Postgraduate program:
Environment and Development

Course: Energy and Environment

National Technical
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Overview of hydropower systems

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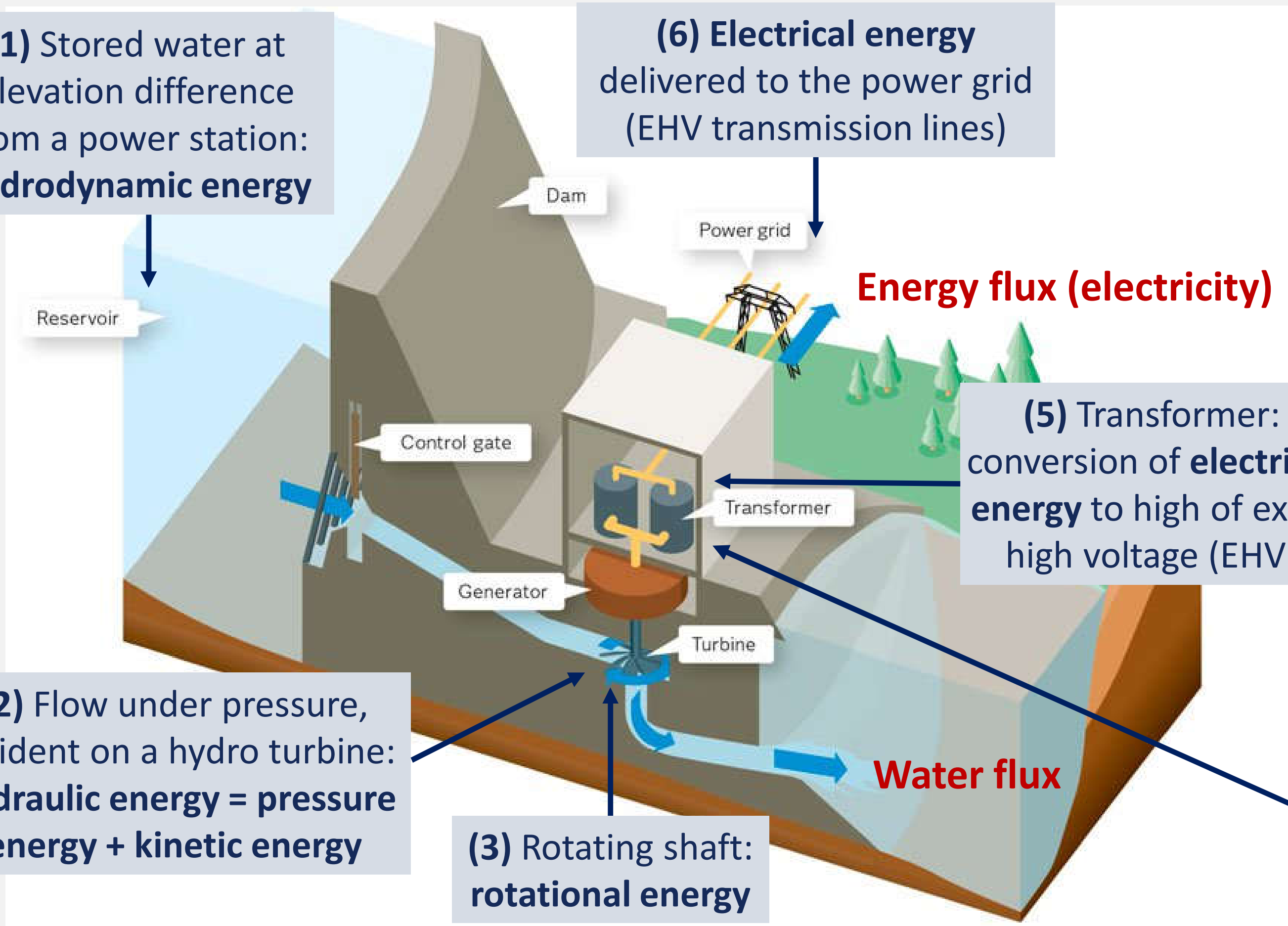
Hydroelectricity as a cascade of energy conversions



(1) Stored water at elevation difference from a power station: **hydrodynamic energy**

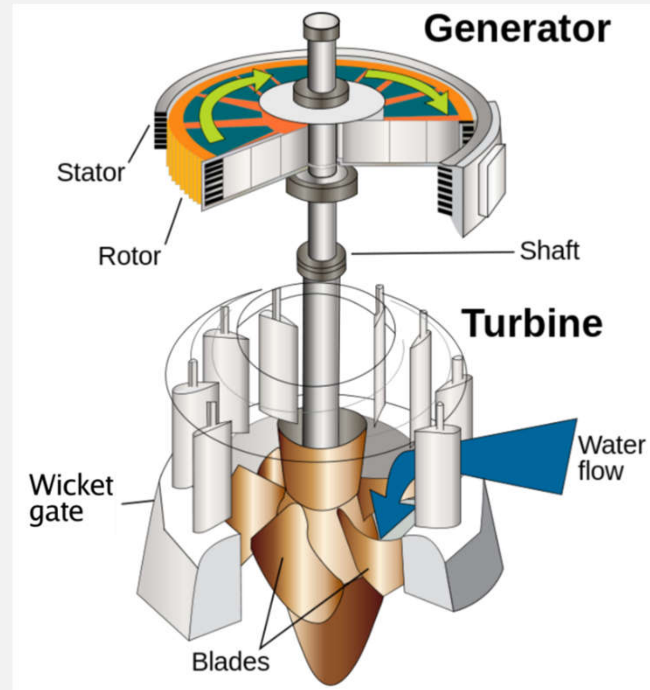
(2) Flow under pressure, incident on a hydro turbine: **hydraulic energy = pressure energy + kinetic energy**

