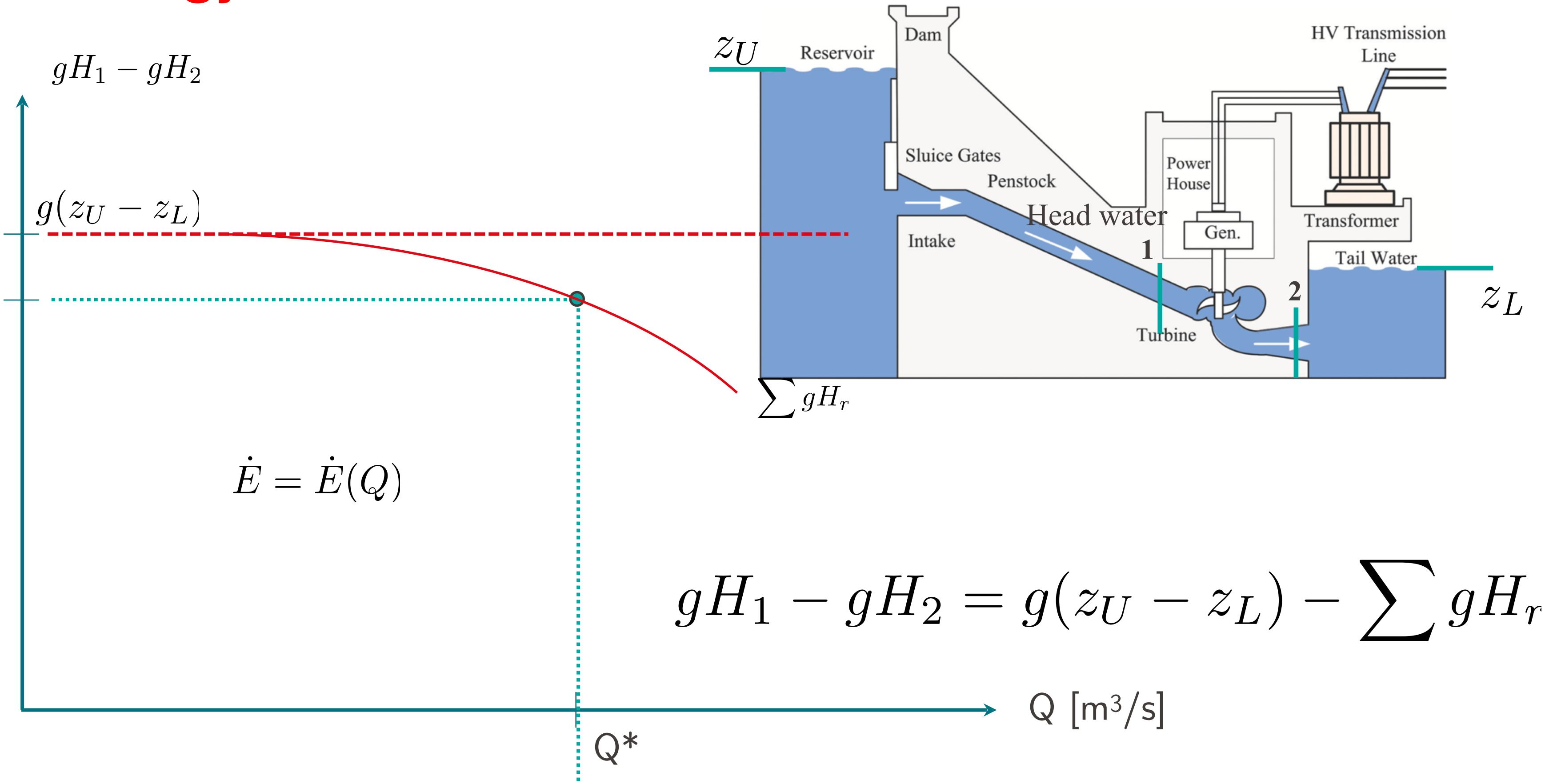
Physics of hydro
Energy balance



$$gH_1 - gH_2 = g(z_U - z_L) - \sum gH_r$$

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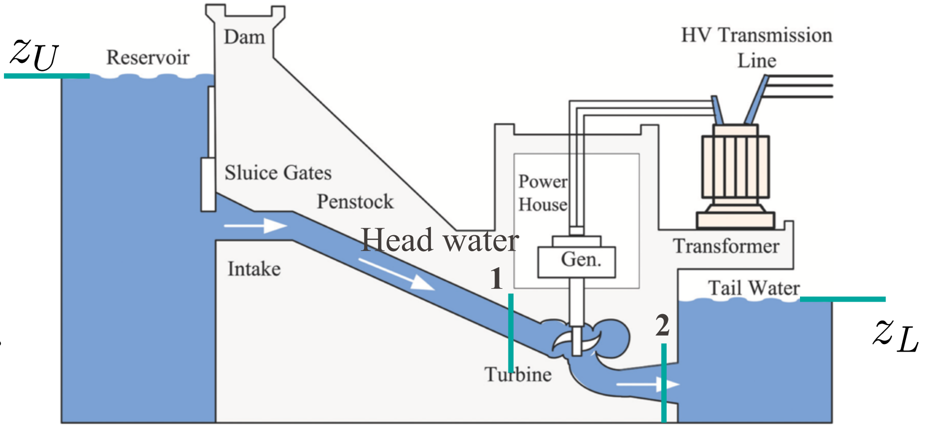
Physics of hydro
Energy balance

- At the turbine:



$$e_{12} = gH_1 - gH_2 = g(z_U - z_L) - \sum gH_r$$

$$= \underbrace{\left(\cancel{gz_1} + \frac{P_1}{\rho}\right) - \left(\cancel{gz_2} + \frac{P_2}{\rho}\right)}_{e_p \text{ potential}} + \underbrace{\frac{1}{2}\left(v_1^2 - v_2^2\right)}_{e_k \text{ kinetic}} - e_{loss}$$

- Degree of reaction: $\tau_r = \dfrac{e_p}{e_{12}}$

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Physics of hydro
Buckingham theorem

- "if there is a physically meaningful equation involving a certain number *n* of physical variables, then the original equation can be rewritten in terms of a set of $p = n - k$ dimensionless parameters $\pi_1, \pi_2, \ldots, \pi_p$ constructed from the original variables [k = # independent dimensions.]"
  - e.g. for *t* (time), *d* (distance), *v* (speed): n = 3; k = 2 ([m], [s]); p = 1 → $\pi = t*v/d$.
- Dimensionless quantities are fundamental in engineering as they allow studying systems in lower scales → similarity
- The specific speed is a dimensionless quantity which summarizes the essential characteristics of a water turbine:

Angular speed [rad/s]

Discharge [m³/s]

$$\nu = \frac{\omega Q^{\frac{1}{2}}}{\pi^{\frac{1}{2}}(2e)^{\frac{3}{4}}}$$

Specific energy available at the turbine [J/kg] → depends on the head [m]

