Renewable Energy & Hydroelectric Works

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Energy storage & hybrid renewable energy systems

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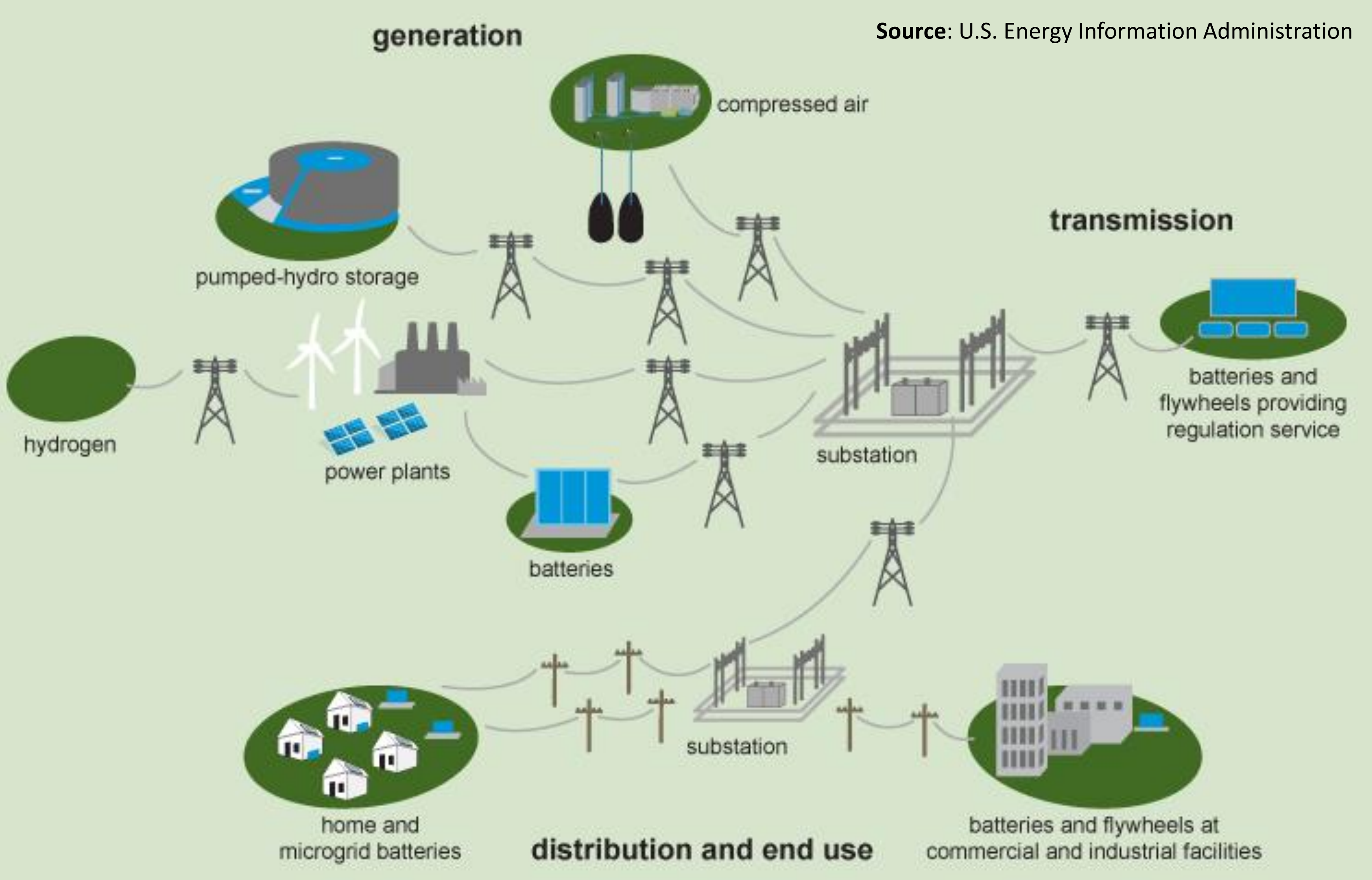
The concept of electrical energy storage (EES)

- Electricity cannot itself be stored on any scale, but it can be **converted to other forms of energy**, which can be stored and later **reconverted to electricity on demand**.
- Based on the mechanism used, energy storage systems can be classified into **electrochemical**, **chemical**, **electrical**, **thermal** and **mechanical**.
- EES objectives, with respect to **time scale** (short, medium, long):
  - regulating **imbalances** between energy demand and energy production;
  - lowering **electricity supply costs** by storing energy at off-peak rates;
  - improving **reliability** at times of unexpected failures or disasters;
  - maintaining and improving **power quality** across the grid (frequency, voltage).
- All types of EES induce power losses within **conversion** and due to **self-discharge** effects.
- Generic principles:
  - Charge during low-demand periods and discharge to fulfill peak demands;
  - Multiple technologies with different characteristics in terms of efficiency, response time, etc.

Energy storage technologies across electricity systems

- ☐ **Mechanical**: pumped hydro (PHPS), compressed air (CAES), flywheels (FES)
- ☐ **Electrochemical**: E/C batteries (lead acid, nickel-based, sodium-based, Li-ion), flow batteries (redox, hybrid)
- ☐ **Electrical**: supercapacitors, superconducting magnetic (SMES)
- ☐ **Chemical**: hydrogen
- ☐ **Thermal**: low or high temperature