(3) Rotating shaft: **rotational energy**

(4) Electro-generator (stator & rotor): **electromagnetic energy**, in the form of low-voltage alternating current (AC)

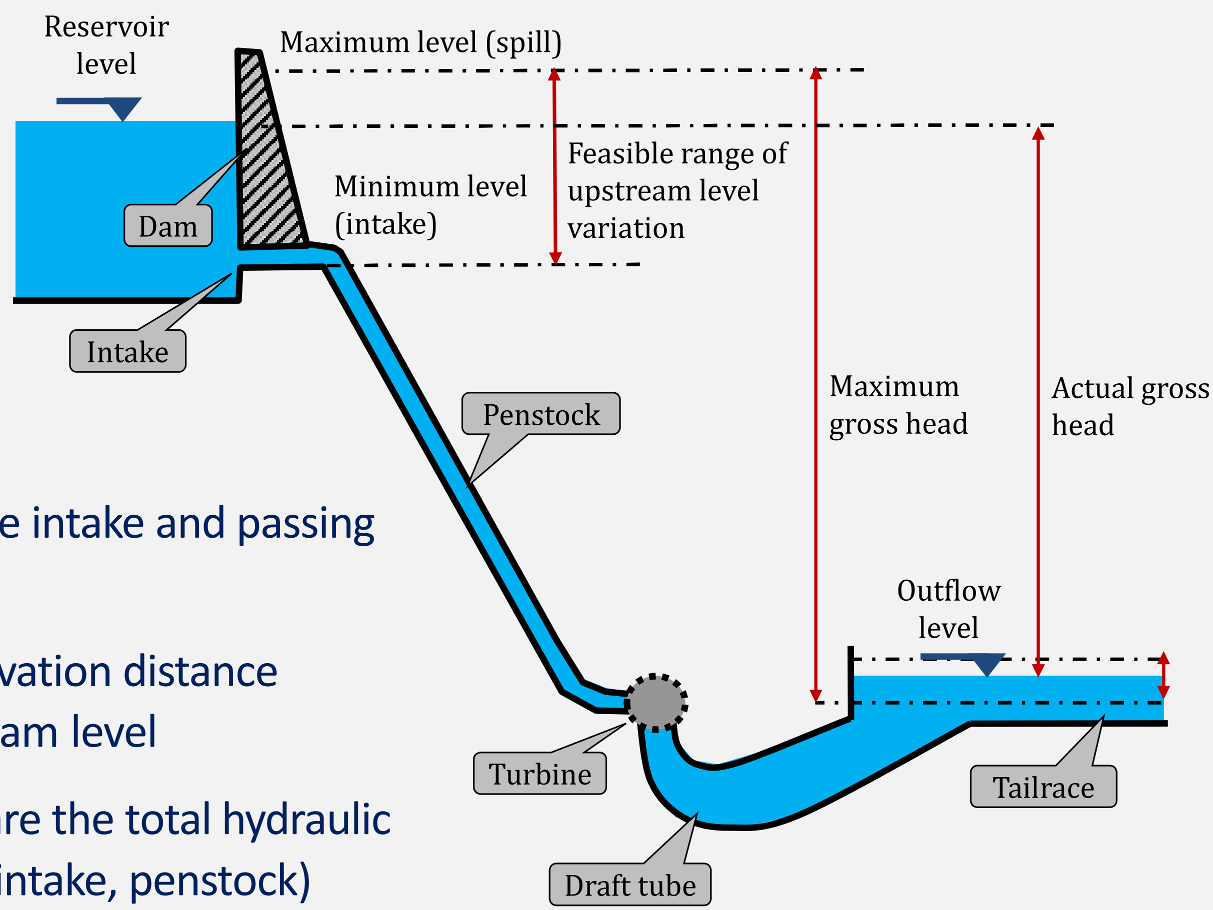
(5) Transformer: conversion of **electrical energy** to high of extra high voltage (EHV)

(6) Electrical energy delivered to the power grid (EHV transmission lines)



Key components

- Two-phase energy conversions:
  - Hydrodynamic to hydraulic energy
  - Hydraulic energy to electricity in the grid
- Hydraulic variables of interest:
  - Water volume, V
  - Discharge, $Q = dV/dt$, released by the intake and passing through the hydro turbines
  - Gross head, H, defined in terms of elevation distance between an upstream and a downstream level
  - Net head, $H_n = H - \Delta H$, where ΔH are the total hydraulic losses across the conveyance system (intake, penstock)



Governing equations

- **Hydrodynamic energy** of a water mass m at an elevation difference (**gross head**) H:

$$E_0 = m\ g\ H = \rho\ g\ V\ H = \gamma\ V\ H$$

where ρ is the water density (1000 kg/m^3), g the acceleration of gravity (9.81 m/s^2), γ the specific weight of water (9.81 kN/m^3) and V the volume (m^3).

- Theoretical input power:

$$P_0 = \frac{dE}{dt} = \frac{d(\gamma\ V\ H)}{dt} = \gamma\ H \left(\frac{dV}{dt}\right) = \gamma\ Q\ H$$

where Q is the **discharge** (m^3/s).

- Hydraulic power, after subtracting the **hydraulic losses**, ΔH, across the conveyance system (H_n: **net head**):

$$P_H = \gamma\ Q\ (H - \Delta H) = \gamma\ Q\ H_n$$

- **Output electrical power** to the grid:

$$P = \eta\ \gamma\ Q\ H_n$$

where η is the **total efficiency** of the electromechanical (E/M) system (in fact, the product of individual efficiency factors across the hydro turbines, the electro-generator and the transformer).

