Renewable Energy & Hydroelectric Works

8th semester, School of Civil Engineering

2nd semester, Master's Programme "Water Resources Science & Technology"

Pumped hydropower storage

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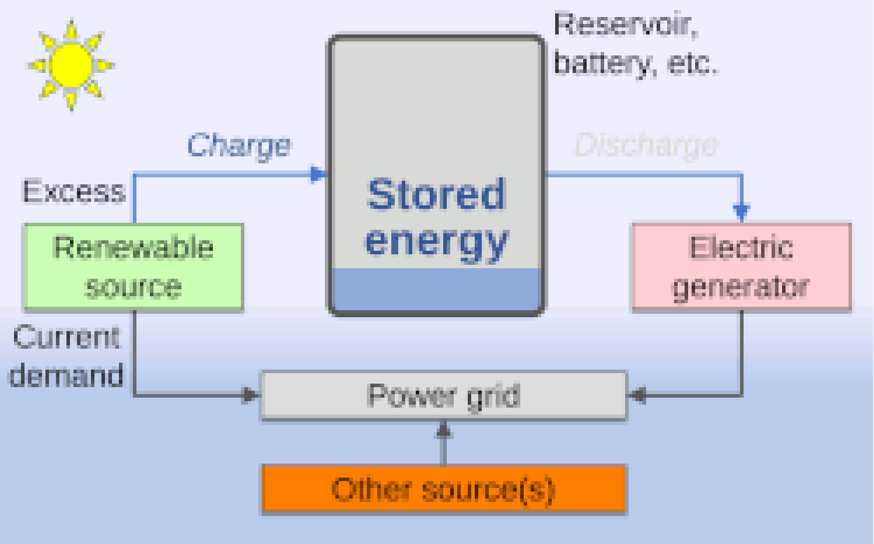
The concept of electrical energy storage (EES)

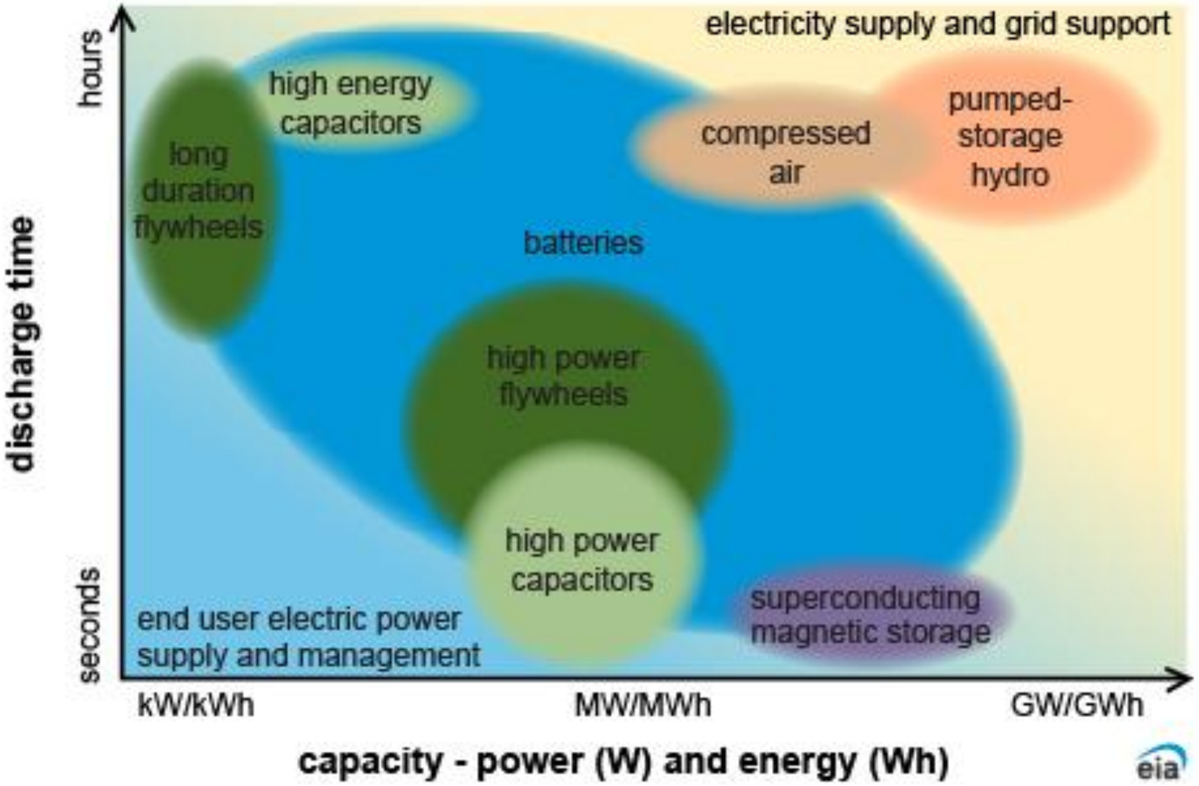
- The key idea of EES relies upon the fact that **electrical energy can be converted into other forms of energy** (chemical, mechanical, thermal, gravity) which can be permanently stored and later converted back (discharged) to generate electricity when needed, at desired levels and quality.
- **Charge-discharge cycle**: electricity to the grid → conversion & storage (charge losses) → self-discharge losses (wherever applicable) → electricity to the grid (discharge losses)
- **Power capacity**: maximum instantaneous amount of electric power that can be generated on a continuous basis
- **Energy capacity**: total amount of energy that can be stored in or discharged from the storage system
- **Round-trip (cycle) efficiency**: ratio of usable energy discharged from a EES system to the total energy required to charge it
- **Maximum depth of discharge**: percentage of total capacity that can be safely used without causing significant degradation or voiding warranties (typically applicable to batteries)



The issue of scale in EES systems

- The scale of EES systems involves two major characteristics, also determining their autonomy:
  - their size, expressed in terms of power or energy capacity;
  - the time extent of the charge-discharge cycle.
- ESSs are designed to supply electricity on **varying time scales**, which is reflected in the duration of their discharge-generation cycle length.
- Typical classification according to their usual duration and main use:
  - **Short duration**, on the scale of minutes, and power-oriented
  - **Diurnal or daily duration**, on the scale of hours, and energy-oriented

Energy storage technologies for electricity generation by type, range of capacities, and general applications



Source: U.S. Energy Information Administration, adapted from Energy Storage Association
Note: This is a general representation of the range of capacities and duration of electricity discharge for the types of energy storage technologies for electricity generation that are currently deployed in the United States. Excludes hydrogen, which potentially could encompass the entire range of capacities and discharge times. Some types, especially batteries, include technologies with a range of capacities and applications. kW is kilowatts; H is hours, MW is megawatts; GW is gigawatts.

Short-term vs. long-term storage

- **Short-term storage**:
    - Distributed power generation applications, where generation takes place close to the location of demand, which can respond to electricity demand fluctuations over short periods of time.
    - Allow for balancing grid supply and demand to improve quality and reliability, also maintaining a constant voltage in cases of dips or ripples, lasting a few seconds to minutes.
    - Typical cases: flywheels, supercapacitors, superconducting magnetic energy storage (SMES)
- **Long-term storage**:
    - Large-scale systems, charging during periods of lower electricity demand and discharging during higher demand periods
    - Peak electricity demand shaving and price arbitrage opportunities
    - Storing and smoothing renewable electricity generation by stochastic, non-controllable sources
    - Typical cases: pumped hydropower storage, electrochemical energy storage (batteries), hydrogen storage, compressed air energy storage (CAES), thermal energy storage

Schematic layout of energy storage profiles (daily cycle)

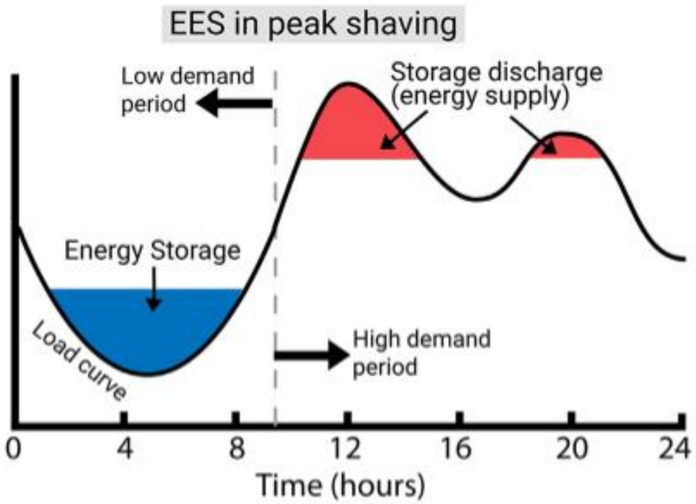
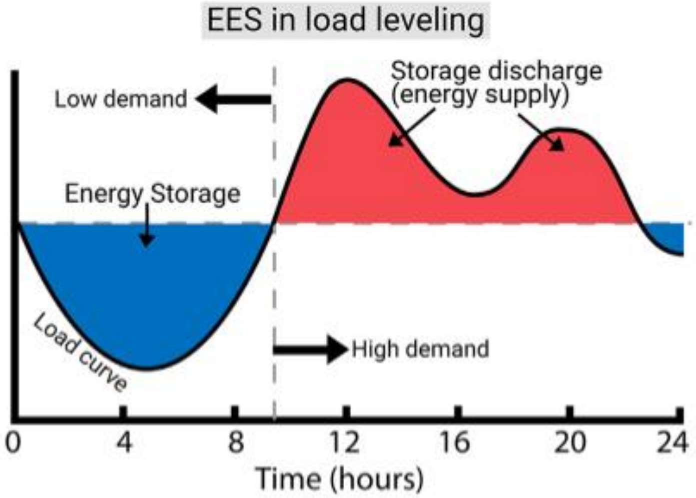
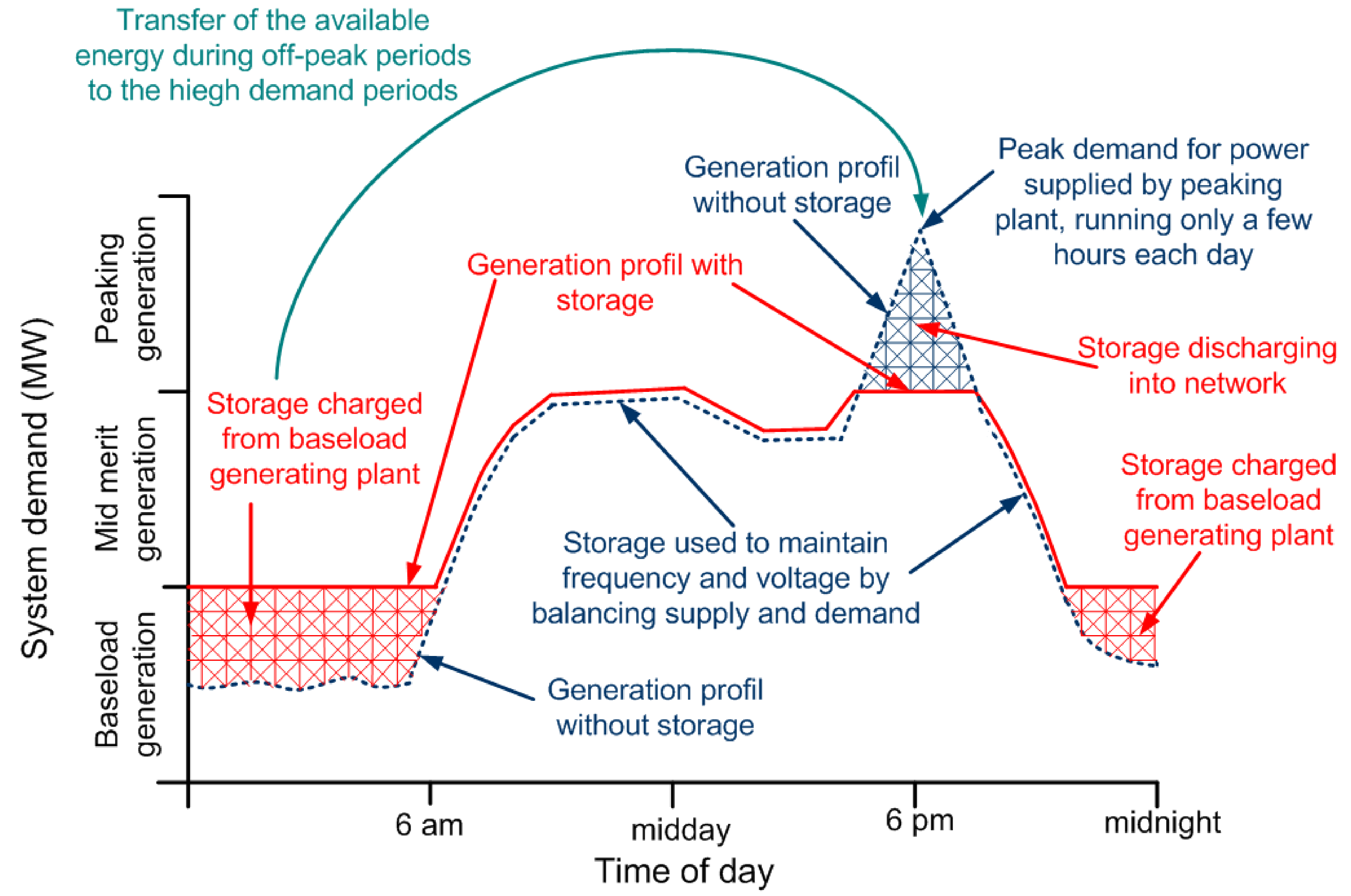


Fig. 20. Energy storage load profile in peak shaving.