Source: U.S. Energy Information Administration

The EES rationale

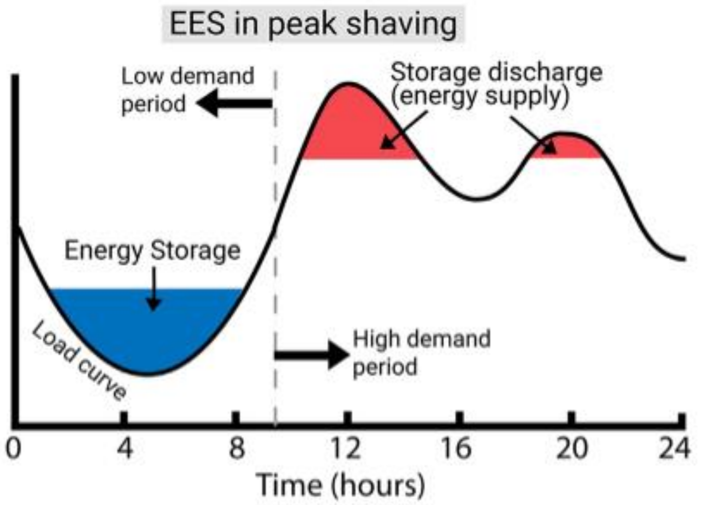
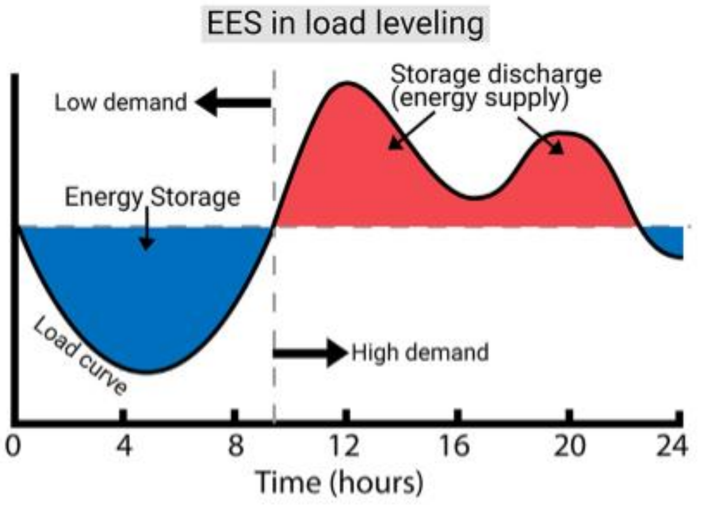
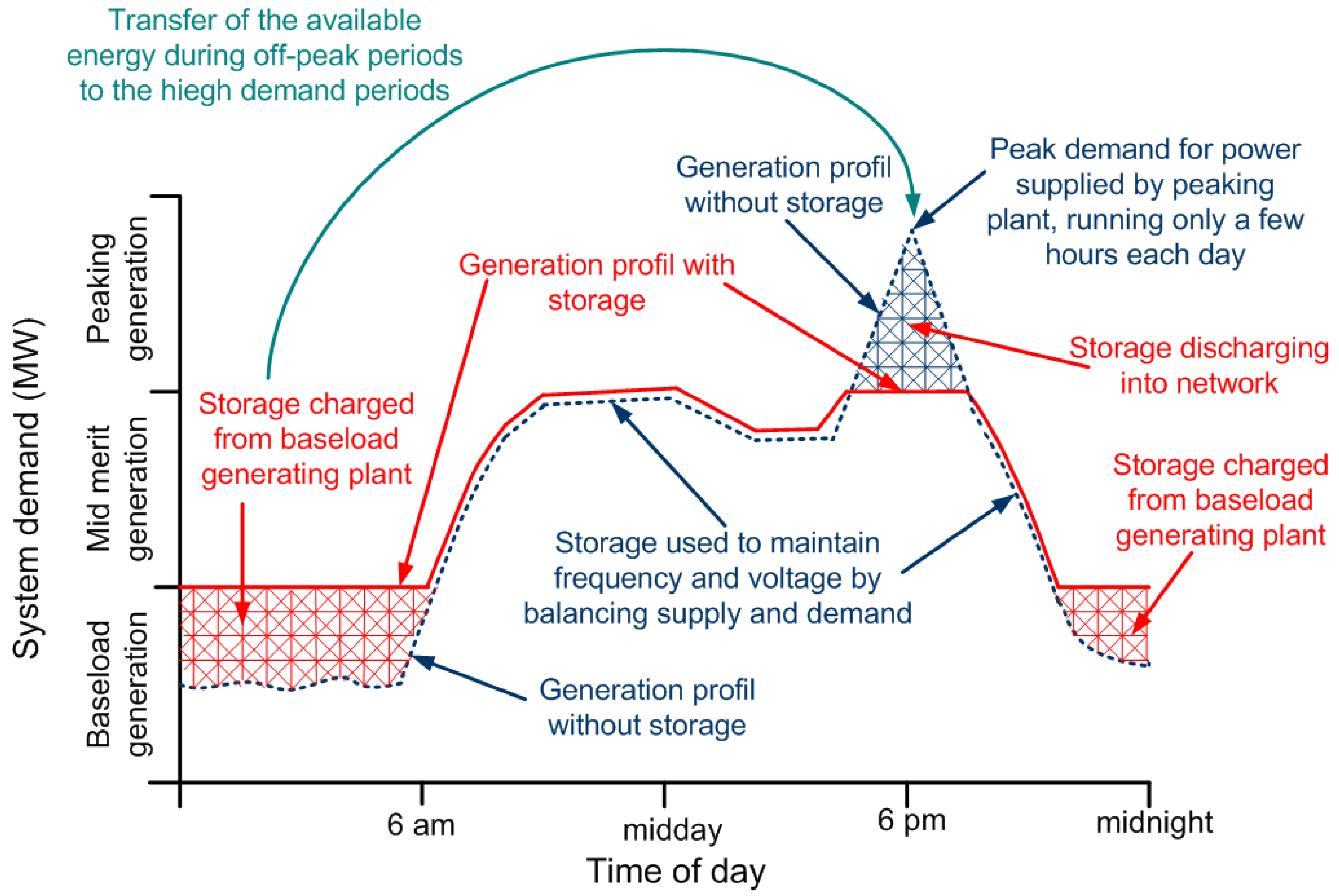


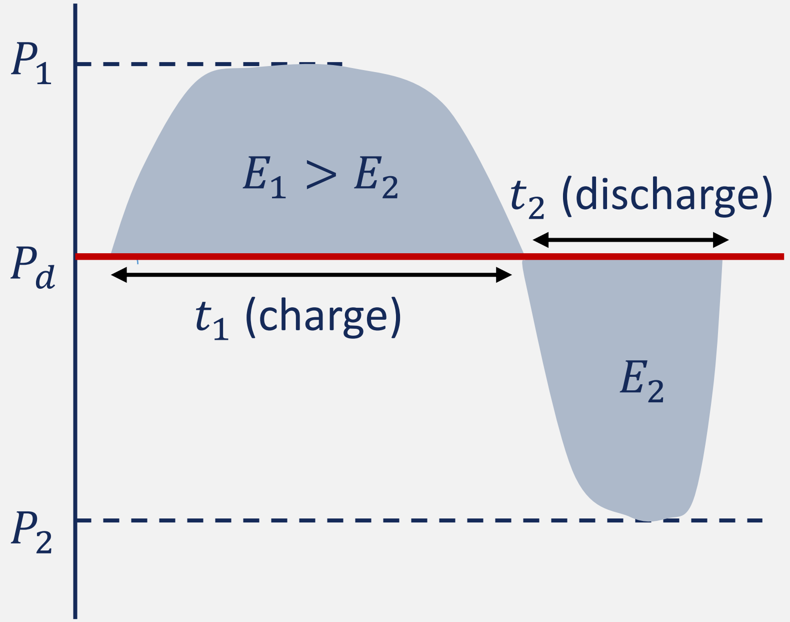
Fig. 20. Energy storage load profile in peak shaving.