Remarks

- The **gross head** is the elevation difference between the water level in the upstream reservoir and the energy grade level at the point in the water course where the water is conveyed back after having passed the turbine (which depends on the turbine type).
- The power formula is nonlinear, since both the efficiency and the net head are functions of discharge, i.e.:

$$P = \eta(Q)\,\gamma\,Q\,H_n(Q) = \eta(Q)\,\gamma\,Q[H - \Delta H(Q)]$$

- The net head is decreasing function of discharge, while the efficiency generally increases with Q.
- The maximum value of P is called **nominal power capacity**.
- Considering η and H_n as approximately constants over a time interval (t_1, t_2), the hydroelectrical energy is:

$$E = \int_{t_1}^{t_2} P(t)dt = \int_{t_1}^{t_2} \eta\,\gamma\,Q(t)\,H_n dt = \eta\,\gamma\,H_n \int_{t_1}^{t_2} Q(t)\,dt = \eta\,\gamma\,V\,H_n$$

- By setting $\psi = \eta\,\gamma H_n/H$, we get the equivalent formula:

$$E = \psi\,V\,H$$

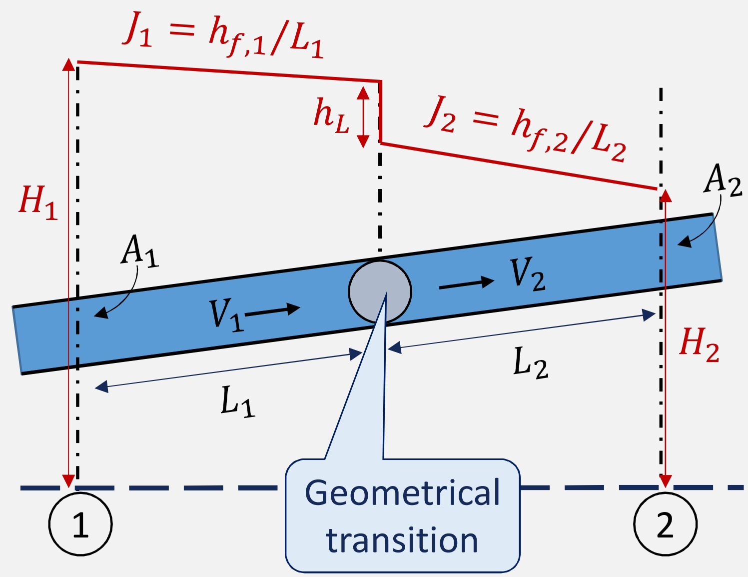
where ψ is the **specific energy** of the overall system, with theoretically maximum value 0.002725 kWh/m^4 (or 0.2725 GWh/hm^4); this refers to unit efficiency, i.e. $\eta = 1$, and zero hydraulic losses, i.e., $H_n = H$.

Analytical estimation of hydraulic losses

- The total hydraulic losses are the sum of friction and minor losses across the conveyance system, i.e.:

$$\Delta H = \sum h_{f,i} + \sum h_{L,j} = \sum L_i \, J_i + \sum h_{L,j}$$

where L_i is the length of a pipe segment i and J_i is the slope of the hydraulic grade line.



- The **friction losses** h_f (also referred to as linear or major losses) are caused by the movement of fluid molecules against each other (effect of **viscosity**) and against the pipe wall (effect of **roughness**).
- The **minor losses** h_L (also referred to as local losses) are taking place in all kinds of geometrical transitions (flow entrance through the intake, change of diameter, flow split, elbows, joints, valves, etc.) that cause vortices due to flow separation or flow mixing, thus eventually resulting in turbulence production.
- Major design objective: minimization of ΔH (hydraulic losses → loss of power)

Calculation of friction losses

- The friction losses across a pipe of length and diameter L and D, respectively (both expressed in m), are estimated through the **Darcy-Weisbach** formula:

$$h_f = f \frac{L}{D} \frac{V^2}{2g} = f \frac{8\, L\, Q^2}{g\, \pi^2 D^5}$$

where V is the velocity (m/s) and f is a dimensionless friction factor.

- For turbulent flow conditions, the friction factor is estimated through the **Colebrook-White** formula:

$$\frac{1}{\sqrt{f}} = -2.0 \log\left(\frac{k_s/D}{3.71} + \frac{2.51}{Re\sqrt{f}}\right)$$

where k_s is the **equivalent roughness** (typical design values 0.5-2.0 mm), and Re the **Reynolds number**:

$$Re = \frac{V\, L}{\nu}$$

where ν is the **kinematic viscosity** of the fluid (m^2/s); for water under typical temperature and pressure conditions (i.e., $T = 16\ ^{\mathrm{o}}\mathrm{C}$, $P = 1.0\ \mathrm{atm}$), we get $\nu = 1.1 \times 10^{-6}$ m^2/s.

Calculation of minor losses

- The minor losses are generally expressed as a fraction of kinetic energy:

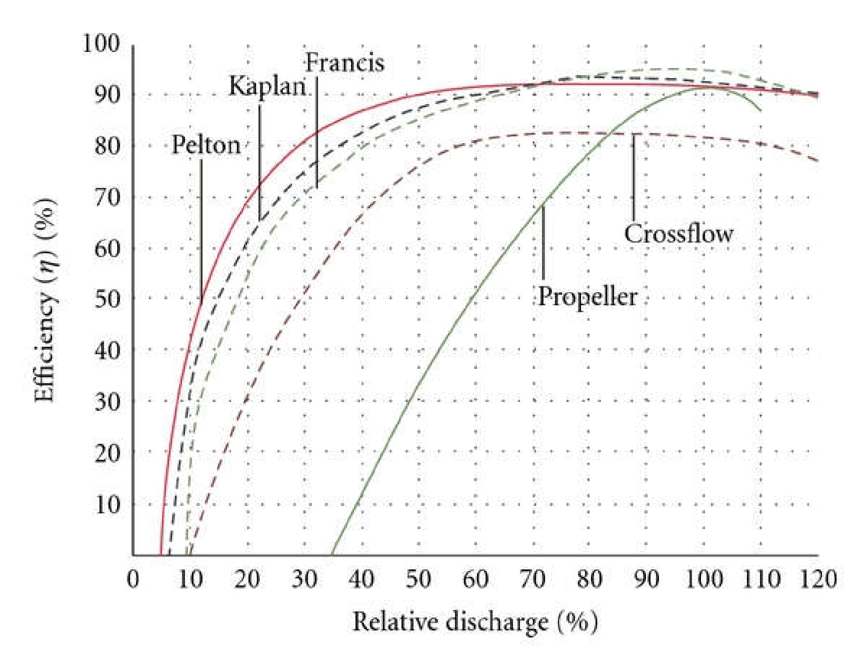
$$h_L = k\frac{V^2}{2g}$$

  where V is the larger velocity value across the transition and k is a dimensionless factor, depending on the geometrical and hydraulic characteristics of the transition.

- The value of k is strongly affected by the shape of the transition. Well-rounded transitions ensure minimal local losses (which is an issue of good design and good construction, as well).
- Typical values that are applied in hydroelectric systems are:.
  - Intakes: $k = 0.04$
  - Grids: $k = 0.10$-0.15
  - Contractions: $k = 0.08$
  - Elbows: $k = 0.10$
  - Valves, fully open: $k = 0.10$-0.20
  - Outflow to tailrace: $k = 1$ (default)
- In preliminary design studies, local loss calculations cannot be estimated analytically, since the geometrical details are not specified; in this vein, we apply a aggregate value of k.

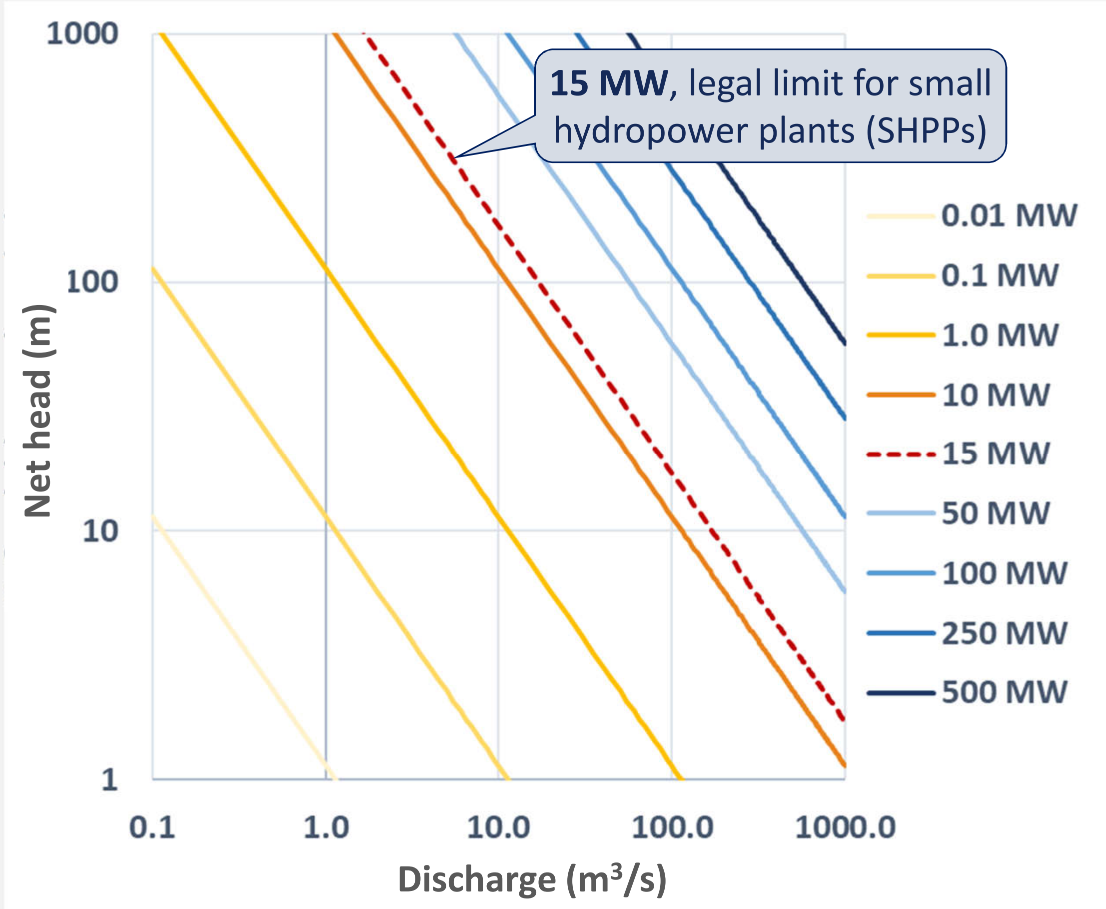
First tips on efficiency

- The efficiency of hydro turbines and rest of E/M components cannot be calculated analytically, thus being expressed in terms of **nomographs**, derived through laboratory measurements.
- The turbine efficiency is maximized at the so-called **nominal discharge**, which in general differs (it is little smaller) from their discharge capacity.
- As result of storage, the operators of **large hydroelectric reservoirs** can regulate the flow provided to the turbines, thus operating them around their nominal discharge, which in turn ensures a practically constant efficiency of the order of $\eta = 90\%$ (*higher than any other energy source, either conventional or renewable, which is converted into electricity*).
- In contrast, in the **absence of storage capacity** (e.g., run-off-river small hydropower plants), the flow passing through the turbines is uncontrolled, thus the efficiency exhibits significant variability (depending on turbine type).



