Pumped storage hydropower

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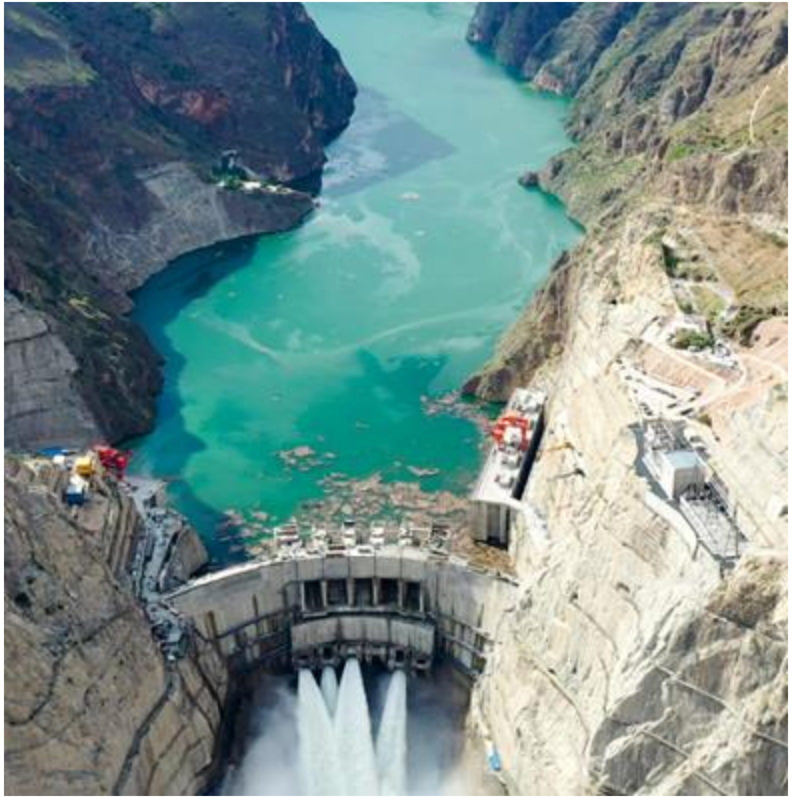
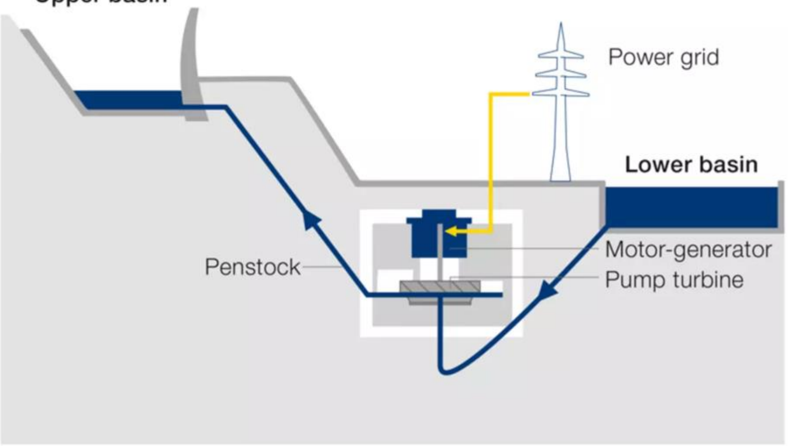


Introduction

- Pumped Storage Hydropower (PSH) is a type of hydropower that stores and generates electricity by using gravitational potential energy of the water
- At times of low demand and low electricity prices, the water is pumped to the higher reservoir
- At times of high demand and higher prices, the water is then released to drive a turbine in a powerhouse and supply electricity to the grid
- The energy storage capacity of a pumped hydro facility depends on the size of its two reservoirs, while the amount of power generated is linked to the size of the turbine.

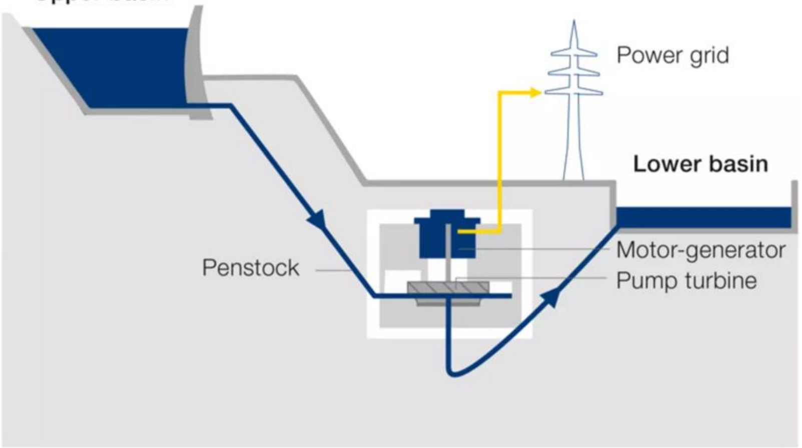
PSH operating principle

Pump operation



- Power from the grid is used to operate the electric motor
- The electric motor powers the pump turbine
- The water is pumped from the lower basin to the upper basin