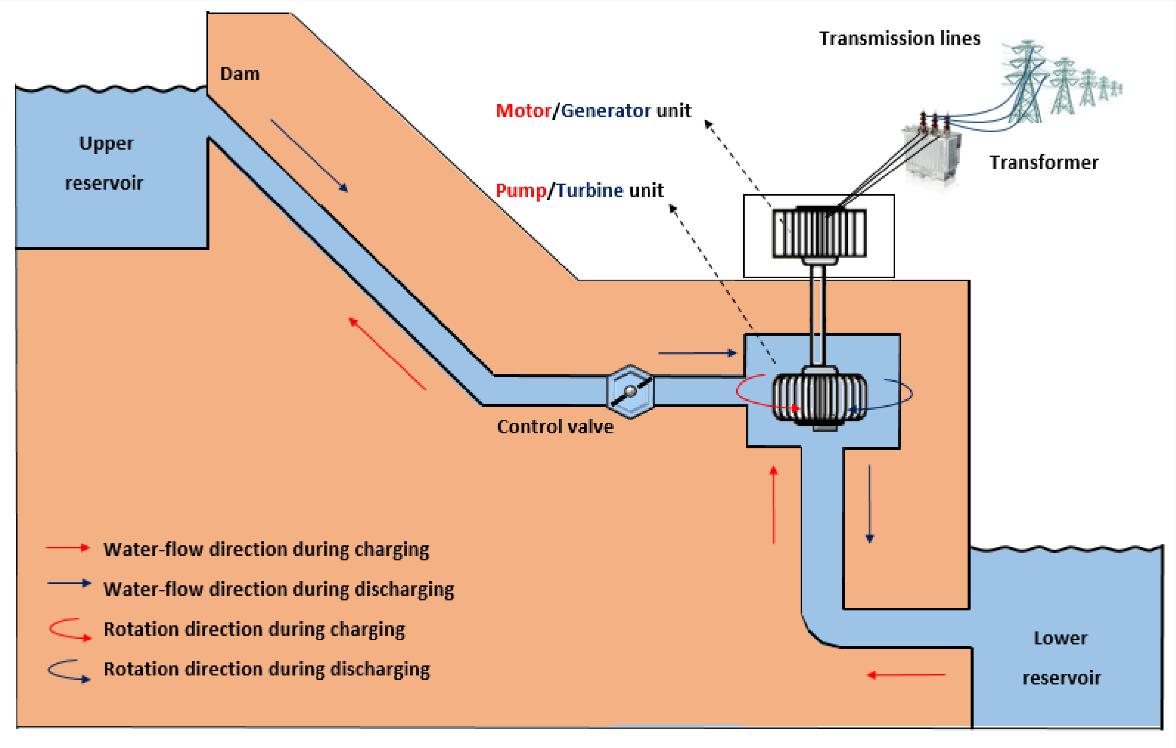


Pumped hydropower storage (PHS) at a glance

- Two **water storage** elements (reservoirs, tanks), located at a **large elevation difference** yet a **small distance**, and interconnected through a conveyance element (less often, two parallel pipes).
- A **reversible hydrodynamic machine**, used as a pump, to lift water from the lower to the upper reservoir, and as a hydroturbine, in the opposite direction, to produce hydroelectricity; in the case of parallel pipes, the two machines operate independently (and may also operate *simultaneously*).

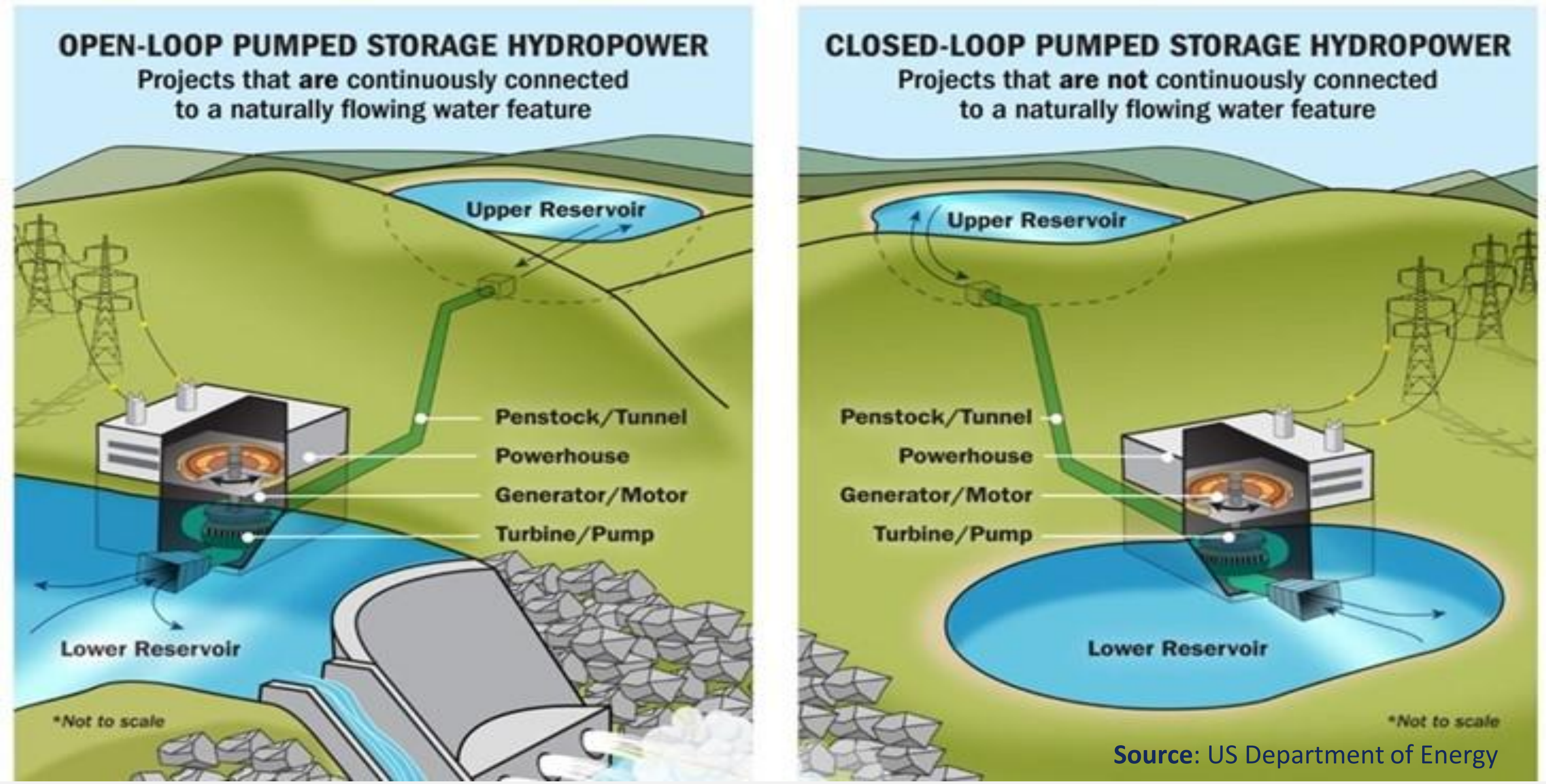
Some global statistics:

- Represents over 94% of the world’s energy storage
- Total power capacity: ~200 GW
- Total storage capacity: ~9000 GWh
- Future projections, to meet global net-zero emissions scenarios by 2050: addition of ~220 GW
- Global potential: 22 000 TWh
- First project: 1907 (Engeweiher, Swizerland)
- Largest project: 3.6 GW, 40 GWh (Fengning, China)



Open-loop vs. closed-loop configurations

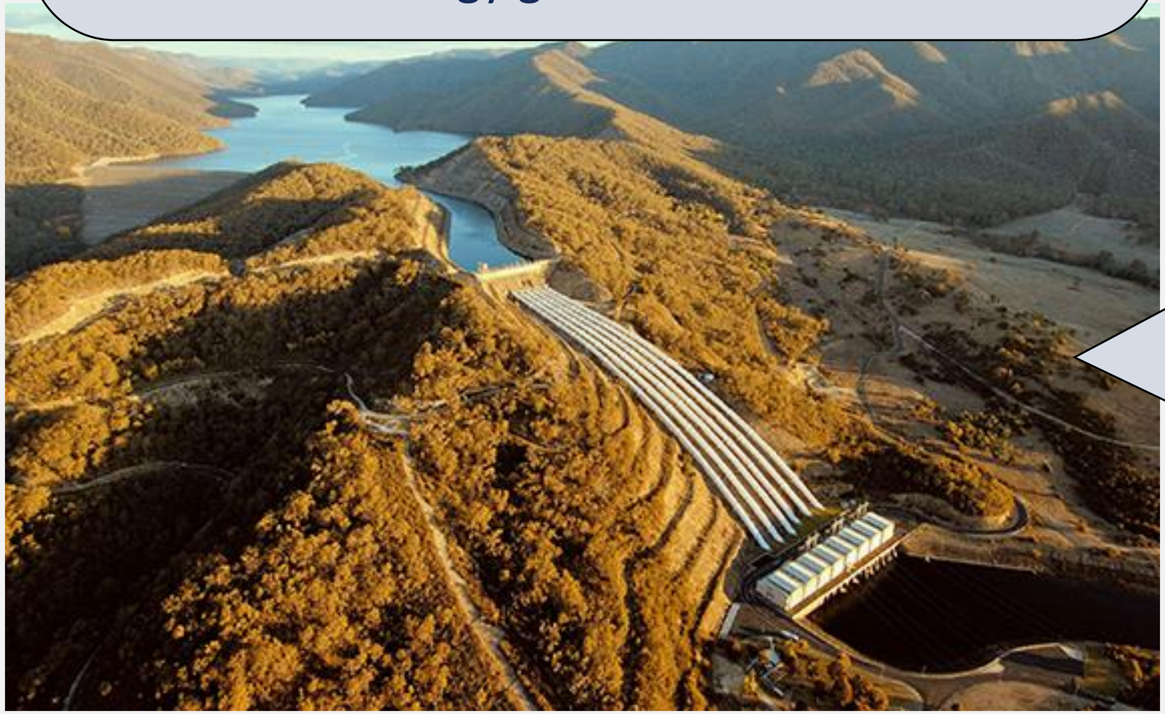
- **Open-loop systems**: At least one of the reservoirs is connected to a natural water body (river or lake), thus the reservoirs can be replenished naturally, yet the project must carefully manage its impact on surrounding ecosystems and water flows (as made with any conventional reservoir).
- **Closed-loop systems:** Both reservoirs are man-made and isolated, with water circulating only within the system. This reduces the environmental impact and makes it easier to control, while it requires a reliable initial water supply and careful maintenance.