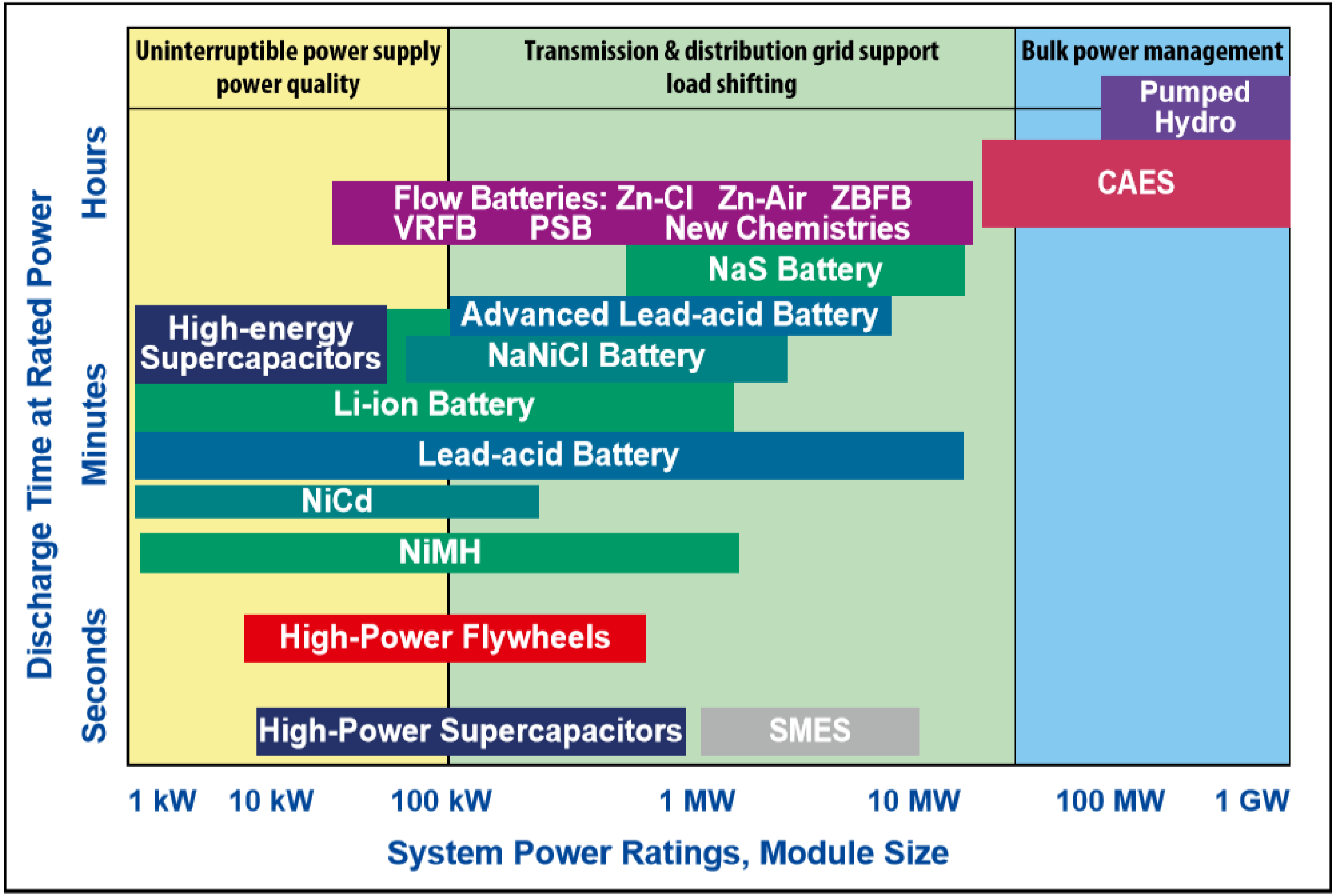
Key concepts on designing EES systems

- Let consider a theoretically constant power demand, P_d, and a varying power production $P(t)$, where $P(t) > P_d$ during a time interval t_1 (**charging**) and $P(t) < P_d$ for the time interval t_2 (**discharging**), where the total time $t_1 + t_2$ corresponds to the time scale of interest (e.g., the daily cycle).
- By contrasting the production profile with the constant load P_d, we get the excess energy E_1 and the deficit E_2, as well as the power capacities P_1 and P_2, for charging and discharging, respectively.
- An optimal design should ensure that $E_1 = E_2 - \Delta E$, where ΔE are the **energy losses** across power conversions (charge → discharge) and due to self-discharging.
- The real-world design is much more complicated, as the power demand profile is varying and as the scale of interest increases, thus requiring the mixing of different ESS with different characteristics, by means of energy and power density.
- The simplest approach for sizing EES systems is to apply a **consecutive period of full energy autonomy**, starting from fully charged state and without considering any excess storage.

