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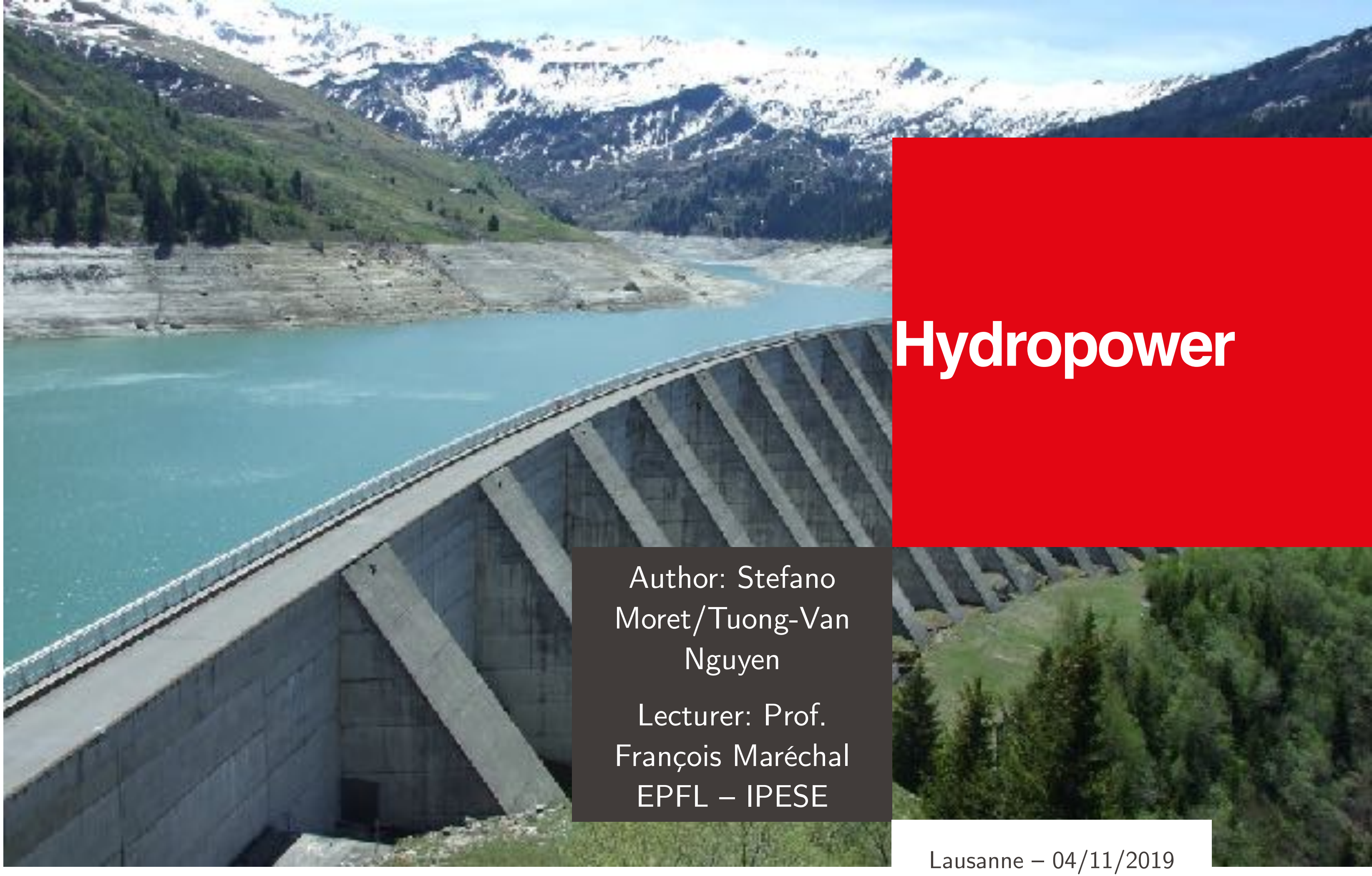

Hydropower

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EPFL – IPESE

Lausanne – 04/11/2019

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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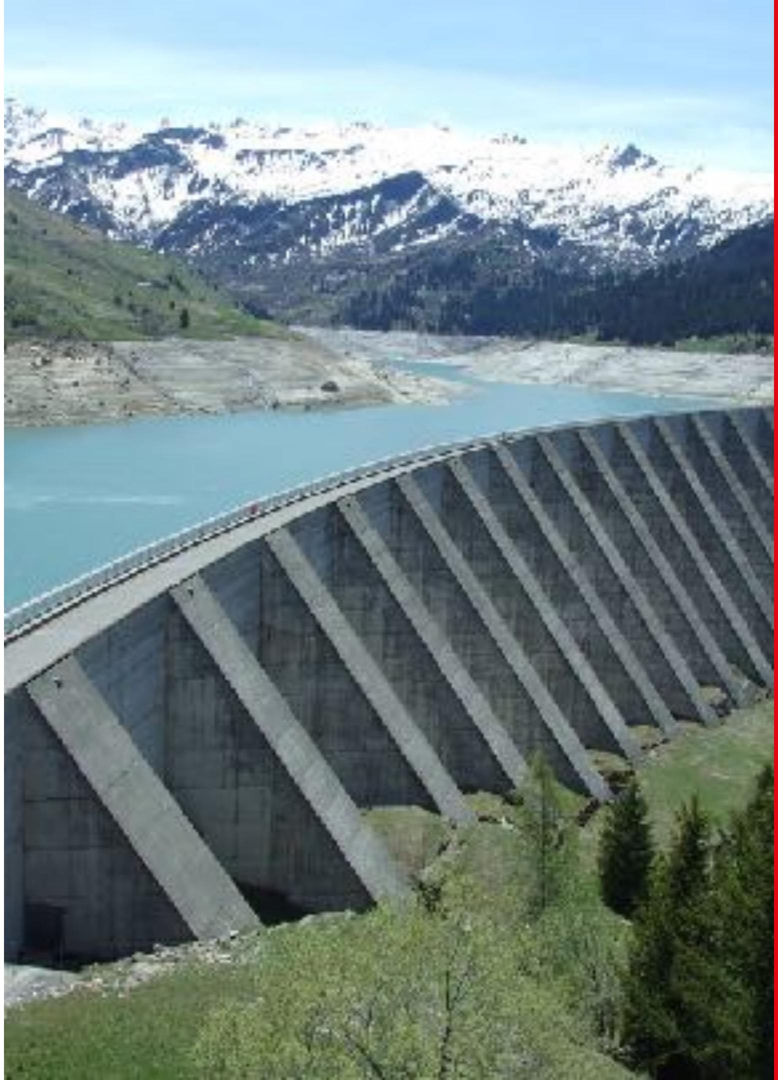
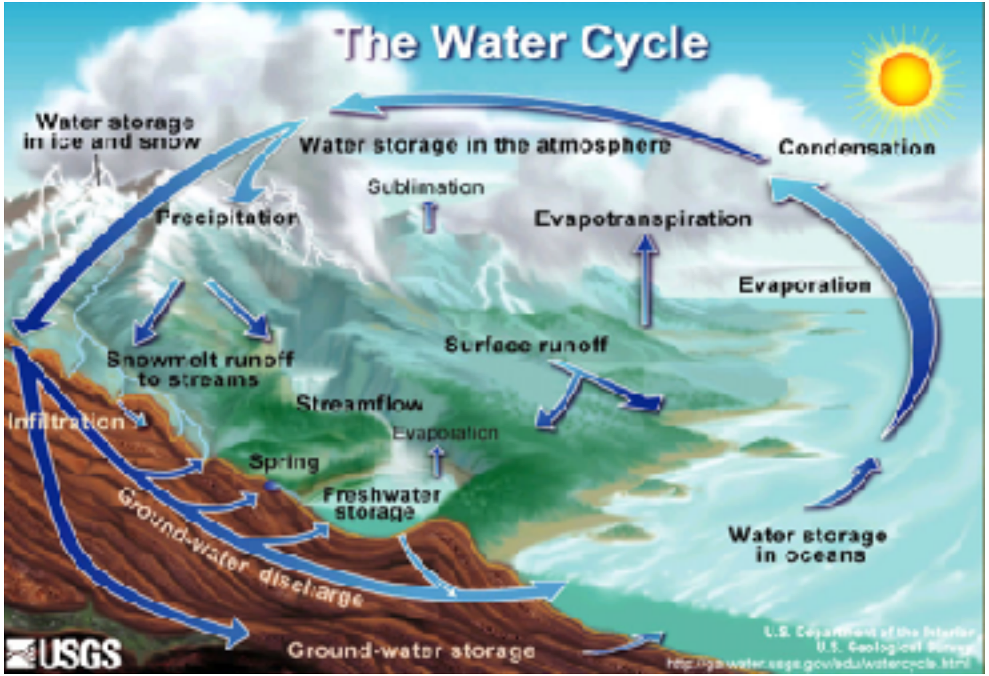


Introduction

What is hydropower?

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

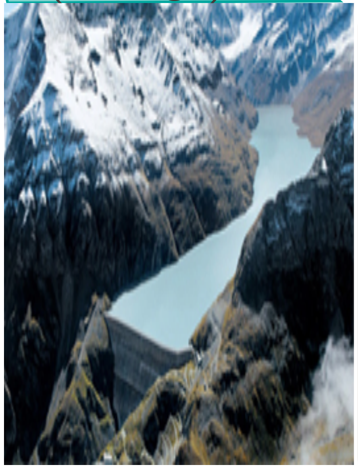
- Used since early history:
  - Water wheels for irrigation
  - Water mills
  - Barbegal, 260 AD:
    - 10km long aqueduct
    - 18m head
    - 53 kW



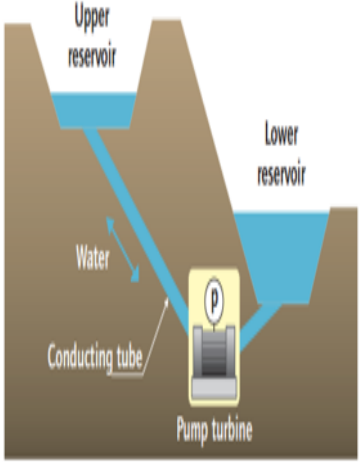
Types of hydro power plants

Hydro run-of-river

Hydro dam (storage)

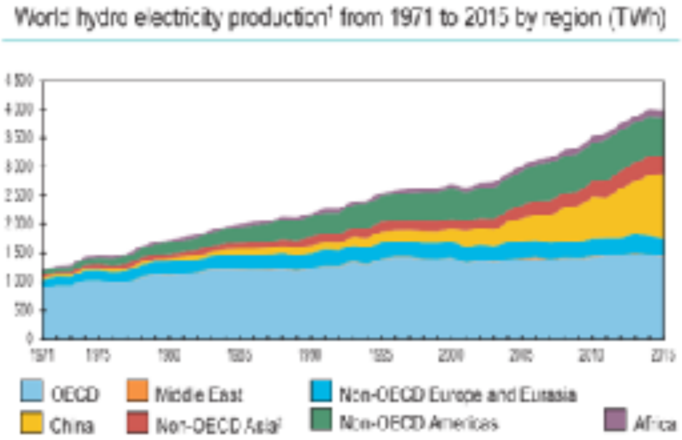


Pumped storage

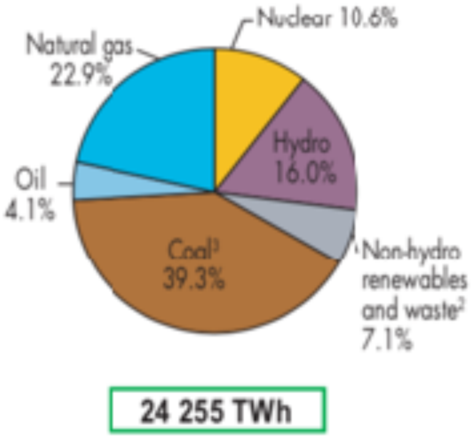


What is hydropower?