Source: US Department of Energy

Characteristic examples

Presenzano, Italy (closed-loop): Two reservoirs of equal capacity (6.0 hm^3) at an elevation difference of 495 m, with a total power capacity of 1000 MW (four reversible Francis-type turbines). The system’s construction began in 1979, and it is fully operational since 1991. The mean annual energy generation is 1276 GWh.



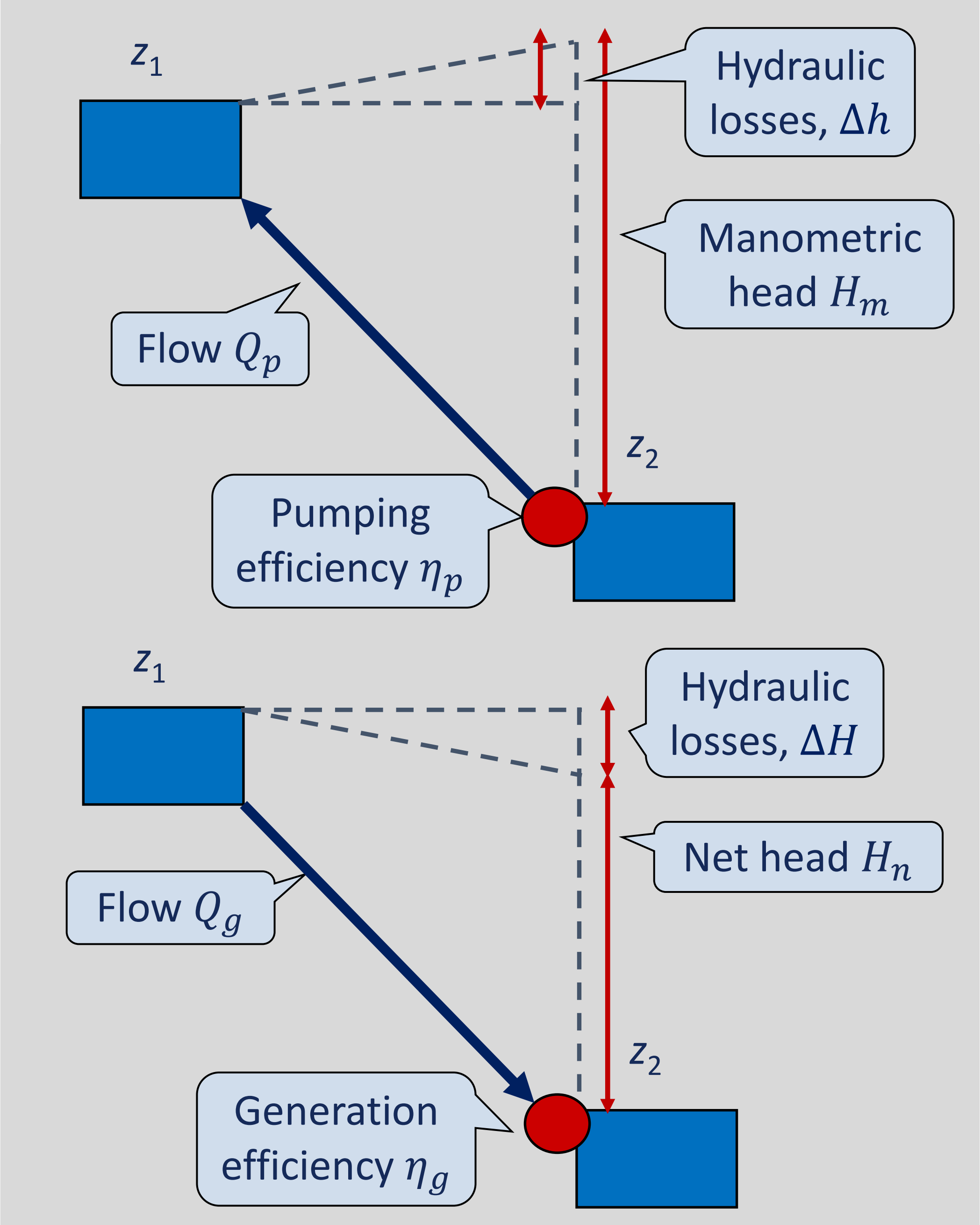
Tumut 3, Australia (open-loop): First major PHS project of the country (construction started: 1968, operation started: 1972, upgrade: 2012); lower reservoir (Talbingo): 920 hm^3, upper reservoir (Jounama): 43.5 hm^3; six 1800 MW turbines, three of which operate in reverse mode; head 150.9 m; conveyance system comprised by six pipes in parallel (length 488 m, diameter 5.6 m).

Major design principles

- Overall requirement: Minimizing horizontal distance and maximizing elevation difference between the two reservoirs, to ensure a **large gross head** with **low hydraulic losses** within water conveyance.
- **Typical layouts**:
  - connection of two cascade reservoirs;
  - use of an existing reservoir (or natural lake) as lower storage element, and configuration of an upper reservoir of much smaller storage capacity (specific case: seawater as lower "reservoir");
  - configuration of fully closed-loop system, comprising two reservoirs of equal storage capacity.
- **Main design quantities**:
  - Maximum water amount, V, to be recycled (i.e., lifted and released) during the charge/discharge cycle → dictates the required **useful storage capacity** of the smaller reservoir (usually the upper one)
  - Charge & discharge times, t_p and t_g → dictate the required **flow rates**, $Q_p = V/t_p$ and $Q_g = V/t_g$, and **power capacities**, $P_p = E_p/t_p$ and $P_g = E_g/t_g$ (in general, P_p is slightly larger than P_g)
  - Generated & consumed energy, E_g and E_p, respectively (by definition: $E_p > E_g$, and $\eta_{PHS} = E_g/E_p$)

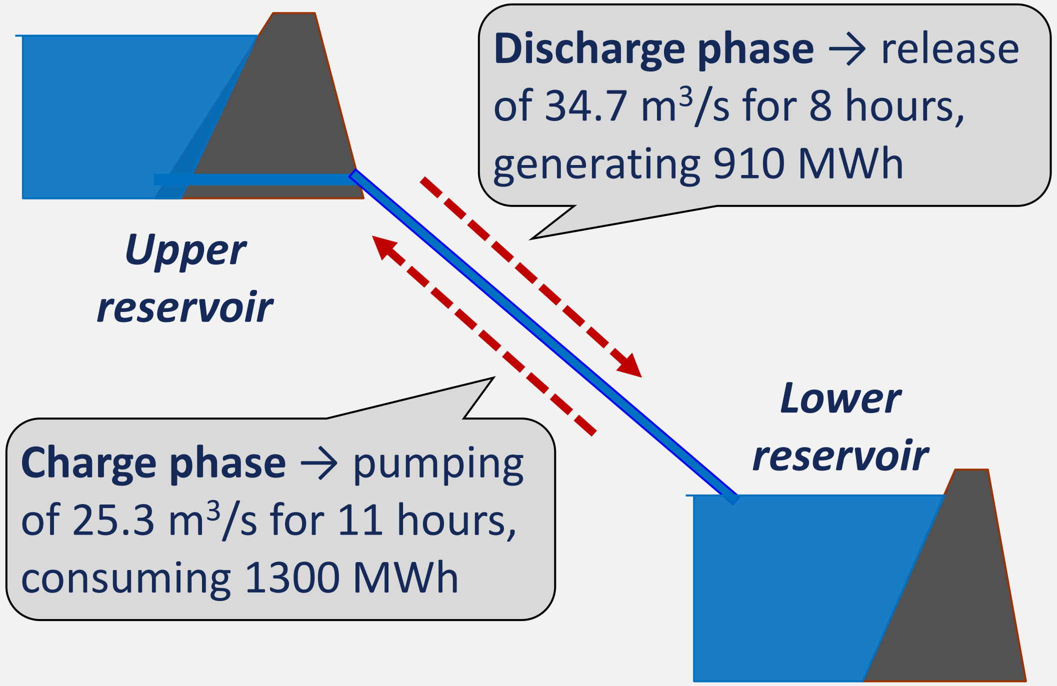
Basic calculations

- Gross head (water level difference): $h = z_1 - z_2 = \Delta z$
- Generation phase: releasing discharge Q_g for time t_g
- Pumping phase: lifting discharge Q_p for time $t_p > t_g$
- Water exchange: $V = Q_g\, t_g = Q_p\, t_p$
- Power generation: $P_g = \gamma\, \eta_g\, Q_g\, H_n$
- Net head: $H_n = \Delta z - \Delta H(Q_g)$
- Power consumption: $P_p = \gamma\, Q_p\, H_m / \eta_p$
- Manometric head: $H_m = \Delta z + \Delta H(Q_p)$
- Energy production: $E_g = P_g\, t_g$
- Energy consumption: $E_p = P_p\, t_p > E_g$
- Round-trip efficiency: $\eta_{PHS} = \frac{E_g}{E_p} = \eta_g\, \eta_p \frac{(\Delta z - \Delta h)}{(\Delta z + \Delta h)}$



Numerical example

- **Inputs and assumptions:**
  - Two reservoirs of equal useful capacity of 1 000 000 m^3, at an elevation distance of 400 m, employing daily regulation → recycling of max. quantity $V = 1\,000\,000$ m^3 during a max. time frame of 24 h
  - Negligible level fluctuations → constant gross head $h = \Delta z = 400$ m
  - Hydraulic losses $\Delta H = 5$ m (approximately common, estimated as 2% of gross head)
  - Efficiencies $\eta_p = \eta_g = 85\%$ (approximately common)
  - Generation time $t_g = 8$ h, pumping time $t_p = 11$ h
- **Results:**
  - Flow rates $Q_g = 34.7$ m^3/s and $Q_p = 25.3$ m^3/s
  - Power capacities $P_g = 114$ MW and $P_p = 118$ MW
  - Energy production $E_g = 910$ MWh
  - Energy consumption $E_p = 1300$ MWh
  - Round-trip efficiency $\eta_{PHS} = 70.5\%$



Discharge phase → release of 34.7 m^3/s for 8 hours, generating 910 MWh

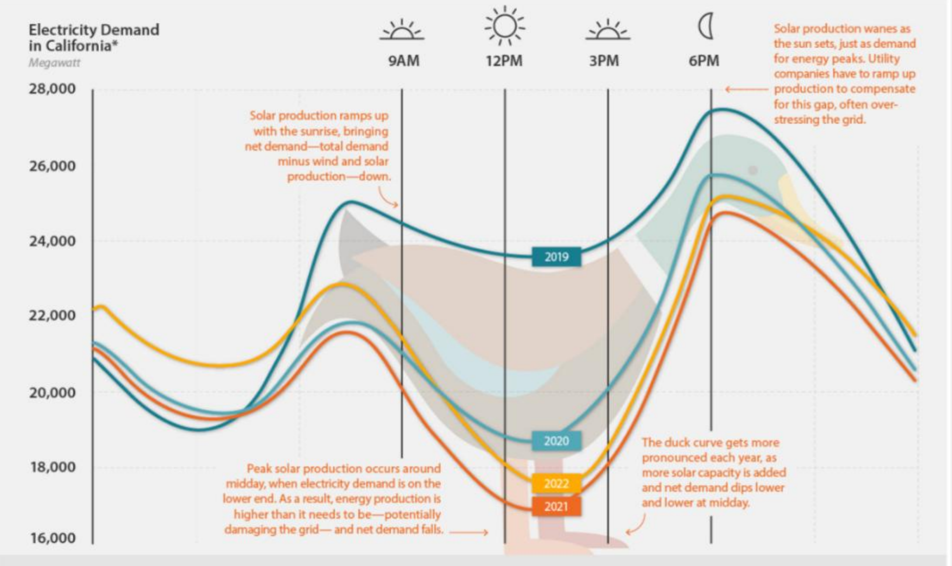
Charge phase → pumping of 25.3 m^3/s for 11 hours, consuming 1300 MWh

Design challenges & operational limitations

- ☐ The **water level fluctuation** of the lower reservoir, from which water is pumped, should be small, on the order of a few meters, for operational and economic reasons.
- ☐ The **horizontal distance** between the two reservoirs should be as short as possible, to minimize the length of water conveyance works (hydraulic losses & cost); on the contrary, their **vertical distance** should be as large as possible, to maximize the hydropower potential.
- ☐ Suitable locations for the formation of the **upper reservoir** are either natural plateaus or valleys that can be inundated through the construction of a dam, or flat areas, where the reservoir may be formed partially or entirely by excavation.
- ☐ Due to operational constraints, the shaft of the pumping unit must be located **well-below the minimum operating level** of the lower reservoir (typically 15 to 20 m).
- ☐ In an operational context, during the charging phase, the **water to be lifted** is subject to the electric power availability, the remaining storage capacity of the upper reservoir, and the conveyance capacity of the pumps. Similarly, during the generation phase, the **water to be released** is subject to the power demand, the remaining storage capacity of the lower reservoir, and the conveyance capacity of the turbines.