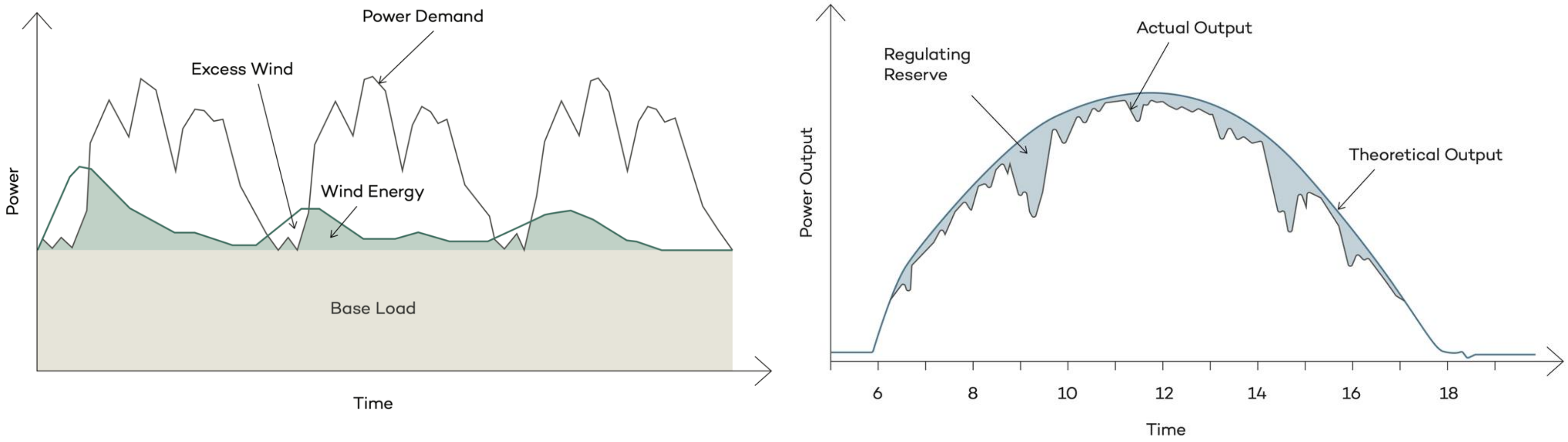
Turbine operation



- Water flows from the upper basin through a penstock to the turbine
- The turbine powers the generator, producing electricity for the grid
- The water is discharged into the lower basin.

The role of PSHs in enhancing grid flexibility

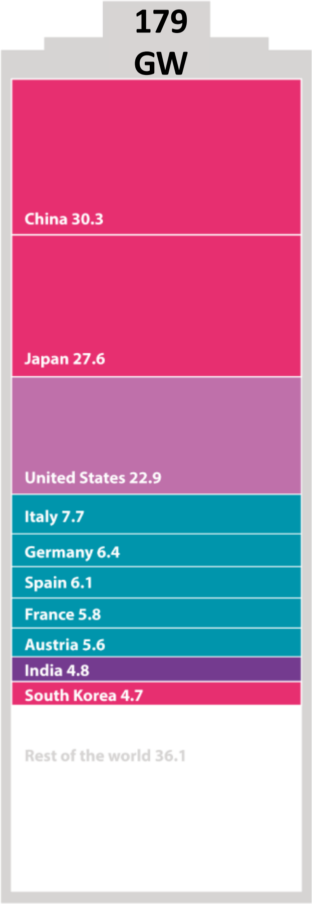
- PSHs can help mitigate the variability of renewable energy sources by providing regulating capacity to match power consumption
- Additionally, they balance the load in the system, absorbing energy during off-peak hours and meeting demand in peak times.



Source: [1] Pumped Storage Systems reliable & economical, *afry.com*

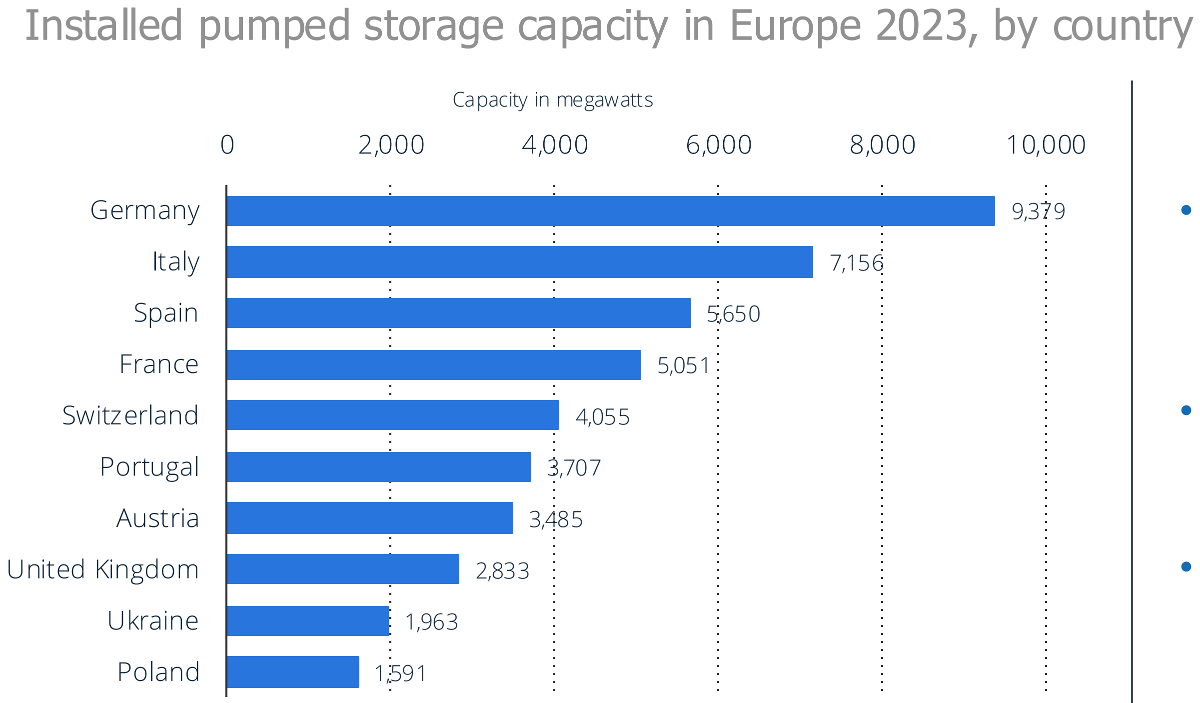
Global pumped storage installed capacity

- In 2024, PSH accounted for over 90% of installed global energy storage capacity and over 92% of energy stored in grid scale applications.
- The total installed capacity is around 179 GW
- PSH storage capacity is expected to increase by 50% to about 240 GW by 2030
- Locations and data for existing and planned PSH projects: here



Source: [2] International Hydropower Association, *hydropower.org/statusreport*

Cumulative installed PSH capacity in Europe in 2023, by country (in MW)