- World final energy consumption: 109100 TWh/y (2015)
- World electricity production: 24255 TWh/y (2015)
- Hydro electricity production: 3978 TWh/y (2015)
- Most developed and mature renewable technology



Electricity 2015



Hydro today : World

- World final energy consumption: 109100 TWh/y (2015)
- World electricity production: 24255 TWh/y (2015)
- Potential (from table below): 30 EJ/y → 8300 TWh/y
- IEA technical potential: 15000 TWh/y

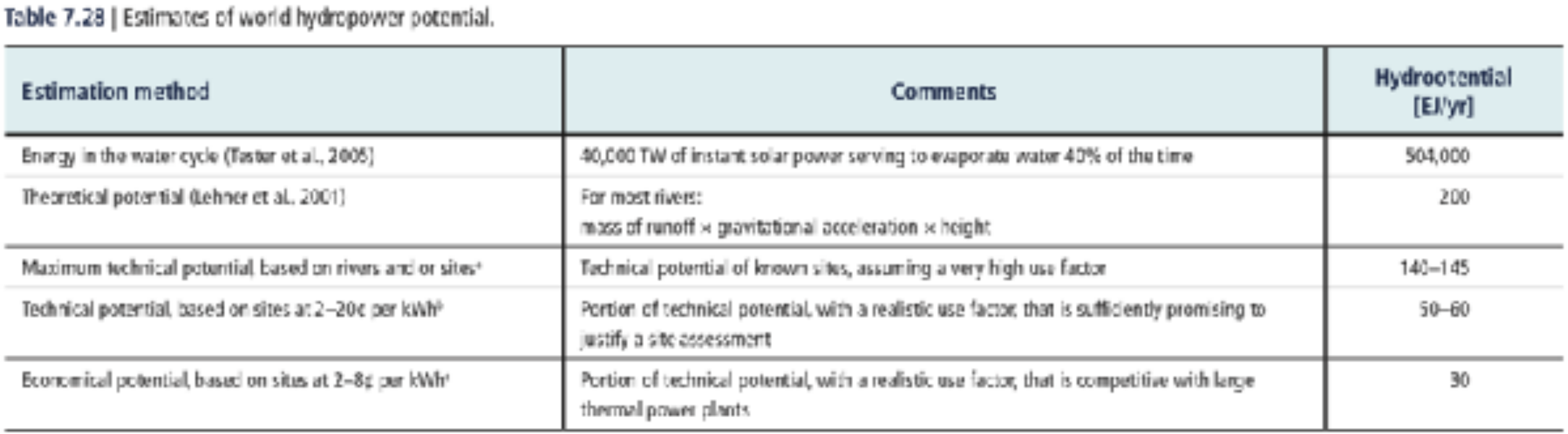


Table 7.28 | Estimates of world hydropower potential.

Estimation method	Comments	Hydropotential [EJ/yr]
Energy in the water cycle (Taster et al., 2006)	40,000 TW of instant solar power serving to evaporate water 40% of the time	504,000
Theoretical potential (Lehner et al. 2001)	For most rivers: mass of runoff × gravitational acceleration × height	200
Maximum technical potential, based on rivers and or sites[a]	Technical potential of known sites, assuming a very high use factor	140–145
Technical potential, based on sites at 2–20¢ per kWh[b]	Portion of technical potential, with a realistic use factor, that is sufficiently promising to justify a site assessment	50–60
Economical potential, based on sites at 2–8¢ per kWh[c]	Portion of technical potential, with a realistic use factor, that is competitive with large thermal power plants	30

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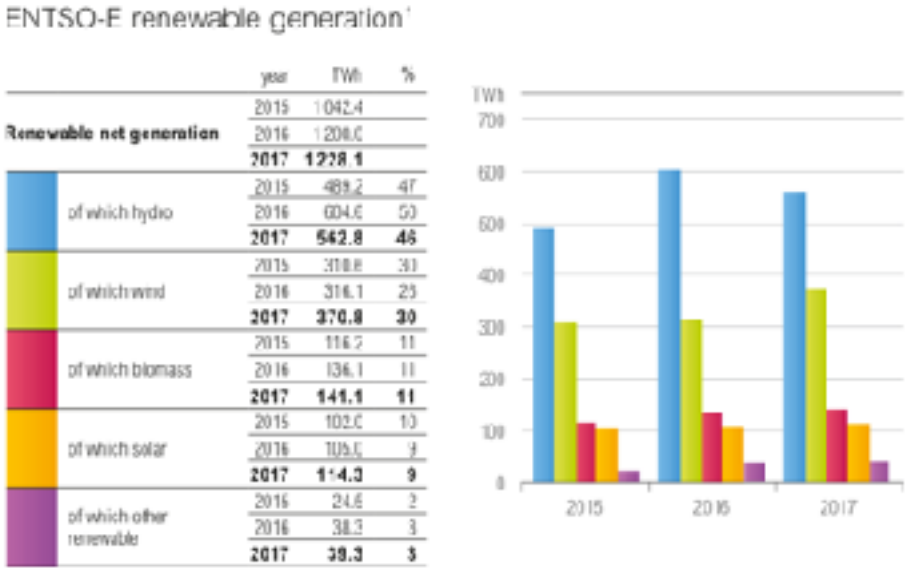
Hydro today : Europe

- Hydro capacity relatively stable
- ENTSO-E hydro electricity: 562.8 TWh/y (2017) → 15.3%
- ENTSO-E hydro capacity: 212.4 GW (2017) → 18.4%



ENTSO-E renewable generation[1]

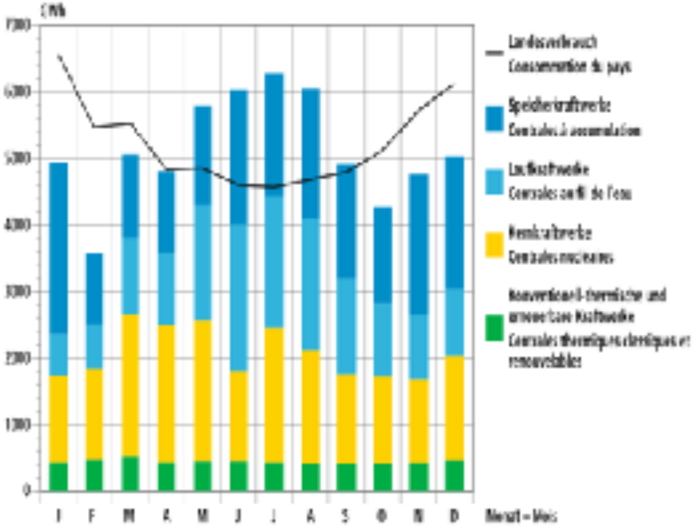
		year	TWh	%
Renewable net generation		2015	1042.4	
		2016	1208.0	
		2017	**1228.1**	
🟦	of which hydro	2015	489.2	47
		2016	604.0	50
		2017	**562.8**	**46**
🟩	of which wind	2015	310.8	30
		2016	316.1	26
		2017	**370.8**	**30**
🟥	of which biomass	2015	116.2	11
		2016	136.1	11
		2017	**141.1**	**11**
🟧	of which solar	2015	102.0	10
		2016	105.0	9
		2017	**114.3**	**9**
🟪	of which other renewable	2015	24.6	2
		2016	38.3	3
		2017	**39.3**	**3**

Hydro today : CH

- Swiss final energy consumption: 236 TWh/y (2017)
- Swiss electricity production: 61.5 TWh_e/y - 4.16 TWh_e/y (pumping) = 57.3 TWh_e/y net (2017)
- Of which hydro:
  - Dams: 20.72 TWh/y in 2017; 8.1 GW
  - Rivers: 15.95 TWh/y in 2017; 3.8 GW

  → ~60% of Swiss gross electricity production

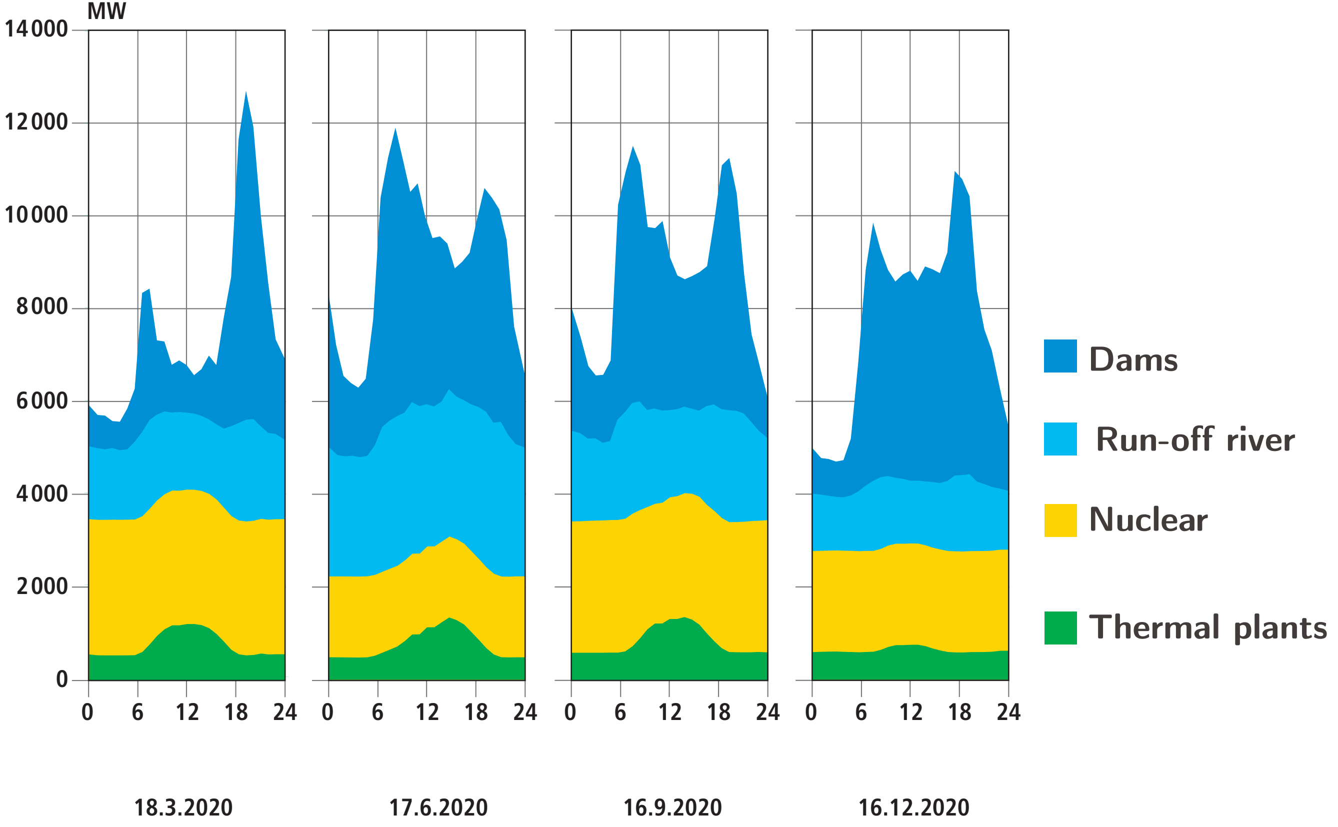
Fig. 10 Monatliche Erzeugungsanteile und Landesverbrauch im Kalenderjahr 2017
Quotes-parts mensuelles et consommation du pays durant l'année civile 2017