Financial and energy market issues

- ☐ As made with all kinds of hydropower works, PHS systems are subject to significant **capital expenditures** (CAPEX) due to civil works, tunneling, dam construction, and electromechanical equipment, yet rather low and stable **operation and maintenance costs** (OPEX).
- ☐ Their revenues are generated by means of **arbitrage**, i.e., purchasing electricity at low prices (e.g., during off-peak hours or high solar/wind generation), and selling it at higher prices (e.g., during peak hours).
- ☐ Since PHS plants can rapidly switch between pumping and generating, they may also take advantage of **ancillary services towards grid stability** (frequency regulation, black-start capabilities, spinning).
- ☐ To ensure **financial viability**, the mean **energy selling price** needs to be at least $1/\eta_{PHS}$ times higher than the purchasing price for pumping. The profitability of arbitrage is highly dependent on the daily spread between peak and off-peak electricity prices, also amplified due to the "**duck curve**" effect.
- ☐ Due to the massive **upfront capital investment**, PHS projects may take ~20 years to amortize (while their time life >50 years).



Solar production ramps up with the sunrise, bringing net demand—total demand minus wind and solar production—down.

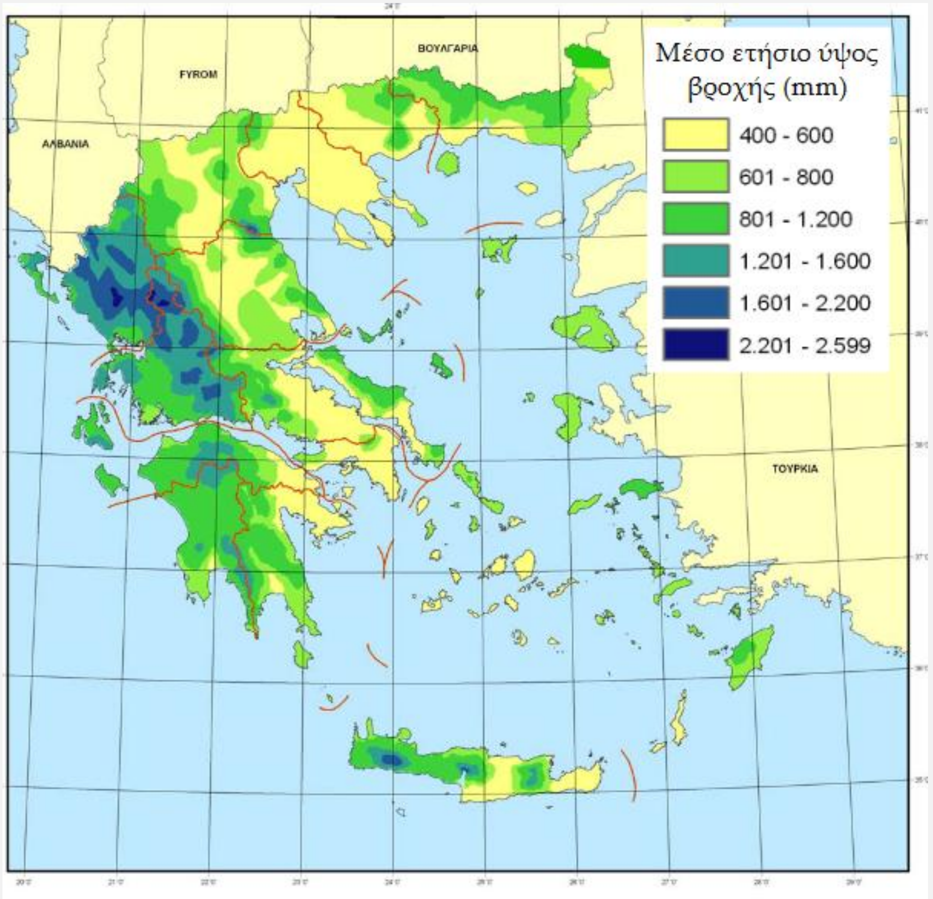
Solar production wanes as the sun sets, just as demand for energy peaks. Utility companies have to ramp up production to compensate for this gap, often over-stressing the grid.

Peak solar production occurs around midday, when electricity demand is on the lower end. As a result, energy production is higher than it needs to be—potentially damaging the grid— and net demand falls.

The duck curve gets more pronounced each year, as more solar capacity is added and net demand dips lower and lower at midday.

“Self-discharge” losses in closed-loop PHS systems

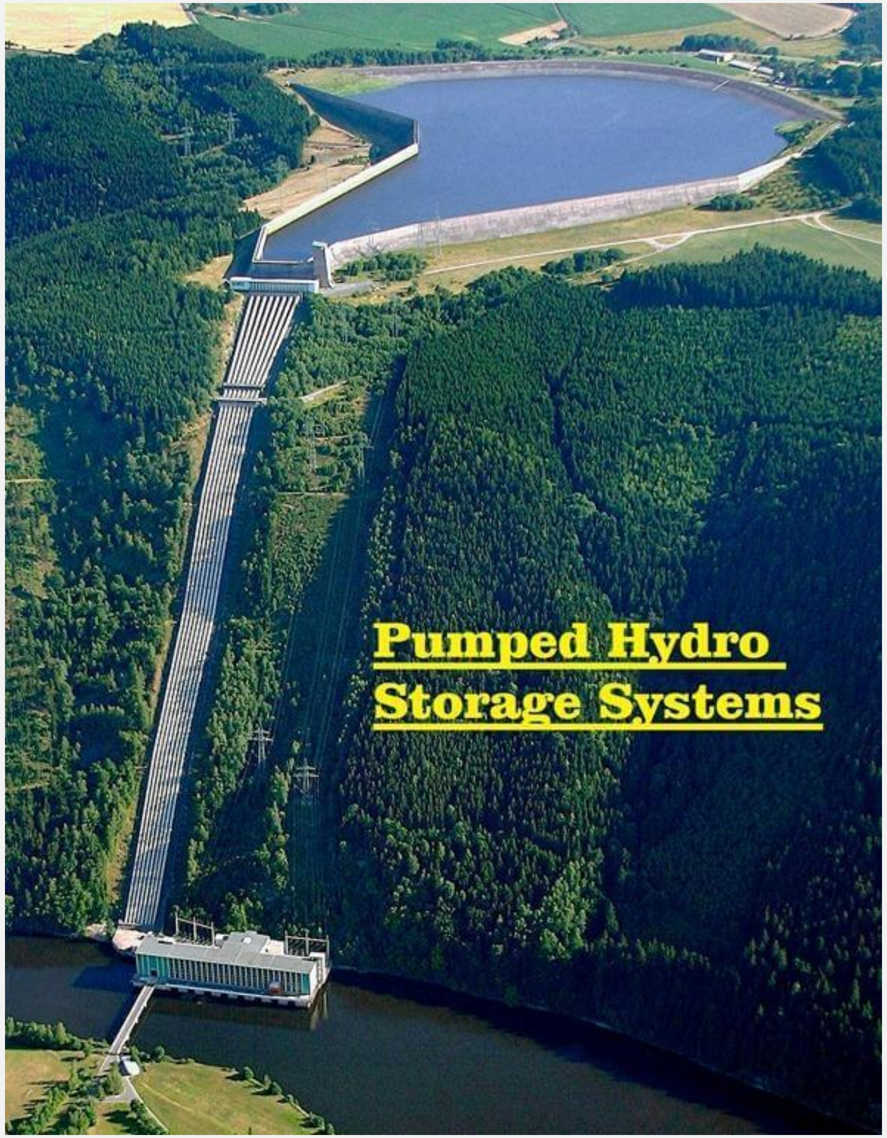
- **Water losses** across conveyance and storage elements of PHS systems result to **electricity losses**, which are equivalent to the self-discharge of other storage media (e.g., batteries).
- Their main causes are **lack of satisfactory waterproofing** and **evaporation losses**.
- **Geomembrane** lining systems can be used to waterproof reservoirs, waterways (canals, pipes, tunnels) that are subject to large velocities and/or pressures, and (occasionally) the underground powerhouse.
- In wet climates, evaporation losses may be counterbalanced by rainfall, while in dry areas **the missing water storage must be systematically replaced**.
- For instance, in Western Greece, the mean annual rainfall slightly exceeds evaporation (rainfall > 1500 mm, evaporation ~1500 mm). On the other hand, in extended parts of Eastern Greece and the Cyclades, the associated balance is significantly negative (rainfall <500 mm, evaporation >1800 mm).



Cascade pumped hydropower storage systems in Greece

- Two open-loop projects across **cascade hydroelectric reservoirs**:
  - Aliakmonas: Sfikia-Asomata (1986), 315 MW, generation 380 GWh (200 GWh from pumping)
  - Nestos: Thesavros-Platanovrysi (1999), 384 MW, total generation 440 GWh