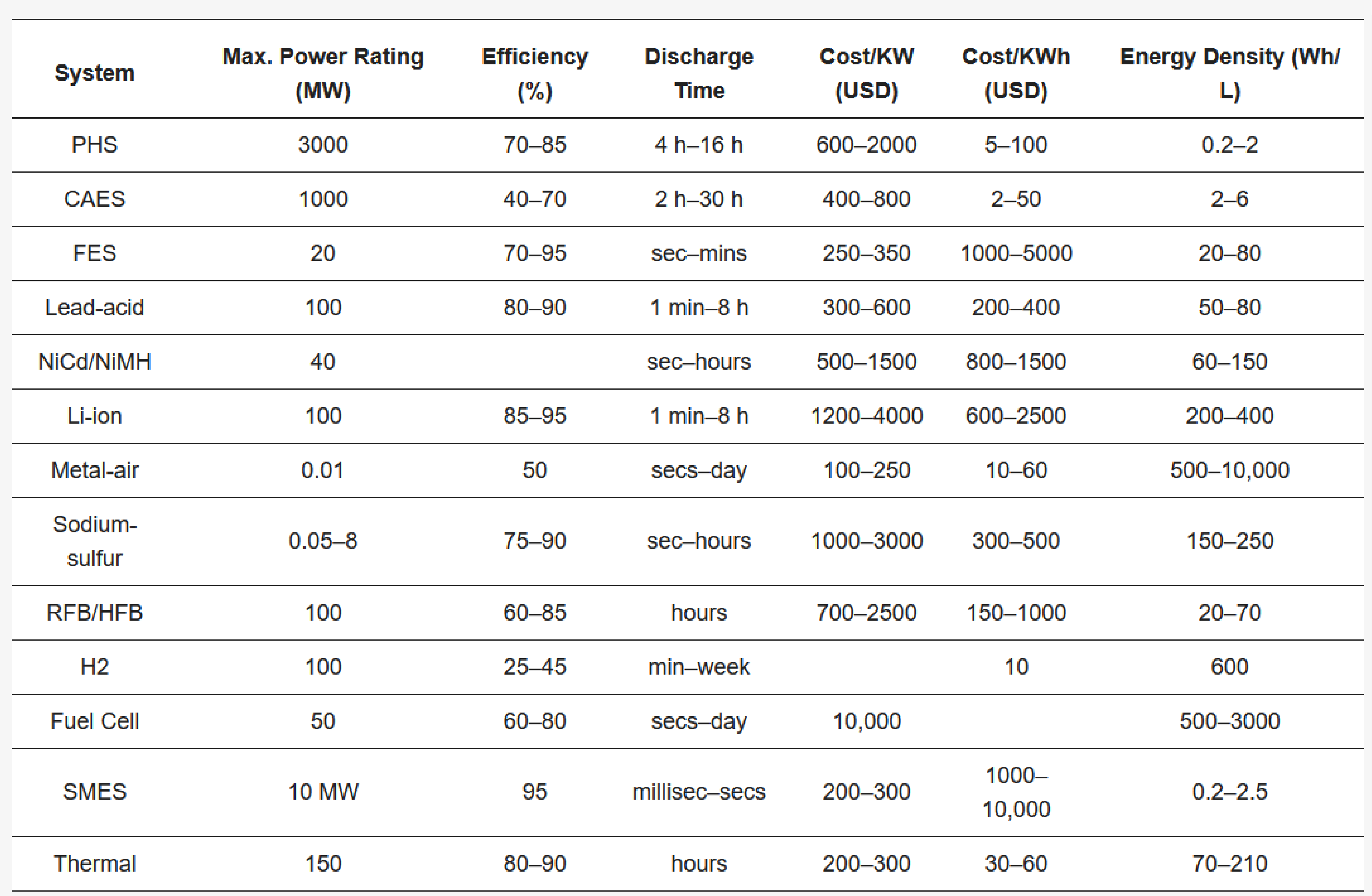


The issue of scale across different EES technologies

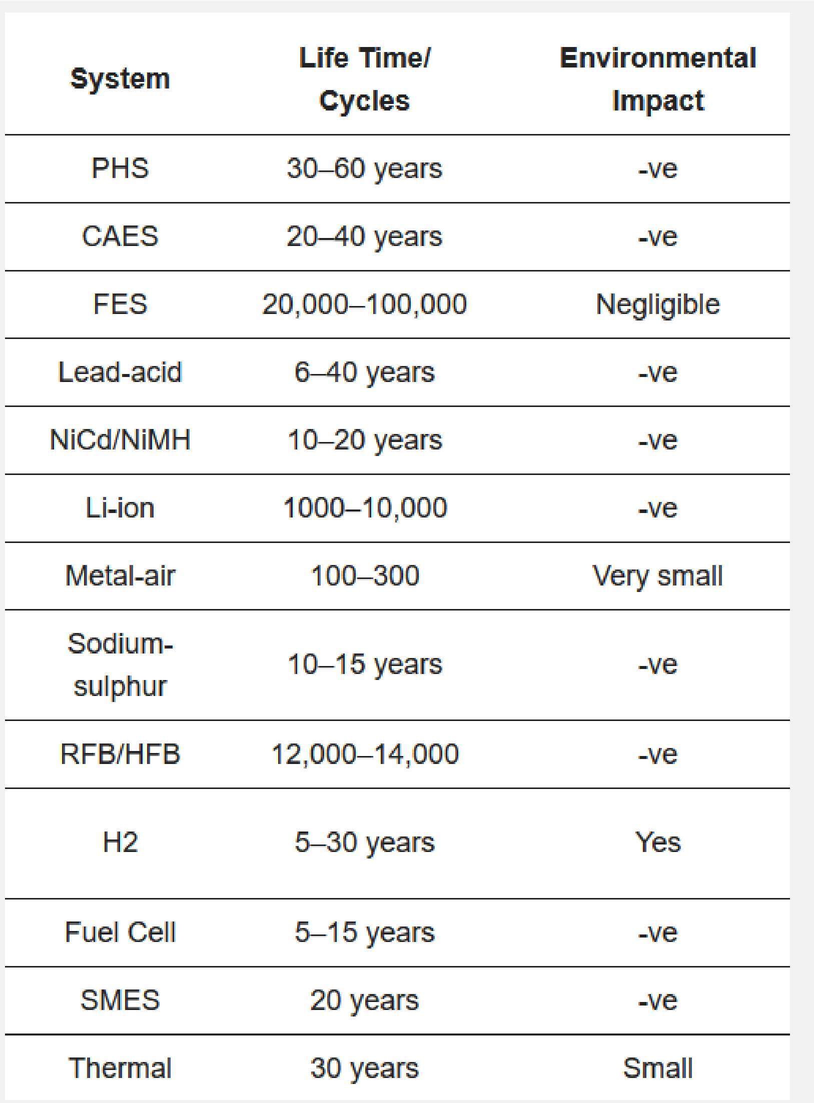
- The issue of scale involves:
  - the size of the system, in terms of **power capacity**;
  - the **discharge time**.
- The two characteristics are associated with the **energy autonomy** of the EES system.
- Small-scale systems ensure **power supply quality** across the electricity grid.
- **Pumped hydropower storage** is the unique large-scale technology with respect to both characteristics.



Comparison of EES technologies



System	Max. Power Rating (MW)	Efficiency (%)	Discharge Time	Cost/KW (USD)	Cost/KWh (USD)	Energy Density (Wh/L)
PHS	3000	70–85	4 h–16 h	600–2000	5–100	0.2–2
CAES	1000	40–70	2 h–30 h	400–800	2–50	2–6
FES	20	70–95	sec–mins	250–350	1000–5000	20–80
Lead-acid	100	80–90	1 min–8 h	300–600	200–400	50–80
NiCd/NiMH	40		sec–hours	500–1500	800–1500	60–150
Li-ion	100	85–95	1 min–8 h	1200–4000	600–2500	200–400
Metal-air	0.01	50	secs–day	100–250	10–60	500–10,000
Sodium-sulfur	0.05–8	75–90	sec–hours	1000–3000	300–500	150–250
RFB/HFB	100	60–85	hours	700–2500	150–1000	20–70
H2	100	25–45	min–week		10	600
Fuel Cell	50	60–80	secs–day	10,000		500–3000
SMES	10 MW	95	millisec–secs	200–300	1000–10,000	0.2–2.5
Thermal	150	80–90	hours	200–300	30–60	70–210

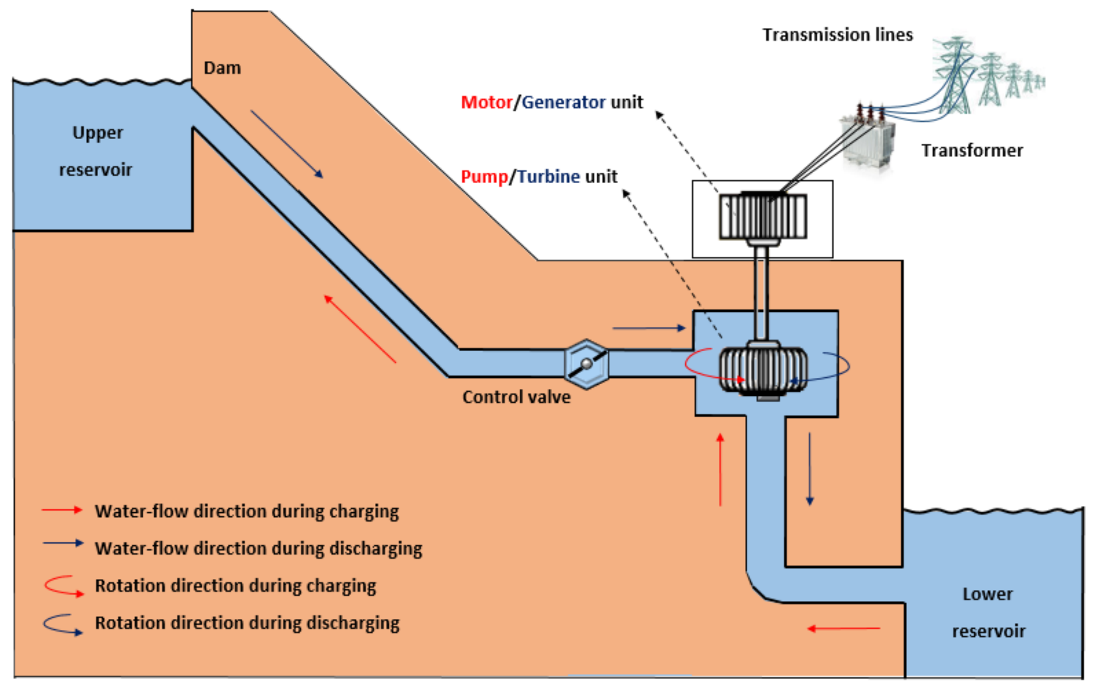


System	Life Time/ Cycles	Environmental Impact
PHS	30–60 years	-ve
CAES	20–40 years	-ve
FES	20,000–100,000	Negligible
Lead-acid	6–40 years	-ve
NiCd/NiMH	10–20 years	-ve
Li-ion	1000–10,000	-ve
Metal-air	100–300	Very small
Sodium-sulphur	10–15 years	-ve
RFB/HFB	12,000–14,000	-ve
H2	5–30 years	Yes
Fuel Cell	5–15 years	-ve
SMES	20 years	-ve
Thermal	30 years	Small

Source: Chakraborty, M.R., *et al.*, A comparative review on energy storage systems and their application in deregulated systems, *Batteries*, 8, 124, doi:10.3390/batteries8090124, 2022.

Pumped hydropower storage (PHS)

- Key elements of pumped hydroelectric storage systems:
  - two **interconnected water storage components** (reservoirs) located at a significant elevation difference yet short horizontal distance;
  - a **pump hydro turbine** or **reversible pump turbine** (typically Francis-type), utilized as pump during charging to lift water from the lower to the higher reservoir, and operating as turbine during peak demand to generate hydropower.
- Classified into two main categories:
  - **Open loop systems**: coupled to natural water systems, e.g. two reservoirs in series or an upper reservoir connected to a water source (river);
  - **Closed loop systems**: two independent reservoirs or tanks (upper, lower) of equal capacity.
- Round-trip energy recovery (combined turbine/pump efficiency): 70-80%