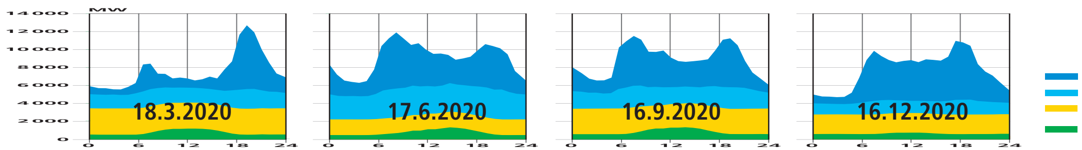
© BFE, Schweizerische Elektrizitätsstatistik 2017 (Fig. 10)
OFEN, Statistique suisse de l'électricité 2017 (fig. 10)

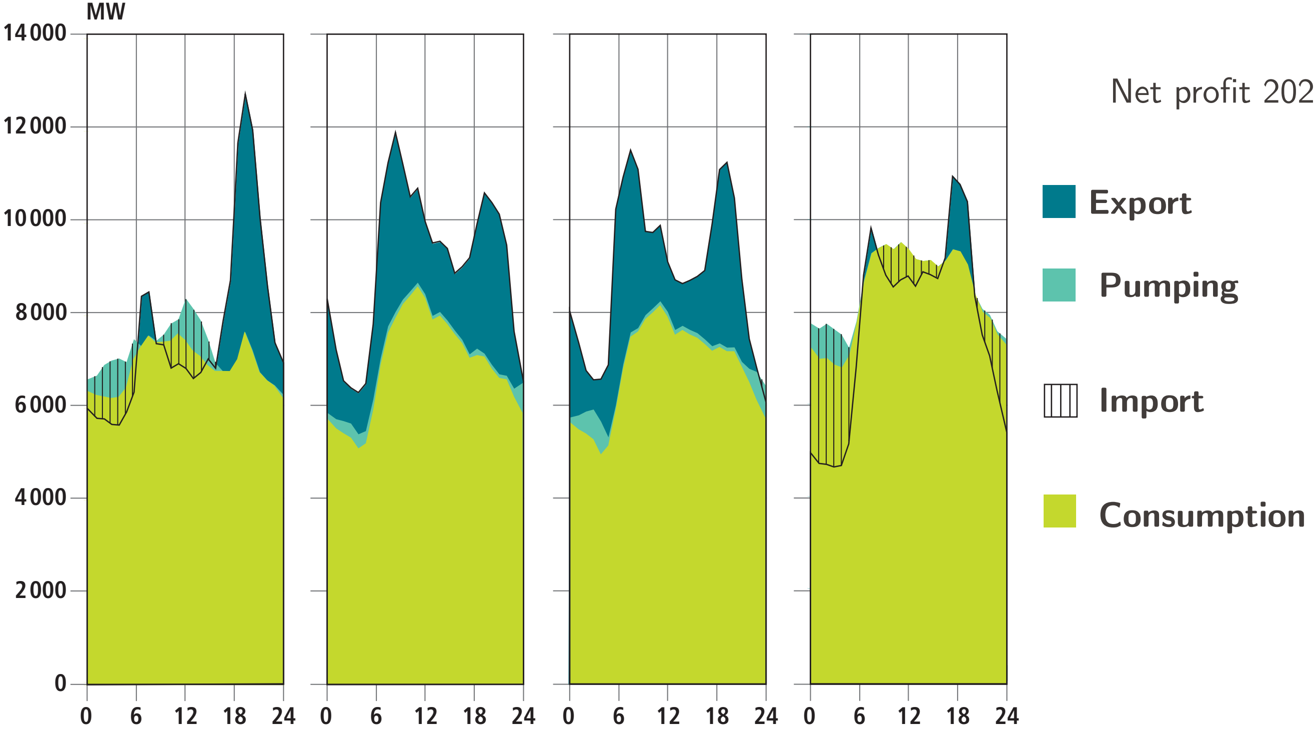
Role of Hydro Power in the electricity in CH : following the demand

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

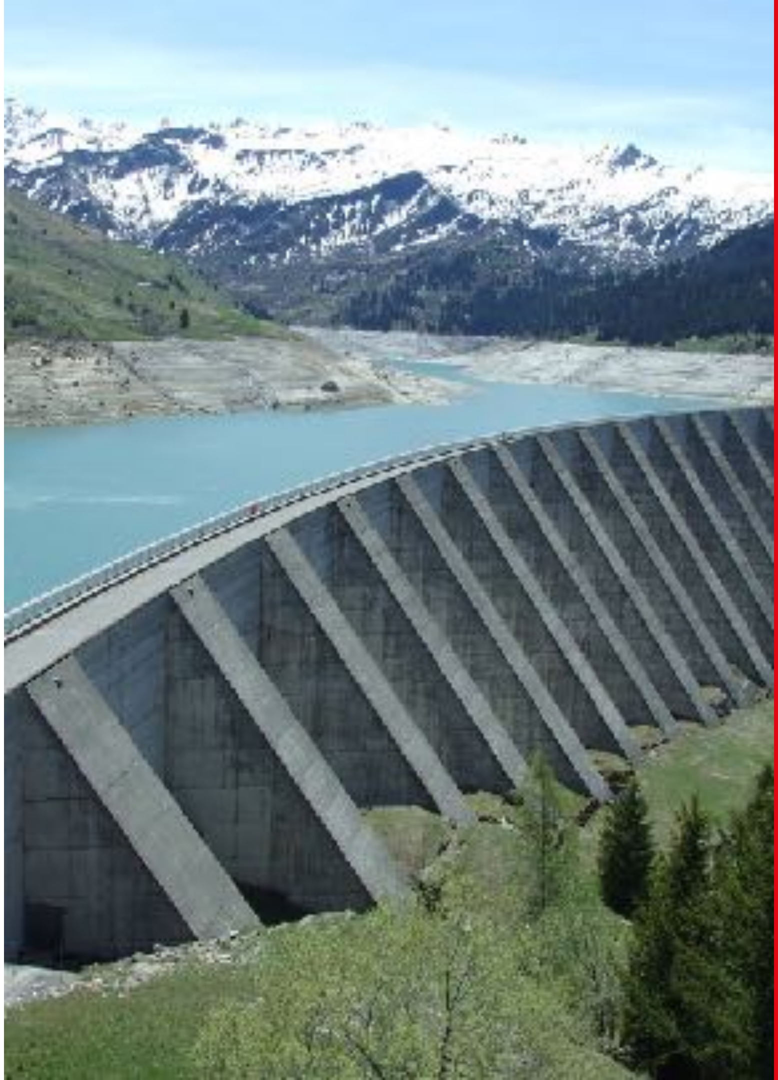


Role of Hydro Power in the electricity in CH : following the market





Net profit 2020 : 230 MCHF/y



Physics of hydro

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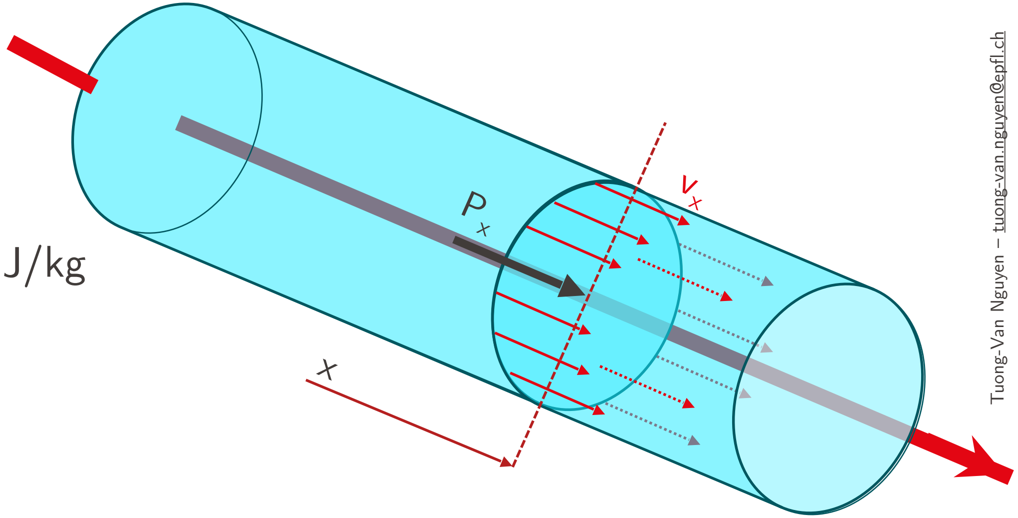
Physics of hydro

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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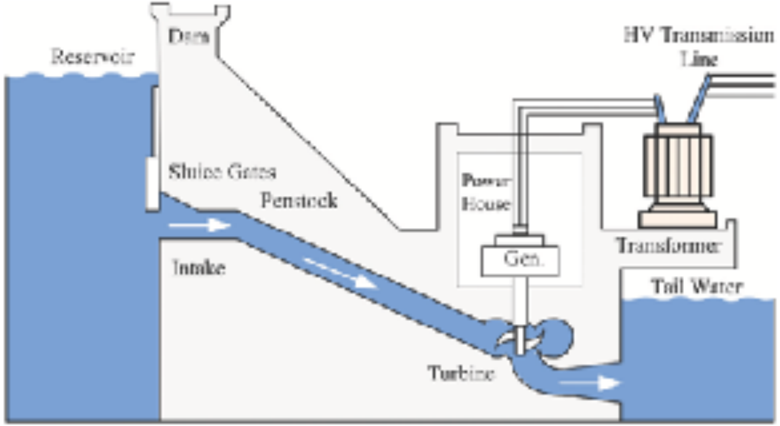
Physics of hydro

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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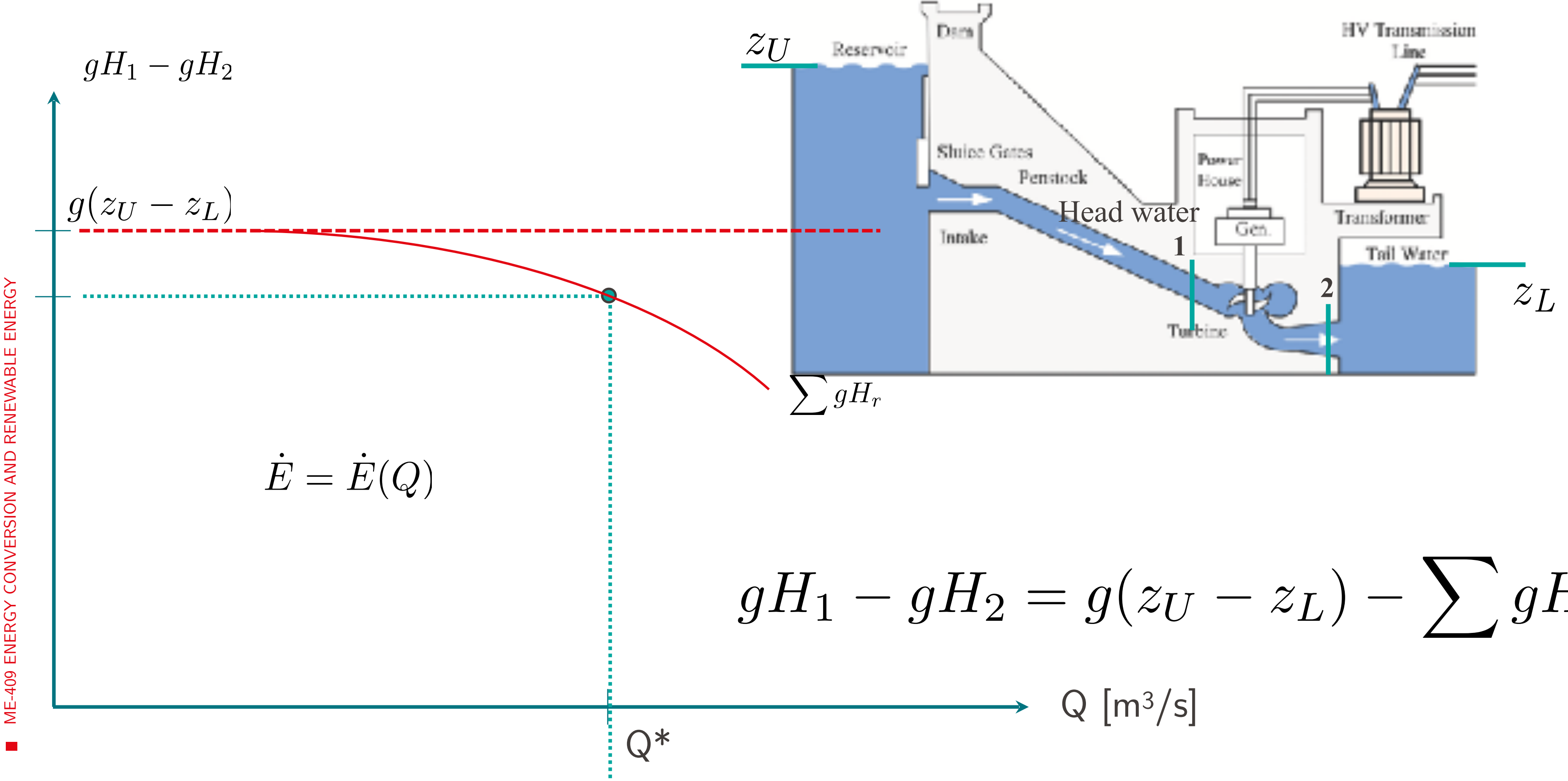
Physics of hydro