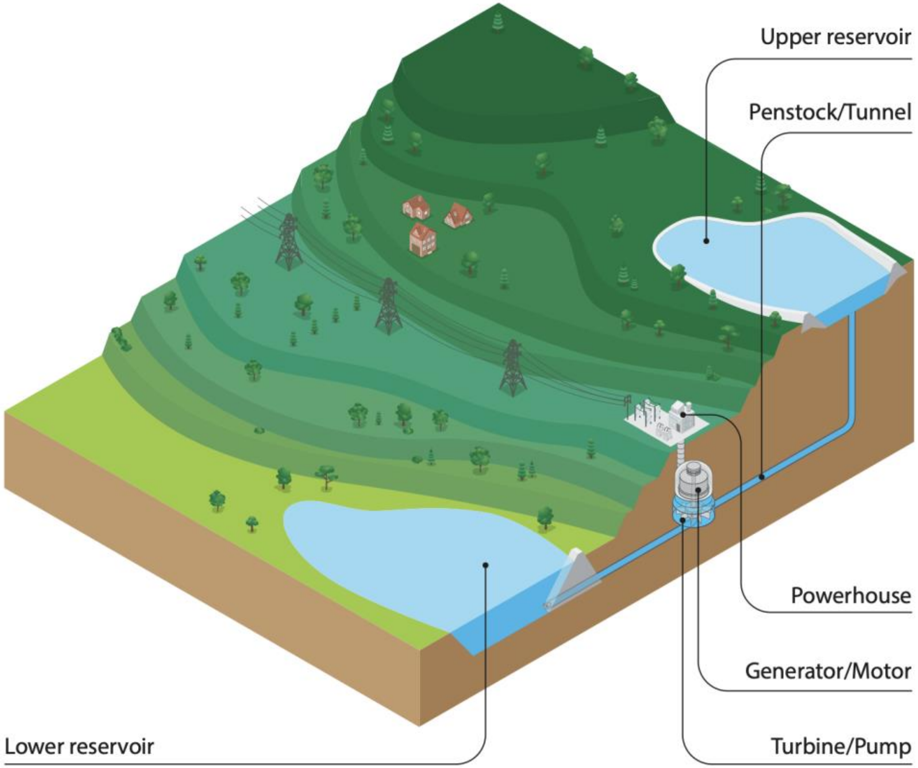
- The EU hosts 46 GW of PHS capacity, which is a quarter of the global installed capacity
- The 1.8 GW Grand' Maison PSH in the French alps is the largest PSH in Europe
- Switzerland is a leader in PSH with several high-capacity plants, including the 900 MW Nant de Drance

statista **Source:** [3] International Hydropower Association; ID 690032

Types of pumped-hydro

There are two main types of pumped-hydro:

- **Open-loop:** with either an upper or lower reservoir that is continuously connected to a naturally flowing water source such as a river.
- **Closed-loop:** an 'off-river' site that produces power from water pumped to an upper reservoir without a significant natural inflow

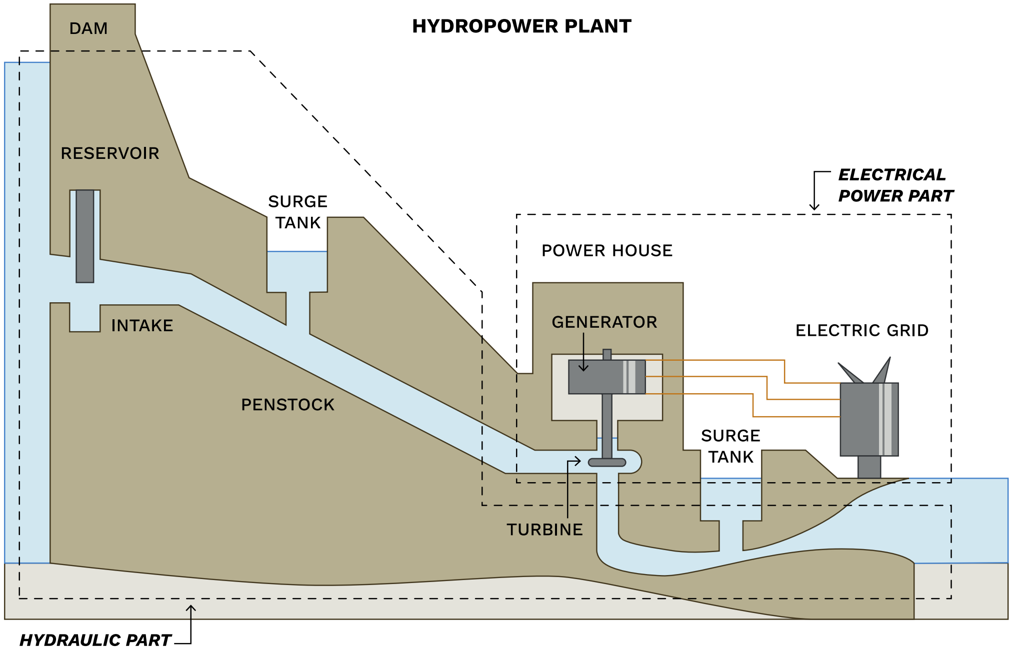


Source: [4] Enabling new pumped storage hydropower: A guidance note for key decision makers to de-risk pumped storage investments, *hydropower.org/pubblications*

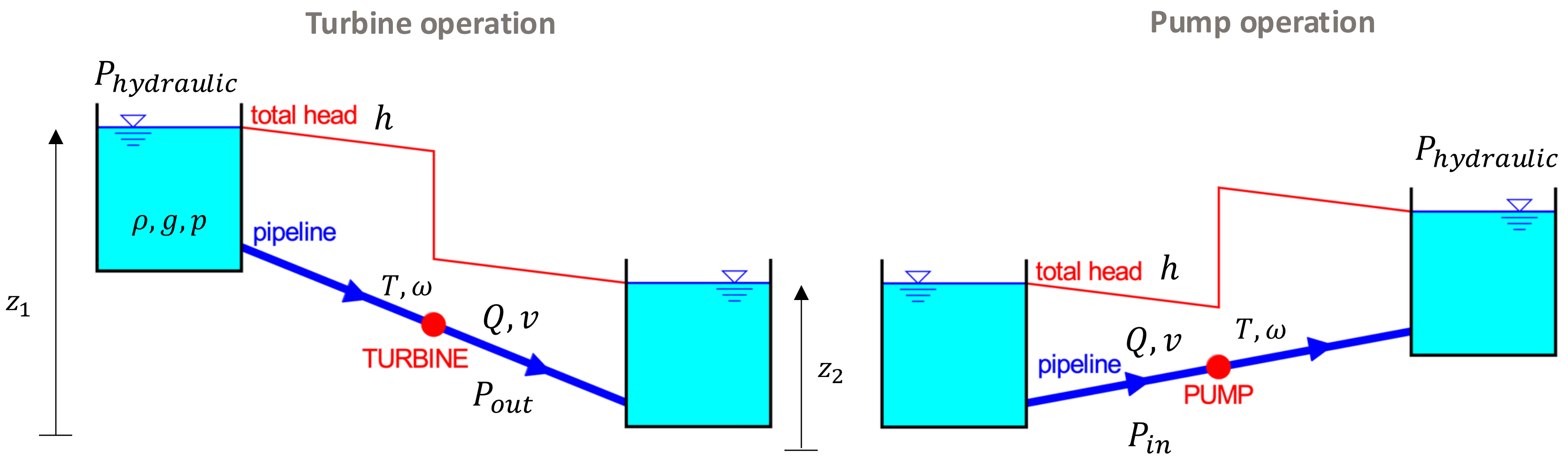
Components of a PSH

The main components of a PSH are:

- **Dam:** a barrier that stops or restricts the flow of surface
- **Reservoir:** an enlarged lake behind a dam built to store water
- **Penstock:** open or closed channel to flow the water from the reservoir to the turbine
- **Surge tank:** cylindrical tank open at the top to control the pressure in penstock
- **Pump/Turbine:** convert the hydraulic energy of the water into the mechanical energy or pump the water upstream
- **Power house:** building provided to protect the hydraulic and electrical equipment such as the **generator**



Hydraulic and mechanical quantities



where:

- v is the fluid flow speed [m/s]
- g is the gravity acceleration [m/s2]
- z is the elevation of the point above a reference plane [m]
- p is the pressure at the chosen point [Pa]
- ρ is the density of the fluid at all points in the fluid [kg/m3]
- Q is the flow rate = fluid flow speed x section of the tube [m3/s]

- T is the mechanical torque [Nm]
- ω angular speed [rpm]

Energy conversion

Energy balance

$$E_{tot} = E_{pressure} + E_{potential} + E_{kinetic}$$

Pressure energy = work done to lift a fluid column due to pressure

$$E_{pressure} = p \cdot V$$

where V is the volume

Potential energy = energy held by a mass because its elevation

$$E_{potential} = mgz$$

Kinetic energy = energy held by a mass due to its motion

$$E_{kinetic} = \frac{1}{2} m v^2$$

In terms of **Head, h** (energy per unit weight = $E/_{mg}$) in meters:

$$h = \frac{E_{tot}}{mg} = \frac{p}{\rho g} + z + \frac{v^2}{2g}$$

Pressure head **Elevation head** **Velocity head**

Power in turbine and pump modes

Hydraulic power = Energy / time

$$P_{hydraulic} = \frac{E_{tot}}{t} = \frac{m}{t} gh = \rho g Q h$$

where $\frac{m}{t} = \rho Q \left[\frac{kg}{\cancel{m^3}} \cdot \frac{\cancel{m^3}}{t}\right]$

Power balance in turbine mode:

$$P_{hydraulic} = P_{electric} + P_{losses} = P_{electrical} + P_{penstock,loss} + P_{turbine,loss} + P_{generator,loss}$$

Power balance in pump mode:

$$P_{hydraulic} = P_{electric} + P_{losses} = P_{electrical} + P_{penstock,loss} + P_{pump,loss} + P_{motor,loss}$$

Efficiency in turbine and pump modes

Overall efficiency in turbine mode, η:

$$\eta = \frac{P_{electric}}{P_{hydraulic}} = 1 - \frac{P_{losses}}{\rho g Q \mathrm{h}} = \eta_{penstock} \cdot \eta_{turbine} \cdot \eta_{generator}$$

Overall efficiency in pump mode, η:

$$\eta = \frac{P_{ydraulic}}{P_{electric}} = 1 - \frac{\rho g Q \mathrm{h}}{P_{losses}} = \eta_{penstock} \cdot \eta_{pump} \cdot \eta_{motor}$$

Turbine efficiency, $\eta_{turbine}$:

$$\eta_t = \frac{P_{out}}{P_{in}} = \frac{P_{mech}}{\rho g Q \mathrm{h}} = \frac{T \cdot \omega}{\rho g Q \mathrm{h}}$$

Pump efficiency, η_{pump}:

$$\eta_p = \frac{\rho g Q h}{P_{mech}} = \frac{\rho g Q h}{T \cdot \omega}$$

Penstock efficiency, $\eta_{penstock}$:

$$\eta_{penstock} = \frac{P_{hydraulic,out}}{P_{hydraulic}}$$

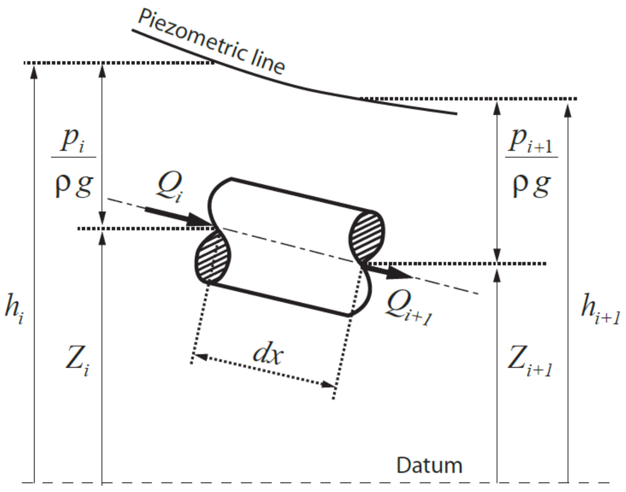
Penstock losses

Head loss h_f due to friction (Darcy-Weisbach equation)

$$h_f = f \cdot \frac{L}{D} \cdot \frac{v^2}{2g}$$

where:

- f is the Darcy friction factor
- D is the penstock's diameter
- L is the penstock's length



Penstock efficiency, $\eta_{penstock}$:

$$\eta_{penstock} = \frac{P_{hydraulic,out}}{P_{hydraulic}} = \frac{\rho g Q(h - h_f)}{\rho g Q h}$$

Types of hydraulic machines (1/2)

$$h = \frac{p}{\rho g} + z + \frac{v^2}{2g}$$

Impulse turbines:

Fluid's kinetic energy converted to mechanical work at the atmospheric pressure

- Change in velocity → Change in head

Reaction turbines:

Both fluid's kinetic and potential energy is converted to mechanical work

- Change in pressure → Change in head

Types of hydraulic machines (2/2)

The most common hydraulic machines used in hydropower plants are:

- **Pelton turbine** (impulse turbine)
  - very high head
  - nozzle

- **Francis pump-turbine** (reaction turbine)
  - medium head
  - reversible machines

- **Kaplan turbine** (reaction turbine)
  - low head
  - double control system

1-D Modelling of hydraulic circuits (1/2)