Adding an upper tank to an existing reservoir



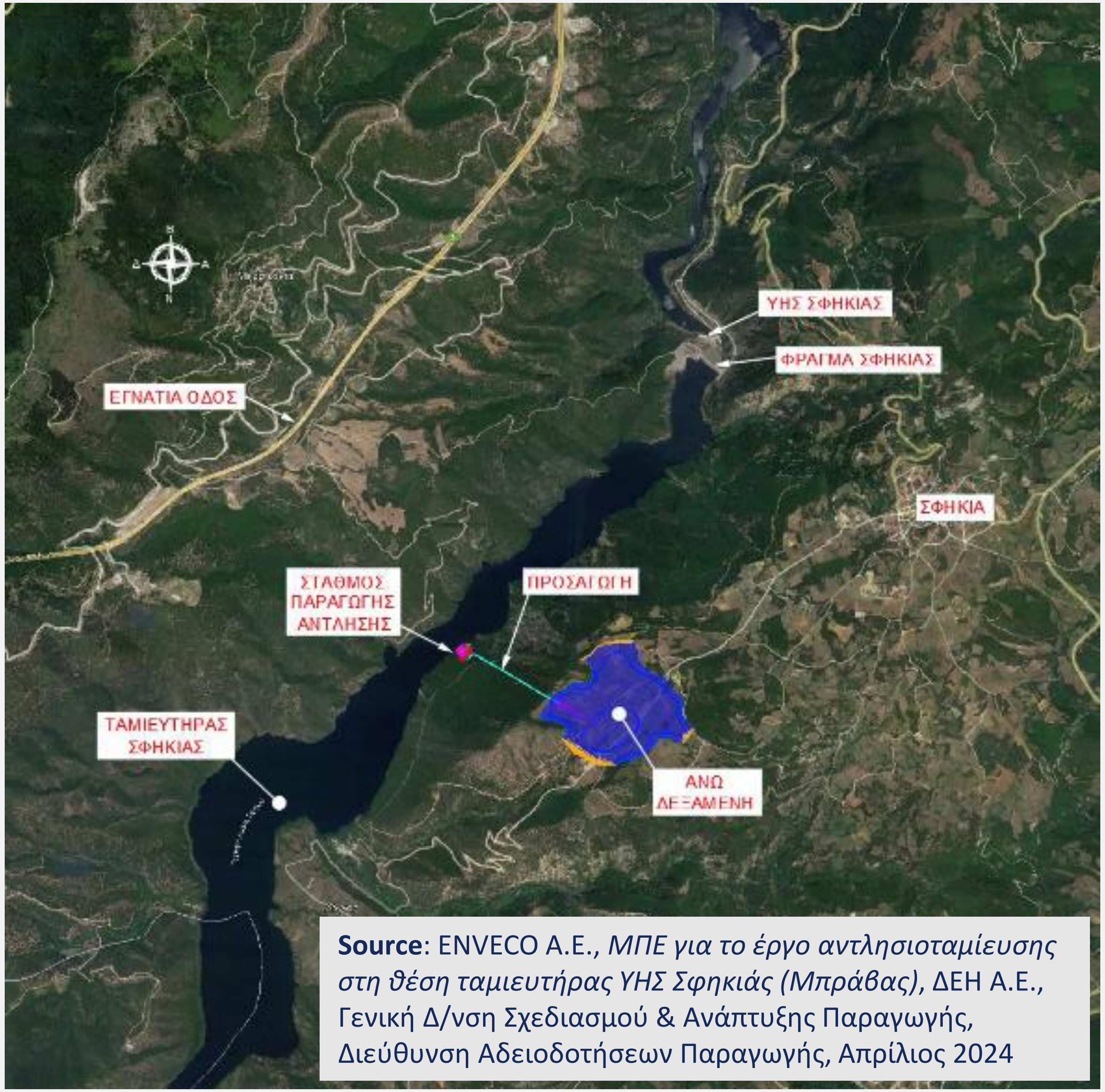
Geesthacht (Germany)

- Start of operation: 1958
- Power capacity: 3×40 MW
- Mean head: 83 m
- Lower reservoir located on the Elbe River: 8.2 hm^3
- Upper reservoir: 3.3 hm^3
- Energy storage: 600 MWh
- Autonomy time: 4.5 h
- Filling time: 9.0 h
- Response time: 90 s

Adding multiple upper tanks to an existing reservoir

Sfikia-Mprava pumped storage project

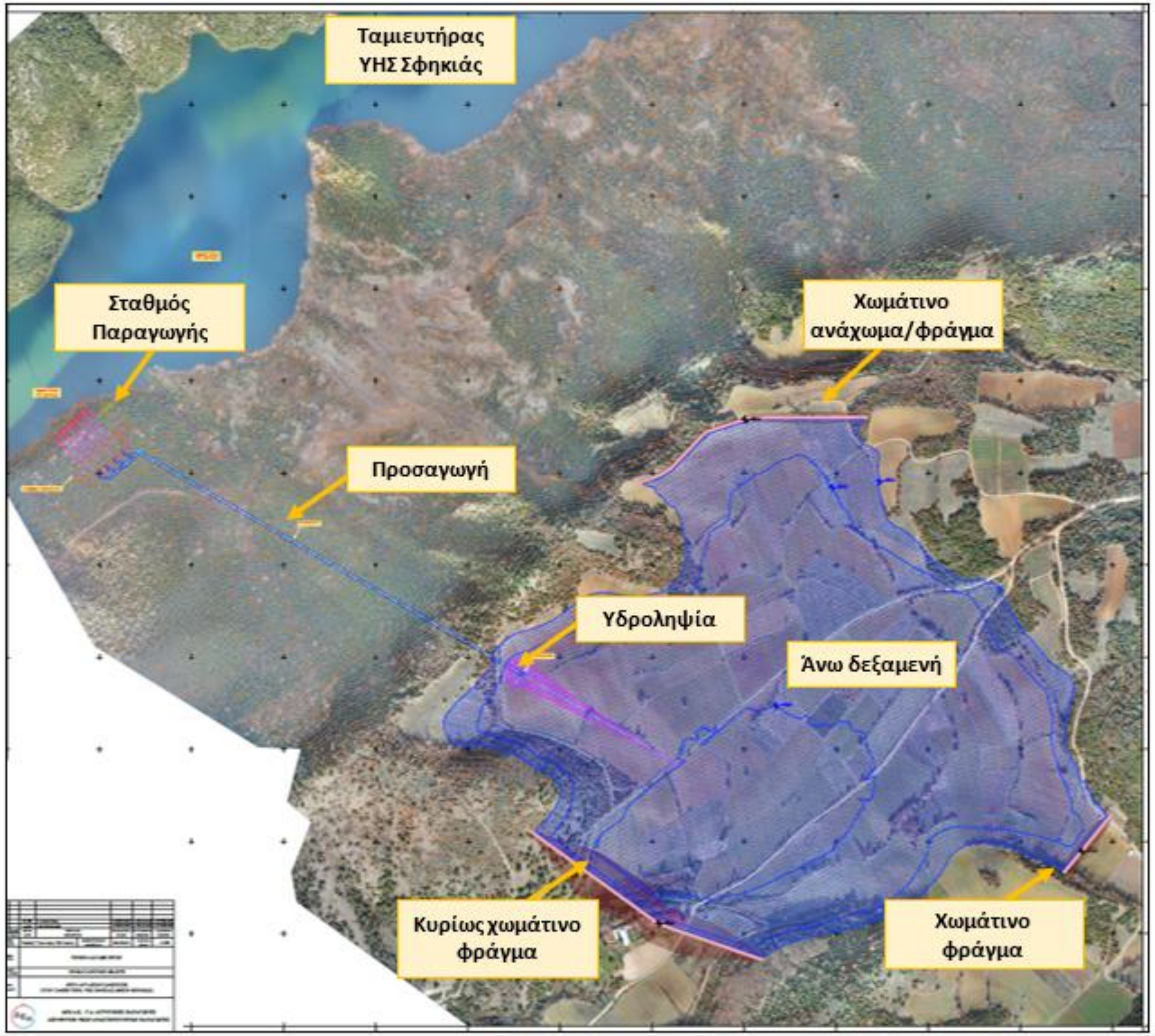
- Utilization of Sfikia hydroelectric reservoir as the lower storage element, and connection to an upper reservoir, which will be formed on a nearby plateau (Mprava location)
- Sfikia: intermediate of Aliakmon complex, already operating as a cascade PHS component (Sfikia-Asomata system)
- Main characteristics: useful storage capacity 18 hm^3, minimum operational level +141.8 m, maximum operational level +146.0 m, feasible range 4.2 m
- Upper reservoir at Mprava:
  - Maximum operational level +560.0 m (area: 0.544 km^3)
  - Minimum operational level +552.3 m for 8 h production (+530.0 m for 21 h)
  - Useful storage capacity 3.8 hm^3 for 8 h production and 11 h pumping (10.0 hm^3 for 21/29 h)
  - Generation capacity 441 MW, pumping capacity 467 MW

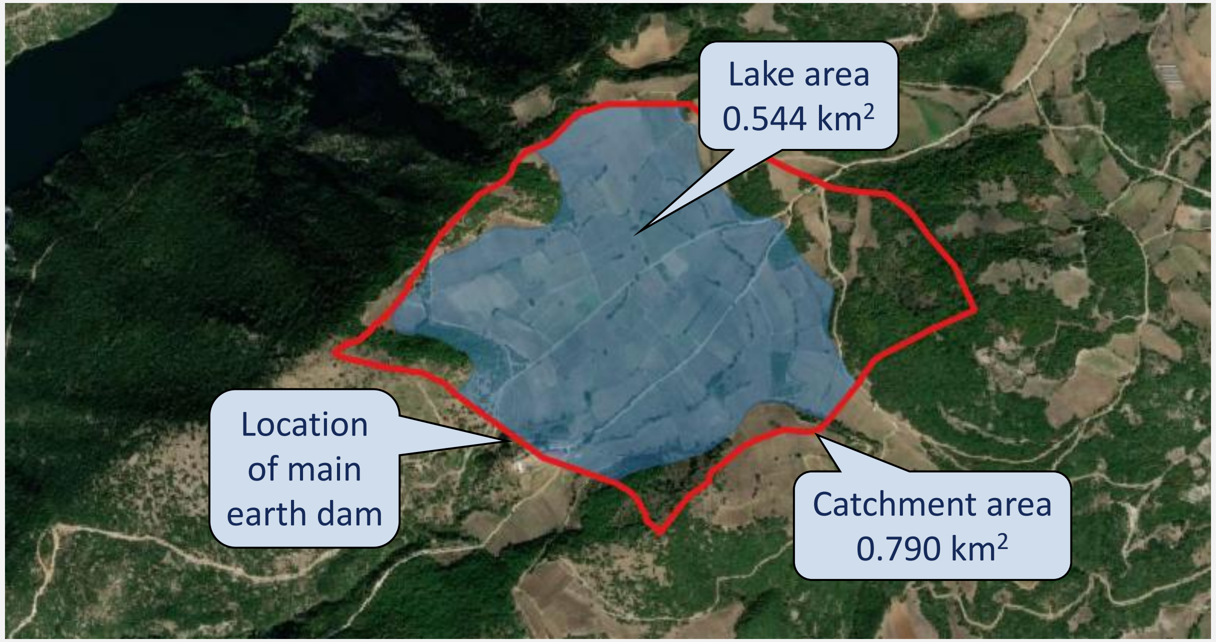


Source: ENVECO A.E., *ΜΠΕ για το έργο αντλησιοταμίευσης στη θέση ταμιευτήρας ΥΗΣ Σφηκιάς (Μπράβας)*, ΔΕΗ Α.Ε., Γενική Δ/νση Σχεδιασμού & Ανάπτυξης Παραγωγής, Διεύθυνση Αδειοδοτήσεων Παραγωγής, Απρίλιος 2024