Energy balance



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

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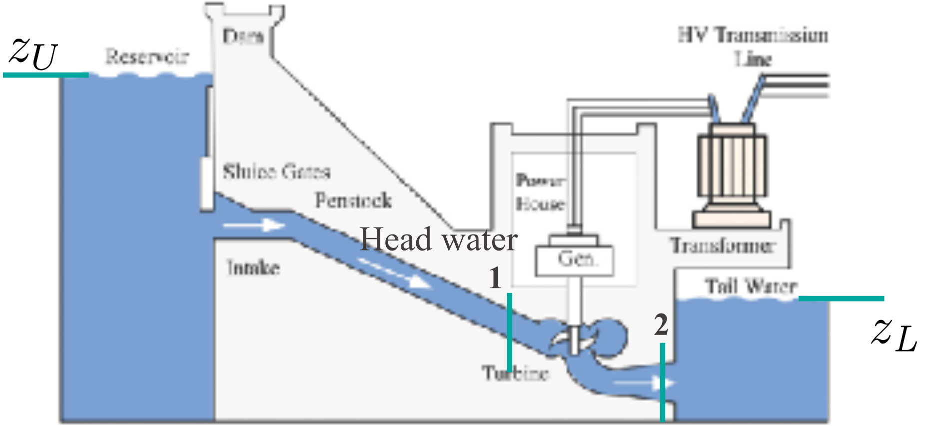
Physics of hydro

Energy balance



- At the turbine:

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

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

- 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 $\pi_1, \pi_2, \dots, \pi_p$ 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:

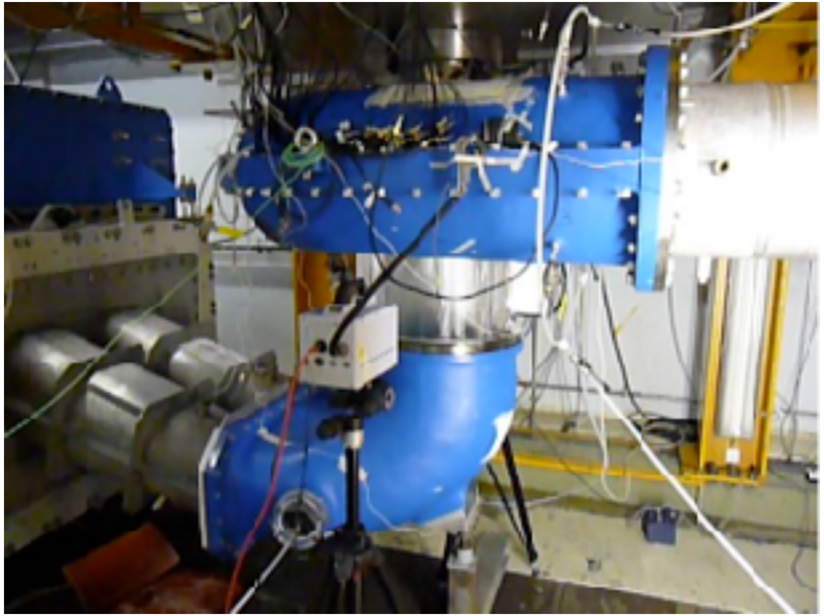
Angular speed [rad/s]

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]

Physics of hydro



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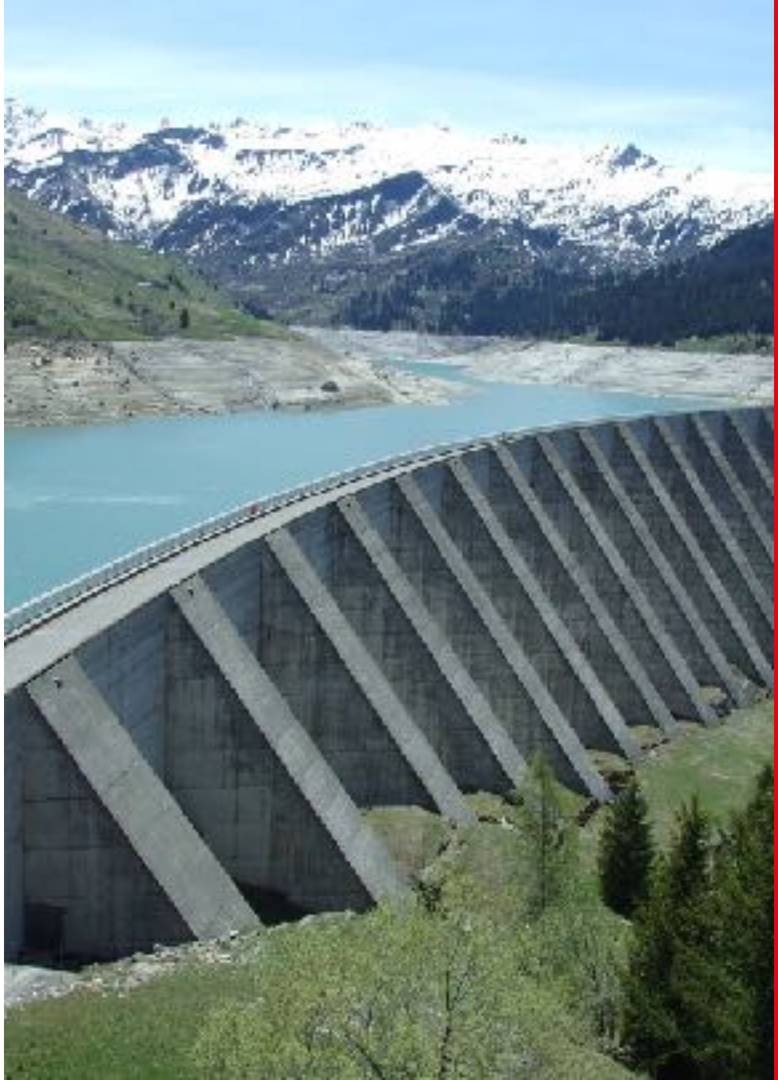

Hydraulic turbines

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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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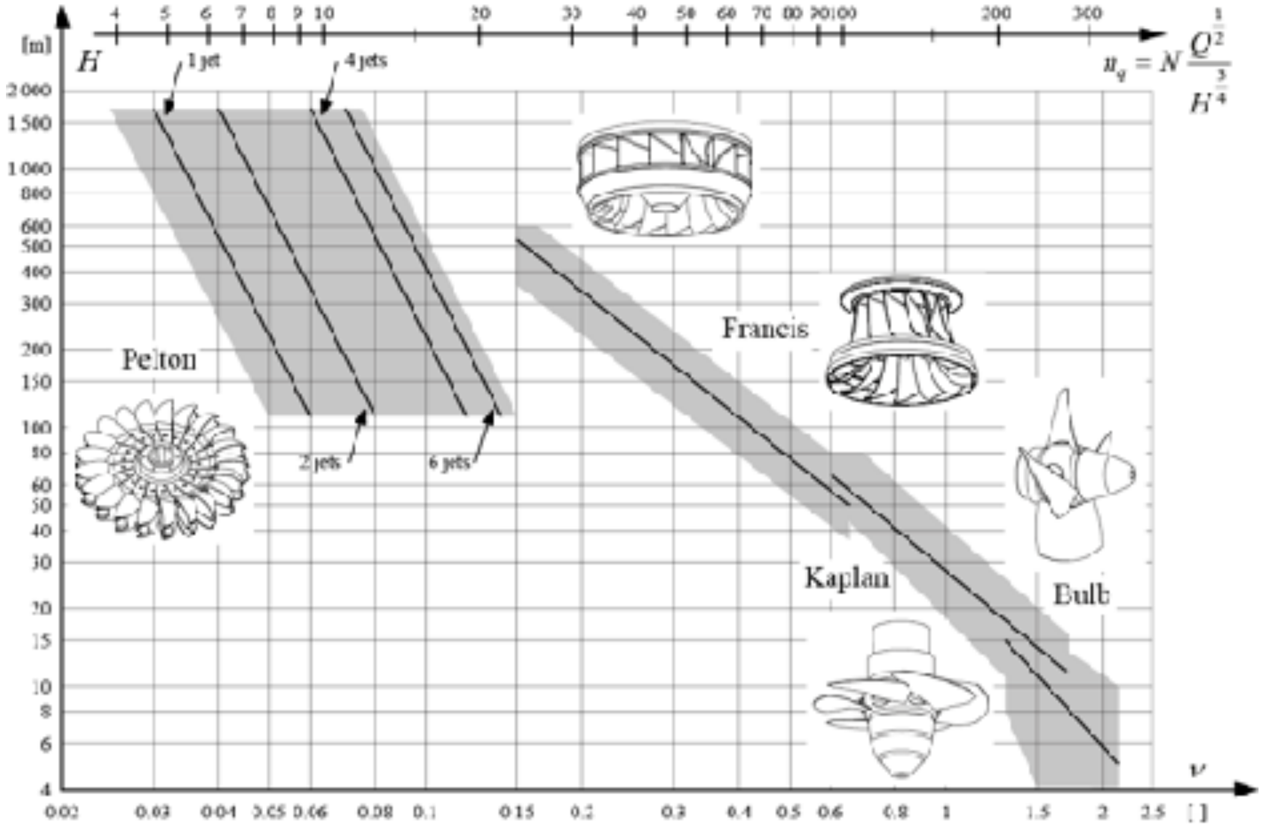
Hydraulic turbines

