UNIVERSITÀ DI TRENTO

DIPARTIMENTO DI
INGEGNERIA INDUSTRIALE

Hydroelectric Power

Renewable Energy Conversion Systems Course

Lecture 1

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UNIVERSITÀ DI TRENTO
Dipartimento di Ingegneria Industriale

Technological Overview

Technological Overview

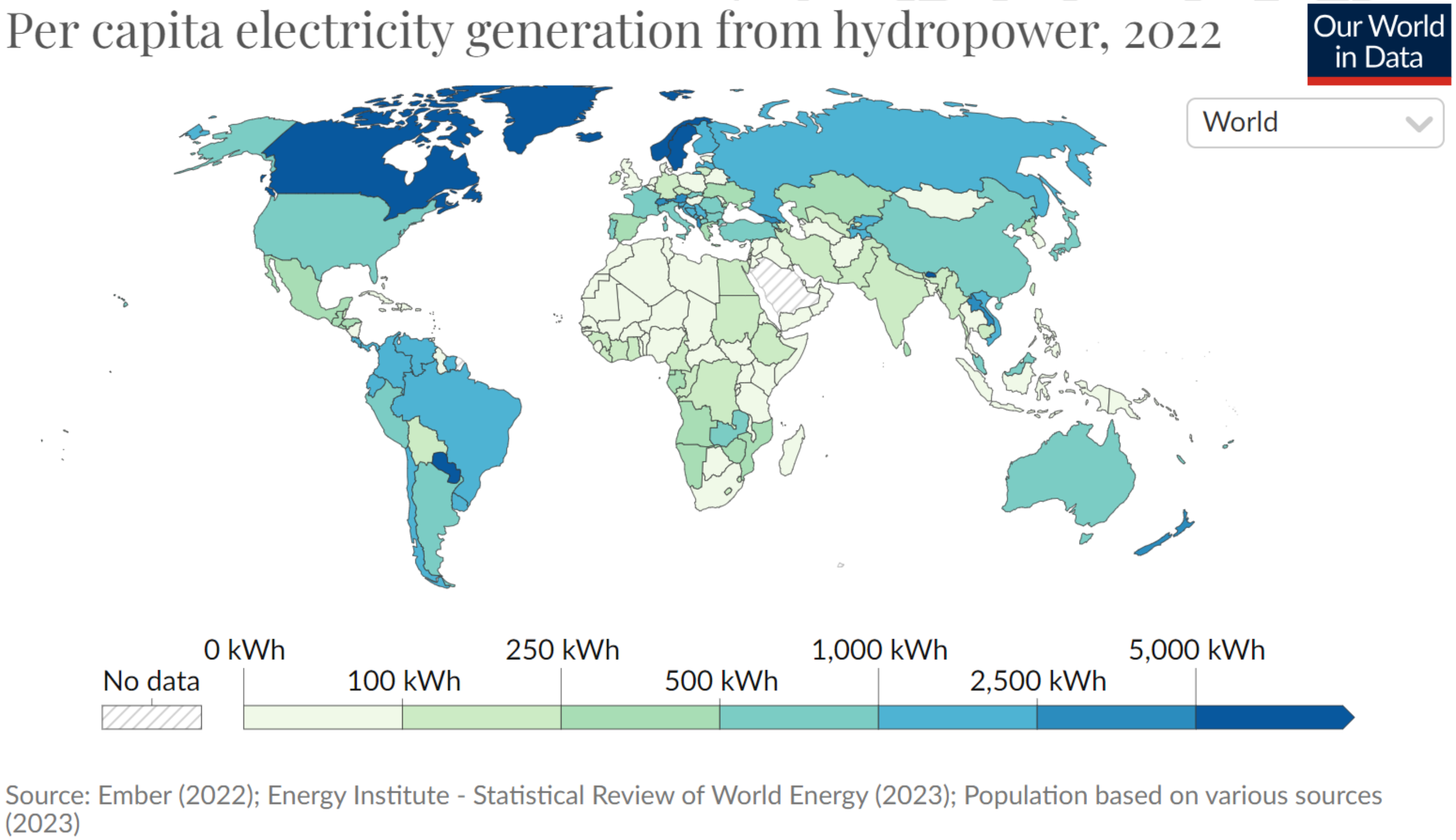
Statistics	World	Italy
Share of hydroelectric plants in total electrical generation	17%	17%
Share of hydroelectric plants in total renewable capacity generation	45%	38%
Untapped economic potential	47%	7%
Current average age of the plants fleet	31.3 years	51.1 years

Source: IEA (2021), *Hydropower Data Explorer*, International Energy Agency

2020 Annual World Generation 4 418 TWh = 4,4 * 10^6 MWh

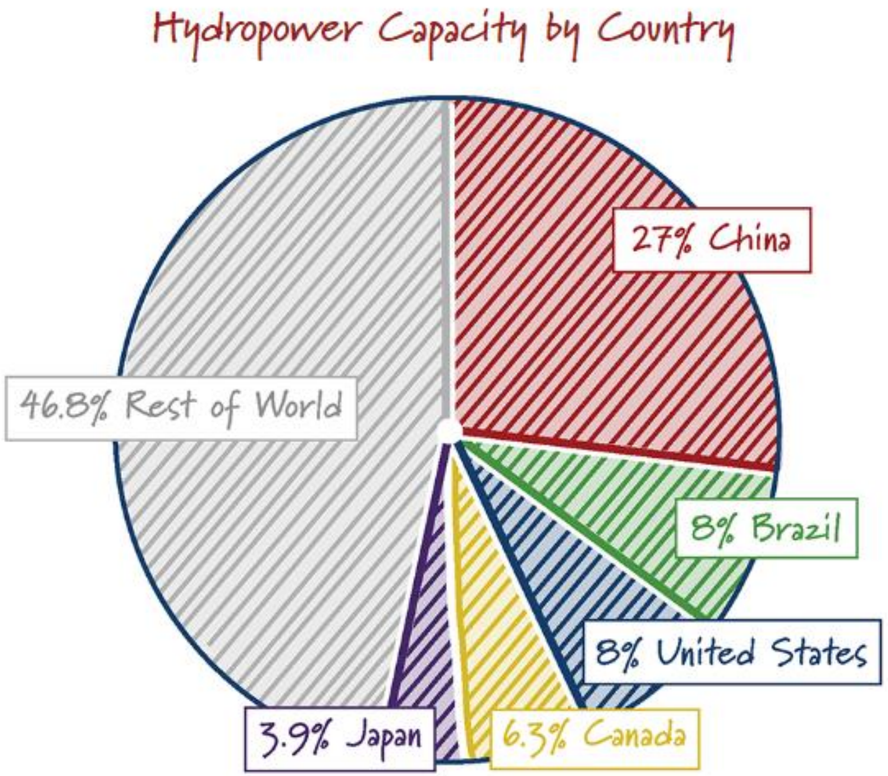
(Average annual electrical consumption per person in Italy = 5 MWh, in Niger 0,15 MWh)

Technological Overview



Technological Overview

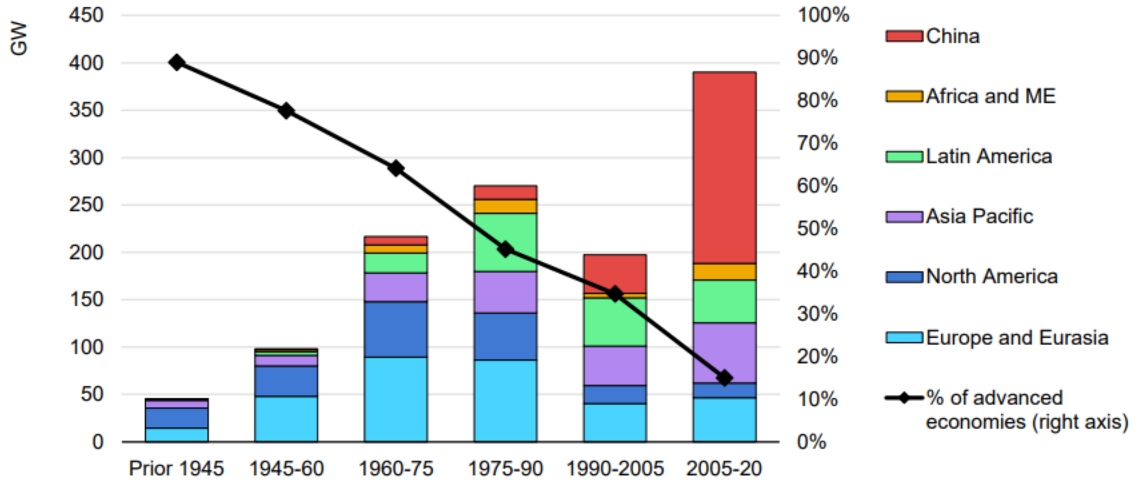
Top 5 Countries Depending on Hydropower	Capacity GW	Hydro % of Total Domestic Production
Paraguay	8.81	100%
Norway	31.6	96%
Nepal	1.02	95%
Tajikistan	5.8	95%
Brazil	100.27	64%



Technological Overview

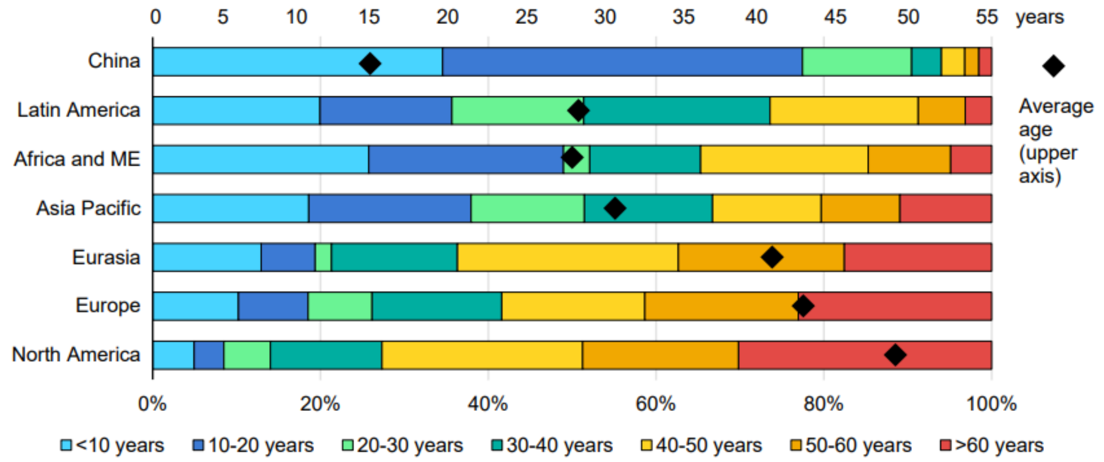
Statistics - World

Hydropower gross capacity additions by region



Notes: ME = Middle East. “Advanced economies” refers to OECD member countries and non-OECD EU member states.