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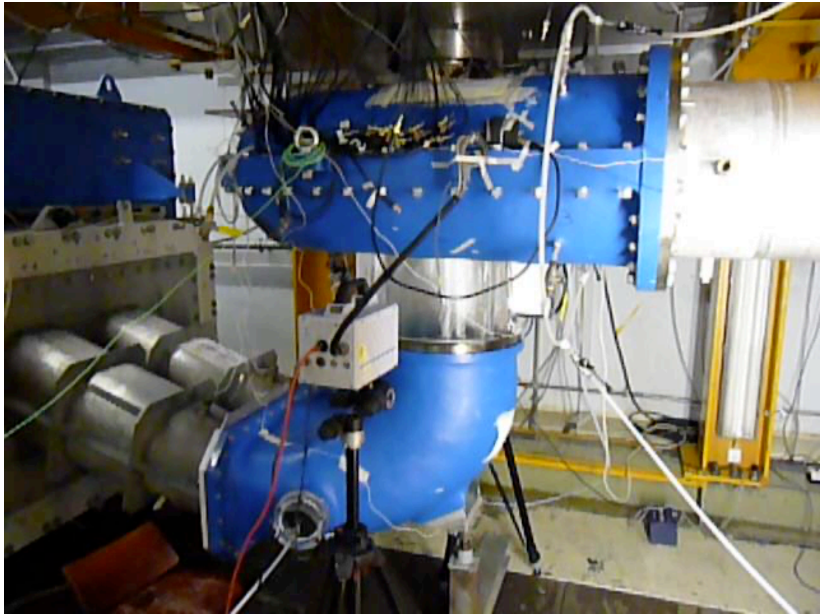
Physics of hydro



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Hydraulic turbines

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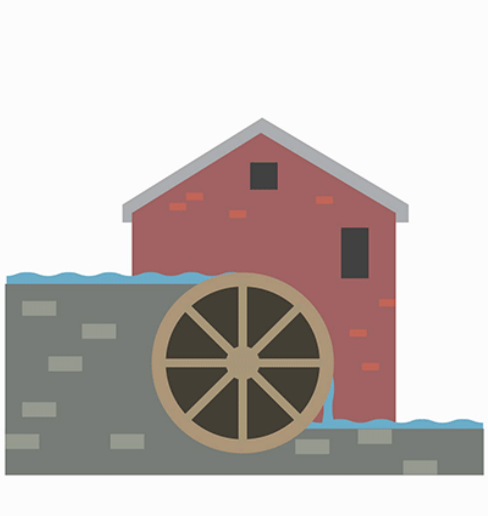
Hydraulic turbines
Classification

$$e_{12} = \underbrace{\left(\frac{P_1}{\rho} - \frac{P_2}{\rho}\right)}_{\text{displacement}} + \underbrace{\frac{1}{2}(v_1^2 - v_2^2)}_{\text{impulse}} + \underbrace{g(z_1 - z_2)}_{\text{water wheels}} - e_{loss}$$



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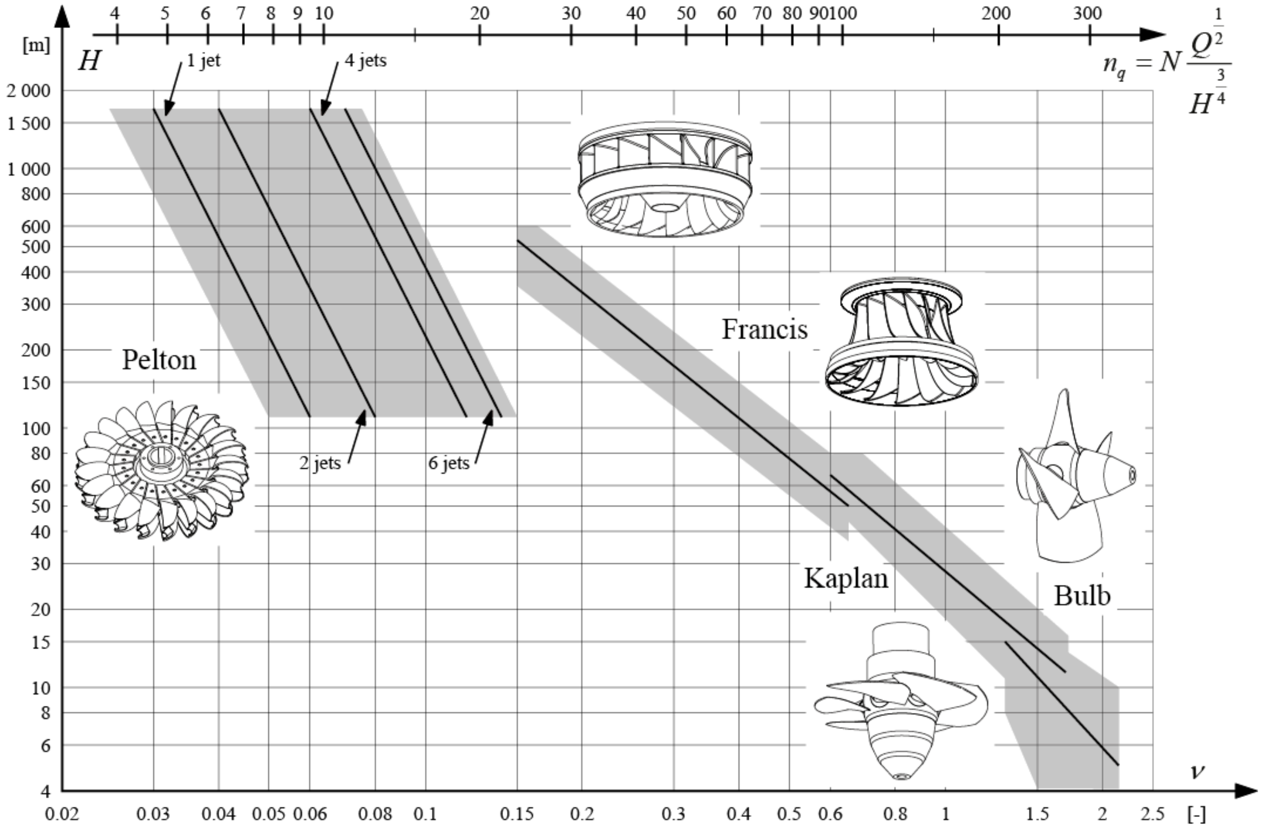
Hydraulic turbines
Classification