Classification



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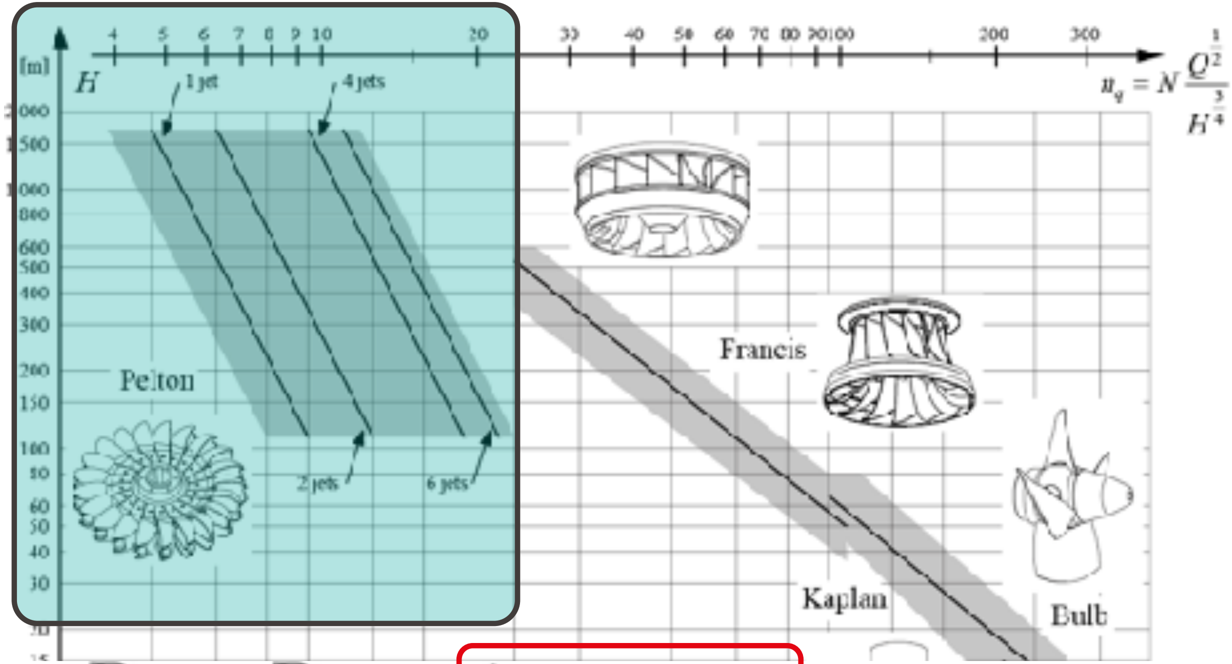
Hydraulic turbines

Classification Pelton turbines



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

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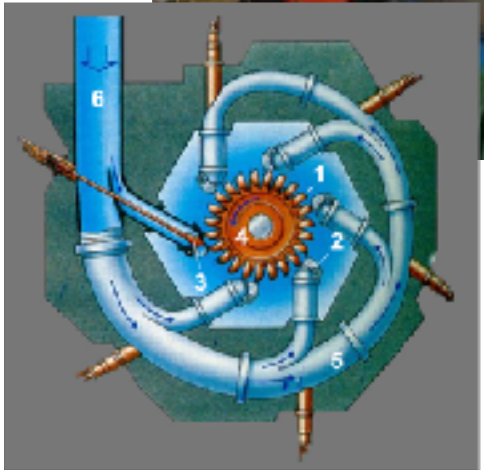
Hydraulic turbines