Age profile of installed hydropower capacity, 2020



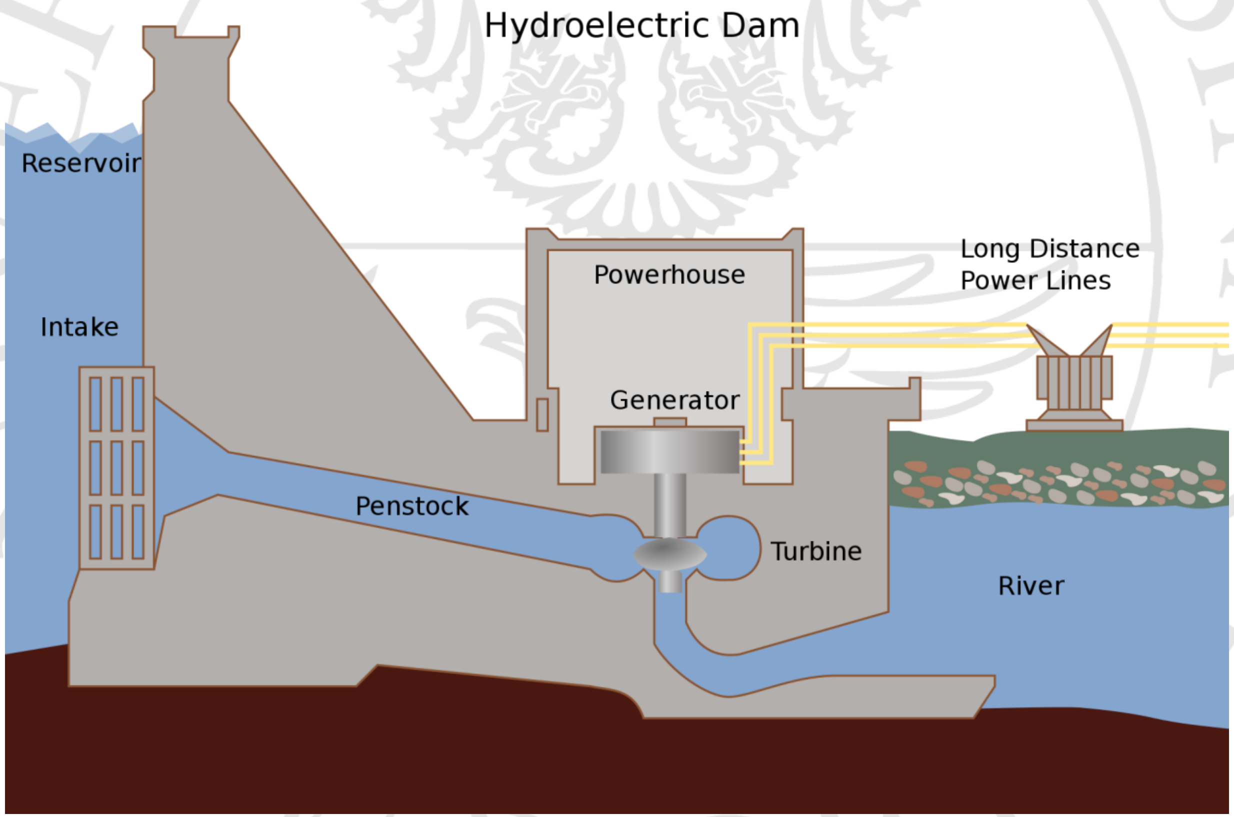
Note: ME = Middle East.

Source: IEA (2021), *Hydropower Special Market Report*, International Energy Agency

Hydroelectric Plants

General Overview of a Plant

- Reservoir
- Intake structures
  (dam, weir, barrages, grids, valves)
- Offtake structures
  (channel, penstock, surge tank, valves)
- Turbine
  (stator, rotor)
- Generator
  (rotor, stator)
- Electrical equipment
  (transformer, switches, HV power lines)
- Outflow channel or tunnel



Hydroelectric Plants Types

Definitions

- Hydraulic Head → Amount of energy that can be theoretically extracted from a specific mass of water, expressed as a difference in altitude.
  Ideally: the difference in altitude between the free water surfaces of the upper reservoir and a lower reservoir (hydrostatic head).

$$H = \Delta h + \frac{\Delta p}{\rho g} + \frac{\Delta\,(u^2)}{2\,g}$$

- Hydraulic Diameter of a Pipe → Diameter of a round pipe with the same cross section area

$$D_h = \sqrt{4\frac{A}{\pi}}$$

- Flow rate → Amount of water flowing in a pipe cross section

$$Q = \frac{\dot{m}}{\rho} = u\,A = u\,4\pi D_h^2$$

Hydroelectric Plants Types

Power and Energy

- Theoretical Power

$$P_t = \dot{m}\, g \left(\Delta h + \frac{\Delta p}{\rho g} + \frac{\Delta\,(u^2)}{2\,g}\right) = \rho\, g\, Q\, H$$

- Effective Power

$$P = \eta\, \rho\, g\, Q\, H$$

- Produced Energy

$$E = \int_0^T P(t)\, dt = \int_0^T \eta(t)\, \rho\, g\, Q(t)\, H(t)\, dt$$

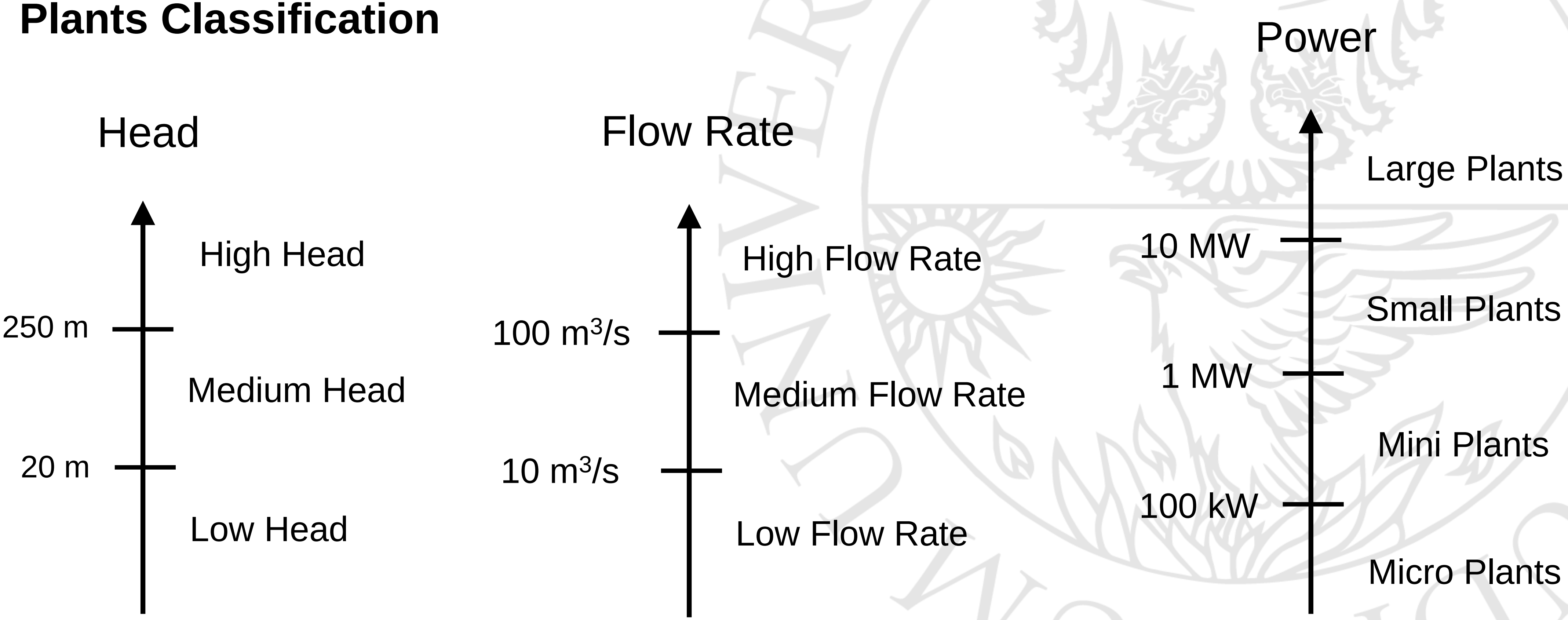
- Capacity Factor → Parameter showing **how much** the plant is used.

$$C_f = \frac{\text{Total amount of energy produced in a year}}{\text{Rated Power} \cdot 24\ \text{h/day} \cdot 365\ \text{day/year}} = \frac{E}{P \cdot T}$$