The governing equations are the continuity of mass and momentum:

$$\frac{\partial h}{\partial t} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} = 0$$

$$\frac{\partial h}{\partial x} + \frac{1}{gA}\frac{\partial Q}{\partial t} + \underbrace{\frac{f|Q|}{2gA^2D}Q}_{\text{friction losses}} = 0$$

with state variables

h : Head

Q : Volumetric flow rate

parameters and constant

A : Pipe cross-sectional area

D : Pipe internal diameter

f : Friction factor

a : Speed wave (or celerity)

g : Acceleration of gravity

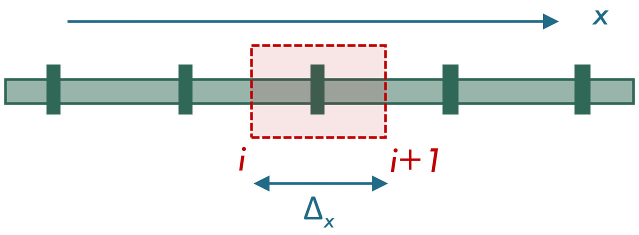
ρ : Water density

1-D Modelling of hydraulic circuits (2/2)

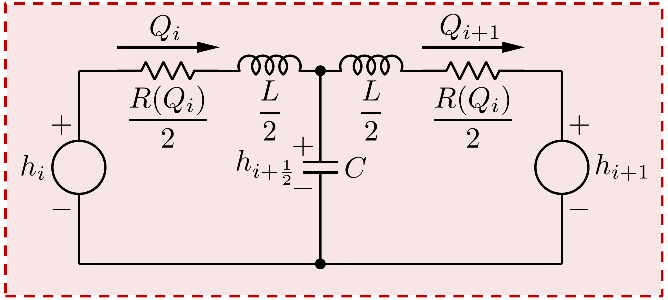
Spatial discretization

$$\left.\frac{\partial h}{\partial x}\right|_{i+\frac{1}{2}} = \frac{h_{i+1} - h_i}{\Delta_x}$$

$$\left.\frac{\partial Q}{\partial x}\right|_{i+\frac{1}{2}} = \frac{Q_{i+1} - Q_i}{\Delta_x}$$



Electrical equivalent circuit



$$\begin{cases} \dot{h}_{i+\frac{1}{2}} = \frac{1}{C}(Q_i - Q_{i+1}) \\ h_{i+\frac{1}{2}} = \frac{L}{2}\dot{Q}_i + \frac{R}{2}Q_{i+1} - h_i \\ h_{i+\frac{1}{2}} = \frac{L}{2}\dot{Q}_{i+1} + \frac{R}{2}Q_{i+1} + h_{i+1} \end{cases}$$

where:

$$C \triangleq \frac{gA}{a^2}\Delta_x$$

$$L \triangleq \frac{1}{gA}\Delta_x$$

$$R(Q) \triangleq \frac{\lambda|Q|}{2gA^2D}\Delta_x$$

1-D Modelling of hydraulic machines (1/2)

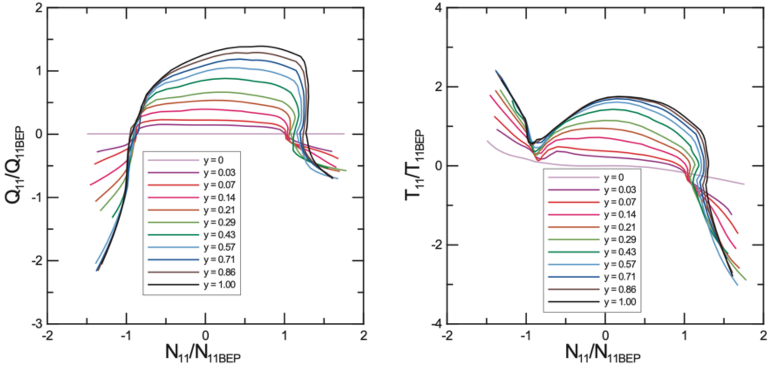
- **Quasi-static model:** The transient behavior of the hydraulic machines can be simulated as a succession of different steady-state operating points

- **Characteristic curves:** capture the relation between the machine state variables (e.g., specific energy (gh), torque, rotational speed, flow, guide vane opening)

1-D Modelling of hydraulic machines (2/2)

To display the characteristic curves it is convenient to eliminate one of the state by means of the **hydraulic machine similitude laws:**

$$N_{11} = \frac{N \cdot D_{ref}}{\sqrt{(E/g)}} \quad ; \quad Q_{11} = \frac{Q}{D_{ref}^2 \cdot \sqrt{(E/g)}} \quad ; \quad T_{11} = \frac{T}{D_{ref}^3 \cdot E/g}$$



Volumetric flow (left) and torque (right) characteristic curves of a Francis pump/turbine

The S-shape between the 1st and 4th quadrant leads to numerical troubles for the numerical tractability

Polar representation

Source: [5] C. Nicolet, "Hydroacoustic modelling and numerical simulation of unsteady operation of hydroelectric systems"

Polar representation of a Francis machine

Hes·so // VALAIS WALLIS

The **pressure source H** of the model is directly driven from the turbine characteristic $W_H(y,\theta(Q,N))$:

$$W_H(\theta) = \frac{H/H_{BEP}}{(Q/Q_{BEP})^2 + (N/N_{BEP})^2}$$

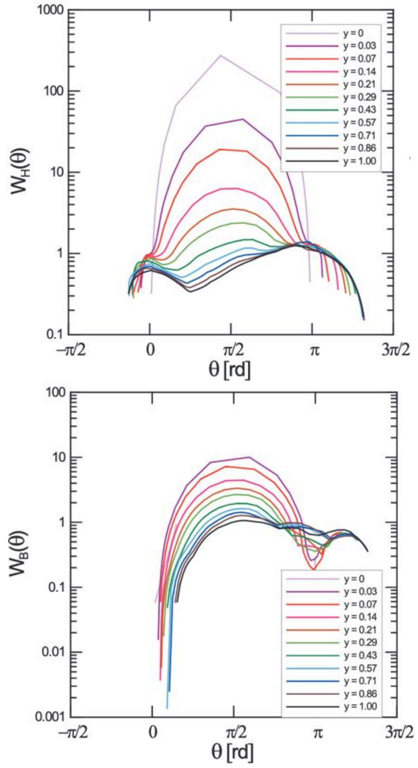
→ Best Efficiency Point

The **mechanical torque T** of the pump-turbine is obtained from the torque characteristic$W_B(y,\theta(Q,N))$:

$$W_B(\theta) = W_H(\theta) \cdot \frac{T_{11}}{T_{11BEP}} = \frac{T/T_{BEP}}{(Q/Q_{BEP})^2 + (N/N_{BEP})^2}$$