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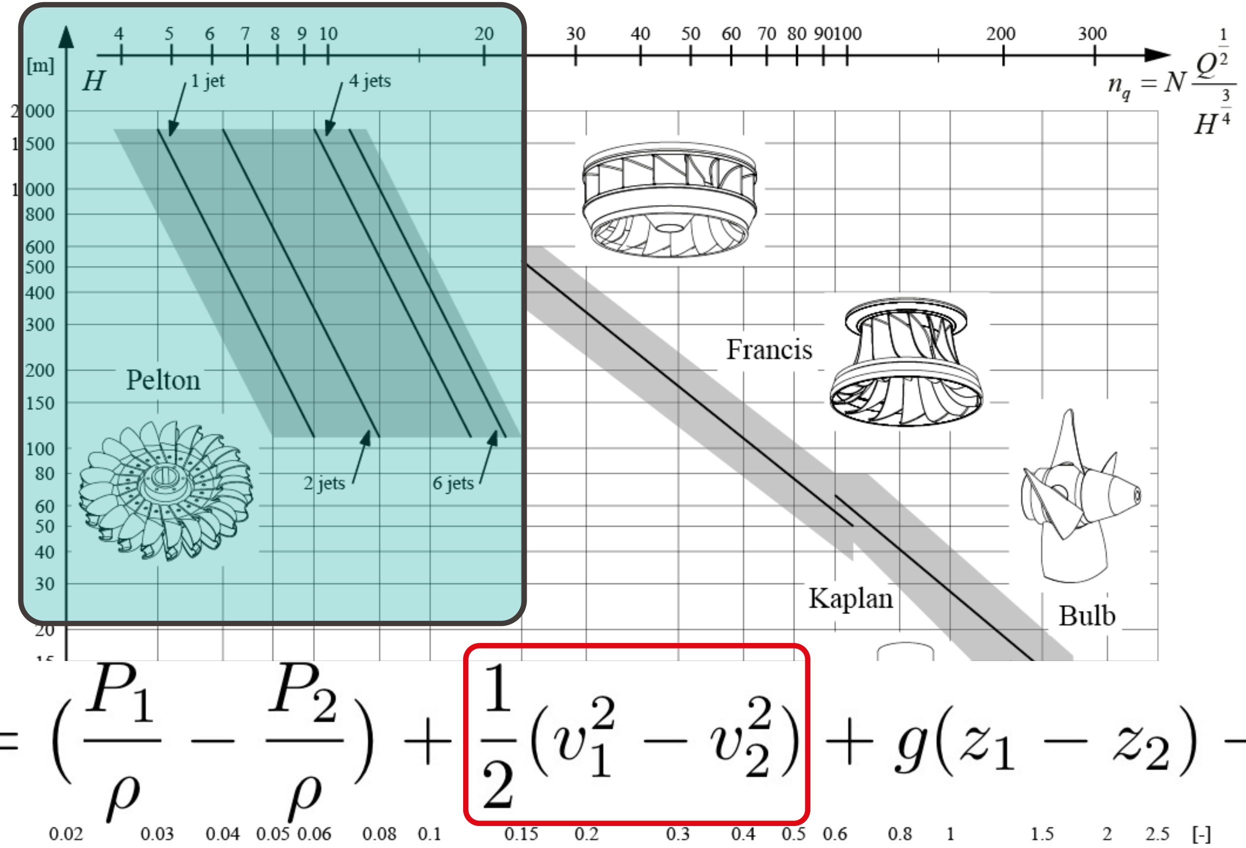
Hydraulic turbines

Classification Pelton turbines



$$n_q = N\frac{Q^{\frac{1}{2}}}{H^{\frac{3}{4}}}$$

$$e_{12} = \left(\frac{P_1}{\rho} - \frac{P_2}{\rho}\right) + \boxed{\frac{1}{2}(v_1^2 - v_2^2)} + g(z_1 - z_2) - e_{loss}$$

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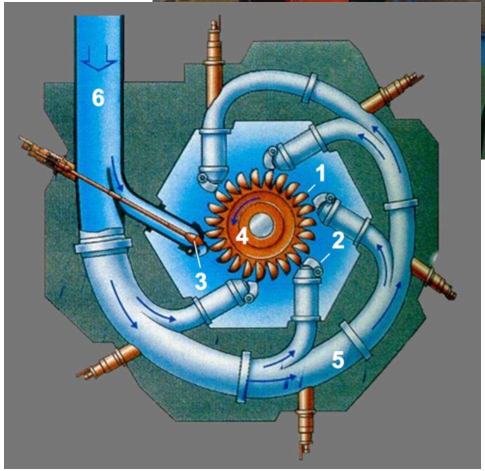
Hydraulic turbines

Pelton

- High head, low discharge
- Impulse/action turbine (only speed)
- Head: 300-2000m
- Power up to ~400 MW_e
- Efficiency up to 92%



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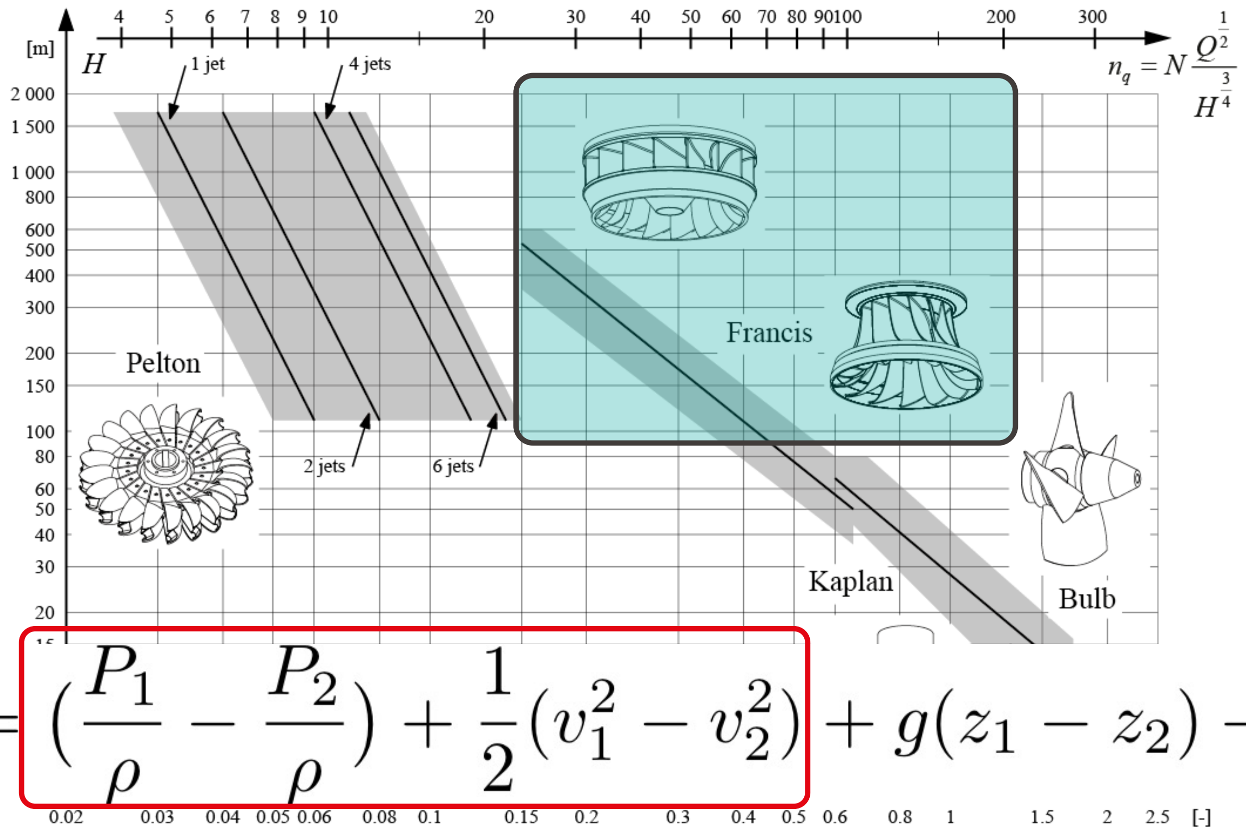
Hydraulic turbines

Classification : Francis turbines



$$e_{12} = \boxed{(\frac{P_1}{\rho} - \frac{P_2}{\rho}) + \frac{1}{2}(v_1^2 - v_2^2)} + g(z_1 - z_2) - e_{loss}$$