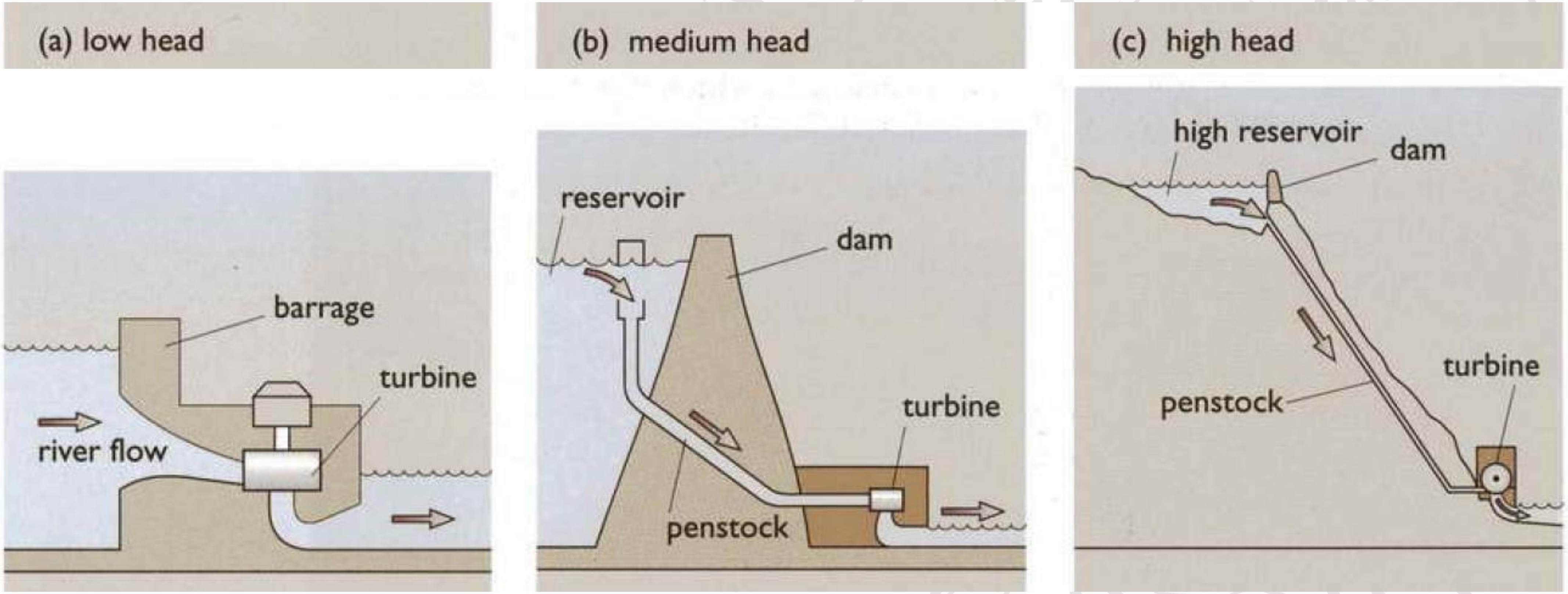
- Hydraulic Head changes depending on the reservoir level (dam) and on the water flow rate (run-on-river)
- Flow rate can change drastically along the year, depending on rainy or dry seasons and specific meteorological events!
- In hydropower plants C_f ranges between 10% (irregular streams) and 70% (stable water flows with reservoirs)

Hydroelectric Plants Types

Plants Classification



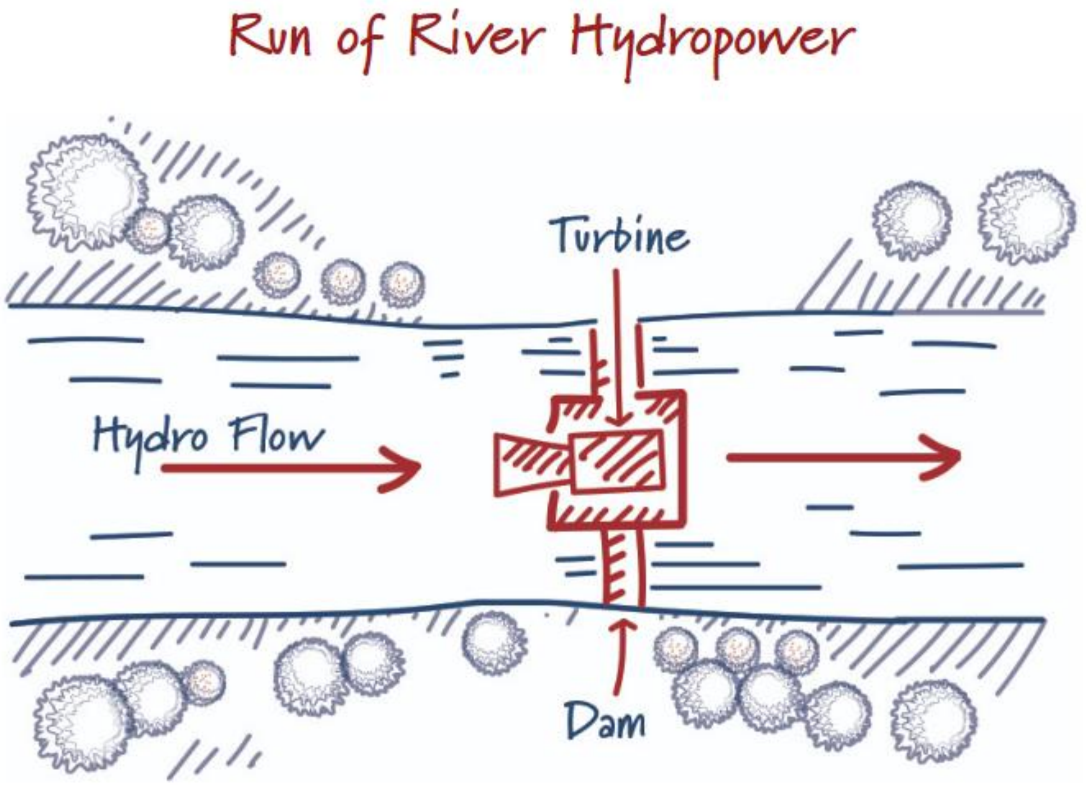
Hydroelectric Plants Types



Hydroelectric Plants Types

Run-of-River Plants

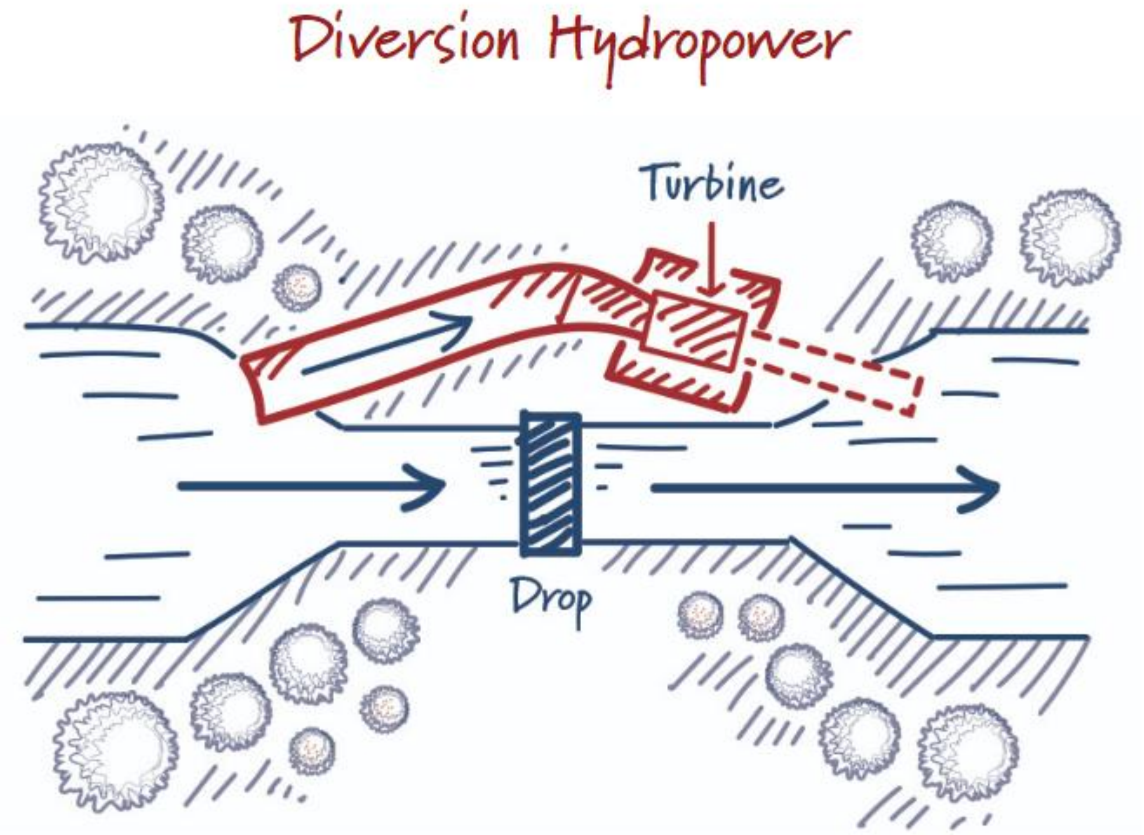
- Running water flow (from large rivers to small streams)
- Weir (barrage) providing controlled damming of the water
- Very low to medium Heads
- Medium to high Flow Rates
- No off-take structures, only spillways
- Little impact on the surrounding environment



Hydroelectric Plants Types

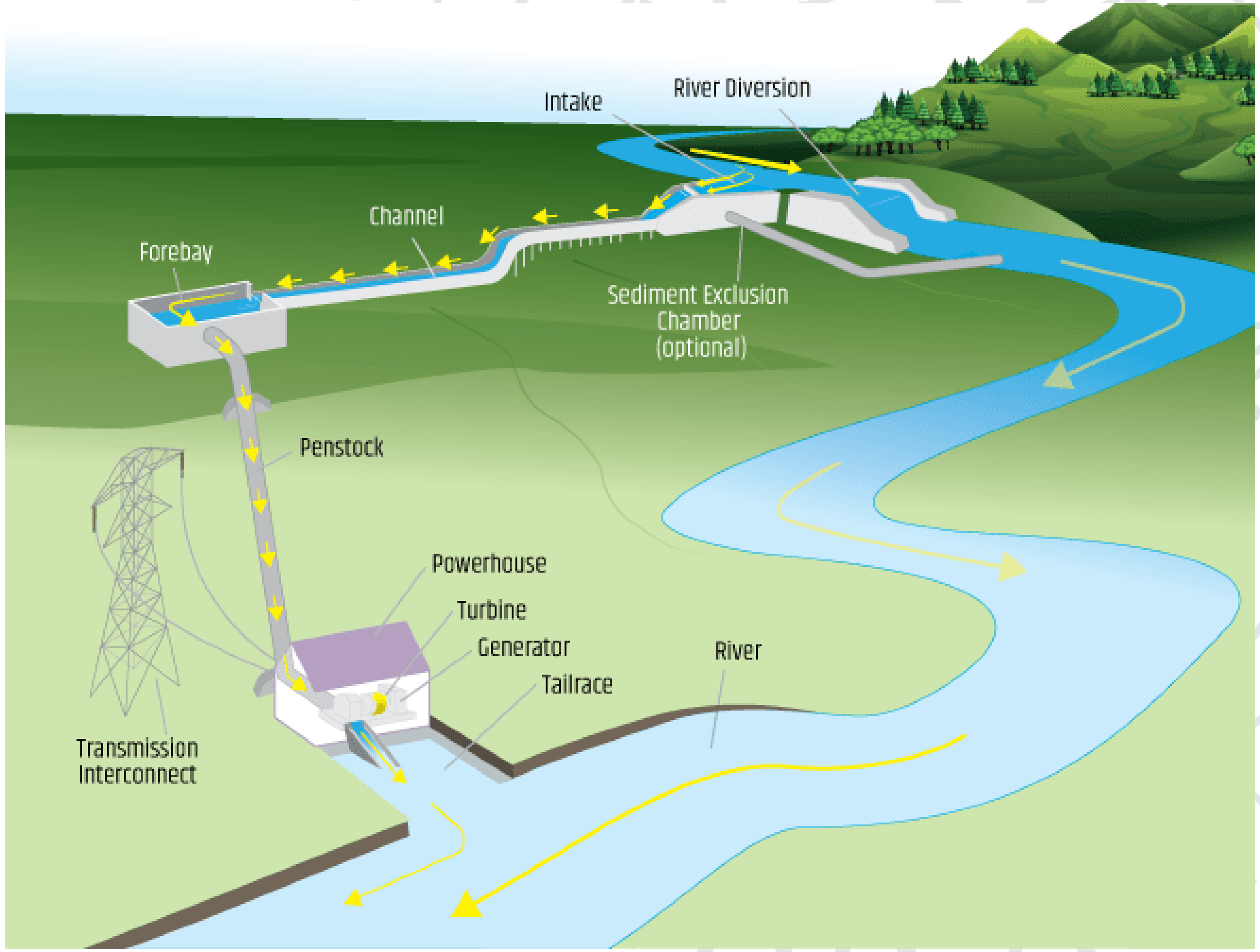
Run-of-River Plants with Diversion

- An offtake channel diverts part of the water flow to the generation site
- A penstock can be used in case of medium to high Hydraulic Head
- Used to preserve the water elevation with respect to the outflow and obtain increased Hydraulic Head
- Lower impact on the riverbed