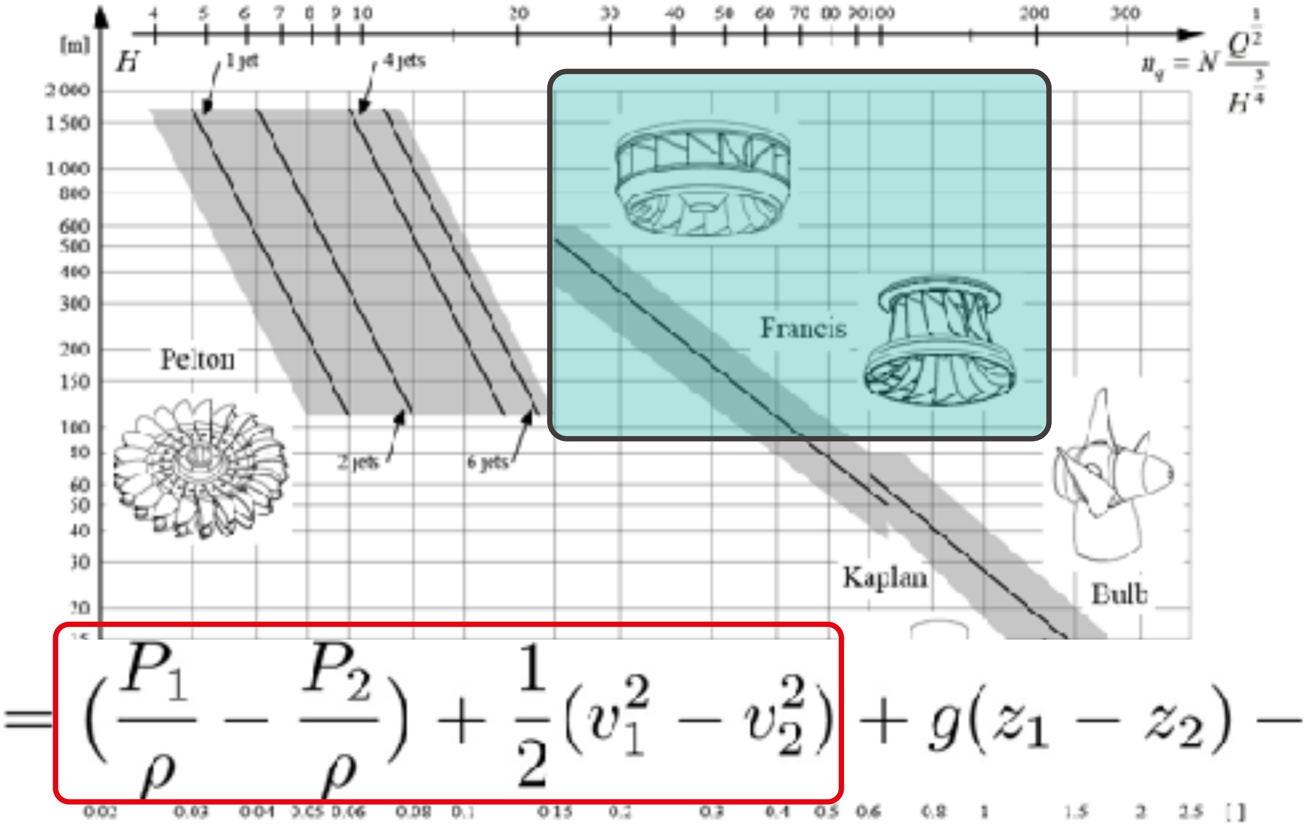
Pelton

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



Hydraulic turbines

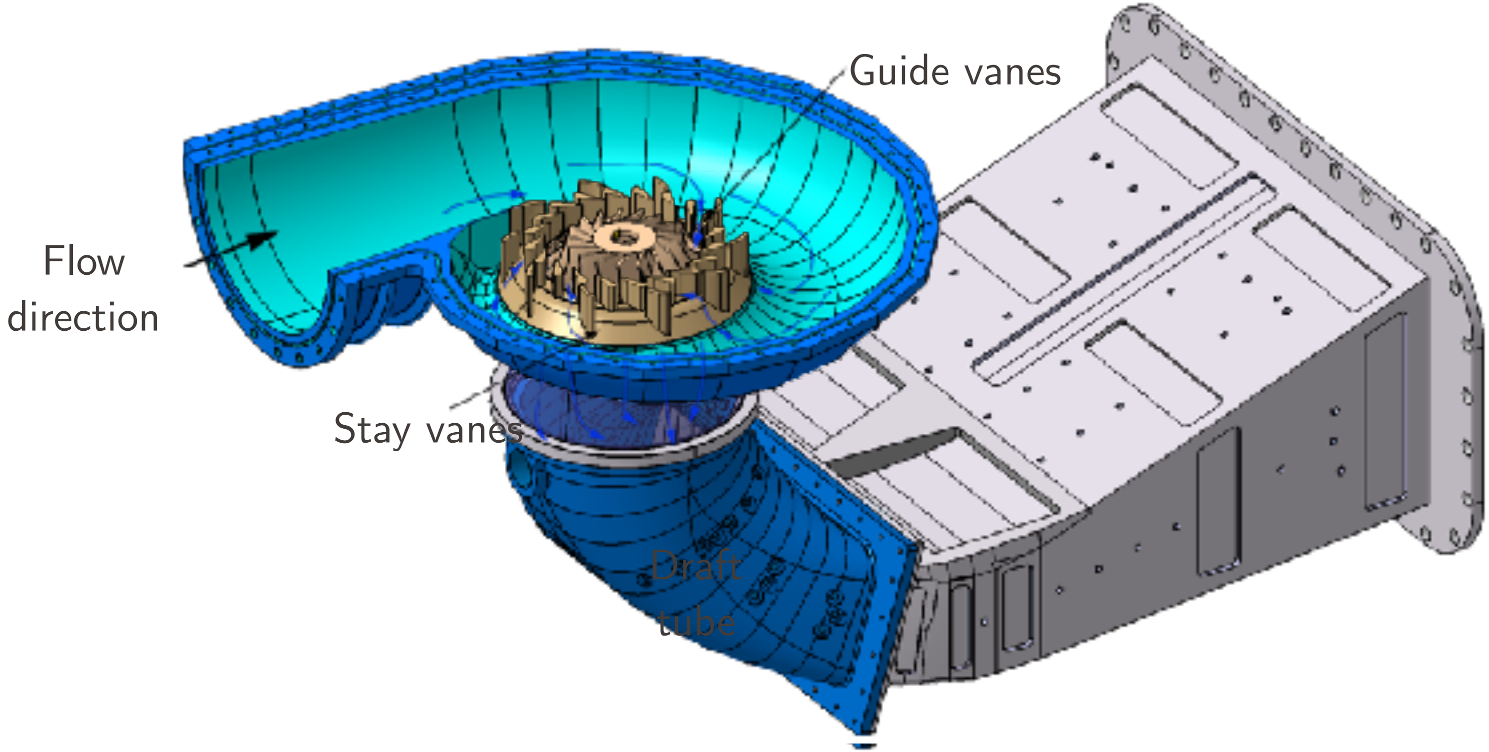
Classification : Francis turbines



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

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

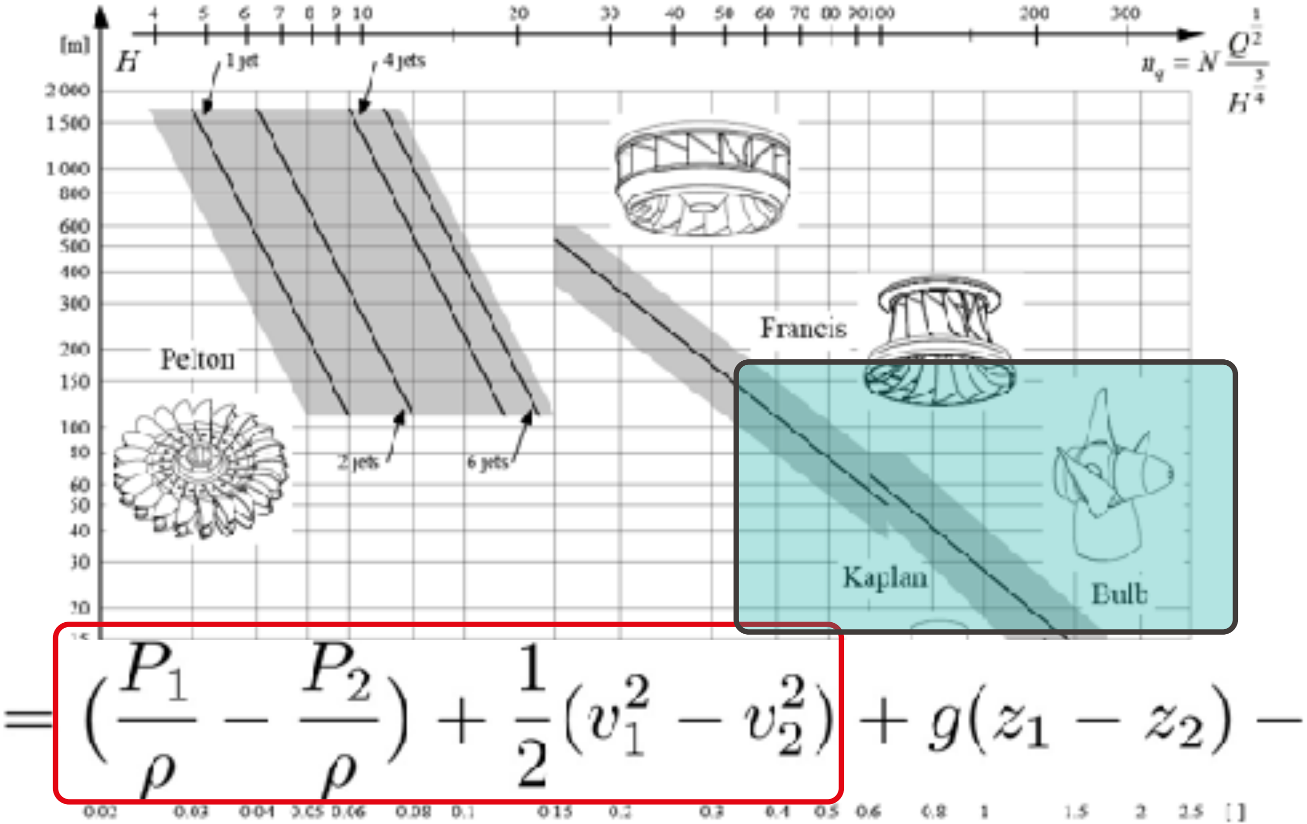
  Total capacity: 22.5 GW_e
- Itaipu (Brazil):

  20*700 MW = 14 GW

  103.1 TWh/y (record 2016)

Hydraulic turbines

Classification Kaplan and Bulb 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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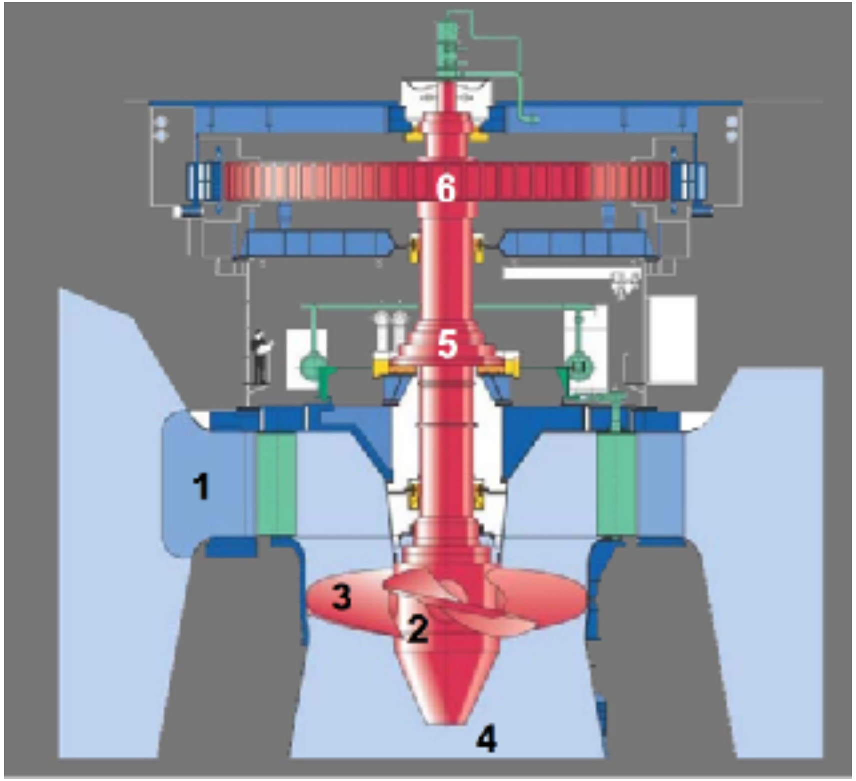
Hydraulic turbines

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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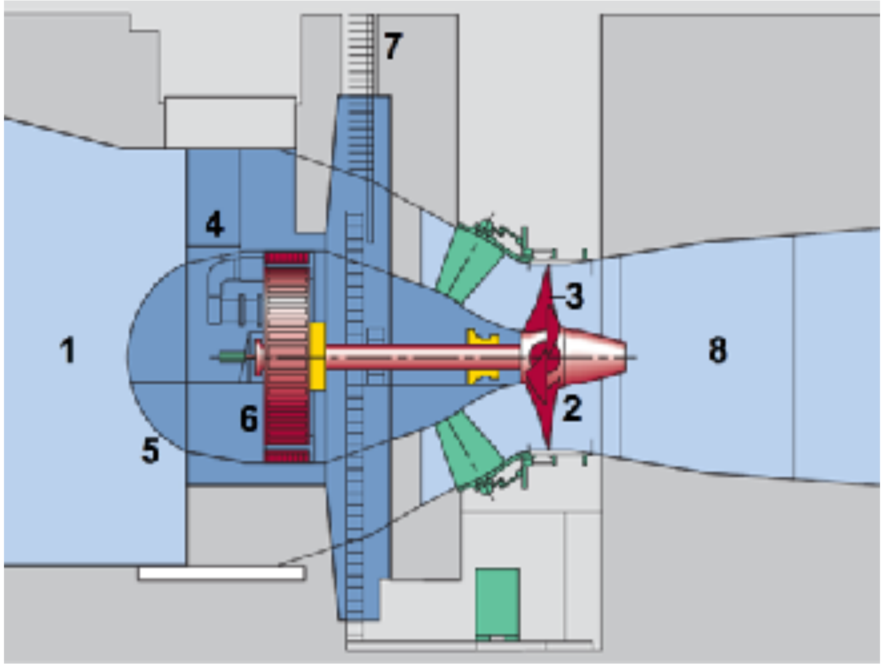
Hydraulic turbines

Bulb

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



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Efficiency of turbine

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

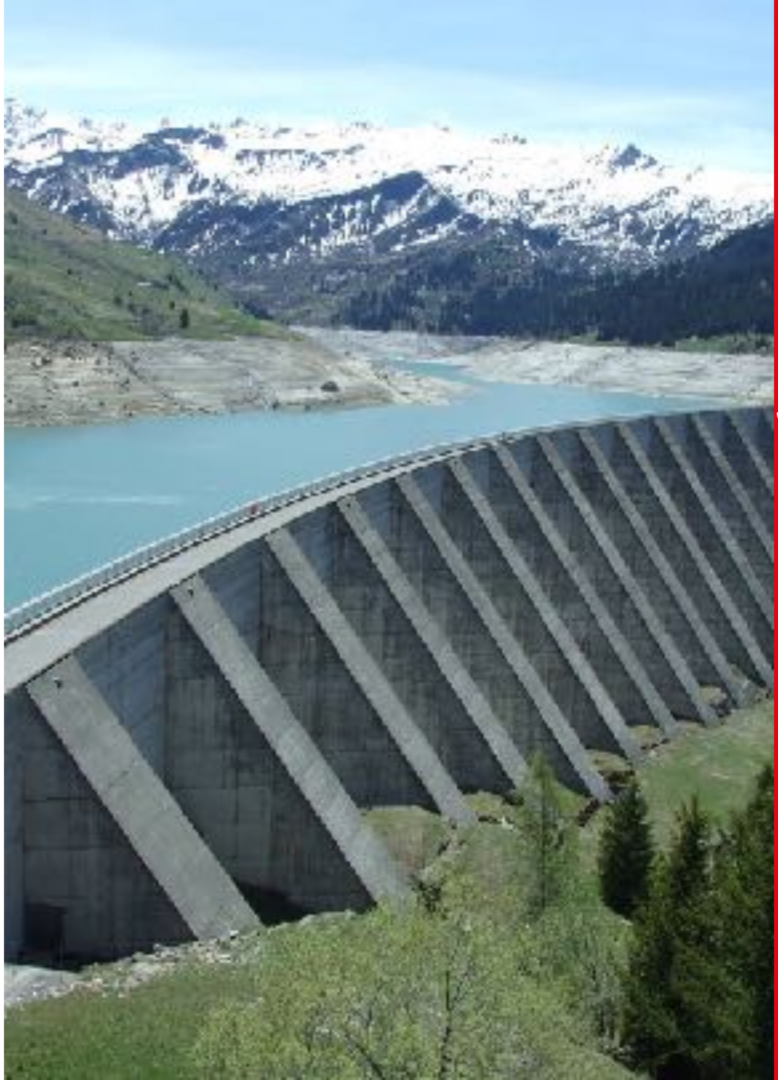
$\eta_T = 92\%$ Mechanical efficiency of the turbine

$\eta_{gear} = 98\%$ 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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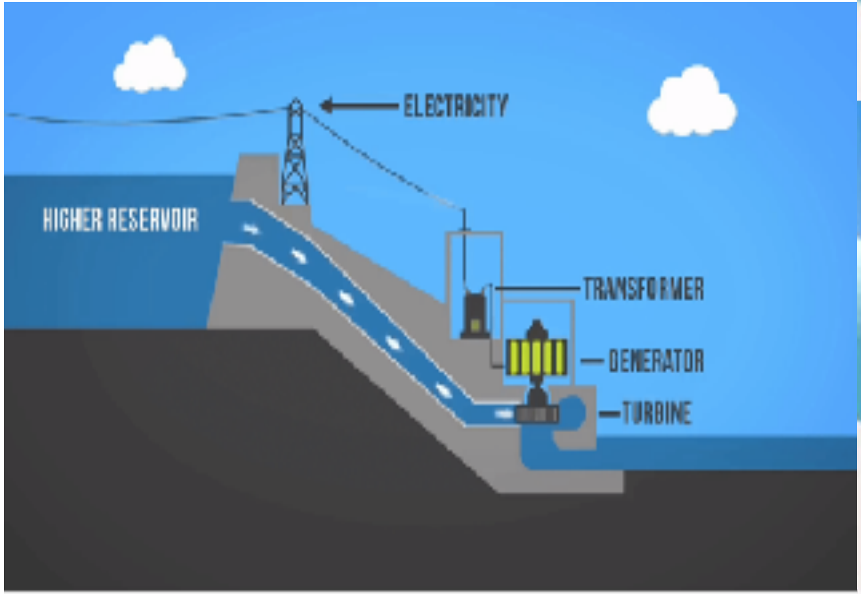
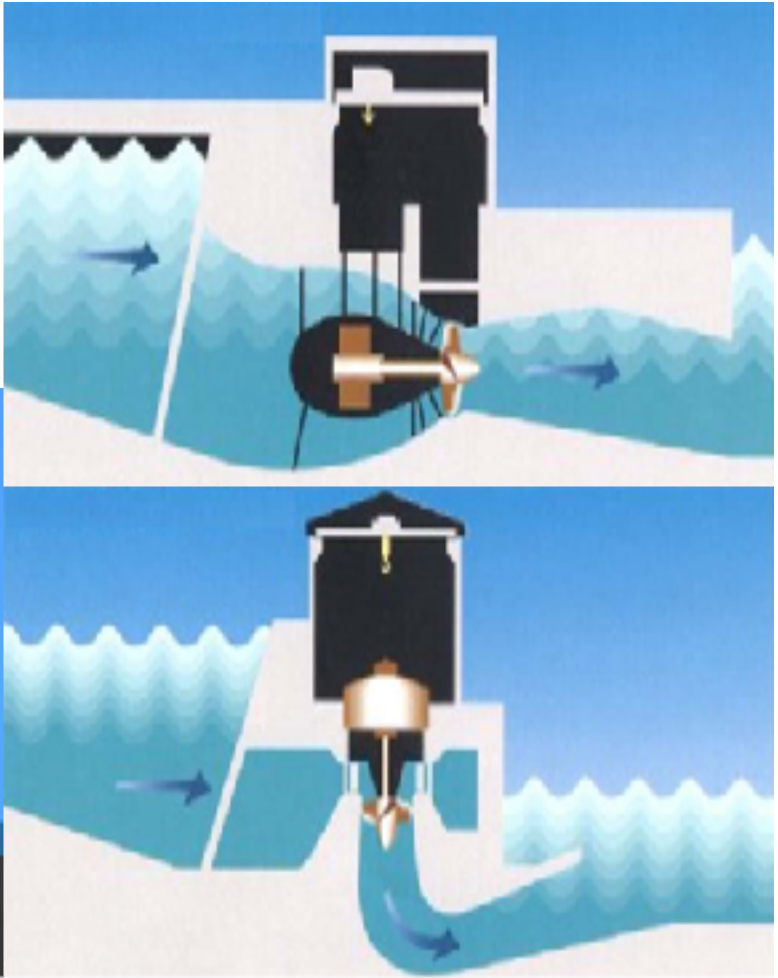
Hydro and energy systems