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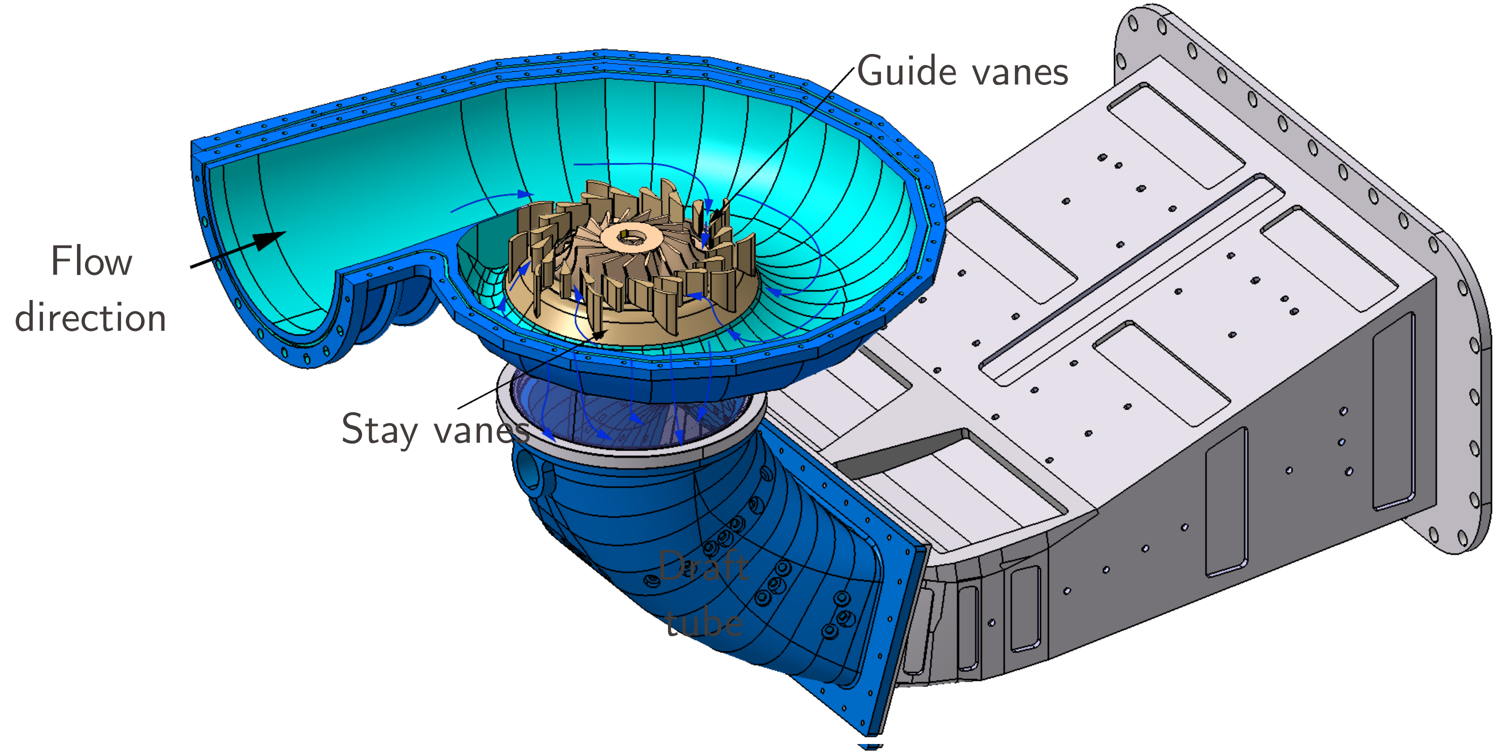
Hydraulic turbines
Francis



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Hydraulic turbines
Francis

- Most used and versatile turbine: ~60% of capacity worldwide
- Reaction turbine
- Medium heads: 40-600m
- Wheel diameters: 0.6-8m
- High efficiency: 96-97%
- Three Gorges dam (China):
  Biggest power plant worldwide
  Total capacity: 22.5 GW_e
- Itaipu (Brazil):
  20*700 MW = 14 GW
  103.1 TWh/y (record 2016)

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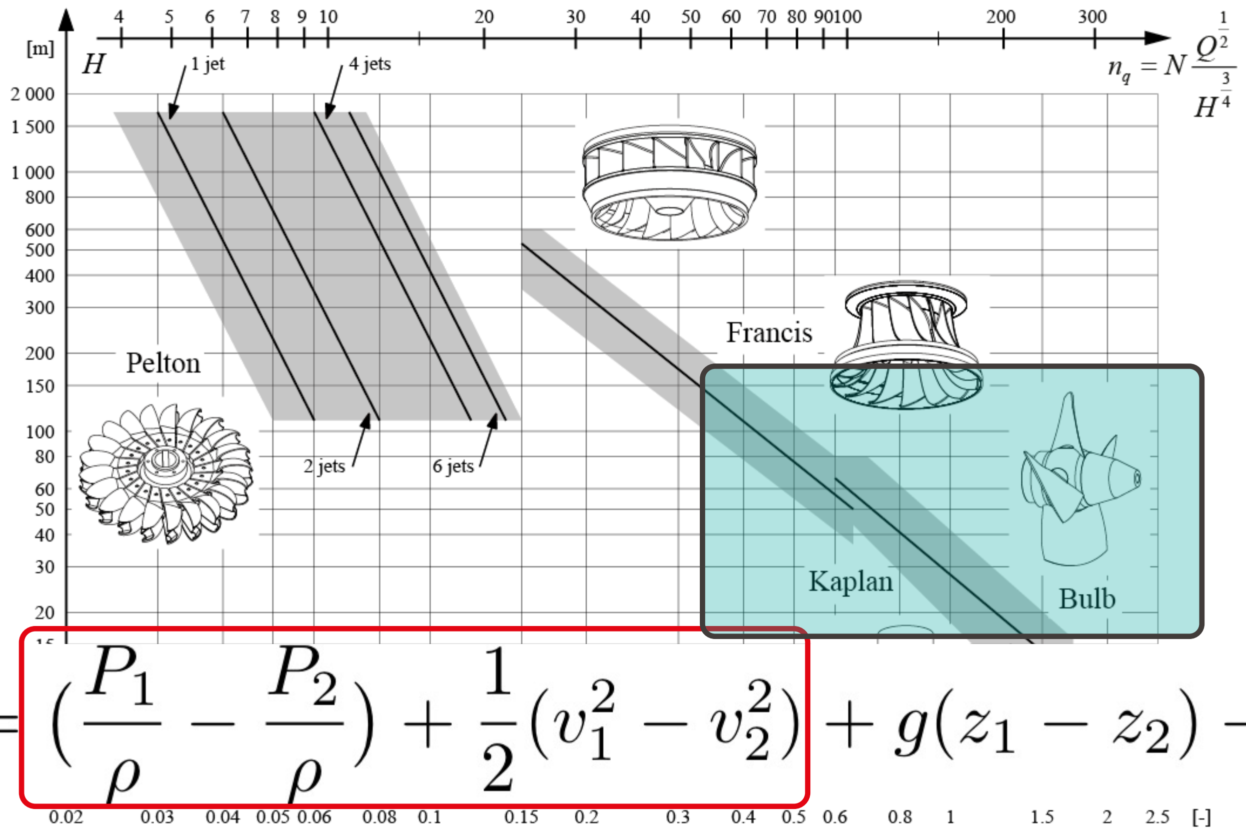
Hydraulic turbines