Hydroelectric Plants Types

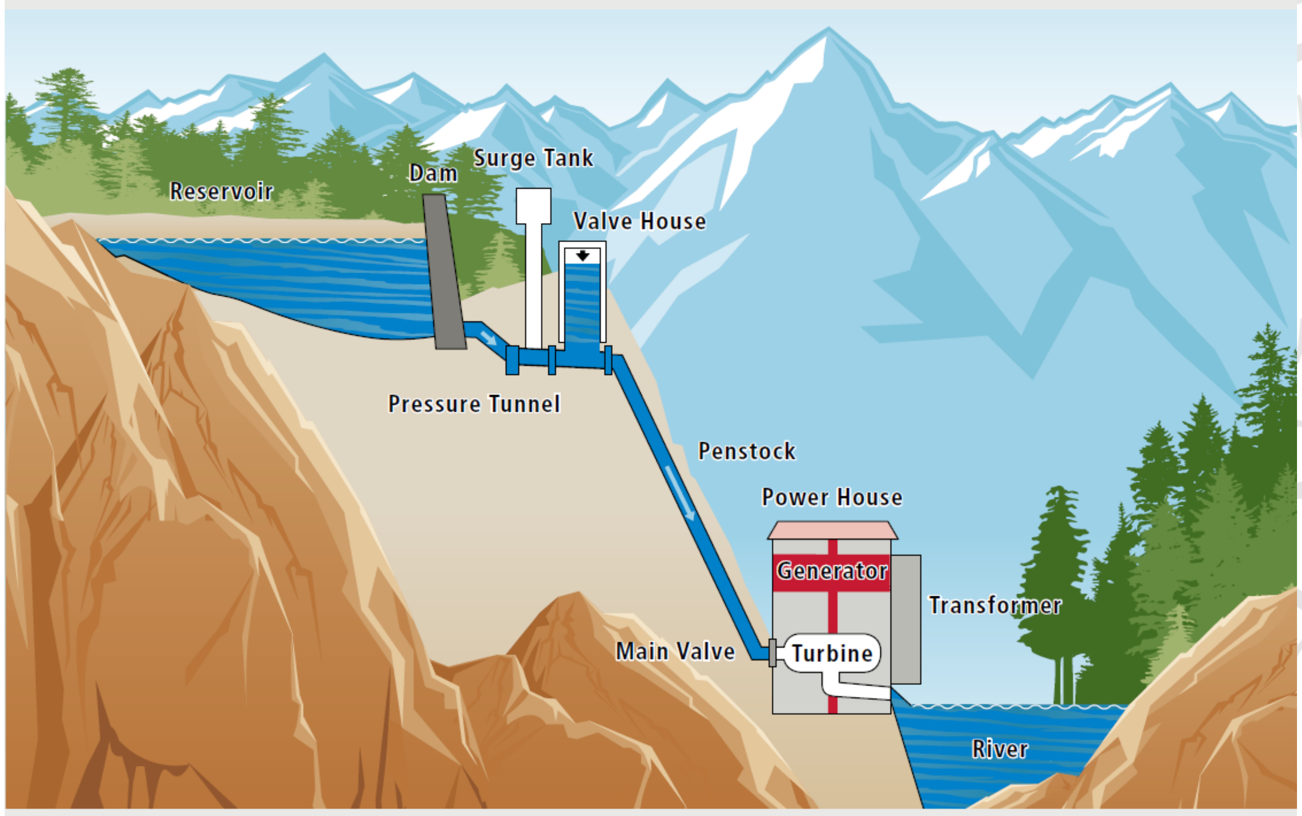
Run-of-River Plants with Diversion



Hydroelectric Plants Types

Reservoir Plants

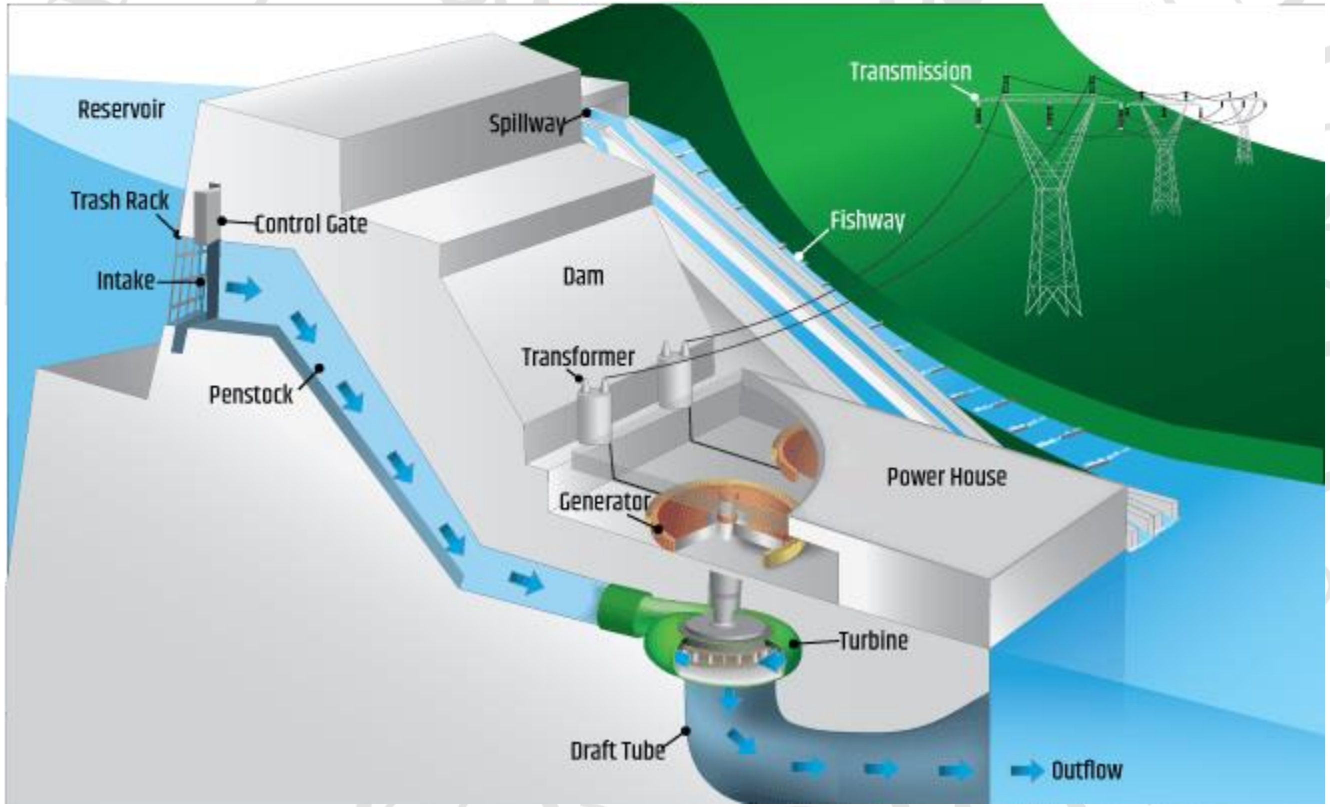
- Reservoir with a dam
- Intake structures (grids, valves)
- Offtake structures
  - Penstock
  - Surge tank or well (water hammer)
  - Main valve
- Turbine
- Electrical equipment
- Outflow channel or tunnel



Hydroelectric Plants Types

Reservoir Plants

- Medium to very large Hydraulic Heads
- Low to medium Flow Rate
- Depending on the local topography, small dams can contain very large reservoirs (lakes)
- High impact on the local environment (often whole valleys are inundated)
- Requires massive civil works
- Reduction of water spilling and maximization of the capacity factor