Setting the design problem

- Hydroelectric systems can be classified in terms of **installed capacity** (micro, mini, ordinary hydro), in terms of **head** (low, medium, high) or in terms of **operative mode** (storage, run-off-river, pumped-storage).
- Overall objective is to maximize the product of **water availability** and **net head**, through a suitable siting and sizing of the individual elements of the system.
- Regarding the generic layout of works, multiple options may exist, drastically depending on the formulation of not of a **storage component**.
- The combination of Q and H also dictates the selection of the **turbine types**.



Major design questions

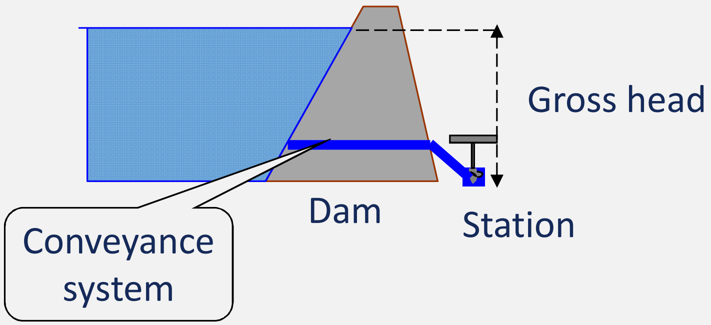
- Regarding the sitting of the **power station** alternative options may exist:
  - close to the dam foot (typical configuration of large hydroelectric systems, where the head is determined by the dam elevation);
  - away of the dam/intake, by diverting the flow to a downstream location of the river (increase of elevation difference vs. increase of diversion length);
  - in a neighboring basin (case of diversion hydroelectric dam).
- For a given layout of the hydropower system, major design quantities to determine are:
  - the **type**, **number** and total **power capacity** of turbines (often configured as a mixing of individual nominal power values);
  - the **discharge capacity** of the conveyance system, depending on its geometrical and hydraulic characteristics (head, length, diameter, roughness);
- The design of the **conveyance system** is also subject to two conflicting criteria, i.e., minimization of hydraulic losses vs. minimization of cost (decreasing and increasing functions of diameter, respectively).
- In general, the acceptable **ratio of hydraulic losses** with respect to gross head ranges within 2 up to 5%.

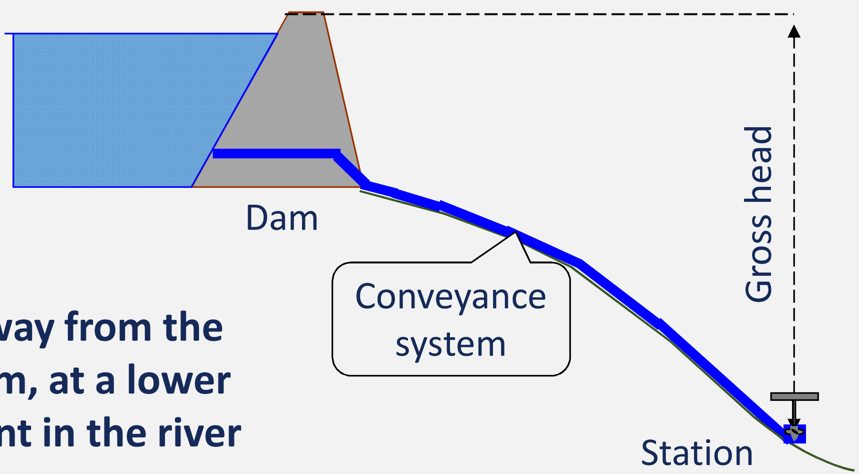
Hydroelectric reservoirs

- The artificial lake (reservoir) is created by constructing a dam on a river, also equipped with a series of ancillary structures (spillway, intakes, control gates, etc.).
- The reservoir **regulates** the hydrological inflows produced over the upstream river basin, which are stochastic processes that exhibit significant variability across all temporal scales (from the flood event scale to the seasonal one, and up to the multi-annual scale).
- The regulation offered by the storage, and the ratio of usable water to the available one (i.e., mean annual runoff, produced over the upstream river basin) depend on the **useful storage capacity** of the reservoir; this is determined by the elevations of the intake and the spillway (minimum and maximum operational levels, respectively), and the geometrical properties (relief) of the impoundment area.
- The output power is determined by the **reservoir level**, which varies within its feasible range, following the variability of inflows and outflows, and the **regulated outflows** through the turbines.
- As the outflows are regulated, the operator can assign a **long-term scheduling of hydropower generation**. Under normal conditions, the turbines are activated during specific time periods (e.g., during peak hours) and operate close to their nominal capacity, thus also ensuring a **constant (and near maximum) efficiency**.

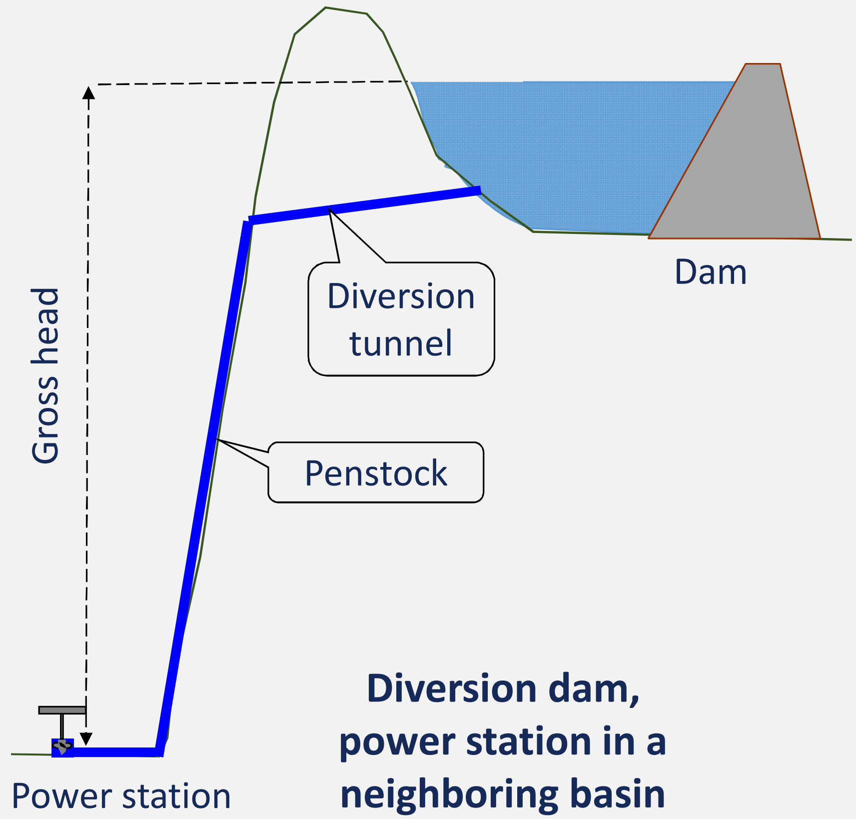
Siting of power station with respect to the dam

