

Design challenges in the renaissance of pumped-storage hydropower to support the energy transition

By Anton J. Schleiss

Renaissance of pumped-storage power plants

In the last century pumped storage hydropower (PSH) plants have been mainly built in combination with large conventional thermal and nuclear power plants producing continuous base load (Fig. 1). During low electricity demand the surplus base load energy with low market price was transformed by PSH into peak energy to satisfy high electricity demand in the grid at higher market prices. Thus, pumping occurred typically during night and daily off-peak hours of consumption and consequently turbine operation during the peak hours of consumption typically around noon and in the evening.

The role of PSH has significantly changed with the energy transition towards renewable and low-carbon energy production with high penetration of solar and wind power in the grid. PSH today mainly complements wind and solar by storing the excess electricity they create and providing the backup for when the wind isn't blowing, and the sun isn't shining¹. Such periods are called in German "Dunkelflaute" ("dark doldrums" in English) and can last several days or even more than a week. Without an adequate storage back up, which can be ensured by PSH, the supply safety and grid stability may be endangered during such "Dunkelflaute" events.

Today the global installed capacity in some 300 PSH stations is nearly 200 GW with a storage energy of 9000 GWh^{1,2} available or dispatchable at any time. In 2024 almost 155 GW of PSH capacity were under construction in some 15 countries worldwide

with most of it in China (83%) followed by India (6%)³. In another 6 countries, between 1000 MW and 4500 MW are under construction namely in Japan, Australia, USA, Indonesia, Philippines and Austria, contributing in total to 10% of the worldwide activity. Thus, in the near future, already in this decade, the installed worldwide PSH capacity will double, revealing the ongoing renaissance of PSH. Furthermore, in some 50 countries worldwide many PSH projects are at different stages of planning and studies, with a potential of several hundreds of GW installed capacity².

Purpose and benefits of pumped storage hydropower

What is the purpose and benefit of pumped storage hydropower? When asking this question to ChatGPT the following answer could be obtained:

"Pumped storage hydropower (PSH) is a type of hydroelectric power generation system that plays a critical role in balancing the electrical grid, ensuring grid stability, and providing a range of economic and environmental benefits. Its primary purpose and benefits include:

- *Energy Storage: PSH facilities store energy by using excess electricity, typically during periods of low demand or when there is surplus power generation, to pump water from a lower reservoir to an upper reservoir. This stored energy can then be released when demand is high or during peak periods, effectively acting as a large-scale energy storage system.*