The **turbine rotational speed** ω is according to the momentum equation applied to the rotational inertias:

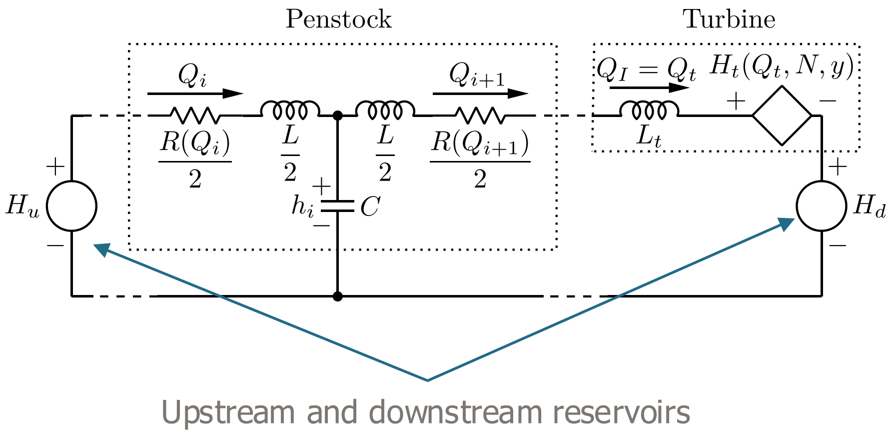
$$J \cdot \frac{d\omega}{dt} = \sum T_{ext} = T_{turb} - T_{elect}$$



Polar representation

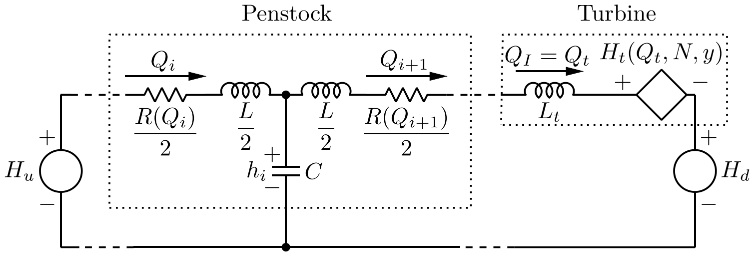
Equivalent circuit model of hydropower plants

Equivalent circuit model (ECM) of the complete plant obtained by combining the penstock model, turbine model, and reservoirs



State-space representation

Equivalent circuit model → State-Space representation



$$\dot{X} = A \cdot X + B \cdot u$$

$$\dot{X} = \begin{bmatrix} \frac{-R}{L} & 0 & \frac{-1}{L} & 0 \\ 0 & \frac{-R}{L} & \frac{1}{L} & 0 \\ \frac{1}{C} & \frac{-1}{C} & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} Q_1 \\ Q_2 \\ H_c \\ \omega \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 & 0 \\ 0 & \frac{-1}{L} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{1}{J} \end{bmatrix} \begin{bmatrix} H_u \\ H_t - H_d \\ T_t + T_{el} \end{bmatrix}$$

H_t and T_t are obtained from W_H and W_B from the polar representation

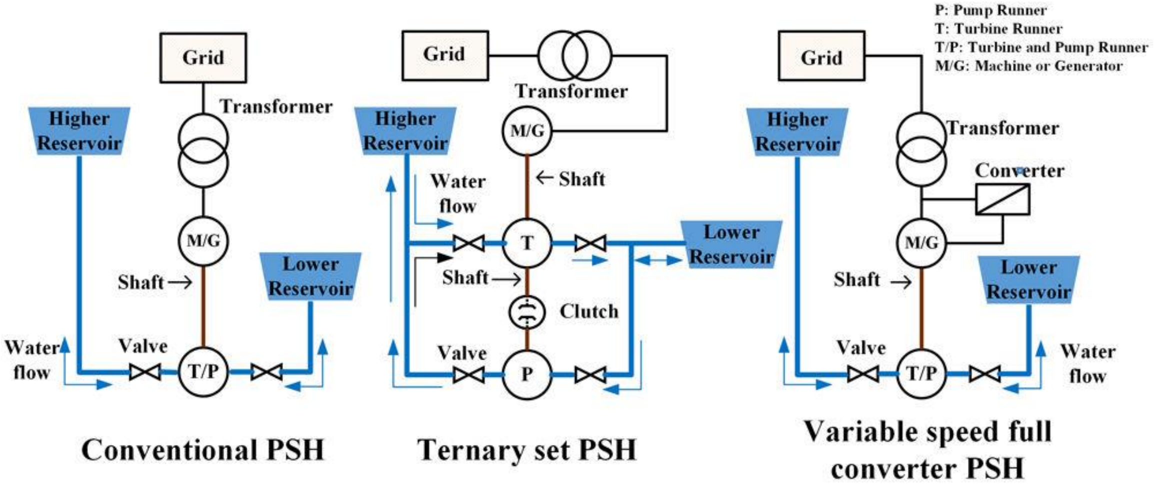
Numerical integration: Runge-Kutta 4th order

Sources: [5] S. Cassano and F. Sossan, "Stress-informed control of medium- and high-head hydropower plants to reduce penstock fatigue"
[6] C. Nicolet, "Hydroacoustic modelling and numerical simulation of unsteady operation of hydroelectric systems"

Pumped storage technologies

The pumped storage technologies can be grouped into three categories:

1. Conventional PSH
2. Tertiary set PSH
3. Variable-speed PSH



Sources: [7] Z. Dong et al., "Modeling and Simulation of Ternary Pumped Storage Hydropower for Power System Studies"

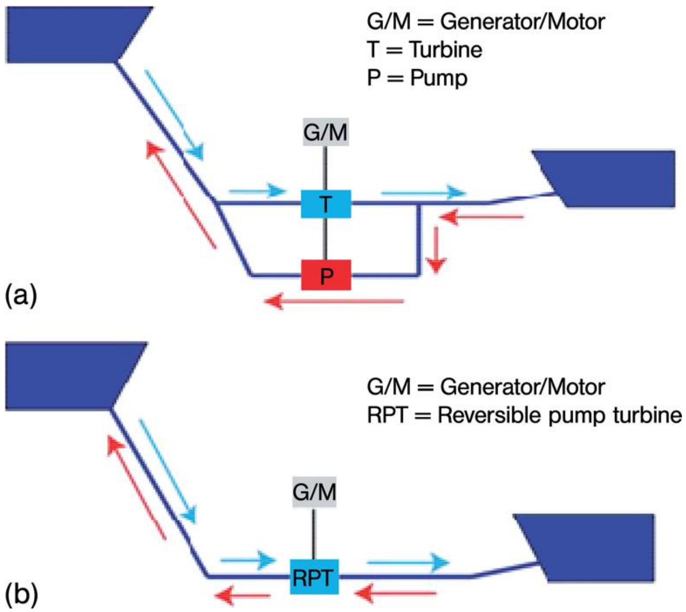
Conventional PSH

Typical layout consists in:

1. install two separate aggregates, one pump and one turbine, or
2. use a machine that runs both ways (reversible pump turbines (RPTs))

PSH are characterized by:

- long lifetime expectancy (typically between 50 and 100 years)
- a round-trip efficiency of 70–80%
- fast response time in the order of seconds or minutes.



Sources: [8] A. Harby et al., "Pumped Storage Hydropower"

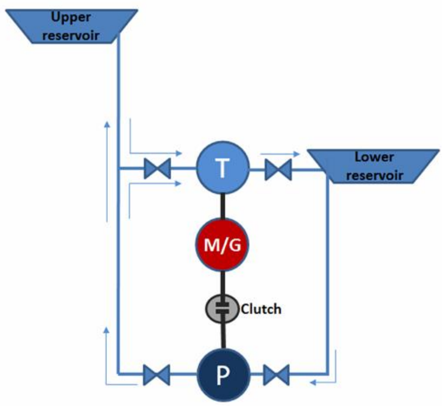
Tertiary set PSH

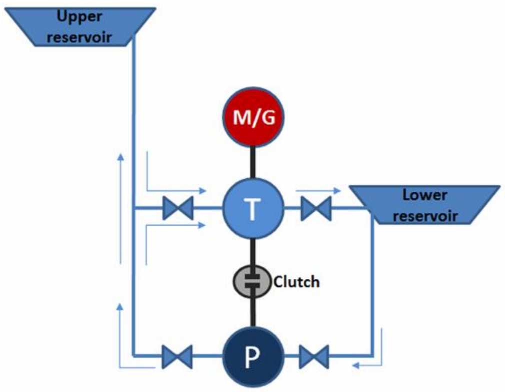
Tertiary set consist of a motor-generator, a separate turbine (e.g., Francis or Pelton) and a pump set

Typical layout consists in:

1. vertical shaft and the motor-generator located between the turbine and the pumps
2. motor-generator located at the top, above both the turbine and the pump

A **clutch** is inserted on the shaft above the pump to disconnect the pump during turbine operation to avoid ventilation losses in the pump

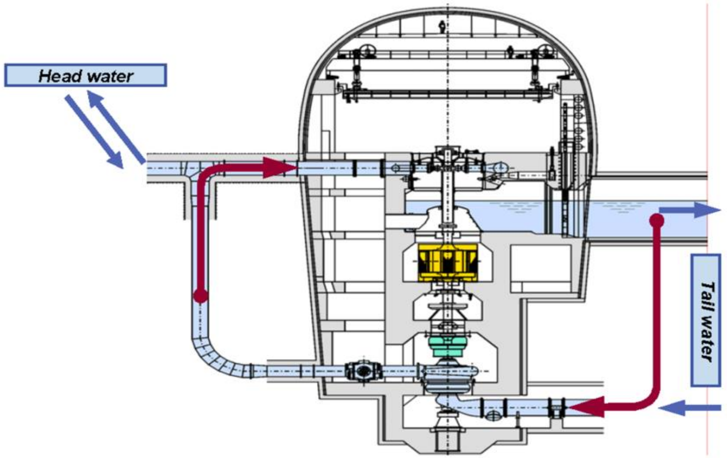




Source: [9] Modeling Ternary Pumped Storage Units, *ceeesa.es.anl.gov/projects*

Operating modes of tertiary units

- **Generating mode**: the guide vanes to the pump are closed and the clutch is not engaged. The amount of generation is controlled by the position of the turbine guide vanes.
- **Pumping mode:** the guide vanes to the turbine are closed and the clutch is enabled. The pump guide vanes are wide open and there is no regulation capability.
- **Pumping/generating mode:** the clutch is enabled and both the pump and the turbine operate

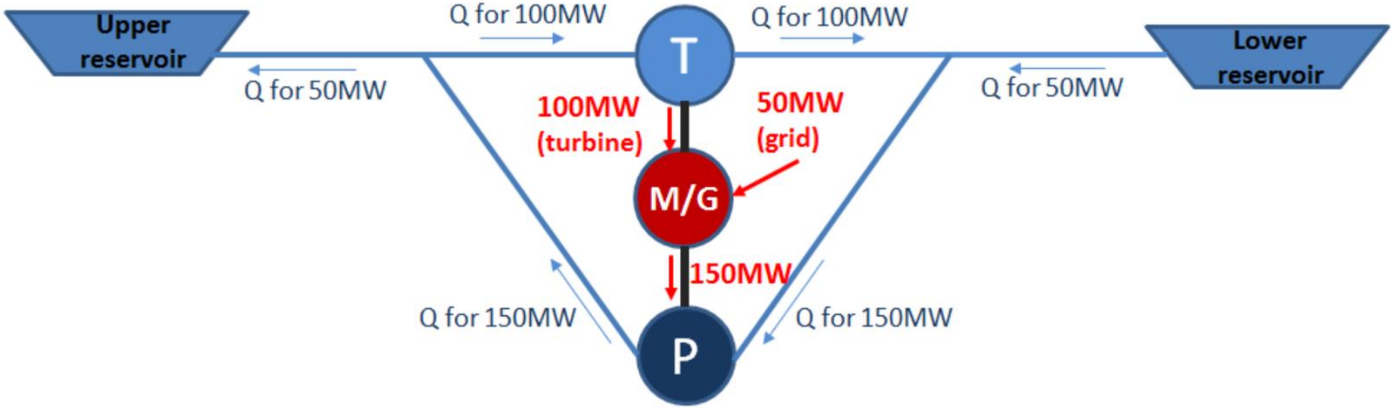


This is referred to as a **"hydraulic short circuit"**

Source: [9] Modeling Ternary Pumped Storage Units, *ceeesa.es.anl.gov/projects*

Hydraulic short circuit

Example of operation in pumping mode with regulation capability using the Hydraulic Short-Circuit concept