Examples

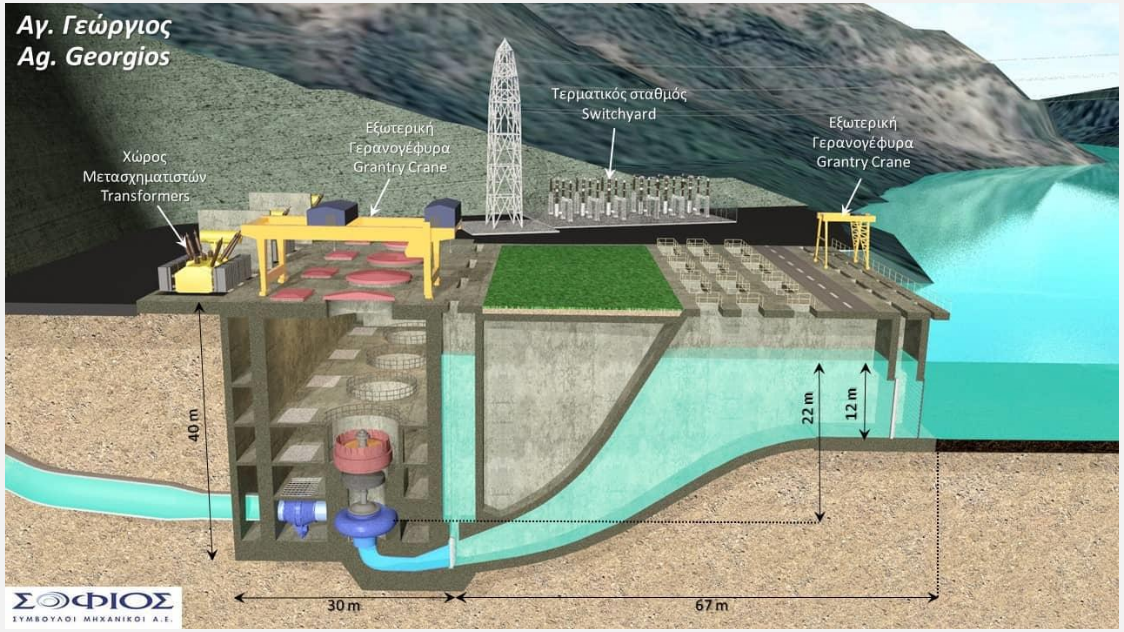
Presenzano, Italy: Two reservoirs of equal storage capacity (6.0 hm^3), total power capacity 1000 MW (four Francis-type reversible generators), gross head 495 m; construction began in 1979, finished in 1990, generators commissioned in 1991

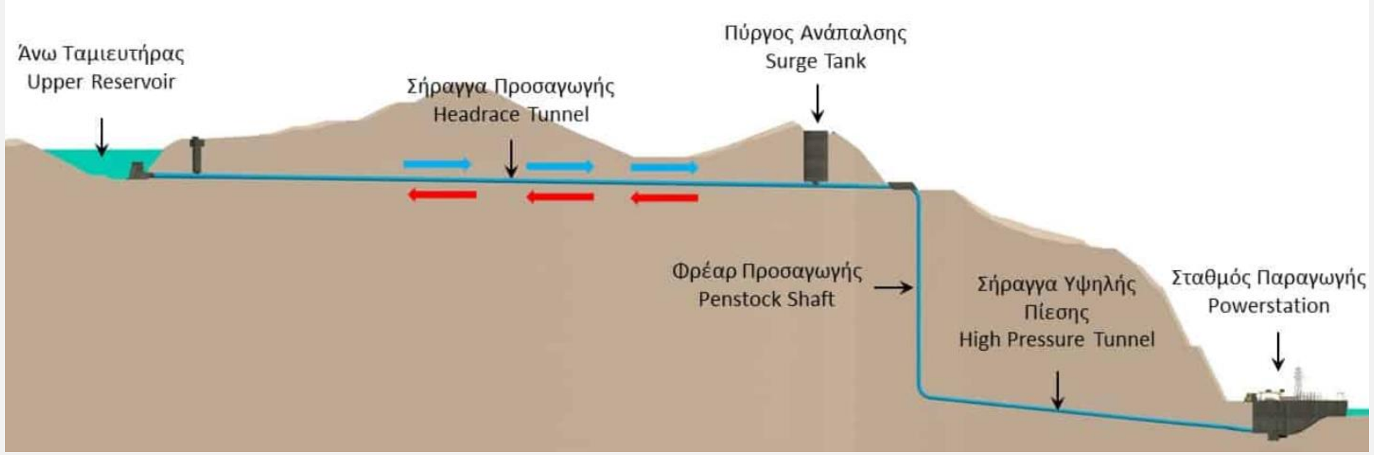
Tumut 3: First major pumped-storage station in Australia (constructed in 1968, entered into operation in 1972, upgraded in 2012); six turbines of combined power capacity of 1800 MW, three of them also operate as pumps; rated head 150.9 m; six pipelines of 488 m length and 5.6 m and diameter; lower storage element: Talbingo reservoir (920 hm^3), upper element: Jounama reservoir (43.5 hm^3)

Hydro Pumped Storage Complex in Amfilochia

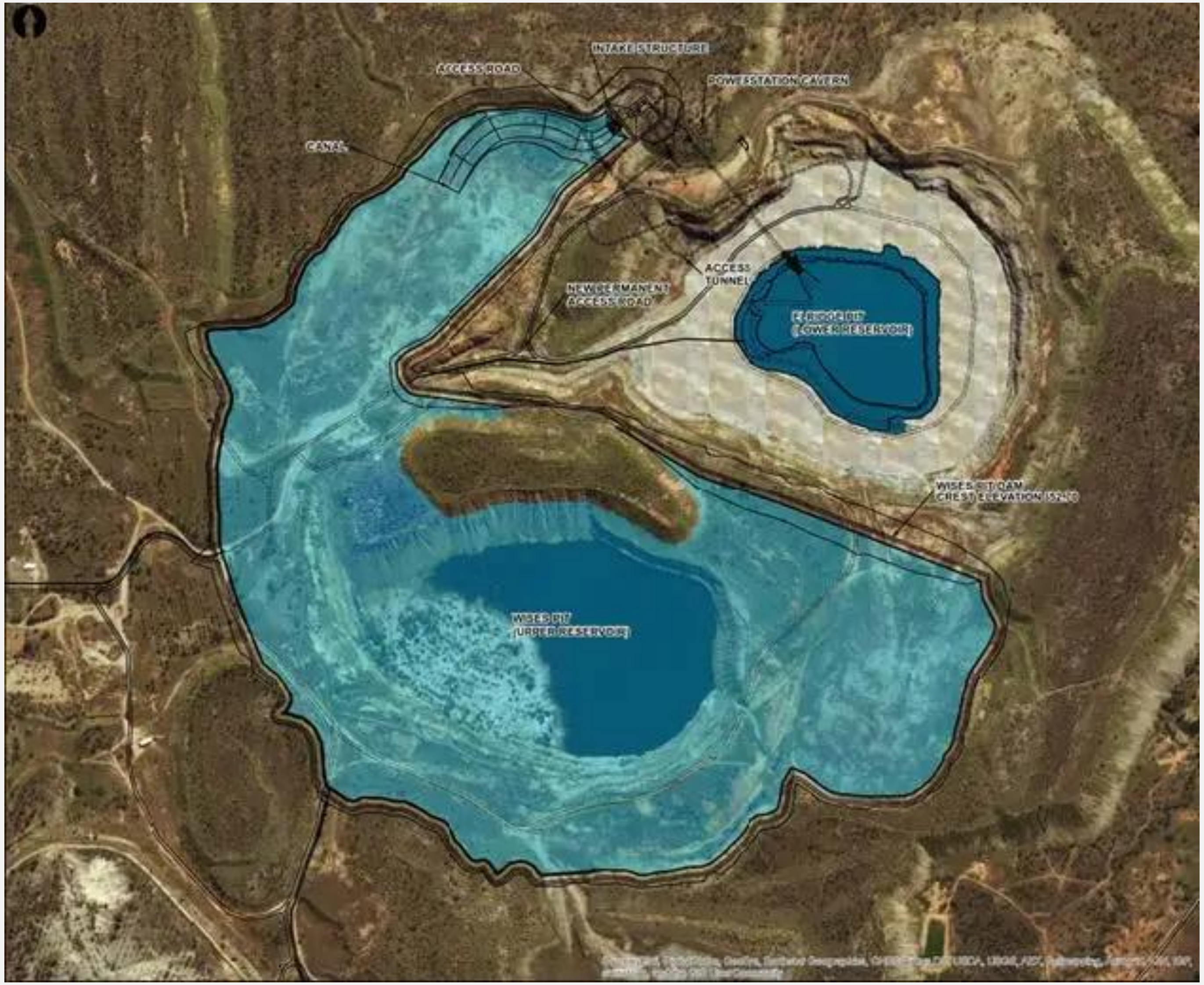
- ☐ Power capacity: 680 MW in turbine mode and 730 MW for pumping
- ☐ AG. Georgios: 238 m, 5.0 hm^3, 460/496 MW
- ☐ Pyrgos: 285 m, 2.0 hm^3, 220/234 MW
- ☐ Annual output: 816 GWh
- ☐ Cost: EUR 500 million