Classification Kaplan and Bulb turbines



$$e_{12} = \boxed{\left(\frac{P_1}{\rho} - \frac{P_2}{\rho}\right) + \frac{1}{2}(v_1^2 - v_2^2)} + g(z_1 - z_2) - e_{loss}$$

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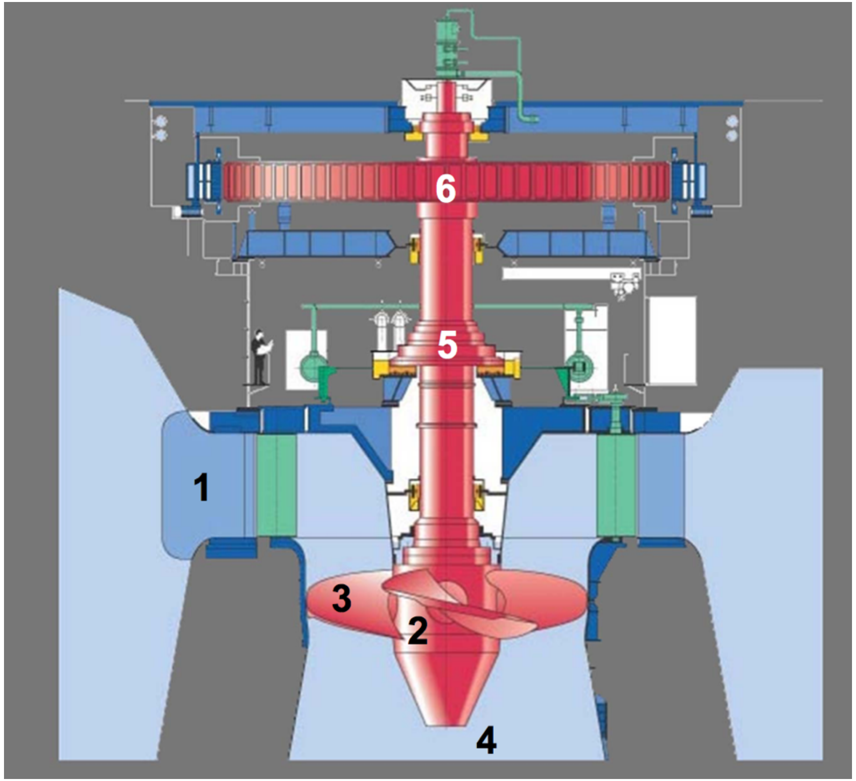
Hydraulic turbines
Kaplan

- V. Kaplan (1913), evolution of Francis for low heads
- Axial flow
- High degree of reaction
- Run-of-river plants
- Low head (10-70m), high discharge
- Typical power: 5-200 MW_e
- Problem: cavitation



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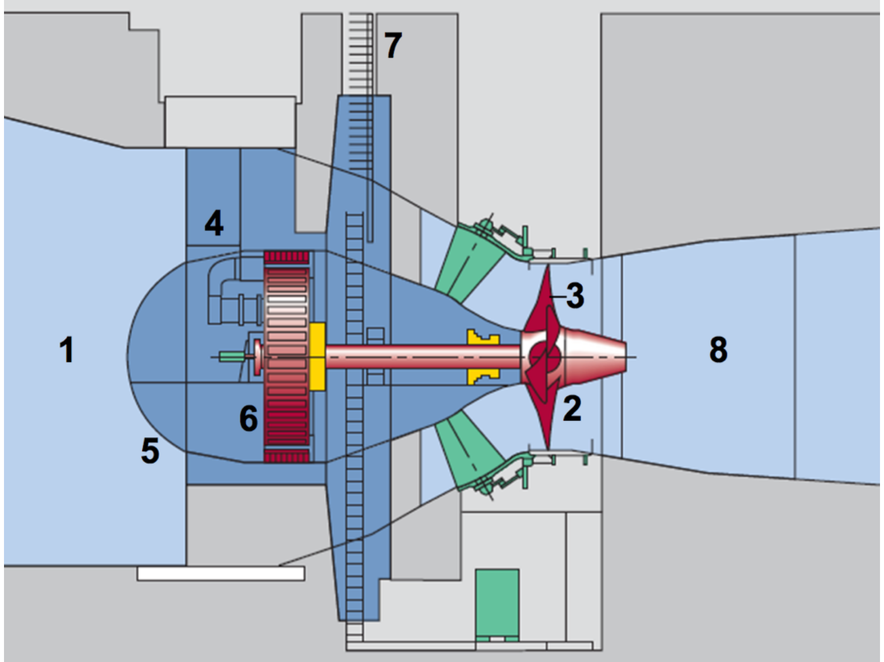
Hydraulic turbines

Bulb turbines

- 1930s: evolution of the Kaplan turbine
- Axial flow → higher efficiencies
- Compact design
- Lower costs



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Efficiency of turbine

$$\dot{E} = \dot{m} \cdot w_{12} \cdot \eta_T \cdot \eta_{gen} \cdot \eta_{gear} \cdot \eta_{transfo}$$