- The power applied to the shaft from the pump is 150 MW drawn from the power system
- The turbine guide vanes are adjusted so that the turbine supplies 100 MW to the power system
- The net result is that 50 MW is drawn from the power system, and the flow pumped up to the reservoir is equivalent to 50 MW

Source: [9] Modeling Ternary Pumped Storage Units, *ceeesa.es.anl.gov/projects*

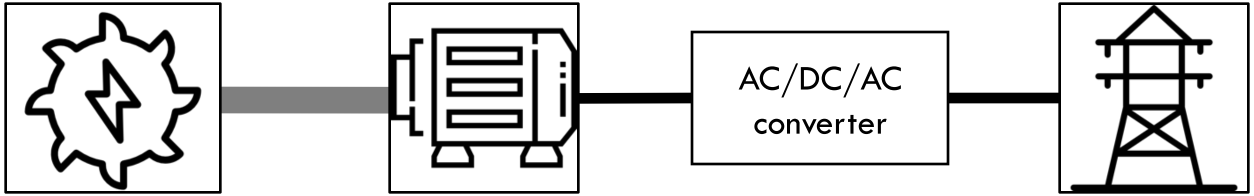
Advantages of tertiary units

Main advantages:

- Ternary plant can simultaneously operate both the pump and turbine
- The shaft rotates in the same direction in both operational mode reducing hydraulic transients and increasing the time to switch from turbine to pump mode
- Round-trip efficiency of up to 82%

Variable-speed pump turbines

The variable-speed technology allows to decouple the grid and generator frequency



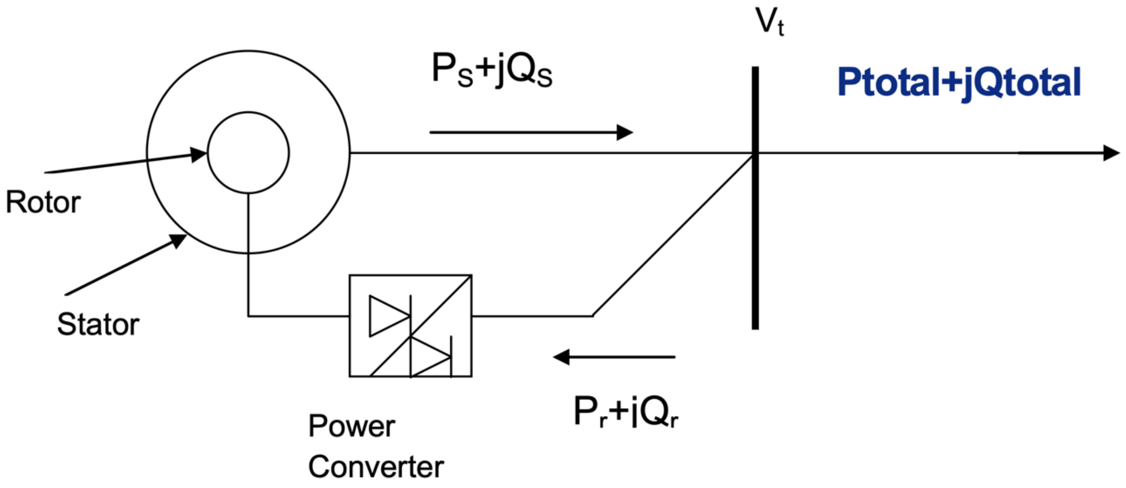
The main procedures adopted to obtain variable speed are:

- Synchronous Generator with back-to-back frequency converter
- Double-Fed Induction Generator (DFIG)

Main Advantage: the recovery of efficiency of the hydraulic turbine (almost to its rated efficiency) when working at a head lower than the design head.

DFIG working principle

- The rotor of the machine is connected to the machine's terminal through a power converter
- The power converter can control the voltage, current and frequency in the rotor circuit
- The DFIG rotor must be excited with a complement frequency to achieve the rated frequency in the stator generated voltage



Source: [10] Modeling Adjustable Speed Pumped Storage Hydro Units Employing Double-Fed Induction Machines, *ceeesa.es.anl.gov/projects*

Grand’ Maison PSH, France

- **Nominal power:** 1.8 GW with 4x 158.5 MW multi-jet Pelton turbines and 8x 154MW Francis pump-turbines
- **Energy capacity:** 1420 GWh
- **Storage capacity:** 137 millions of m^3 of water in the upper reservoir
- **Gross head:** 918 m
- **Technologies tested:** Hydraulic short circuit

Source: [11] XFLEX HYDRO, *xflexhydro.com/test-sites/grand-maison*

Nant de Derance PSH, Switzerland

- **Nominal power:** 900 MW with 6x150 MW Francis pump-turbines
- **Energy capacity:** 200 GWh
- **Storage capacity:** 25 millions of m^3 of water in the upper reservoir
- **Turbine to pump switching time:** less than 5 minutes
- **Net head:** 71.1 m

Source: [12] *https://www.nant-de-drance.ch*

References

[1] Pumped Storage Systems reliable & economical, afry.com

[2] International Hydropower Association (IHA), hydropower.org/statusreport

[3] International Hydropower Association; ID 690032

[4] Enabling new pumped storage hydropower: A guidance note for key decision makers to de-risk pumped storage investments, hydropower.org/pubblications

[5] C. Nicolet, "Hydroacoustic modelling and numerical simulation of unsteady operation of hydroelectric systems"

[6] S. Cassano and F. Sossan, "Stress-informed control of medium- and high-head hydropower plants to reduce penstock fatigue"

[7] Z. Dong et al., "Modeling and Simulation of Ternary Pumped Storage Hydropower for Power System Studies"

[8] A. Harby et al., "Pumped Storage Hydropower"

[9] Modeling Ternary Pumped Storage Units, ceeesa.es.anl.gov/projects

[10] Modeling Adjustable Speed Pumped Storage Hydro Units Employing Double-Fed Induction Machines, ceeesa.es.anl.gov/projects

[11] XFLEX HYDRO, xflexhydro.com/test-sites/grand-maison

[12] Nant de Derance website: https://www.nant-de-drance.ch

To do

1 cluch disaccoppiamento

2 turbine

3 set up grand maison

4 tutte le tecnologie disponibili

5 esercizio in matlab: didattico per spiegare bene le basi metodologiche: trovare la Potenza a partire dalla discharge etc (come il mio modello)

6 definizione di energia

7 efficienza? numeri