Hydroelectric schemes

- Storage and run-of-river power plants





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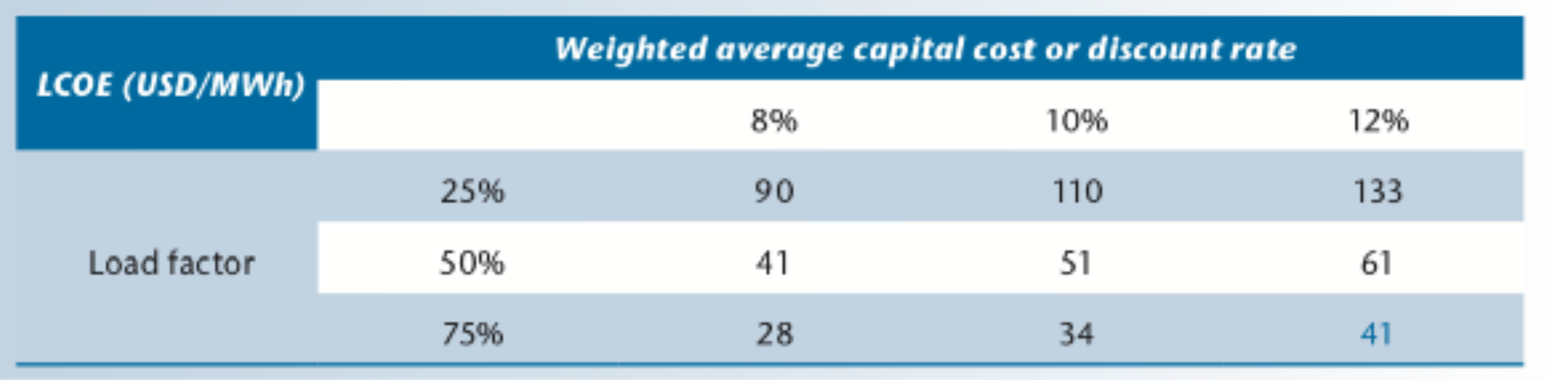
Hydro and energy systems

Costs

- 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%
	25%	90	110	133
Load factor	50%	41	51	61
	75%	28	34	41

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

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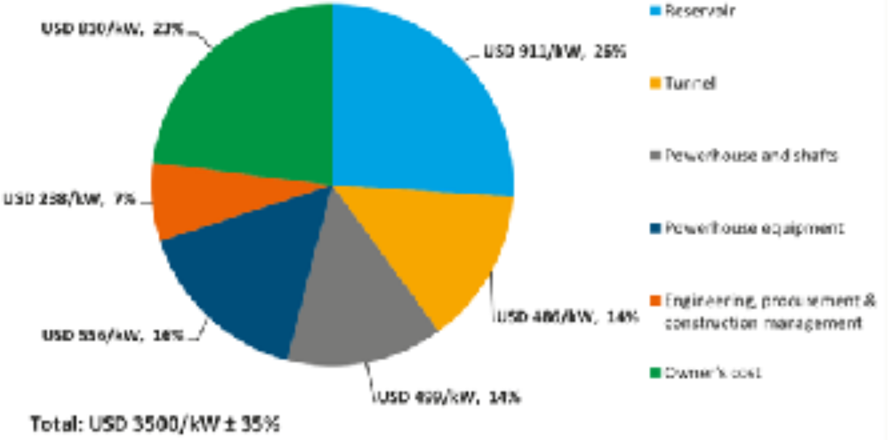
Hydro and energy systems

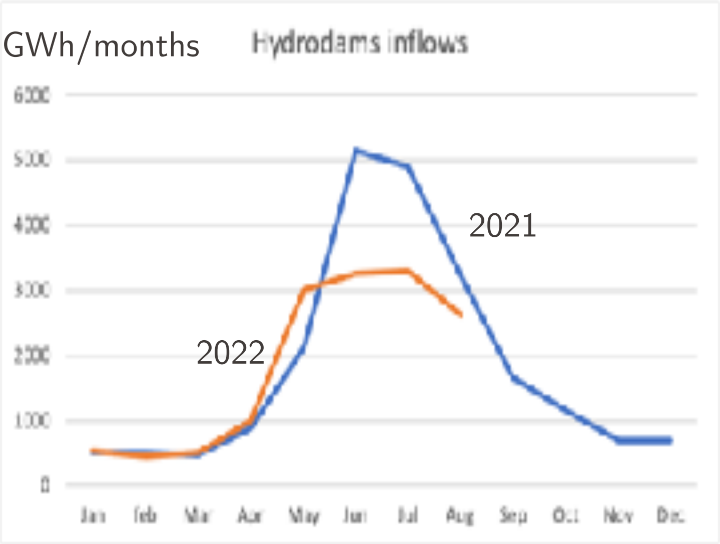
Costs

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

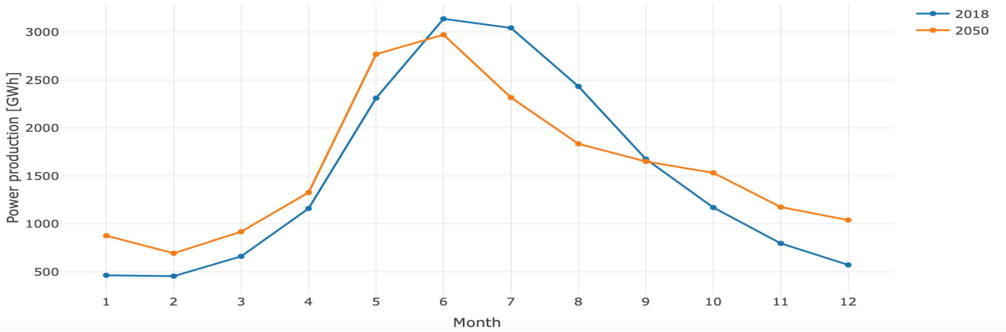


Impact of climate change/meteo

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

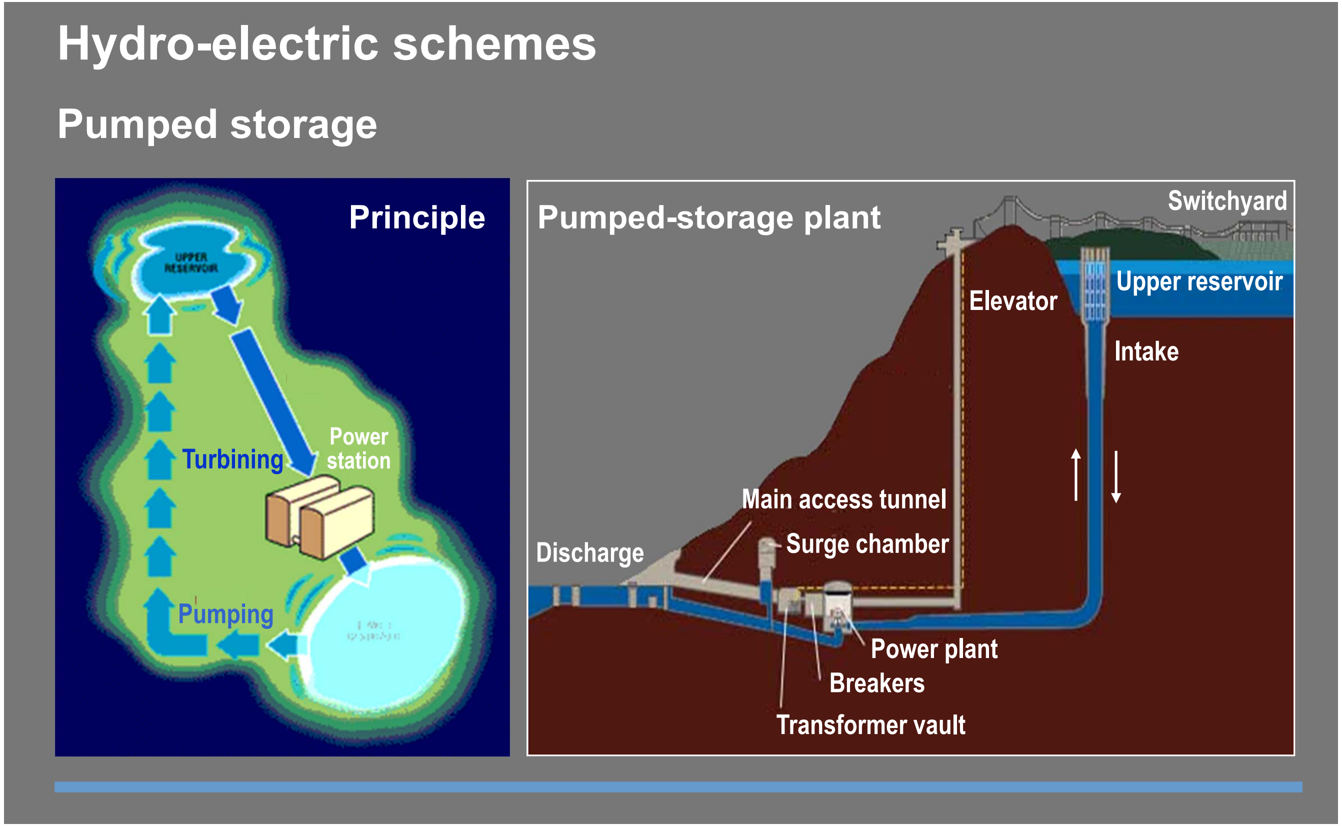


Inflow of water in dams Switzerland [GWh/month]