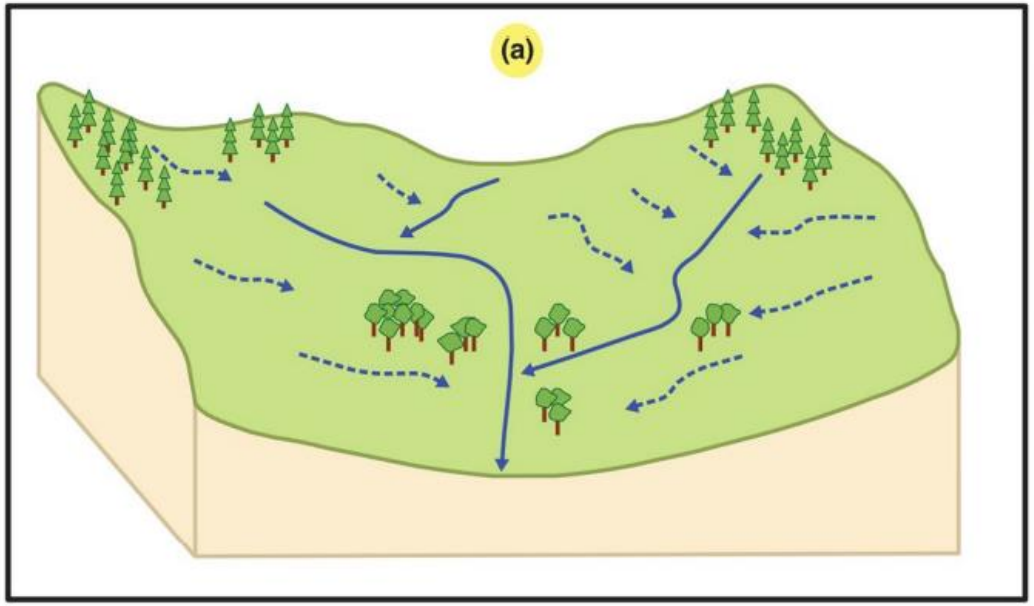


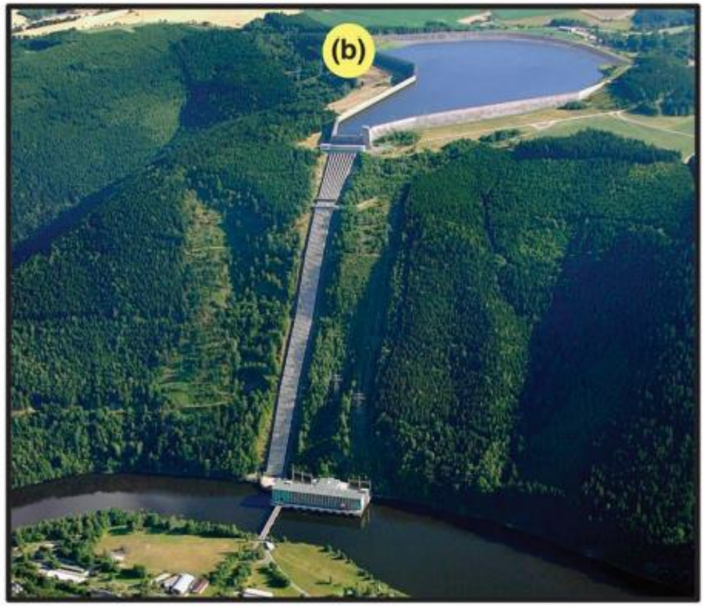
Technological Overview

Reservoir Area

Catchment Area or Source Area

Reservoir-allocated Area
or Inundated Land Area



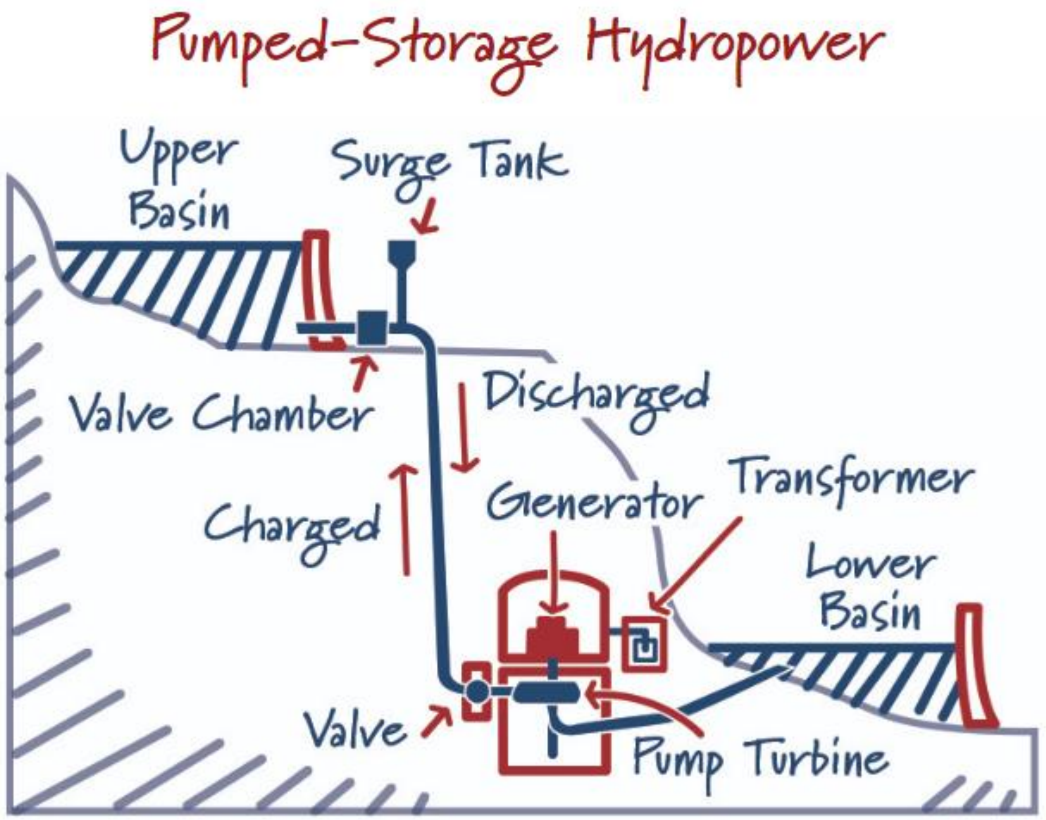


Source: *Nøland, J.K., Auxepaules, J., Rousset, A. et al. Spatial energy density of large-scale electricity generation from power sources worldwide. Sci Rep* ***12****, 21280 (2022).*

Hydroelectric Plants Types

Pumped Storage Plants

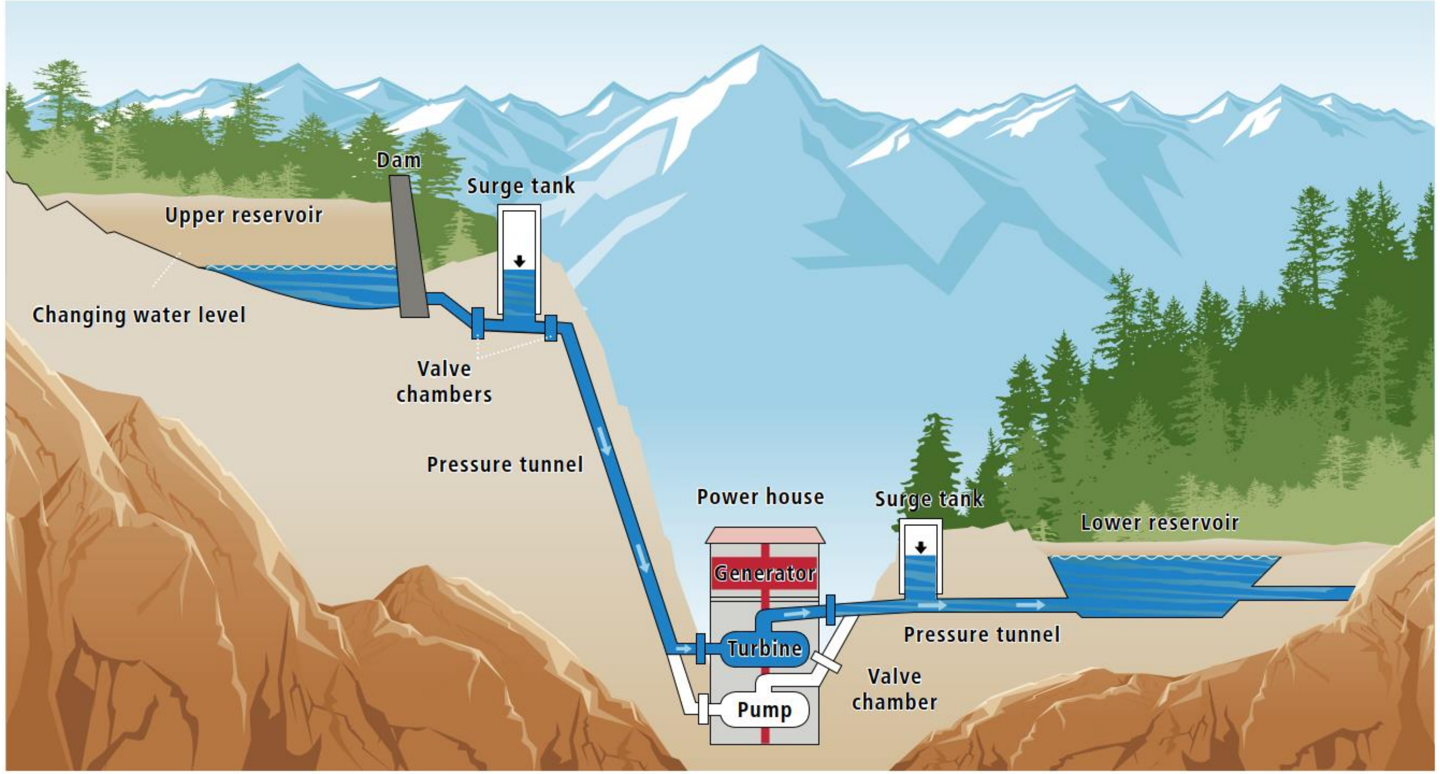
- Use of two water reservoir at two different altitudes
- The plant generates energy by flowing water through the turbine (from upper basin to lower basin)
- The plant can pump back water from the lower basin to the upper basin (consuming energy)
- The plant stores energy thanks to the gravitational potential of the moved water