$\eta_T = 92\%$ Mechanical efficiency of the turbine

$\eta_{gear} = 98\%$ Efficiency of the gear box

$\eta_{gen} = 97\%$ Efficiency of the generator

$\eta_{transfo} = 98\%$ Efficiency of the transformer

$\eta_{total} = 86\%$ Overall efficiency to grid

Hydro and energy systems

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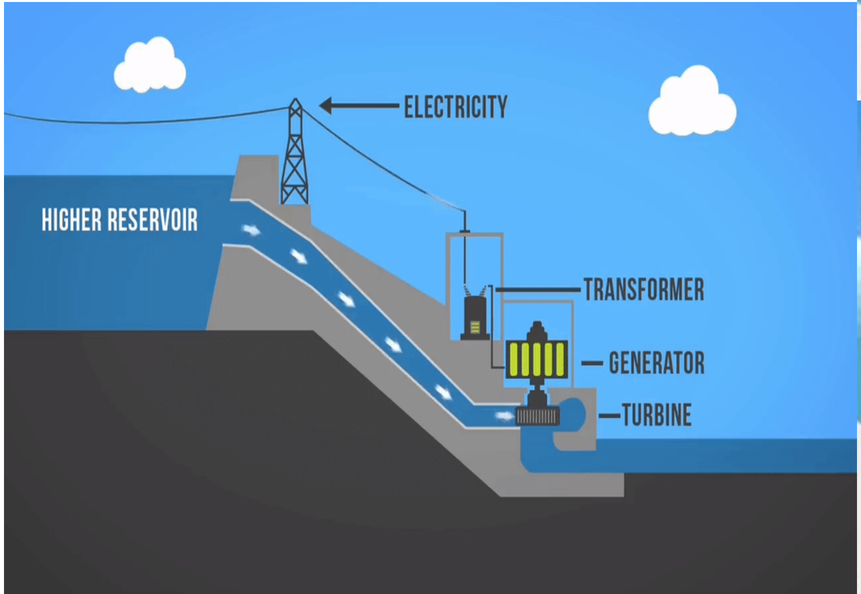
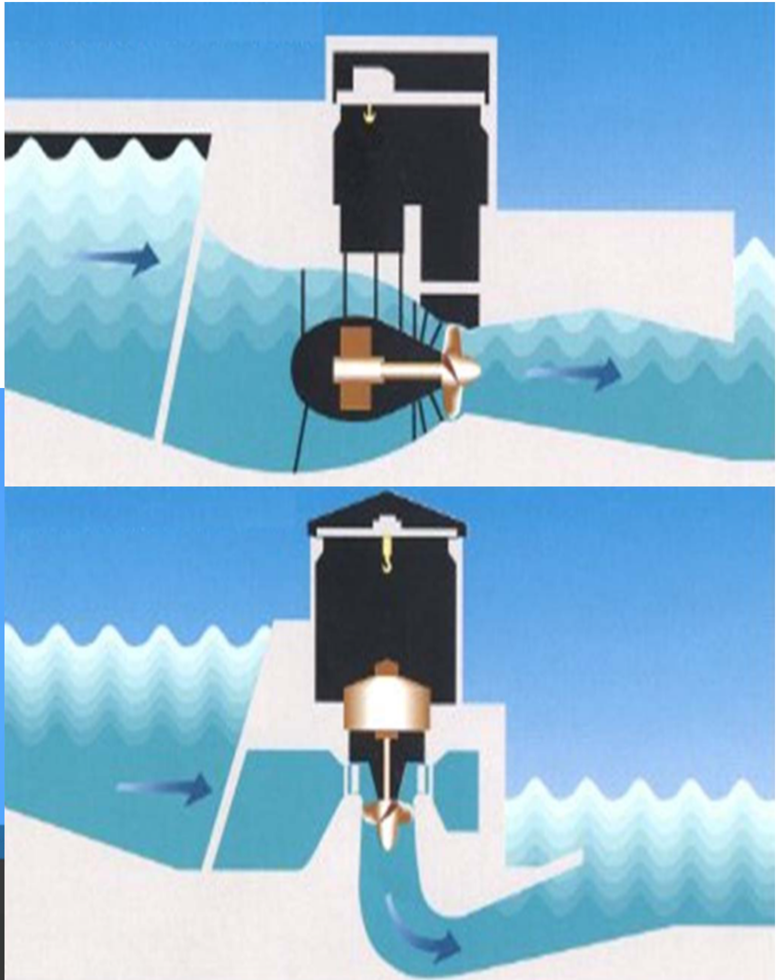
Hydro and energy systems

Hydroelectric schemes

- Storage and run-of-river power plants





Hydro and energy systems

Costs

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- Costs are quite project specific: 1050-7650 USD/kW$_e$ for large projects
- LCOE @ c_p = 50%: 28-90 USD/MWh$_e$ → very competitive!

LCOE (USD/MWh)		Weighted average capital cost or discount rate		
		8%	10%	12%
Load factor	25%	90	110	133
	50%	41	51	61
	75%	28	34	41

LCOE assuming 1500 USD/kW, O&M 2.5% of c_{inv}, 5y construction, 50y lifetime

Hydro and energy systems
Costs

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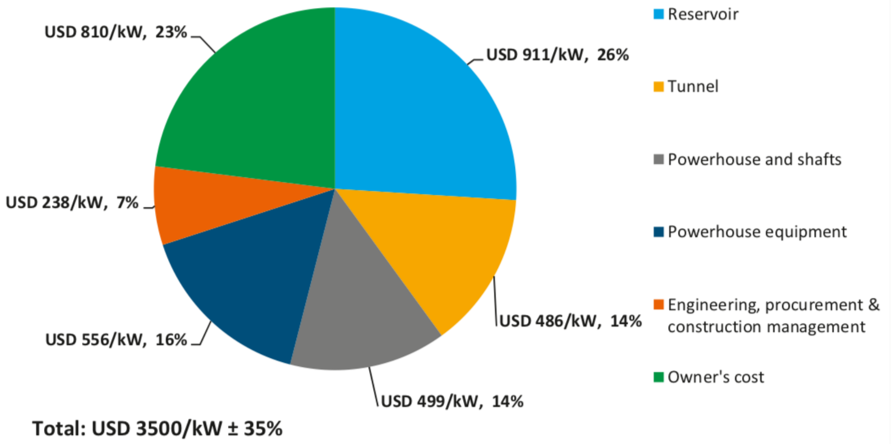
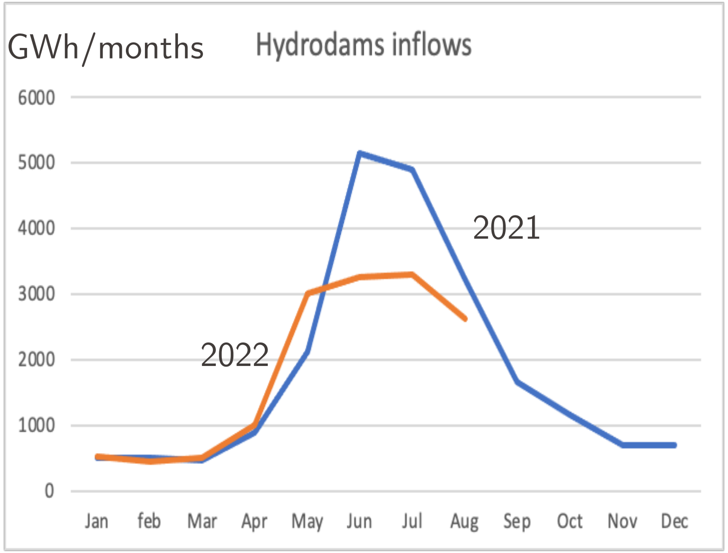
- LCOE @ c_p = 50%: 28-90 USD/MWh$_e$ → very competitive!

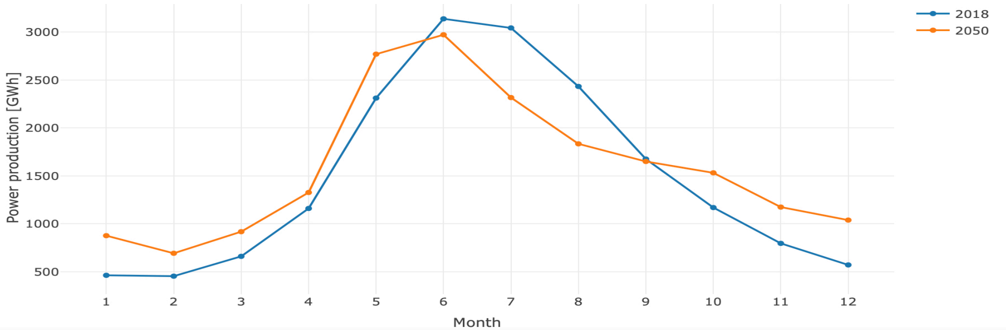


Impact of climate change/meteo

- Glaciers are loosing 1 GT/year (2%) of ice (transformed in power)
- Temperatures will influence storage in snow and precipitation



Inflow of water in dams Switzerland [GWh/month]