Close to the dam foot (head ≈ dam height)





Away from the dam, at a lower point in the river



Diversion dam, power station in a neighboring basin

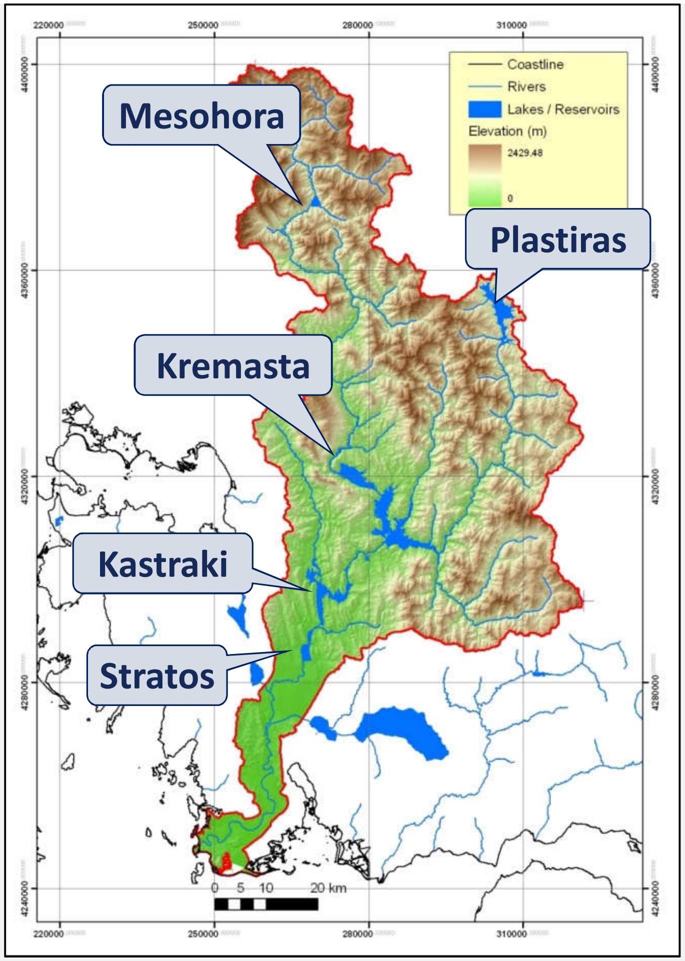
Examples of hydroelectric reservoirs: Kremasta @ Achelous (437.2 MW)

- Highest (earth) dam of Greece (165 m)
- Overannual regulation (head dam of Achelous hydropower complex)
- Total storage capacity: 4000 hm^3; useful capacity: 3300 hm^3
- Underground power station; 4 Francis turbines of 109.3 MW

Examples of hydroelectric reservoirs: Kastraki @ Achelous (320 MW)

- Weekly regulation (intermediate dam of Achelous complex)
- Total storage capacity: 950 hm^3; useful capacity: 50 hm^3 (+ 50 hm^3)
- Surface penstocks; 4 Francis turbines of 80 MW