Hydroelectric Plants Types

Pumped Storage Plants

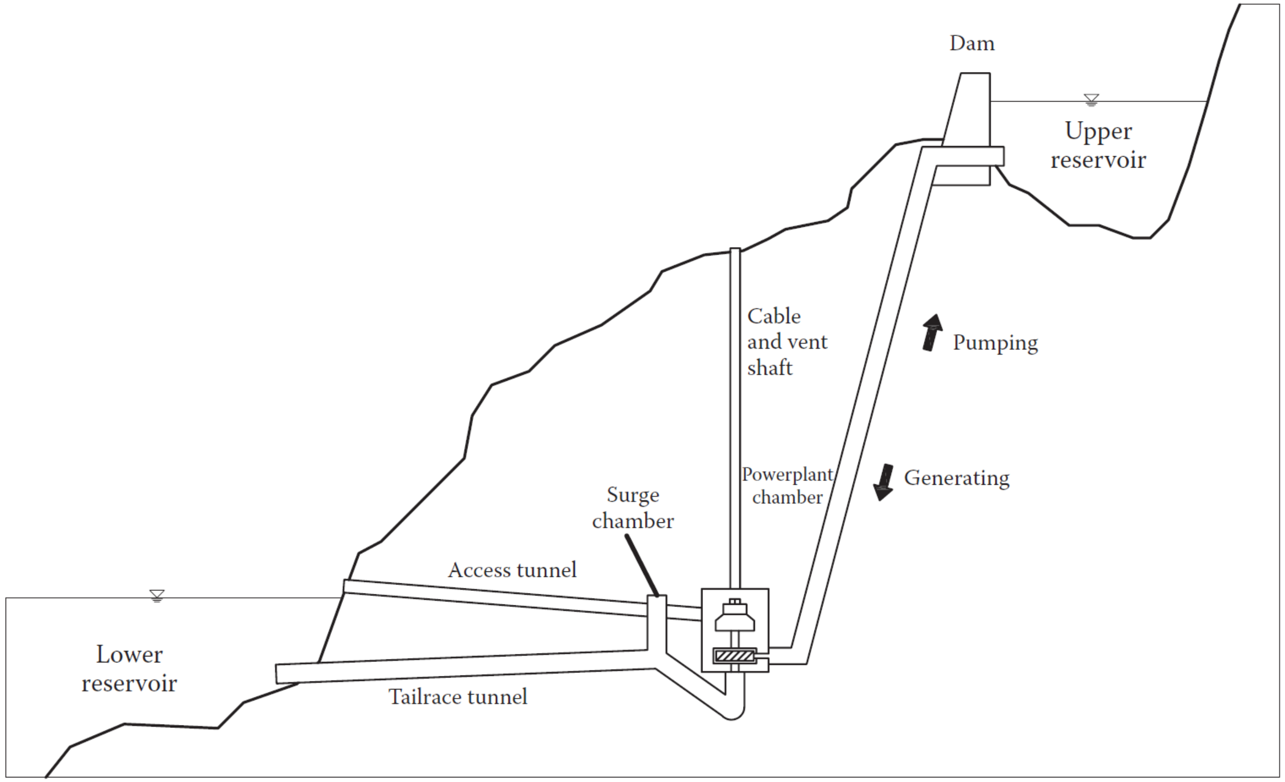
- Upper reservoir (usually with a dam)
- Lower reservoir (with/without a dam))
- Intake / offtake structures
    - Grids
    - Penstock(s)
    - Surge tanks or wells
    - Intake valves, main valve, and diverting valves
- Reversible turbine o turbine and pump
- Reversible electrical generator / motor



Hydroelectric Plants Types

Pumped Storage Plants

- Very similar to Reservoir Plants
- Need of a reversible turbine or need of an additional pump
- Often built underground
- Very high impact on the local environment (need of two lakes)
- Optimal use of water
- Maximization of the capacity factor
- Possibility to store energy
- Supply of additional services to the grid



Technological Overview

Run-of-river

Reservoir

Hydroelectric Plants

Three Gorges Dam (Yangtze River, China)

- Head: 80 m Flow Rate: 30 000 m^3/s Reservoir: 39.3 km^3 Dam Length: 2.34 km
- Rated Power: 22.5 GW Energy Production: 111.8 TWh/year (2020) C_F=56.7% (2020)

Hydroelectric Plants

Itaipu Dam (Paraná River, Brazil + Paraguay)

- Head: 118 m Flow Rate: 14 000 m^3/s Reservoir: 29 km^3 Dam Length: 7.92 km
- Rated Power: 14 GW Energy Production: 76.4 TWh/year (2020) C_F=62.3% (2020)

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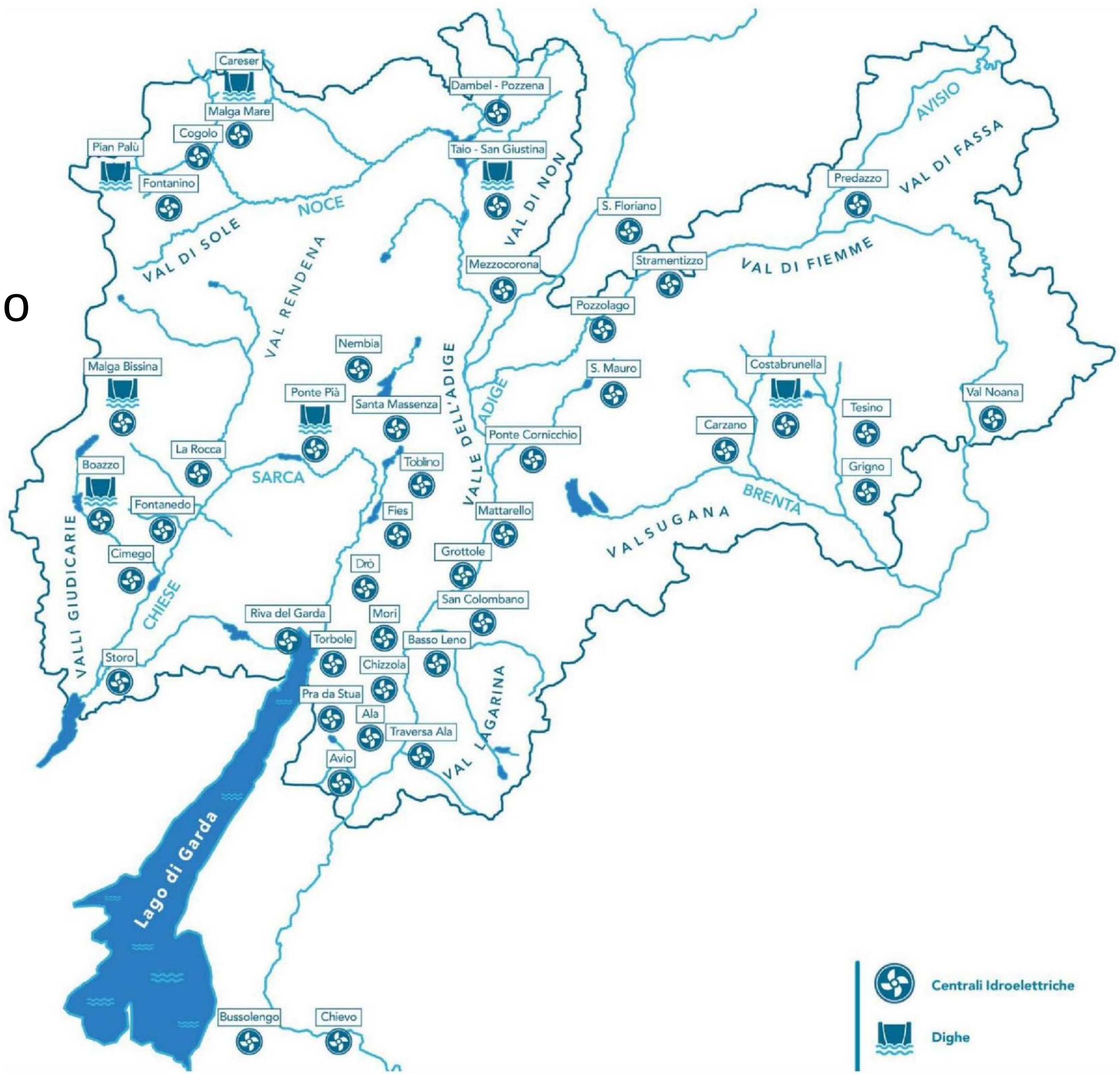
Hydroelectric Plants

Lago Malga Bissina - Centrale Malga Boazzo

- Head: 470 m Flow Rate: 17 m^3/s
- Reservoir: 61 $\cdot 10^6$ m^3 Dam Length: 565 m



Hydroelectric Plant Design

Evaluation of the site

Potential energy production = Precipitation x Catchment area x Gravity x Head

$$E_{pot} = R_{prec}\, A_{catch}\, gH$$

Catchment Area = Area surrounding a river that feeds that river, or whose soil absorb water that will seep into the river.

Precipitation = Volume of water rained over a specific surface in a specific amount of time (year)

$$R_{prec} = \frac{\int_0^T Q_{rain}\, dt}{A\, T} = \frac{h_{prec}}{T}$$

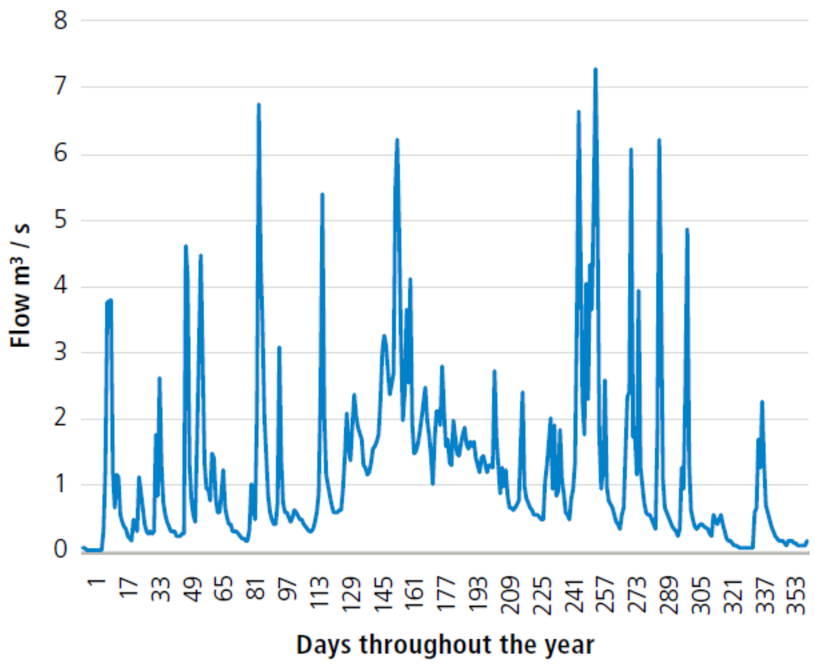
Tools

- Historical river flow rates and precipitation data
- Hydrology studies to predict the overall water flow at the point of intake of the hydropower plant