Sfikia-Mprava pumped storage project: Siting of upper reservoir

Sfikia-Mprava pumped storage project: Generic layout

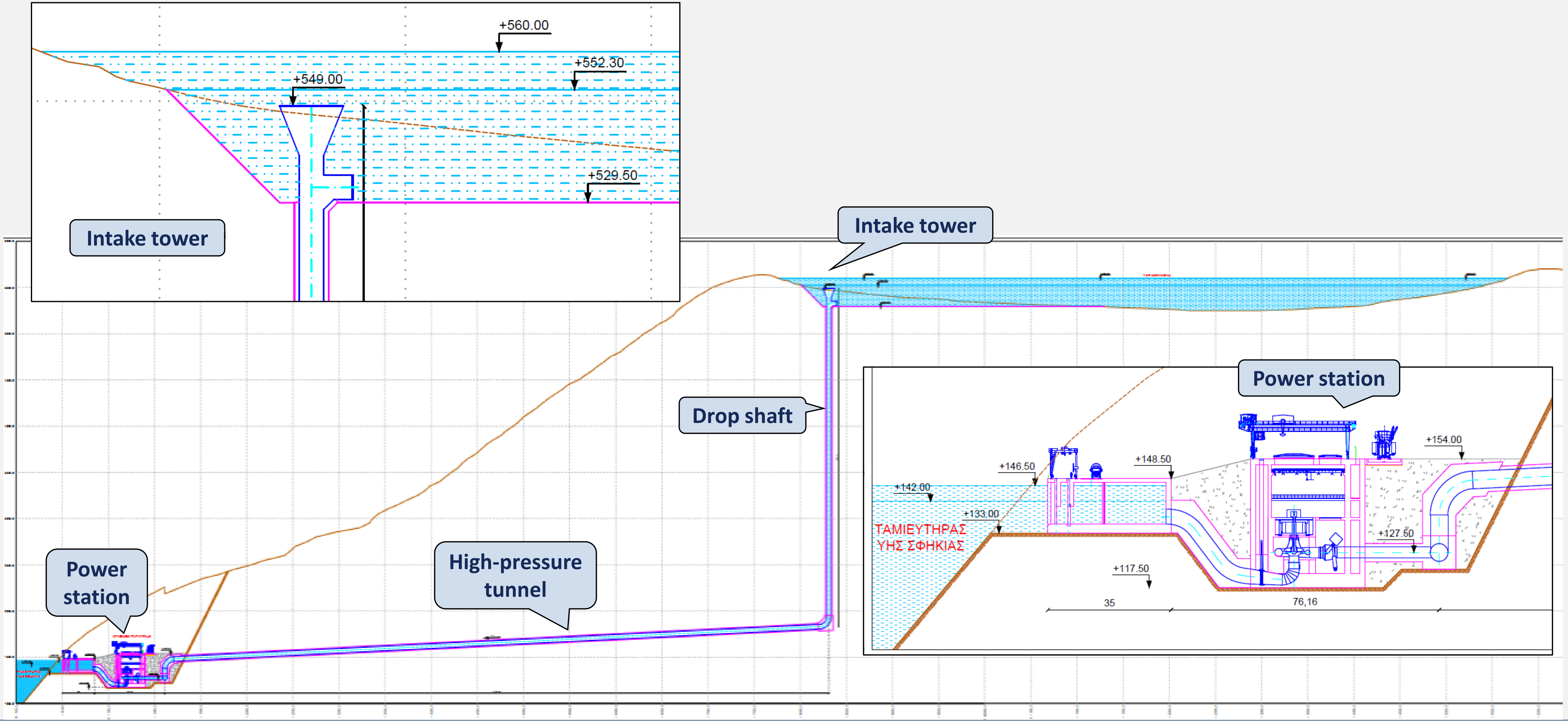




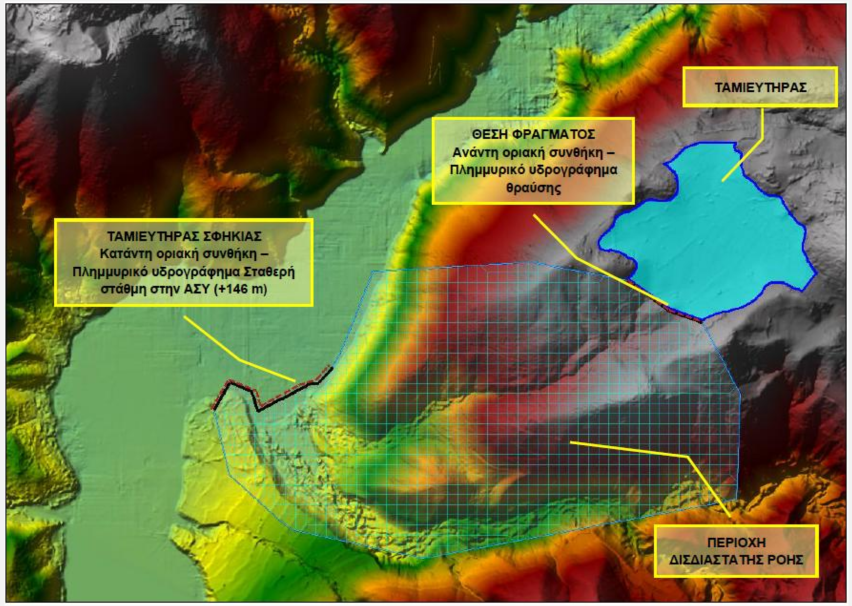
The **upper reservoir** will be formed by enclosing the surroundings of the plateau through the following works:

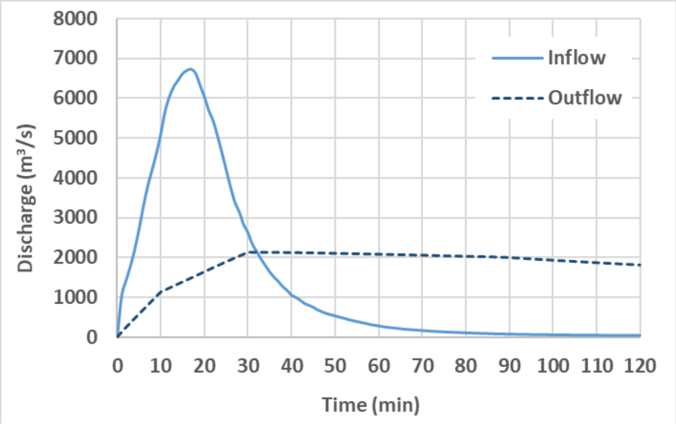
- an earth dam in the basin outlet, located in its SW part (length: 435 m, height: 45 m, most of its part <27 m);
- an earth dam at the SE end (length: 120 m, height: 9 m);
- an earth embankment at the northern end (length: 415 m, height: 6.5 m);

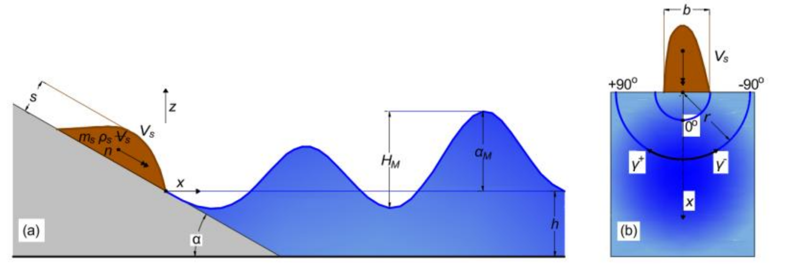
Sfikia-Mprava pumped storage project: Technical plans

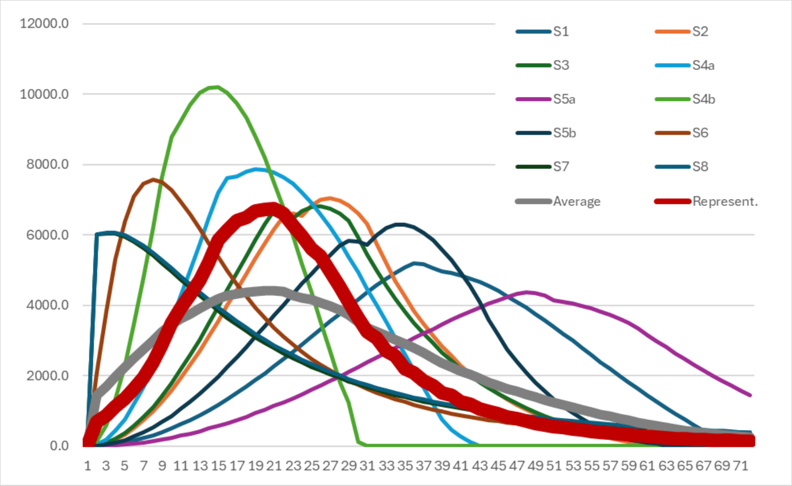


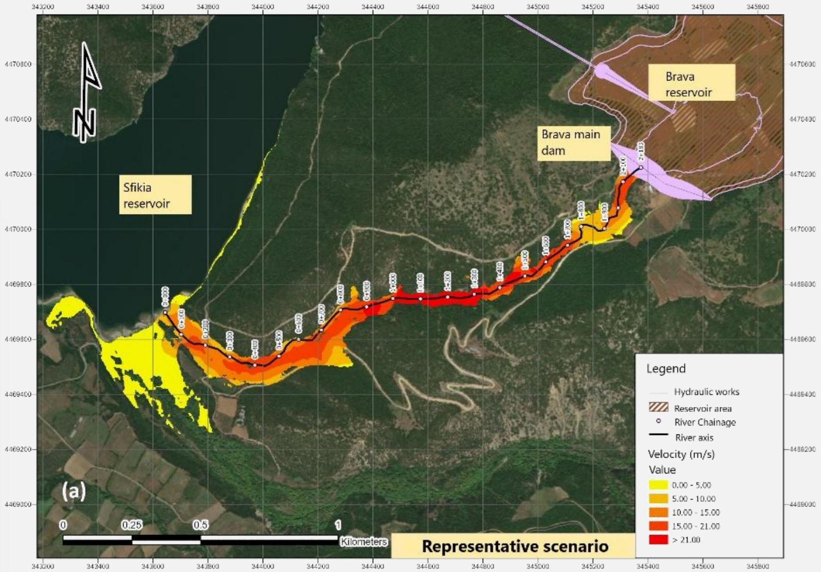
A non-trivial flood modelling problem: Upper dam breach