Source: https://riverviewproject.gr/o-topos-mas/fragmata/

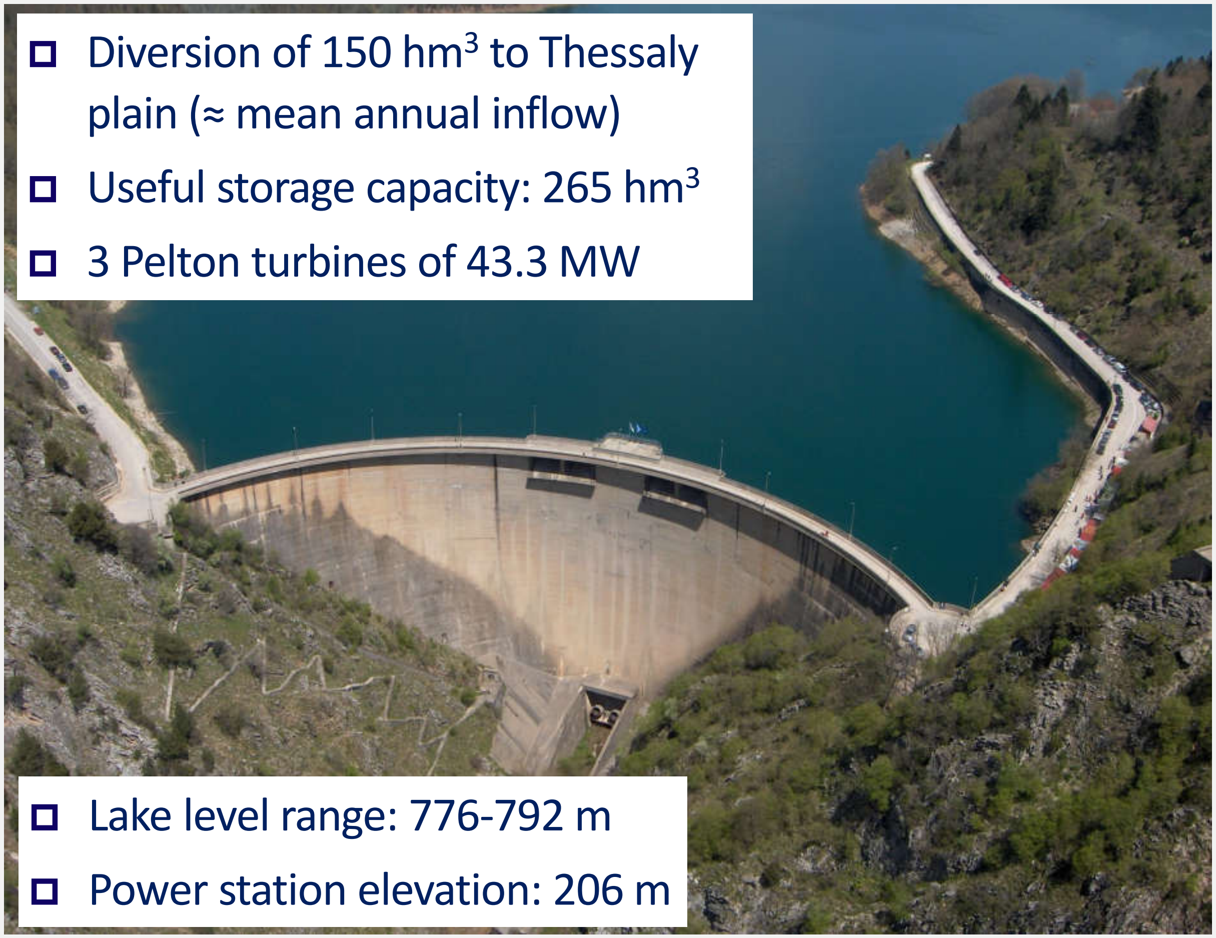


Examples of hydroelectric reservoirs: Sfikia @ Aliakmon (315 MW)

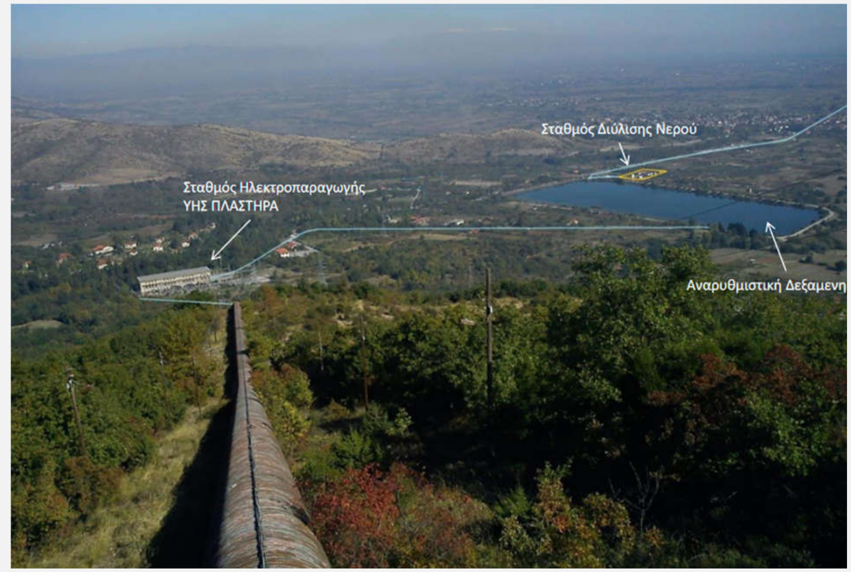
- Daily regulation (intermediate dam of Aliakmon complex)
- Pumped storage project, using as lower basin the downstream reservoir at Asomata
- Total storage capacity: 99 hm^3; useful capacity: 18 hm^3
- 3 reversible Francis turbines of 105 MW (108 MW in pumping)

Source: DEI, personal communication

Examples of hydroelectric reservoirs: Plastiras @ Achelous (129.9 MW)



- Diversion of 150 hm^3 to Thessaly plain (≈ mean annual inflow)
- Useful storage capacity: 265 hm^3
- 3 Pelton turbines of 43.3 MW
- Lake level range: 776-792 m
- Power station elevation: 206 m



Preliminary design of storage hydropower systems

- Estimation of **usable water potential**, V_a, at the dam location, on mean annual basis, by subtracting from the mean annual inflow the hydrological losses (due to evaporation, leakages, and spills) and the water provided to other users, without passing through the turbines.
- Estimation of **mean gross head**, H, by considering a representative reservoir level between its minimum and maximum value, and next subtracting the elevation of the power station.
- Estimation of **mean annual energy production**, E_a, by considering a reasonable value of net head and efficiency (equivalently, assignment of a proper value of specific energy, e.g. $\psi = 0.0023$ GWh/hm^4).
- Selection of **annual hours of operation**, T_a, according to the project's role in the electricity mix (for base energy production 4000-5000 hours, for peak energy 1500-1800 hours).
- Estimation of **nominal power capacity** of turbines (E_a in GWh, T_a in h, P_{max} in MW):