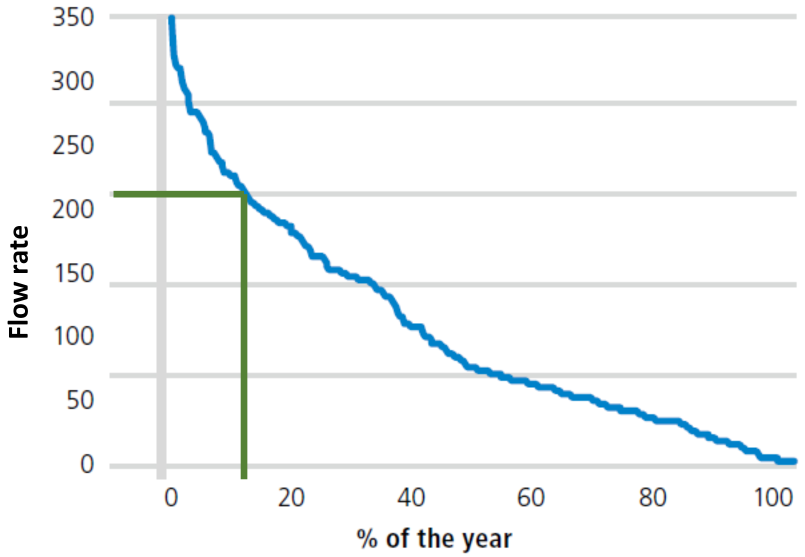
Hydroelectric Plant Design

Water Flow Statistical Distribution

Hydrograph - Water flow through time



Flow Duration Curve



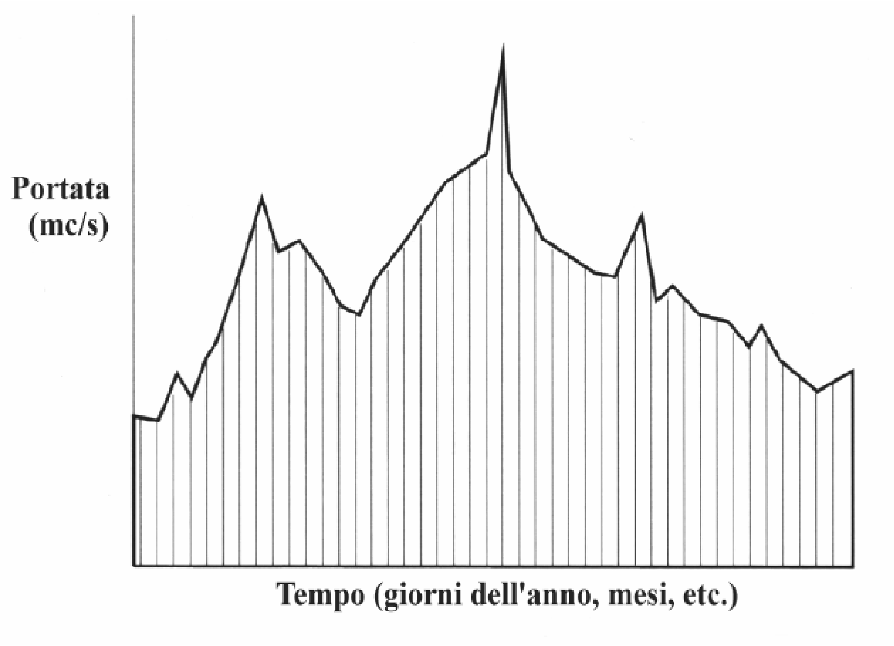
Shows the amount of time (or % of time in the year) in which the flow rate is higher than a specific value

Hydroelectric Plant Design

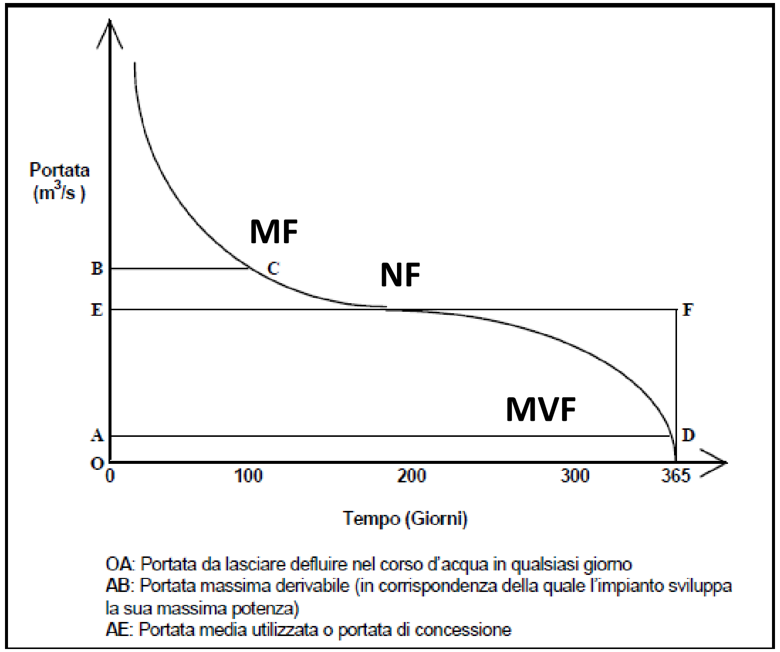
Characteristic Flow rates

- Minimum Vital Flow – MVF
  Minimum flow rate needed to keep the river alive (fish travelling, animal and plant sustenance, ecological needs)
- Maximum Flow Rate - MF
- Nominal Flow Rate - NF

Hydrograph



Flow Duration Curve



Hydroelectric Plant Design

Cut-off flow rates

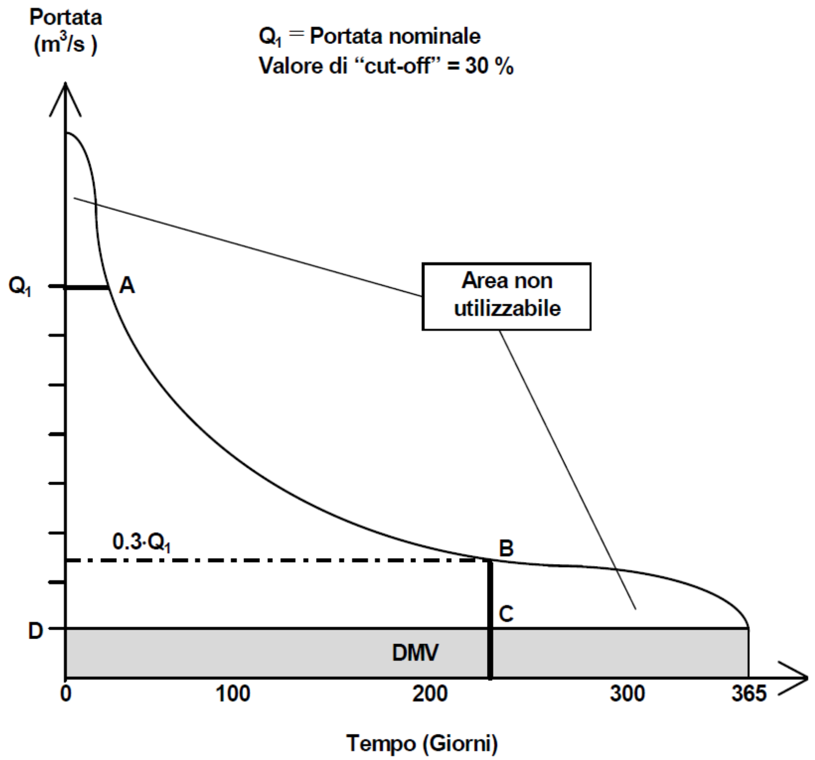
Hydroelectric turbines can be partialized, but usually have a cut-off threshold at 30% of the nominal power.

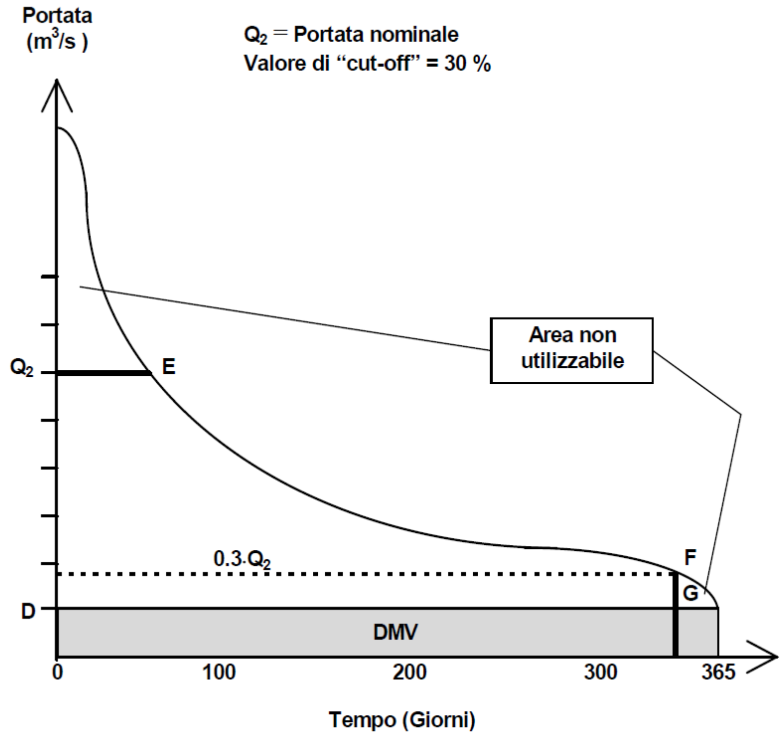
With fixed Head, this means 30% of nominal flow rate

↓

An optimal sizing can be found and depends on the shape of the FDC

Flow Duration Curve





Hydroelectric Plant Design

Efficiency

- Theoretical Power → $\mathrm{P_t} = \rho\, g\, Q\, H$

To evaluate the power available at the turbine, we must consider the losses due to the water intake (concentrated) and transport (distributed)

$$P_{\mathrm{turb}} = \mathrm{P_t} - \Delta P_{\mathrm{conc}} - \Delta P_{\mathrm{dist}} = \rho\, g\, Q\, H\ - Q\, \Delta p_{\mathrm{conc}}\ -\ Q\, \Delta p_{dist}$$

$$H_{\mathrm{net}} = H - \Delta H_{\mathrm{conc}} - \Delta H_{\mathrm{dist}}$$

$$P_{\mathrm{turb}} = \rho\, g\, Q\, H_{\mathrm{net}}$$ → **Net Hydraulic Head**

- Turbine efficiency η_T typically is in the range 85% – 92%.

$$\mathrm{P_{out}} = \eta_T P_{\mathrm{turb}} = \eta_T\, \rho\, g\, Q\, H_{\mathrm{net}}$$

- The efficiency of conversion to electricity, including electric generator, gears, transformer and the consumption of auxiliaries must also be considered ($\eta_{\mathrm{conv}}\eta_{\mathrm{aux}}$)

$$\mathrm{P} = \eta_{\mathrm{aux}}\eta_{\mathrm{conv}}\eta_T\, \rho\, g\, Q\, H_{\mathrm{net}}$$