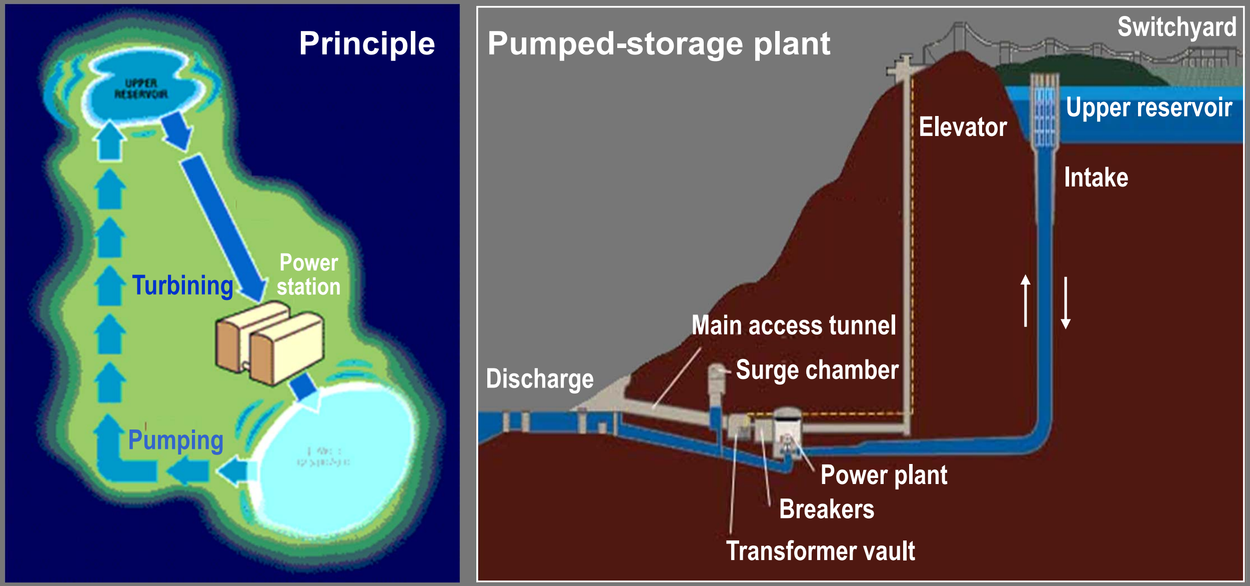


https://www.bfe.admin.ch/bfe/en/home/supply/statistics-and-geodata/energy-statistics/electricity-statistics.html

Pumped-hydro storage

Hydro-electric schemes

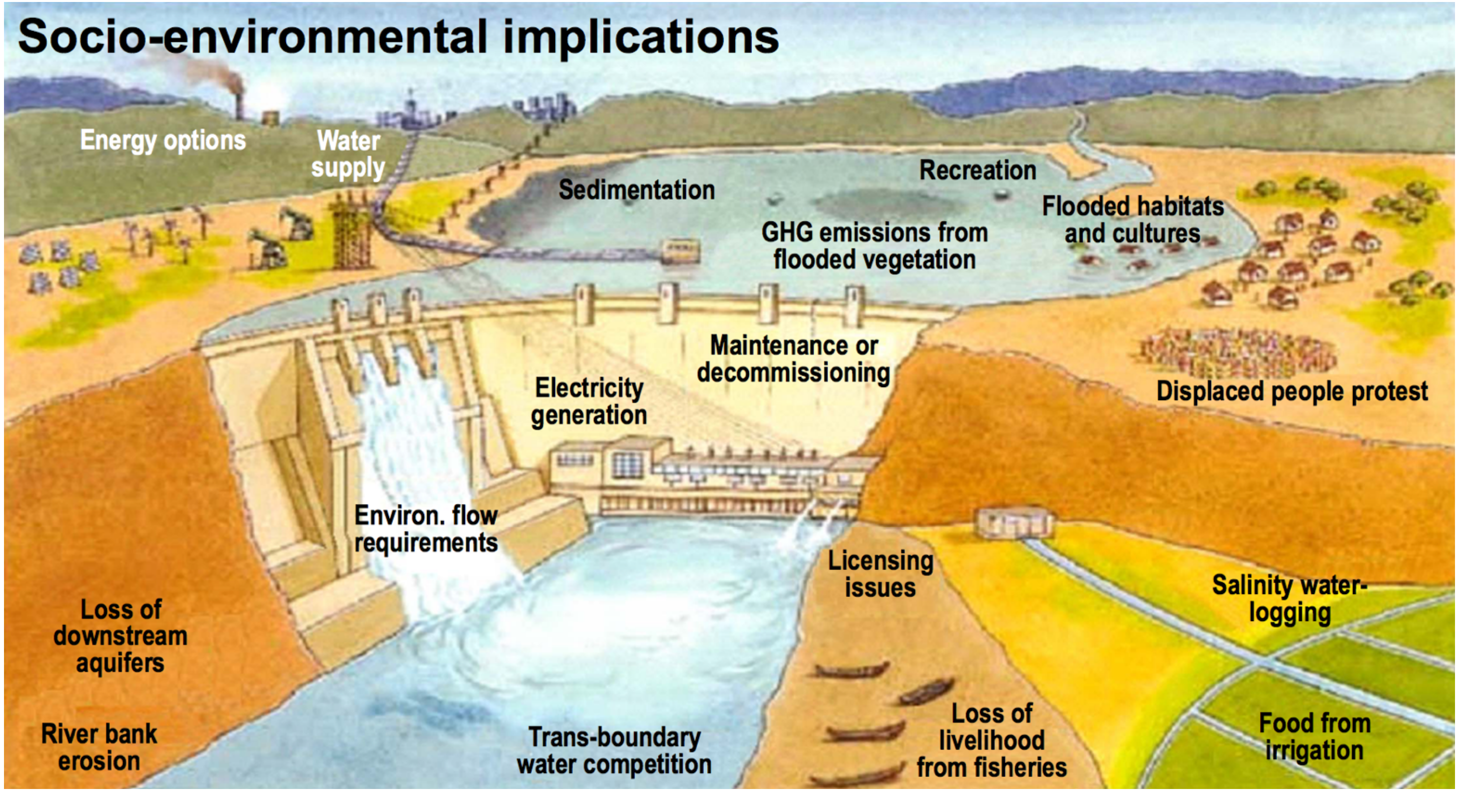
Pumped storage



$$\eta_{RoundTrip} = \frac{E^{out}}{E^{in}}$$

Round trip efficiency = 80%

Hydro and energy systems
Impacts



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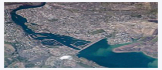
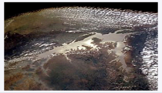
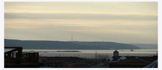
Hydro dams : land occupation & people displacement