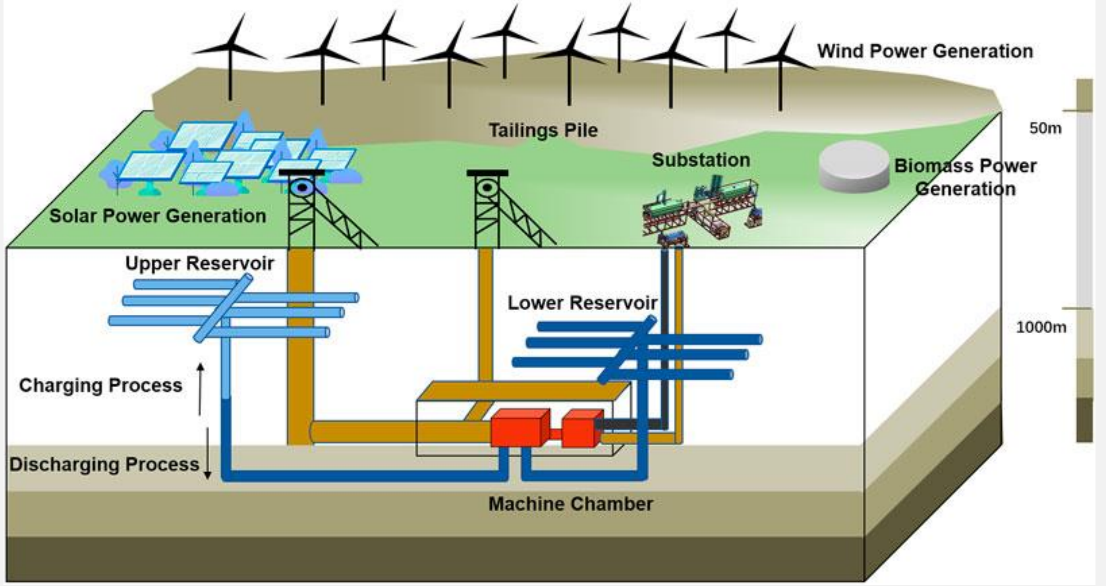
Photo: Terna Energy



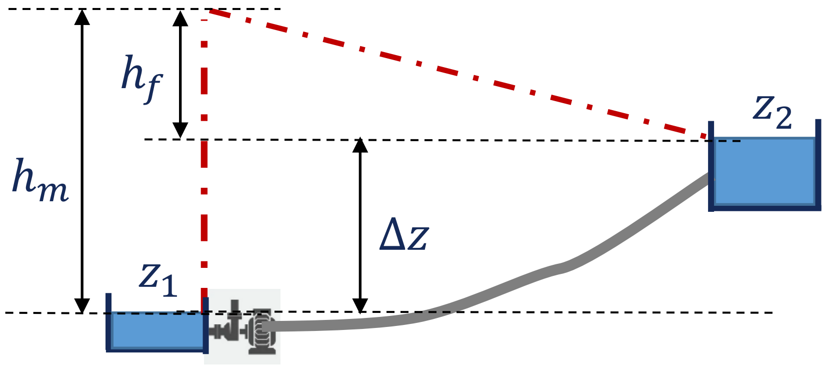


PHS in abandoned mines





Basic elements of pump hydraulics



- Power consumption across conversion of electrical power to mechanical, and then to hydraulic one, to lift water at an elevation difference (**static head**) Δz and conveying it to a distance L:

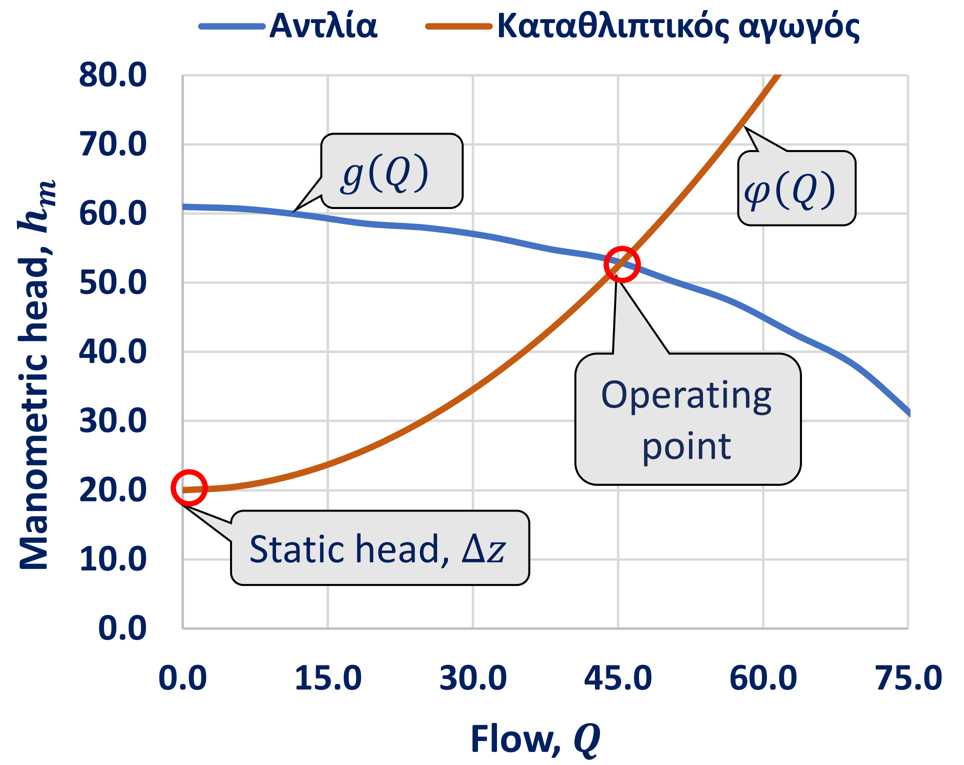
$$P = \gamma\ Q\ h_m /\ \eta$$

where η is the **efficiency**, which is function of Q, and h_m is the **manometric head**, given by:

$$h_m = \Delta z + h_L(Q) \approx \Delta z + J(Q)\ L = \varphi(Q)$$

where h_f are the hydraulic losses across the **suction pipe**.

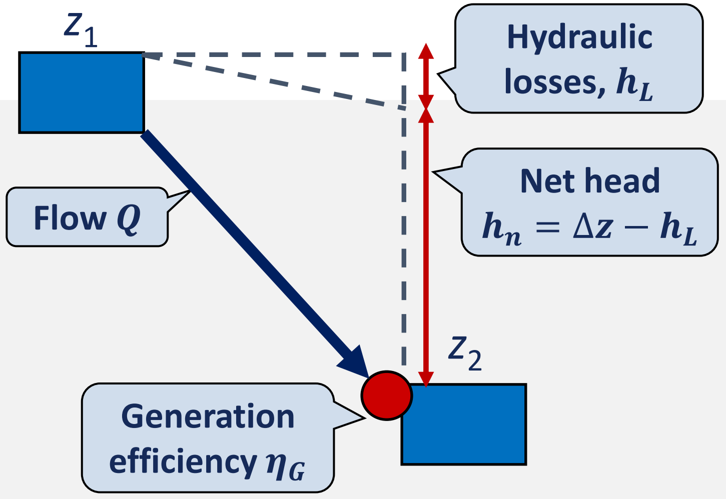
- The (unique) **operating point** of the pumping system is determined as the intersect of functions $g(Q)$ and $\varphi(Q)$; the first is provided by the manufacturer of the pump, while the second one is estimated via hydraulic calculations.
- Different operation points can be determined by applying **multiple pumps** in series or (more frequently) in parallel.