$$P_{max} = 1000\ E_a/T_a$$

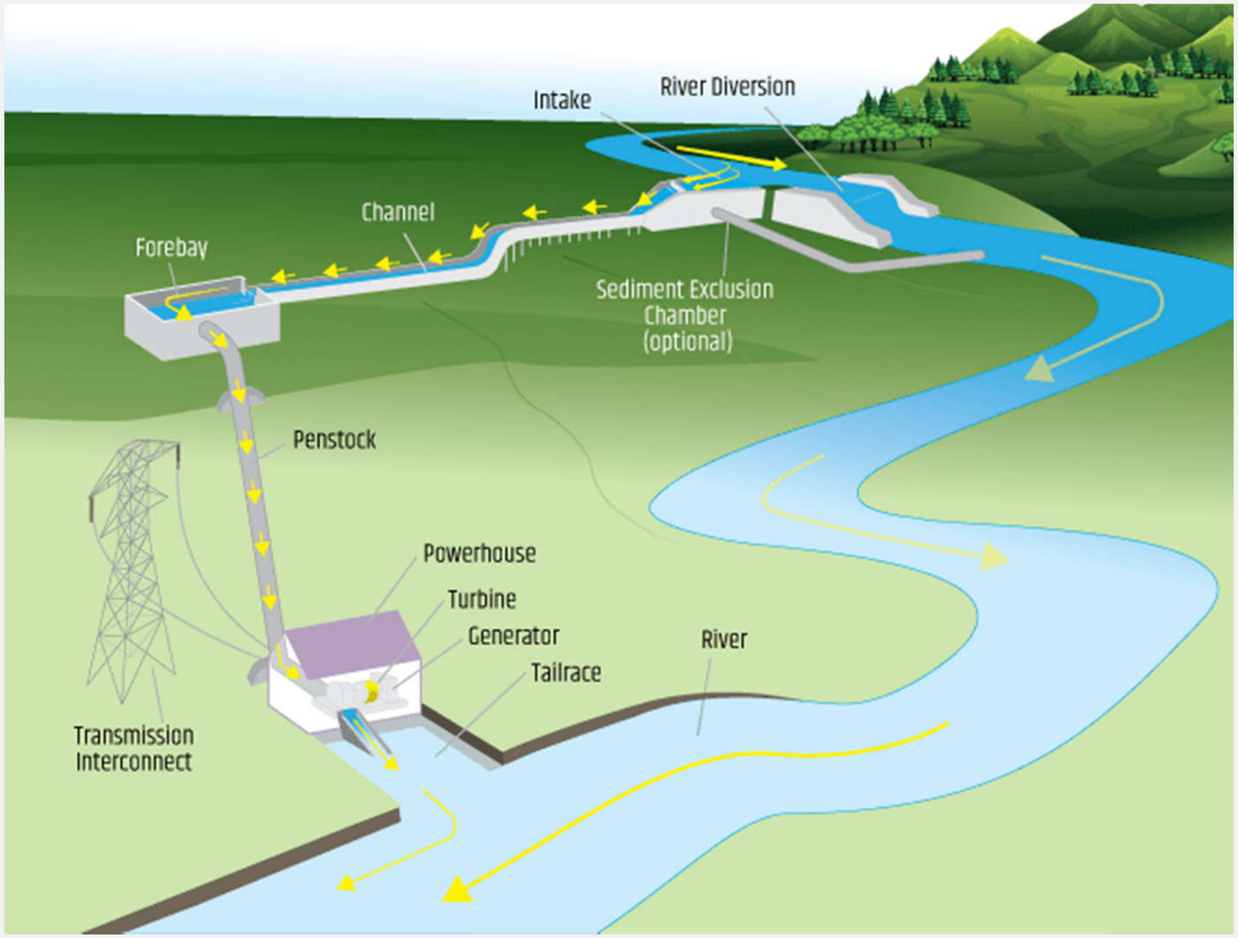
- Estimation of **discharge capacity** of conveyance system (V_a in hm^3, T_a in h, Q_{max} in m^3/s):

$$Q_{max} = 1000\ V_a/3.6\ T_a$$

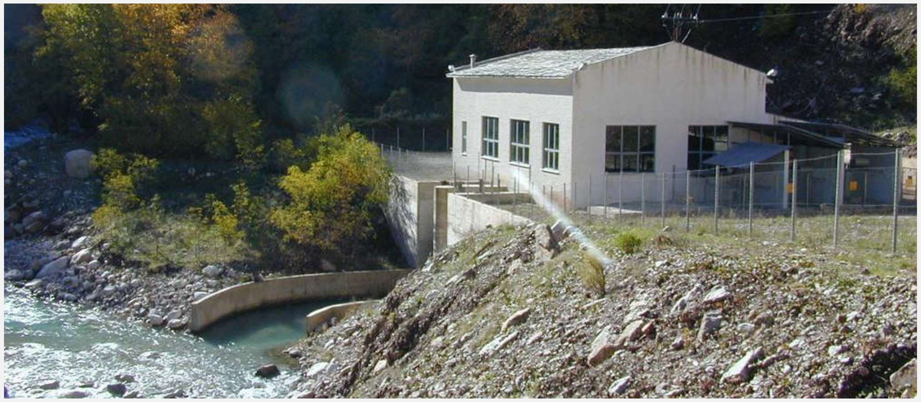
- This procedure is only valid for large hydroelectric reservoirs, offering sufficient regulation capacity.

Small hydropower plants (SHPPs)

- From a **technical perspective**: hydropower systems with zero or very limited storage capacity, thus offering negligible regulation of arriving flows.
- Due to the **lack of regulation**, the design and operation of SHPPs differs substantially from conventional hydroelectric reservoirs, since the power production is just a **direct conversion of the arriving streamflow** (similarly to wind and solar works).
- From a **legal perspective**: hydropower systems with total power capacity less than a specific limit (15 MW in Greece; SHPPs are considered as *renewables*).



Example of run-of-river SHPP: Theodoriana @ Gkoura stream (1.98 MW)



Example of in-stream SHPP: Dafnozonara @ Achelous (8.5 MW)

SHPPs in regulating dams: Pournari II @ Arachthos (33.6 MW)

SHPPs in channels: Gkiona @ Mornos aqueduct (8.67 MW)