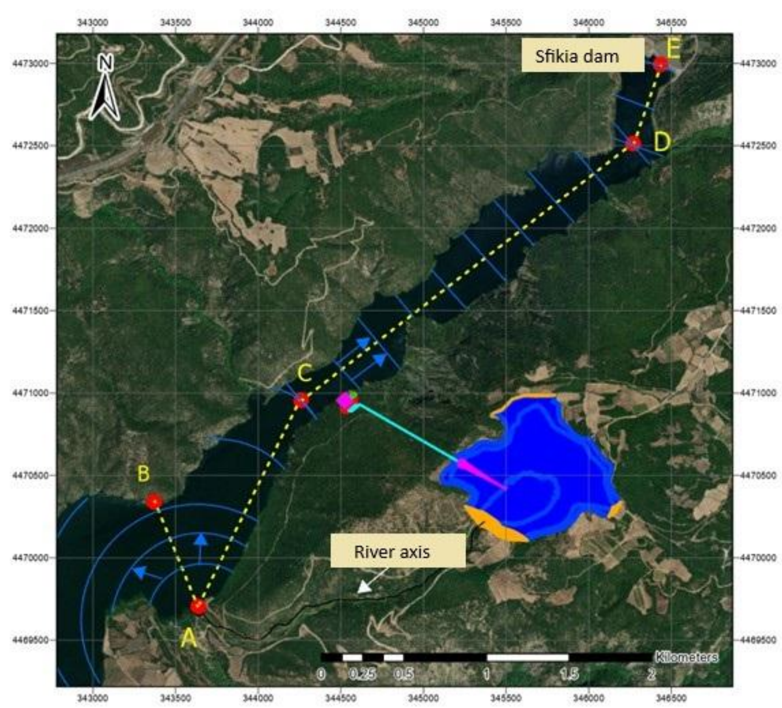








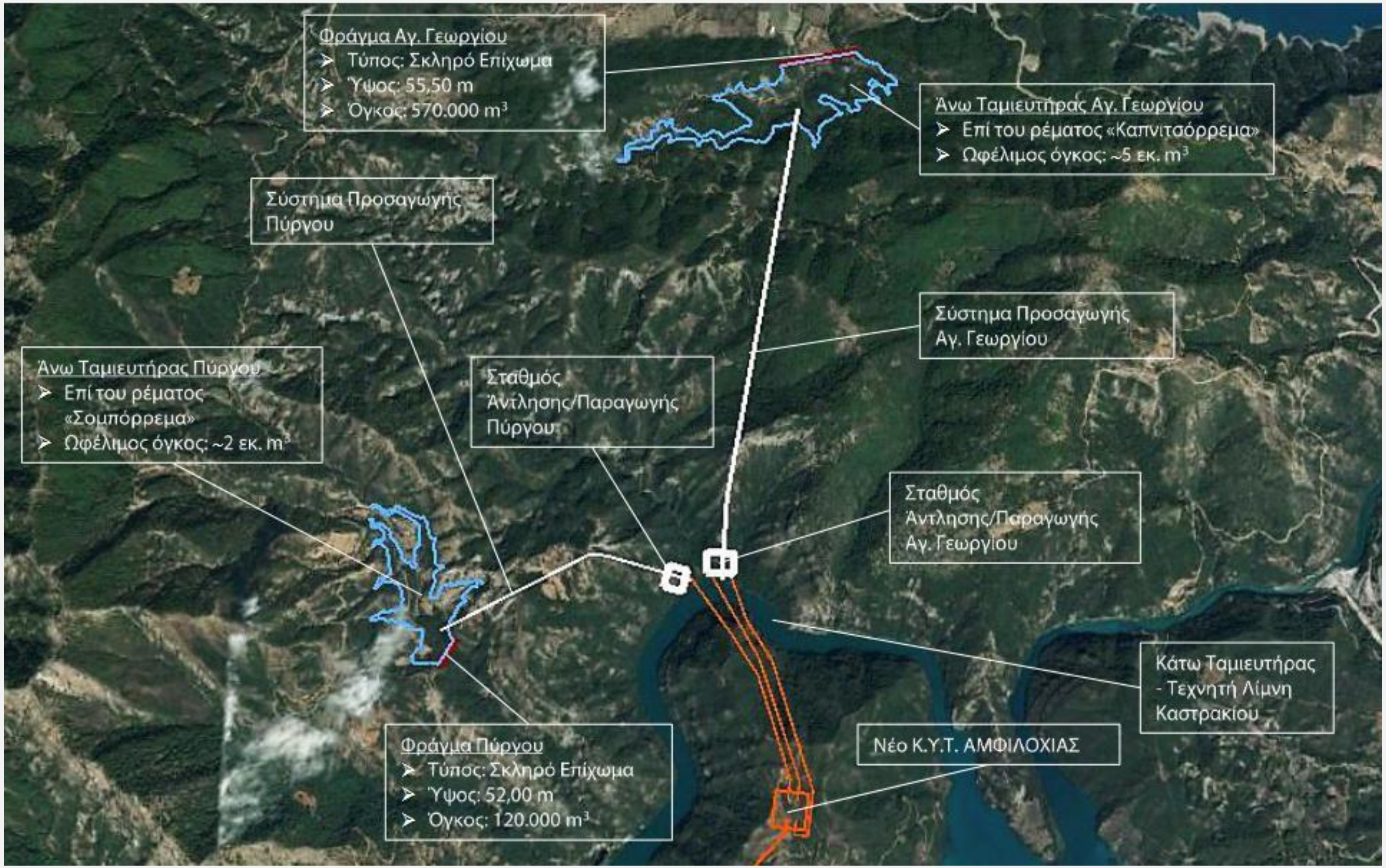




Info: Dimas, P., A. Lykou, A. Zarkadoulas, G.-K. Sakki, A. Efstratiadis, C. Makropoulos, and A. Louloudi, Cascading impacts of individual failures across critical infrastructures: The case of upper dam breach in pumped-storage hydropower schemes, *International Journal of Disaster Risk Reduction*, 128, 105736, doi:10.1016/j.ijdrr.2025.105736, 2025.

Hydro Pumped Storage Complex in Amfilochia: Layout

- Greece’s largest investment in energy storage (estimated construction cost ~650 M€)
- Development of two independent upper reservoirs (Agios Georgios & Pyrgos), and utilization of Kastraki hydroelectric reservoir as a shared lower tank (level range: 142.0 - 146.1 m).
- Negligible impacts to the operation of Kastraki, serving as intermediate (weekly) regulator of the Achelous hydropower complex.



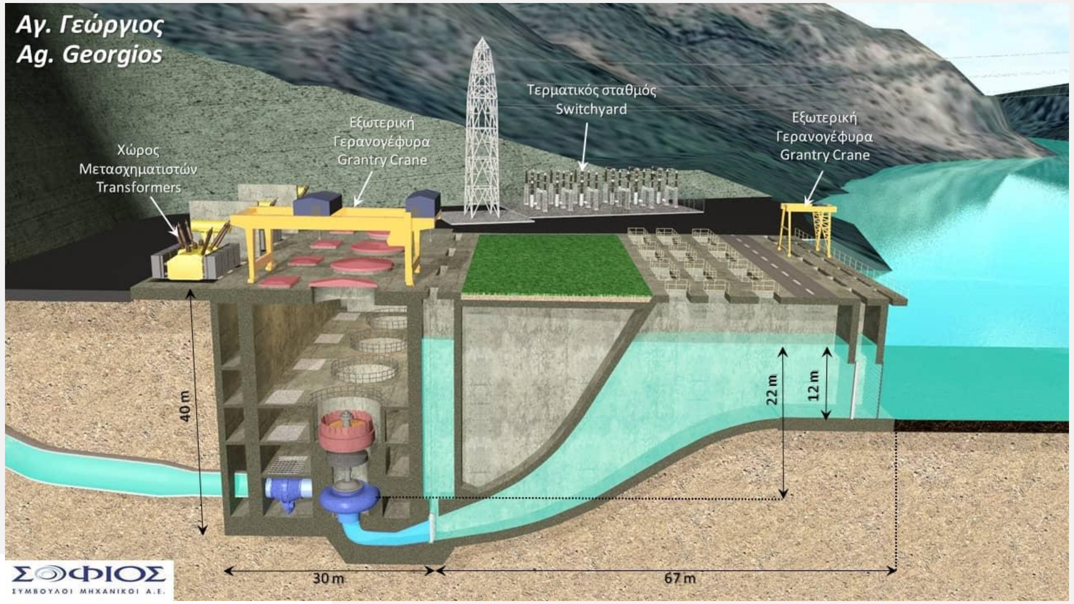
Source: http://hps-amfilochia.gr/wp-content/uploads/2016/11/HPS_Amfilochia_Project-Synopsis_Revised_Sep2016.pdf

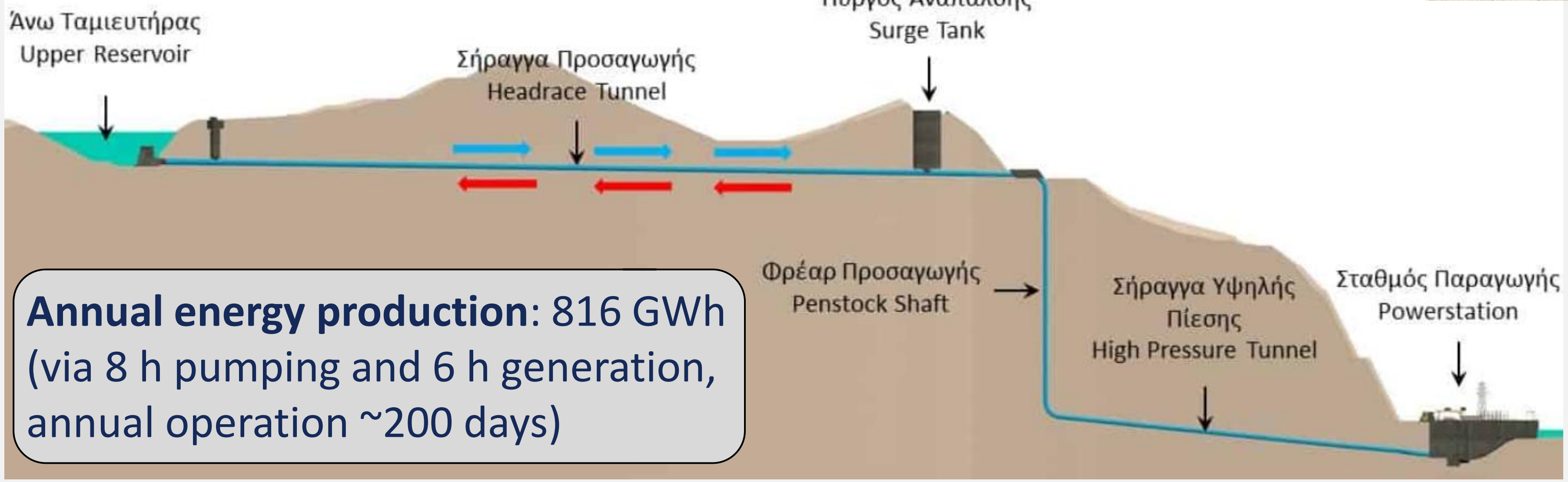
Hydro Pumped Storage Complex in Amfilochia: Key technical data

- **Agios Georgios reservoir**:
  - Dam height: 56 m
  - Useful storage capacity: 5.0 hm^3
  - Elevation difference: 238 m
  - Generation capacity: 460 MW
  - Pumping capacity: 496 MW
  - Pumping 5.0 hm^3 reduces the water level at Kastraki by 20 cm
- **Pyrgos reservoir**:
  - Dam height: 52 m
  - Useful storage capacity: 2.0 hm^3
  - Elevation difference: 285 m
  - Generation capacity: 220 MW
  - Pumping capacity: 234 MW
  - Pumping 2.0 hm^3 reduces the water level at Kastraki by only 8 cm

Hydro Pumped Storage Complex in Amfilochia: Conveyance systems

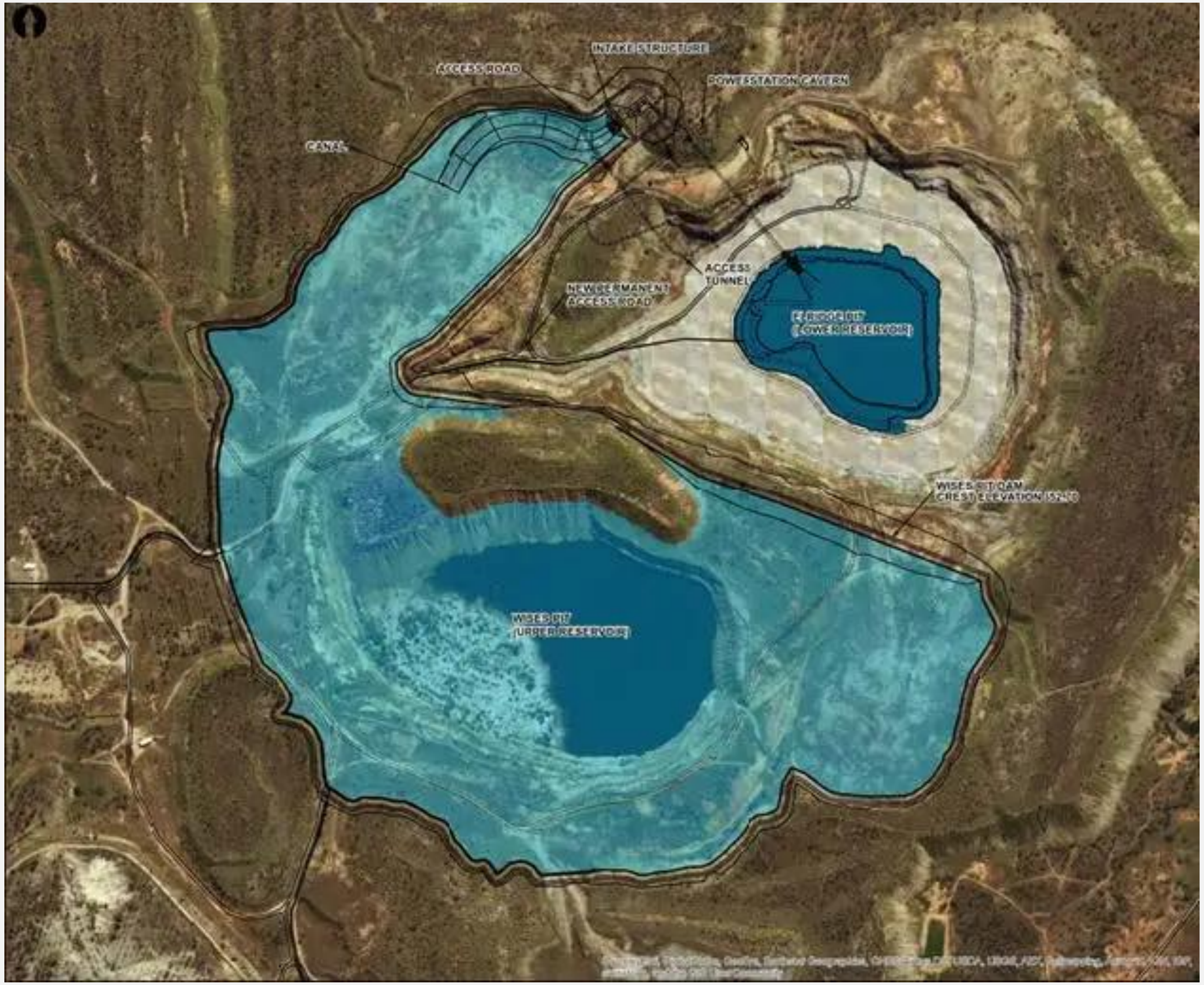
- Both consist of three parts, i.e., a low-pressure tunnel, a drop shaft and a high-pressure tunnel.
- Installation of a surge tower upstream of the high-pressure tunnel to protect against water hammer.
- Installation of power stations at a depth of ~10 m below the minimum operation level of Kastraki.