Hydraulic Losses

Distributed Pressure Losses

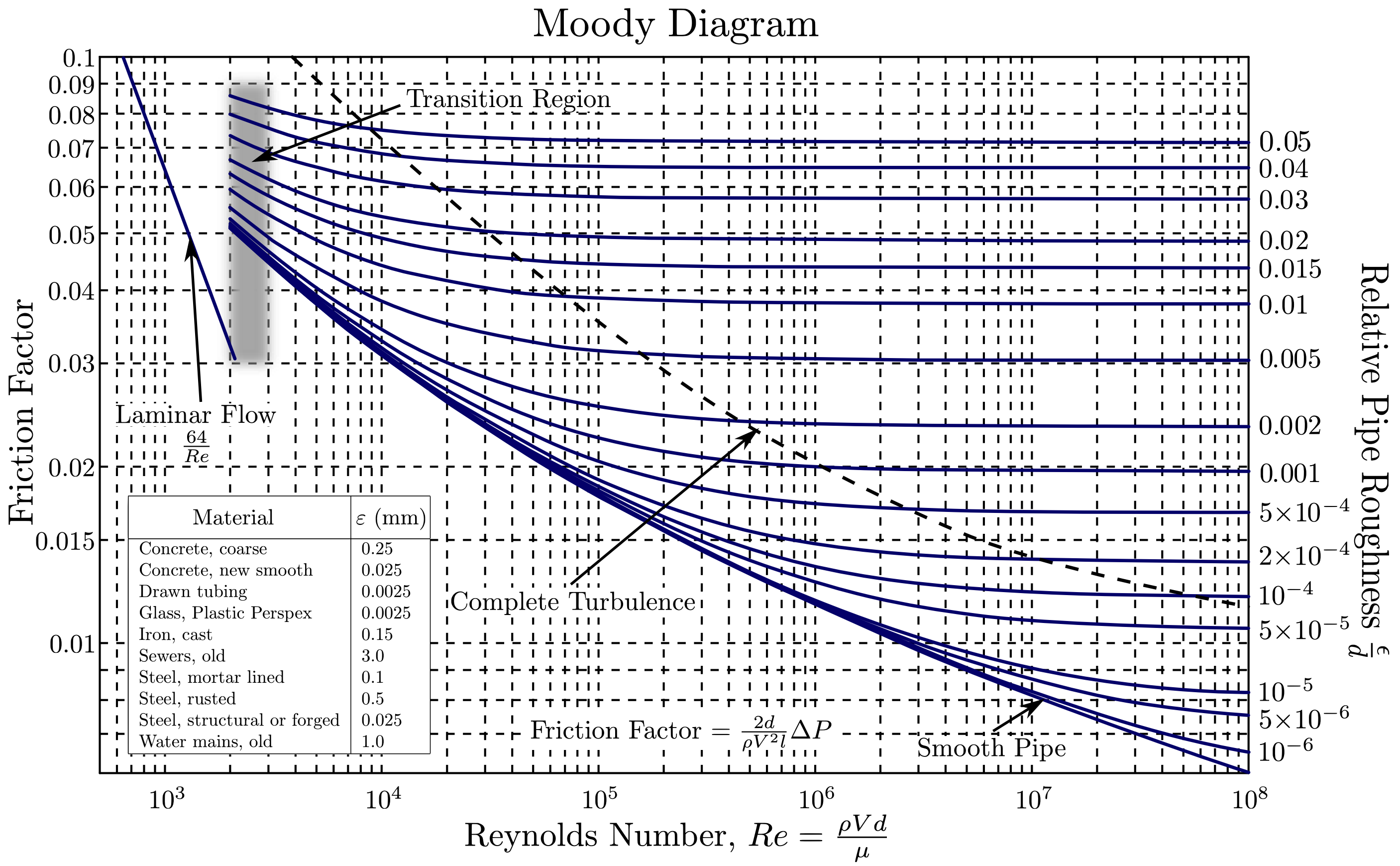
Darcy–Weisbach Equation

$$\frac{\Delta p}{L} = f_{\mathrm{D}} \cdot \frac{\rho}{2} \cdot \frac{\langle v \rangle^2}{D_H}$$

$$\Delta H_{\mathrm{dist}} = f_D \frac{L}{D_h} \frac{\Delta\left(u^2\right)}{2\,g}$$

Darcy Friction Factor

$$K = f_D \frac{L}{D_h} \longrightarrow \Delta H_{\mathrm{conc}} = K \frac{\Delta\left(u^2\right)}{2\,g}$$



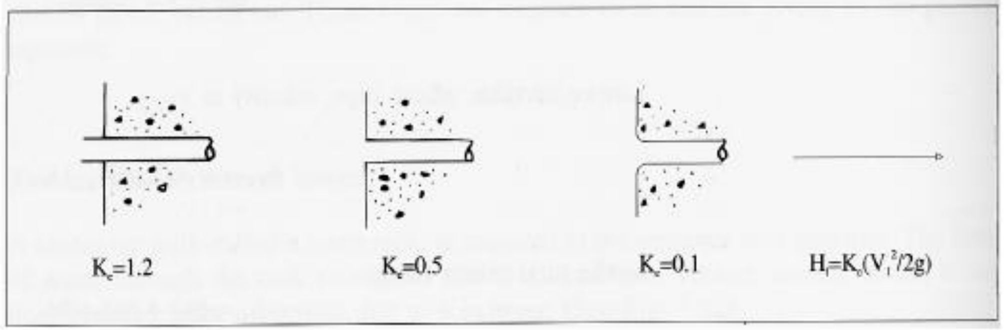
Hydraulic Losses

Coefficients for Localized Losses

Valves

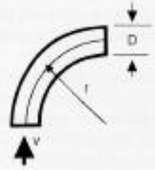
Type of Valve	K_v
Spherical	0.05
Gate	0.2
Butterfly	0.6
Eccentric	1.0

Inlets



Bends

Fig. 5.25. Bend loss coefficient K_b



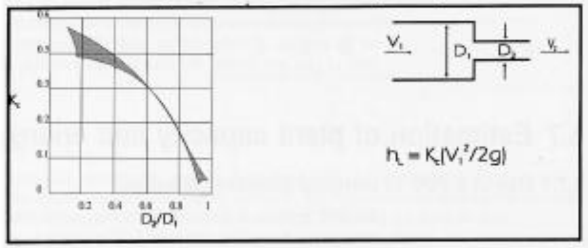
values are for 90°; use 3/4 of these for 45° and 1/2 for 22.5°

R/D	1	2	4	6	10	16
K_b	0.35	0.19	0.17	0.22	0.32	0.38

$$h_L = k_b V^2/2g$$

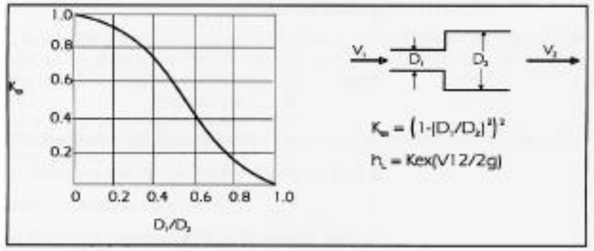
Contractions

Fig. 5.26. Sudden contraction coefficient K_c



Expansions

Fig. 5.27. Sudden expansion coefficient K_{ex}

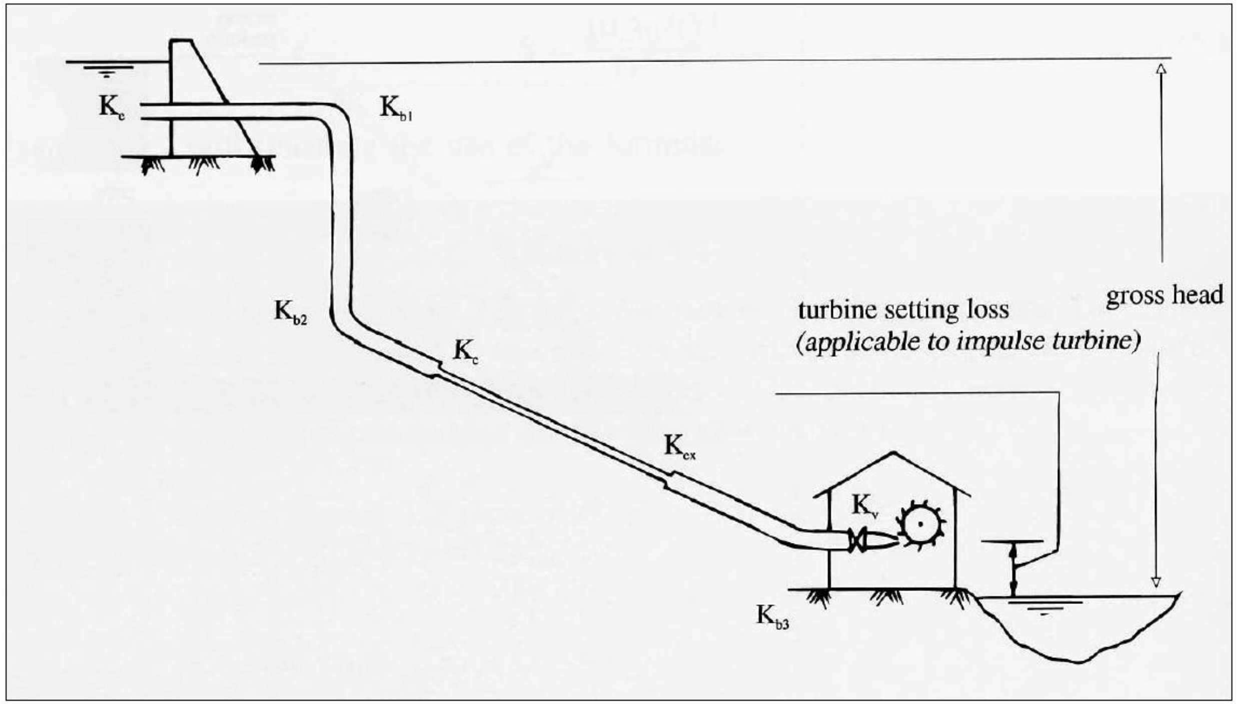


$$K_{ex} = \left(1-(D_1/D_2)^2\right)^2$$

$$h_L = Kex(V1^2/2g)$$

Hydraulic losses

Pressure Losses in the Penstock



- $\Delta H_{con1} = h + v_u^2/2g\,(Ke + Kb1 + Kb2 + Kc)$ (Upper Section)
- $\Delta H_{con2} = h + v_m^2/2g\,Kex$ (Intermediate Section)
- $\Delta H_{con3} = h + v_1^2/2g\,(Kb3 + Kv)$ (Lower Section)
- $\Delta H_{con} = \Delta H_{con1} + \Delta H_{con2} + \Delta H_{con3}$ (Total head losses)

End of the Lesson