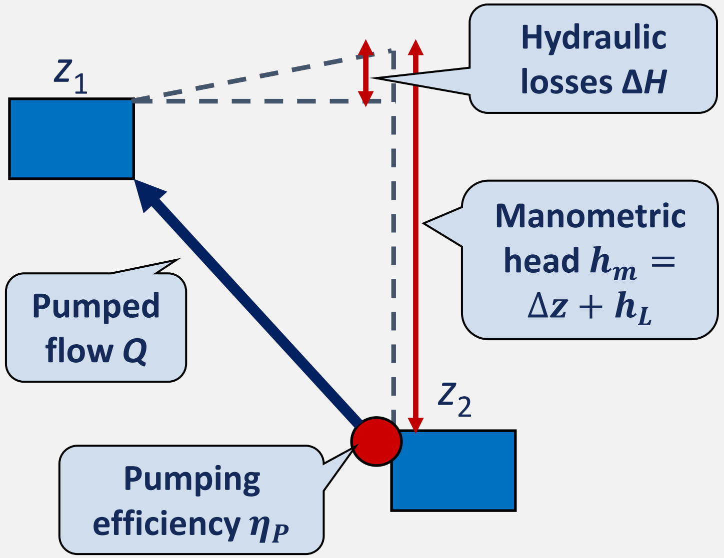
Design issues of PHS

- Major design requirement: minimizing of horizontal distance and maximizing the vertical distance of the two reservoirs, to ensure **large heads** and **minimal hydraulic losses**.
- Typical configurations:
  - Connection of two existing reservoirs;
  - Utilization of an existing reservoir exhibiting small water level fluctuations, as the lower storage component, and construction of a new upper storage component of much smaller capacity;
  - Formulation of two tanks of equal storage capacity (closed loop)
- Specific case: Application of two independent pipes for simultaneous power production and storage (beneficial for regulating highly fluctuating renewable energy sources, particularly wind).
- **Round-trip efficiency**:

$$\eta_{PHS} = \eta_G\, \eta_P (\Delta z - h_L)/(\Delta z + h_L)$$



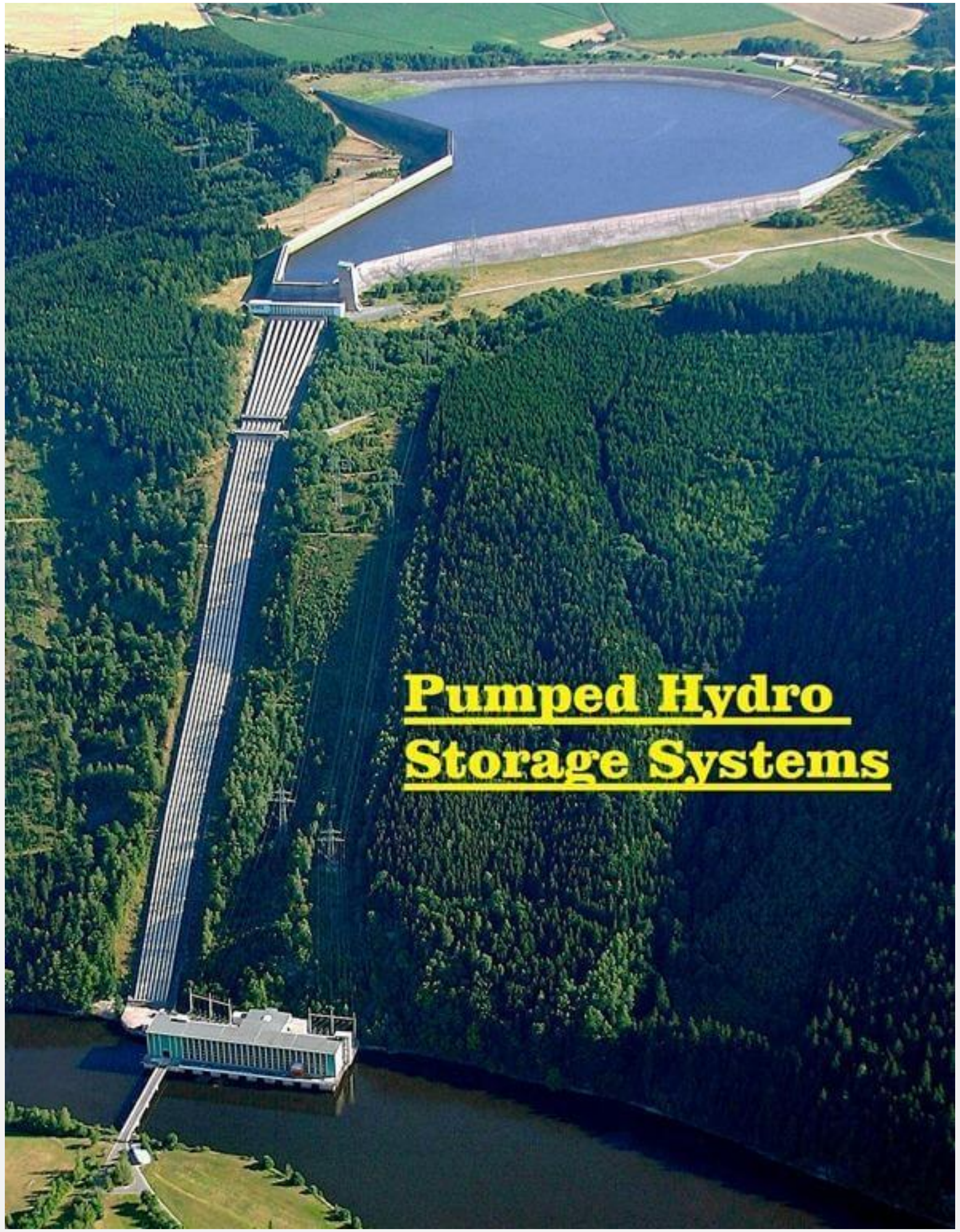
Energy production: $E = \gamma\, \eta_G\, V(\Delta z - h_L)$