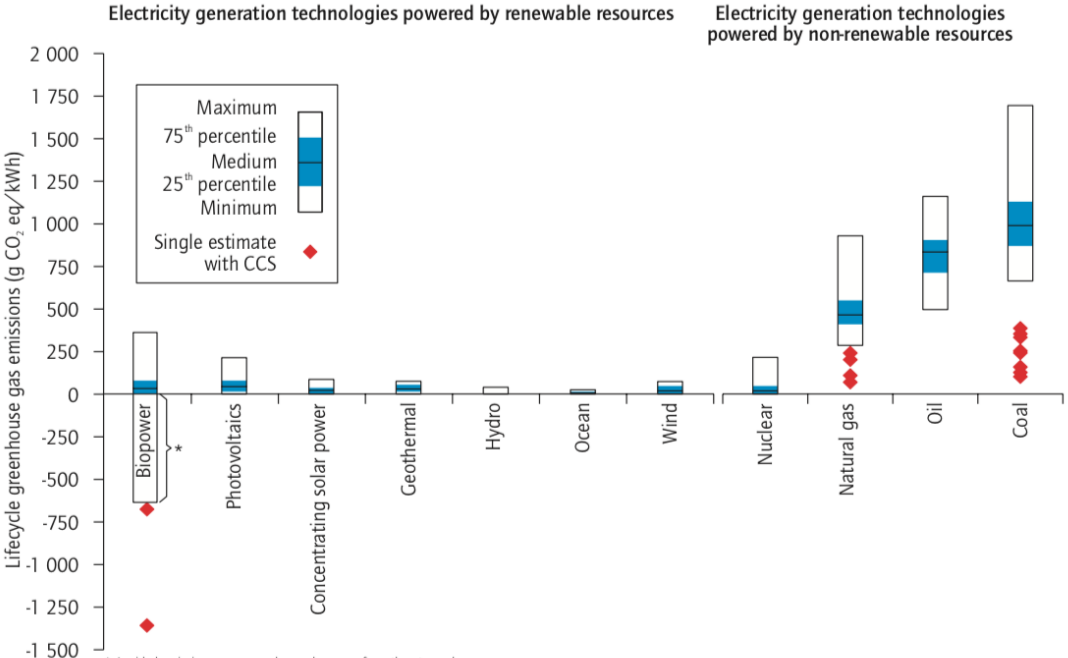
- China : about 15 to 20 Million people relocated

- Land occupation source wikipedia

Name	Country	Dam	Outflow	Surface area		Ref	Image
				km²	mi²		
Lake Victoria[n 1]	Kenya Tanzania Uganda	Owen Falls Dam	White Nile	66,400	25,600	[1]	
Irkutsk Reservoir– Lake Baikal[n 2]	Russia	Irkutsk Dam	Angara River	32,000	12,000	[2]	
Lake Winnipeg[n 3]	Canada	Jenpeg Dam	Nelson River	24,420	9,430	[3]	
Lake Volta	Ghana	Akosombo Dam	Volta River	8,500	3,300	[4]	
Smallwood Reservoir	Canada	Multiple	Churchill River	6,527	2,520	[5]	
Reindeer Lake[n 4]	Canada	Whitesand Dam	Reindeer River	6,500	2,500	[6]	
Kuybyshev Reservoir	Russia	Zhiguli Dam	Volga River	6,450	2,490		
Lake Kariba	Zambia Zimbabwe	Kariba Dam	Zambezi River	5,580	2,150	[7]	
Bukhtarma Reservoir[n 5]	Kazakhstan	Bukhtarma Dam	Irtysh River	5,490	2,120	[8]	
Bratsk Reservoir	Russia	Bratsk Dam	Angara River	5,470	2,110	[9]	

GHG $(kgCO_{2_{eq}}/kWh_e)$

Figure 13: Estimates of lifecycle GHG emissions in electricity generation (excluding land-use changes)



* Avoided emissions, no removal greenhous gas from the atmosphere

	Biopower	Photovoltaics	Concentrating solar power	Geothermal	Hydro	Ocean	Wind	Nuclear	Natural gas	Oil	Coal
Count of estimates	222 (+4)	124	42	8	28	10	126	125	83 (+7)	24	169 (+12)
Count of references	52 (+0)	26	13	6	11	5	49	32	36 (+4)	10	50 (+10)

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Hydro and energy systems

Impacts : fatalities

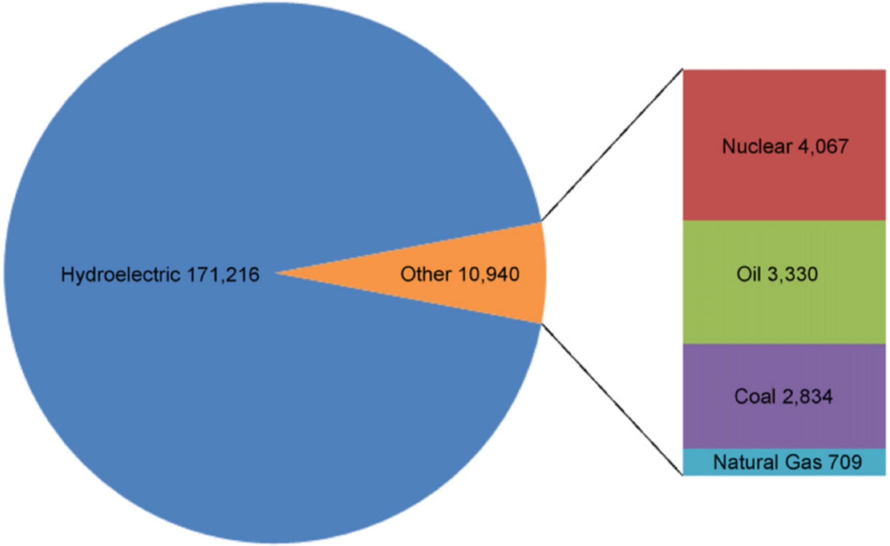

Fig. 1. Energy accident fatalities by source, 1907–2007.

Energy Source	[deaths/ PWh]
Coal – global average	100000
Coal – China	170000
Coal – U.S.	10000
Oil	36000
Natural Gas	4000
Biofuel/Biomass	24000
Solar (rooftop)	440
Wind	150
Hydro – global average	1400
Hydro – U.S.	5
Nuclear – global average	90
Nuclear – U.S.	0.1

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Take-home message

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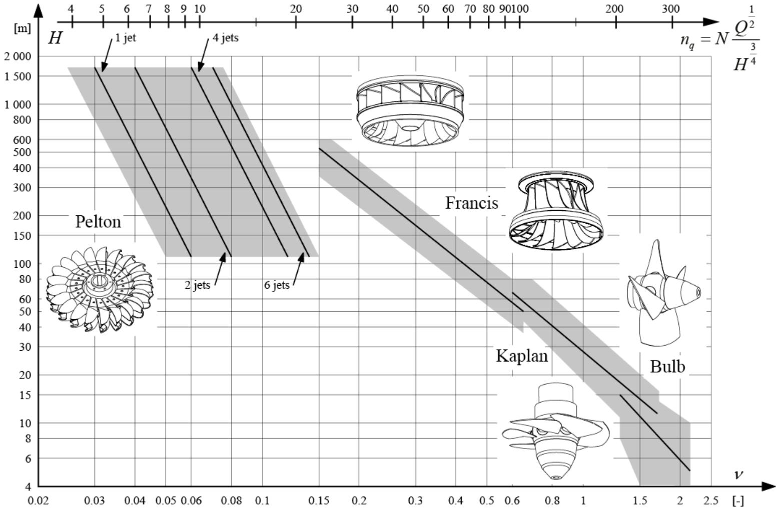
- In general
  - Hydro most developed renewable
  - Key resource in CH
  - Run-of-river & storage power plants
- Physics
  - Specific energy depends on head [m]
  - Total power depends on head & discharge
  - Specific speed ν to characterize turbines
- Hydraulic turbines
  - Pelton: high head, low discharge
  - Francis (60%): medium head/discharge
  - Kaplan/Bulb: low head, high discharge
- Energy system integration
  - Competitive for cost/GHG

$$gH_1 - gH_2 = g(z_U - z_L) - \sum gH_r$$

$$\nu = \frac{\omega Q^{\frac{1}{2}}}{\pi^{\frac{1}{2}}(2e)^{\frac{3}{4}}} \qquad \dot{E} = \rho v_x A g H_x$$



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Questions?

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