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

Pumped-hydro storage



Hydro-electric schemes

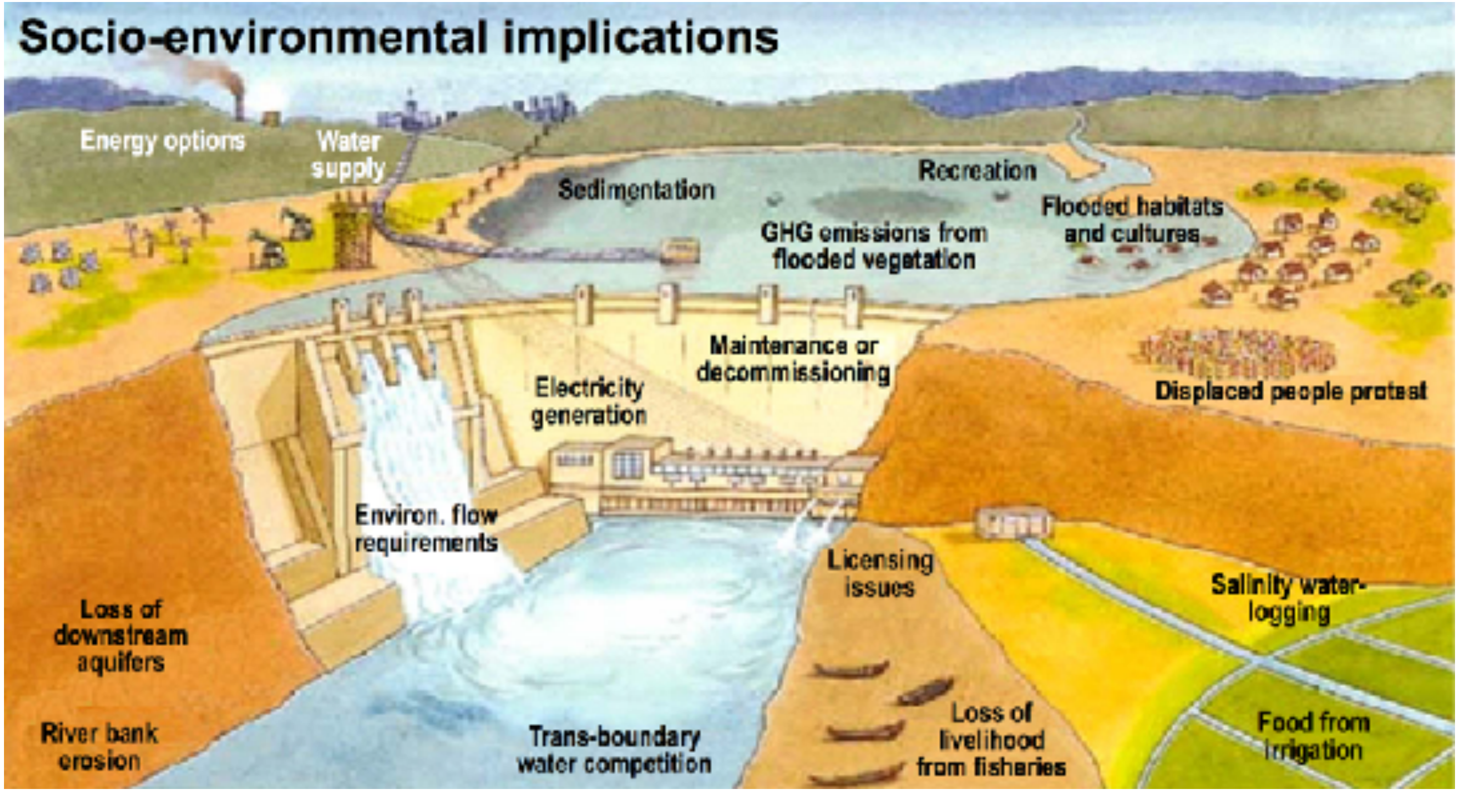
Pumped storage

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

Round trip efficiency = 80%

Hydro and energy systems

Impacts



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Hydro dams : land occupation & people displacement

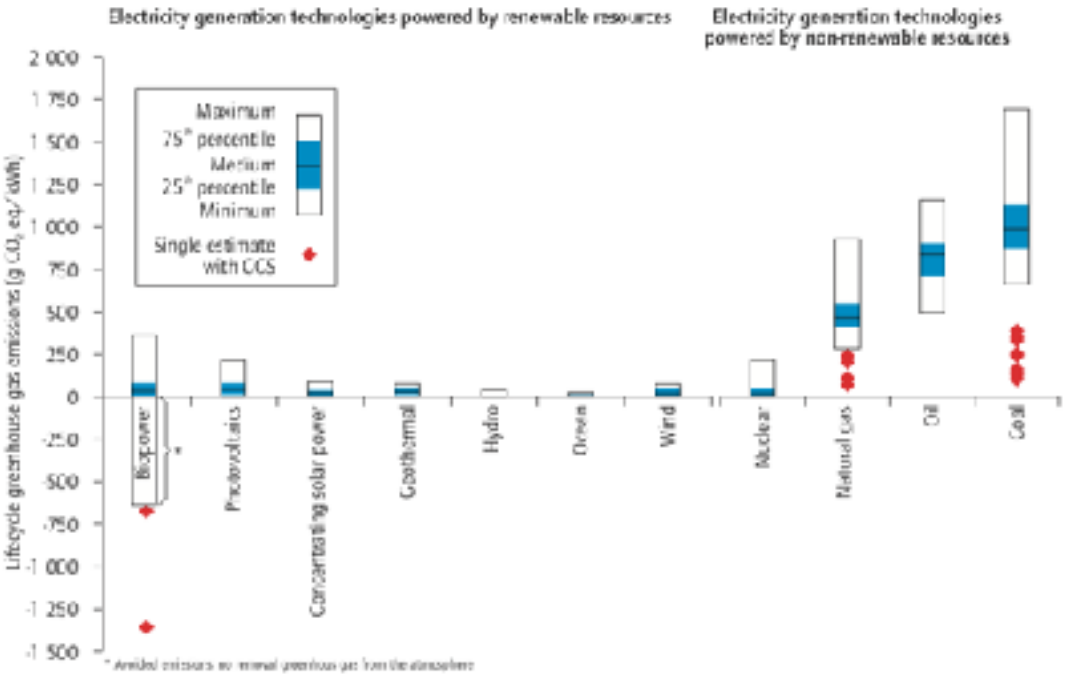
- China : about 15 to 20 Million people relocated

- Land occupation source wikipedia

Name	Country	Dam	Outflow	Surface area		Ref	Image
				km^2	mi^2		
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)



Count of estimates	222 (+4)	124	42	8	28	10	126	125	83 (+7)	24	169 (+12)
Count of references	52 (+0)	26	13	5	11	5	49	32	36 (+4)	10	50 (+10)

Hydro and energy systems

Impacts : fatalities

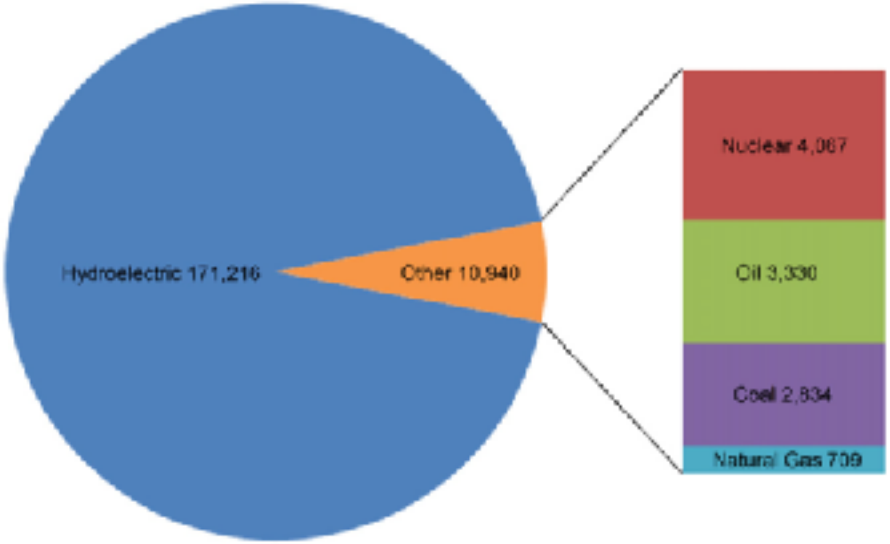


Fig. 1. Energy accident fatalities by source, 1907–2007.

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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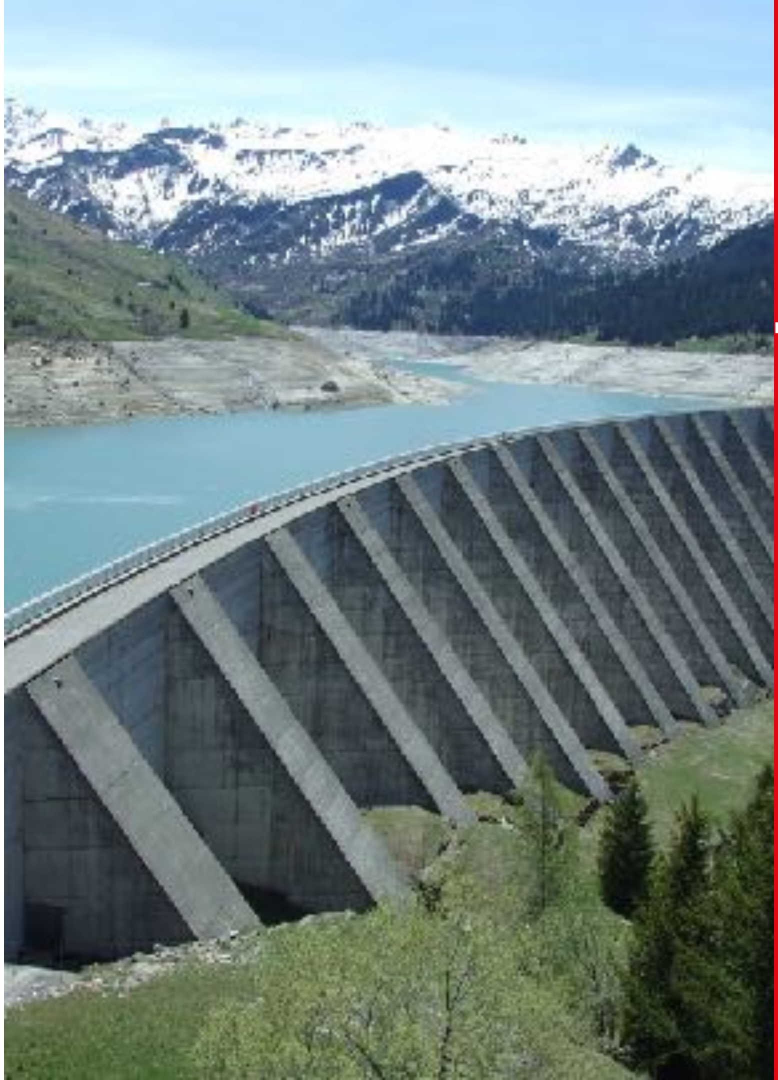

Take-home message

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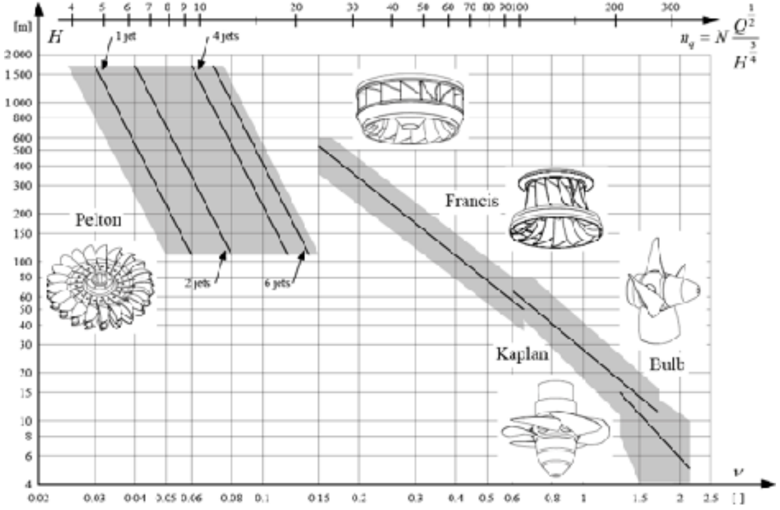
Take-home message

- 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

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

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



Questions?

Prof. François Maréchal