Energy consumption: $E = \gamma\, V(\Delta z + h_L)/\eta_P$

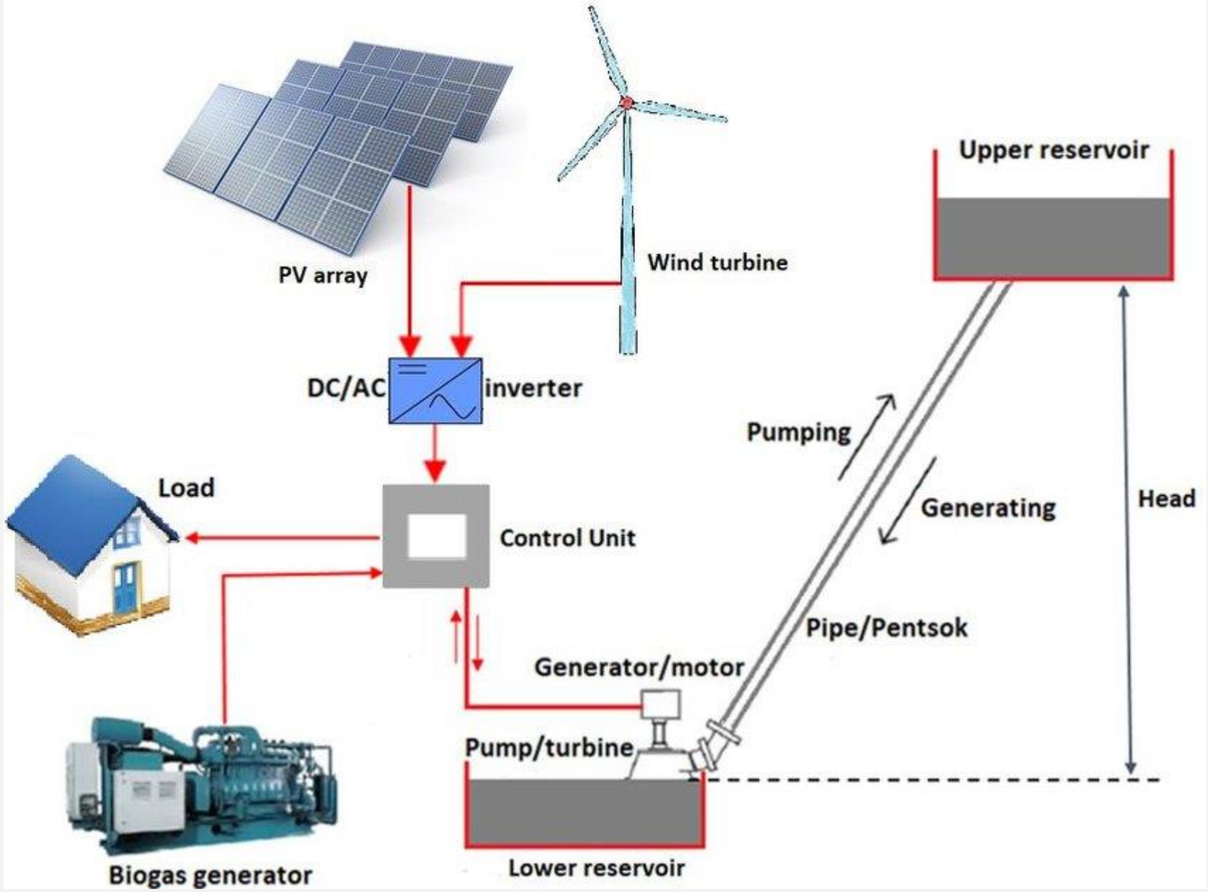
Final remarks on PHS

- **Mature technology**, covering >95% of total in-service electricity capacity over the globe (total capacity >180 GW, total energy storage capacity over 1.6 TWh).
- Their ability of **rapid change** make them ideal for electricity generation and storage and for handling electrical grid fluctuations.
- Traditionally used to regulate excess electricity from continuous base-load sources (e.g., coal or nuclear), to be saved for periods of higher demand,
- Two-fold role, i.e., balancing the grid for demand driven fluctuations, and balancing generation-driven fluctuations.
- Their implementation is expected to increase because of the integration of **intermittent, non-dispatchable renewable energy sources** to the electricity mix.

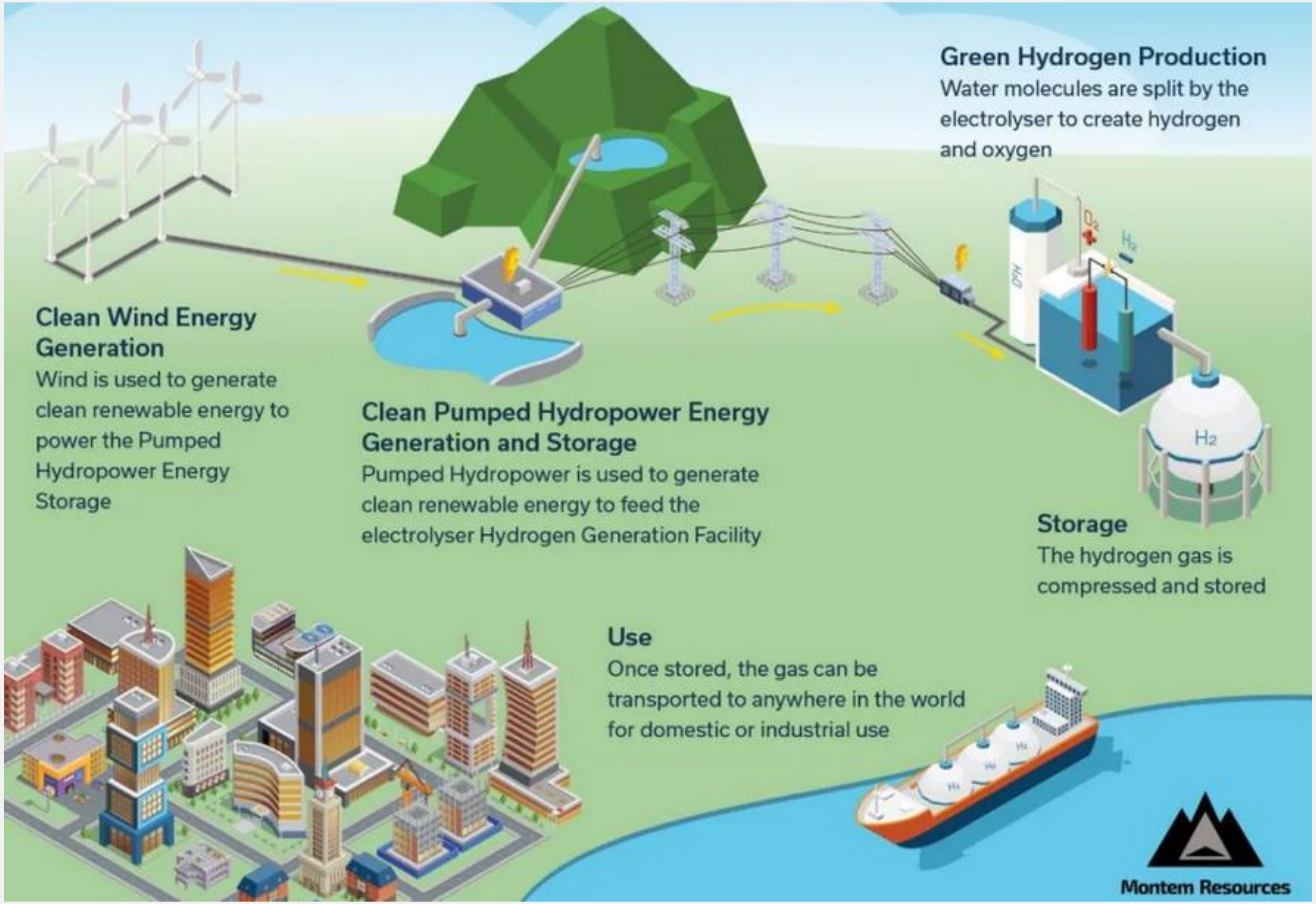


Hybrid renewable energy systems

- ☐ Mixing of at least one RES power plant (non-guaranteed power production), storage power plants and back-up generators (e.g., thermal) to ensure **energy autonomy**.
- ☐ Utilization of surplus energy production by RES, which would be necessarily discarded (small CFs).
- ☐ Combination with “smart" technologies for power saving (networks, devices, meters) and demand management measures (e.g., financial, legal).
- ☐ Other forms of utilization of energy surpluses (without electricity generation):
  - ■ Water pumping and temporary storage, next delivered for domestic/agricultural uses;
  - ■ Desalination → drinking water production;
  - ■ Heat storage → domestic hot water storage;
  - ■ Charging of electric vehicles;
  - ■ “Green” hydrogen production.



A look to the future: “Green energy project” Tent Mountain



Clean Wind Energy Generation
Wind is used to generate clean renewable energy to power the Pumped Hydropower Energy Storage

Clean Pumped Hydropower Energy Generation and Storage
Pumped Hydropower is used to generate clean renewable energy to feed the electrolyser Hydrogen Generation Facility

Green Hydrogen Production
Water molecules are split by the electrolyser to create hydrogen and oxygen

Storage
The hydrogen gas is compressed and stored

Use
Once stored, the gas can be transported to anywhere in the world for domestic or industrial use