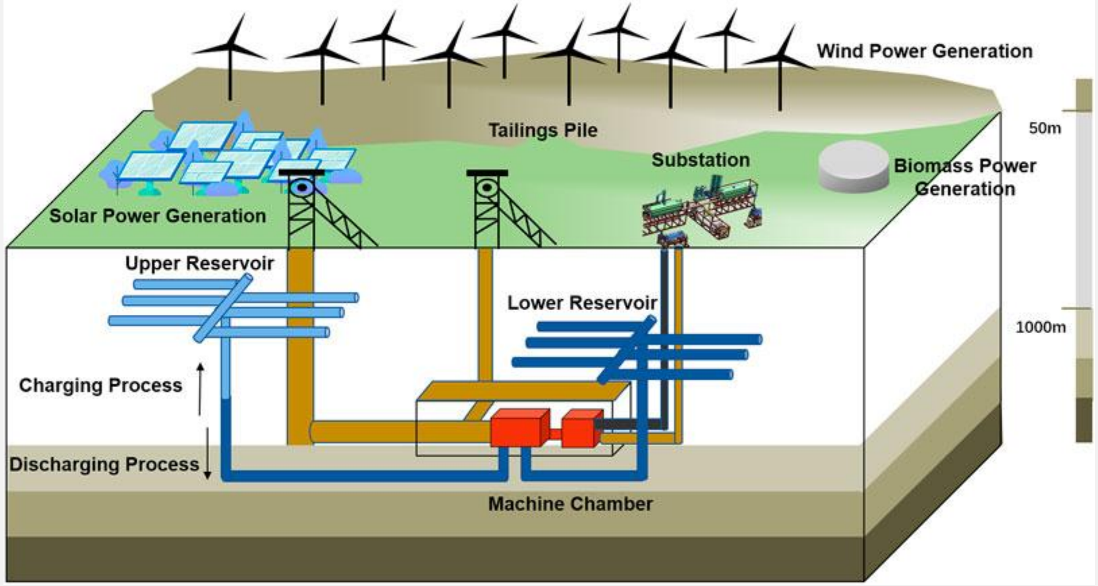




Annual energy production: 816 GWh (via 8 h pumping and 6 h generation, annual operation ~200 days)

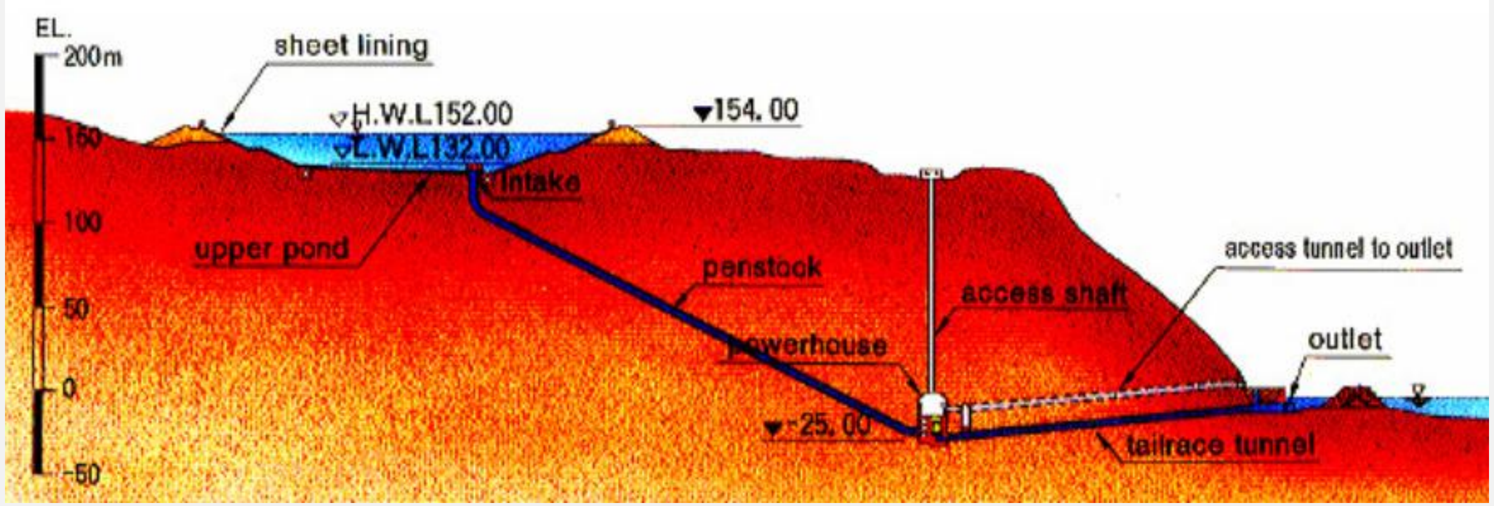
PHS in abandoned open-pit mines





Harnessing seawater as lower reservoir

- Upper reservoir: artificially excavated, at a close distance from the coastline, and with a large elevation difference (suitable solution for non-interconnected islands).
- Technical difficulties due to seawater infiltration from the upper reservoir into the ground, adhesion of marine organisms to the pipes and corrosion of turbines and other metal elements.



Okinawa Yanbaru (Japan): The world's first PHS pilot plant using seawater instead of freshwater for energy storage. Operational since 1999, dismantled in 2016 due to economic reasons (electricity demand in Okinawa had not grown as predicted).

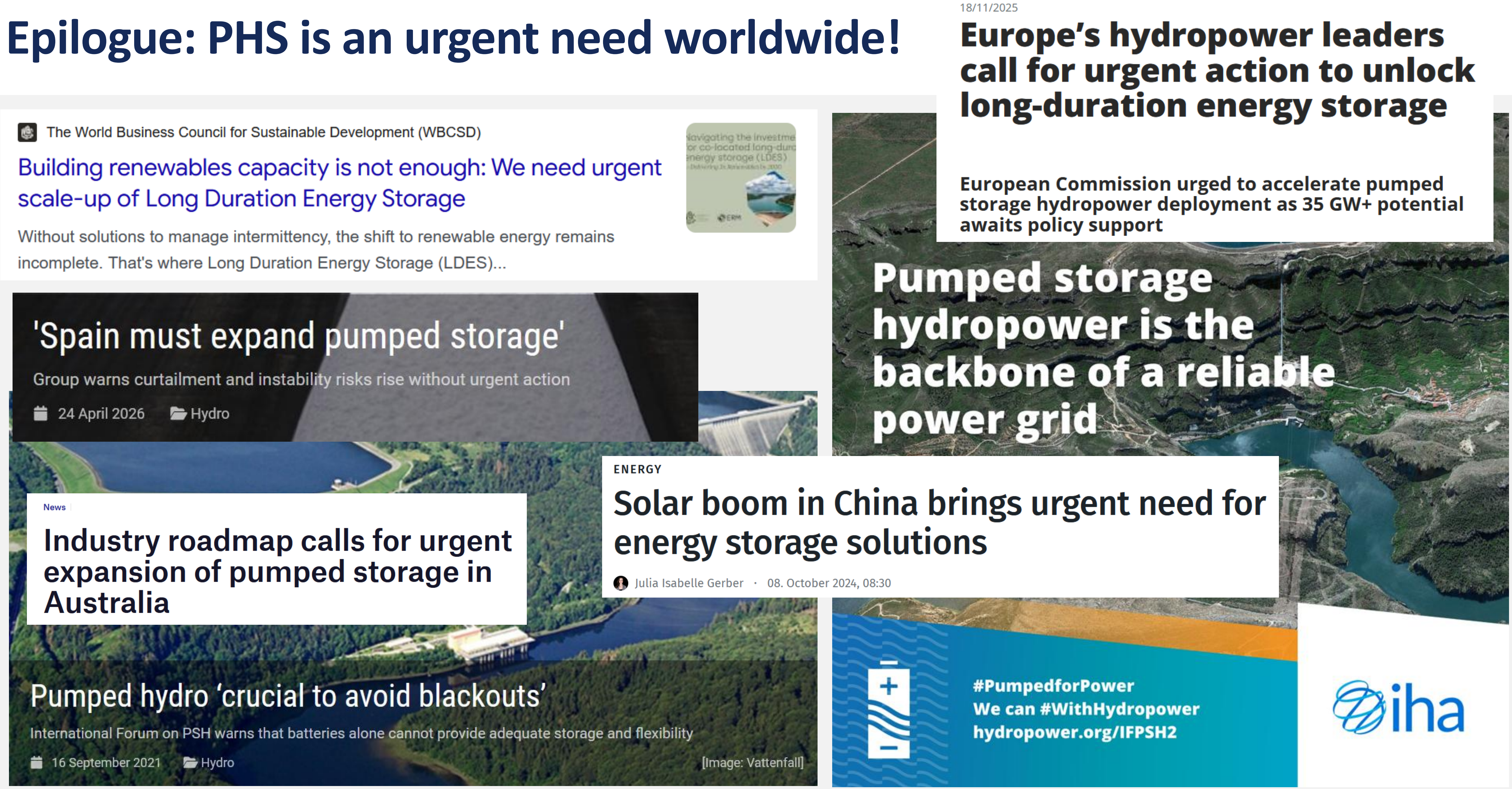
Embedding PHS in the energy system

Role	What it means	Why it matters
Balancing supply & demand	Stores surplus electricity and releases it when demand is high	Keeps the grid stable and prevents waste of renewable energy
Supporting renewables	Smooths out variable solar and wind generation	Ensures clean energy can meet demand even when the sun isn’t shining or wind drops
Grid services	Provides frequency regulation, voltage support, and black-start capability	Maintains reliable electricity supply, even during sudden disruptions
Long-duration storage	Delivers electricity for hours or days, depending on reservoir capacity	Covers extended periods when renewables produce less power
Fast response	Switches between pumping and generating within minutes	Helps operators react quickly to demand spikes or generation dips
Longevity	Operates effectively for decades with proper maintenance	Provides a durable, cost-effective backbone for national grids

Source: https://www.energymatters.com.au/education/technology/how-pumped-hydro-works/

Overall conclusion: PHS is a mature, well-validated EES technology, ensuring economies of scale across all levels of interest

Epilogue: PHS is an urgent need worldwide!



18/11/2025

Europe's hydropower leaders call for urgent action to unlock long-duration energy storage

European Commission urged to accelerate pumped storage hydropower deployment as 35 GW+ potential awaits policy support

The World Business Council for Sustainable Development (WBCSD)

Building renewables capacity is not enough: We need urgent scale-up of Long Duration Energy Storage

Without solutions to manage intermittency, the shift to renewable energy remains incomplete. That's where Long Duration Energy Storage (LDES)...

'Spain must expand pumped storage'

Group warns curtailment and instability risks rise without urgent action

24 April 2026 Hydro

Pumped storage hydropower is the backbone of a reliable power grid

News

Industry roadmap calls for urgent expansion of pumped storage in Australia

ENERGY

Solar boom in China brings urgent need for energy storage solutions

Julia Isabelle Gerber · 08. October 2024, 08:30

Pumped hydro 'crucial to avoid blackouts'

International Forum on PSH warns that batteries alone cannot provide adequate storage and flexibility

16 September 2021 Hydro [Image: Vattenfall]

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hydropower.org/IFPSH2