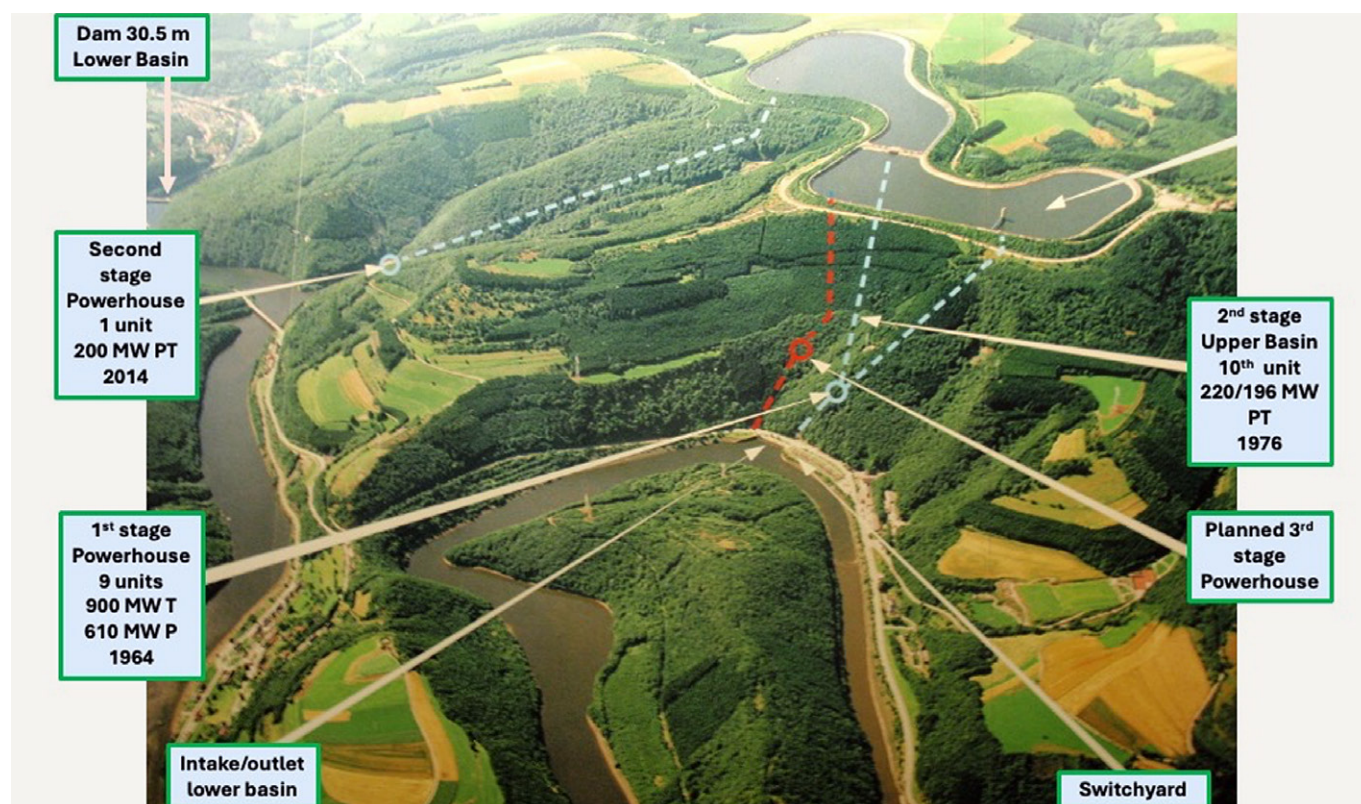


Figure 1 | Pumped storage powerplant Vianden in Luxembourg (total turbine capacity 1300 MW and pump capacity 1040 MW). Lower basin created by the backwater of 30.5 m high dam of a run-of-river powerplant and asphaltic concrete lined upper basin by a ring embankment dam. [Picture adapted from Vianden visitor centre].

- **Grid Balancing and Stability:** PSH is known as a grid-balancing technology because it can quickly respond to changes in electricity demand or supply. When there's a sudden increase in demand or a drop in power supply (e.g., due to fluctuations in renewable energy sources like wind and solar), PSH can release stored water to generate electricity within minutes, helping to stabilize the grid and prevent blackouts.
- **Load Shifting:** PSH allows for load shifting, where excess electricity generated during off-peak hours can be stored and then used during peak demand hours, reducing the need for additional power generation sources and minimizing the reliance on fossil fuels.
- **Renewable Integration:** PSH is especially valuable in integrating intermittent renewable energy sources, such as wind and solar, into the grid. It can store excess energy when renewable sources are producing more electricity than needed and release it when renewable output is low.
- **Increased Energy Efficiency:** PSH systems are highly efficient, with round-trip efficiencies typically exceeding 70-85%. This means that a significant portion of the energy used to pump water uphill is recovered when generating electricity during the downhill flow.
- **Reduced Greenhouse Gas Emissions:** By helping to integrate more renewable energy sources and reducing the need for fossil fuel-based peaker plants, PSH contributes to a reduction in greenhouse gas emissions, making it an environmentally friendly energy storage option.
- **Economic Benefits:** PSH facilities can generate revenue by participating in electricity markets. They can sell electricity at higher prices during peak demand periods, purchase electricity at lower prices during off-peak times, and provide ancillary grid services, such as frequency regulation.
- **Long Lifespan and Reliability:** PSH facilities have long lifespans, often exceeding 50 years, and require relatively low maintenance. They are known for their reliability and can provide a stable source of electricity for decades.
- **Water Management:** PSH facilities can also assist in water management by regulating the flow of rivers and providing water for irrigation, municipal supply, and recreational activities, depending on their design.

Overall, pumped-storage hydropower is a versatile and valuable tool for modern energy systems, helping to ensure a reliable and sustainable energy supply while addressing the challenges posed by intermittent renewable energy sources and grid fluctuations."

This comprehensive answer very well describes the purpose and benefits of PSH of pumped-storage hydropower addressing the most relevant points.

Layout options of PSH

The layout options of PSH are mainly defined by the combination of different types of lower and upper basin as listed in Table 1. Recent new PSH developments in the Alps in Europe have often connected existing large reservoirs of storage power plants.

Lower basin	Upper basin
• Storage hydropower reservoir • Run-of-river hydropower backwater • Natural lake • Artificial basin • Underground mine cavern • Open mine pit	• Storage hydropower reservoir • Natural lake • Artificial basin • Underground mine cavern • Open mine pit

Table 1 | Table 1: Types of lower and upper basins of PSH

This allows to exchange large volumes of water between the two reservoirs allowing long cycles of turbine and pump operations. Since the two large reservoirs have significant inflow for the long-term storage typical seasonal operation, such PSH are working as open cycle. In the case of artificial upper and lower basins with no significant inflow the PSH can be considered as closed cycle. This is also the case if a run-of-river hydropower backwater or a natural lake is serving as a lower basin, but the upper reservoir is an artificial reservoir with no inflow (Fig. 1). The volume of natural small lakes serving as lower or upper basin may be increased by dams to allow longer pumped storage cycles. In greenfield projects, artificial lower basins are created in small catchment valleys with dams. Artificial upper basins are arranged on hilltop topographical depressions requiring often besides a main dam also additional smaller saddle dams. Artificial basins may be also created by a combination of excavation and ring embankment dam construction. Such basins are normally fully lined either by asphaltic concrete or geomembranes for tightening purposes, whereas basins created by dams in valley or depression topography are rarely fully lined. Underground mine caverns and open mine pits can serve as lower or upper basins. However underground mine caverns as upper basins may be rather a rare option.

An idea that has been discussed for some time is for PSH using as lower basin the sea with an artificial, fully lined upper

basin on the coast. However, until now only the 30 MW prototype test project Okinawa Yambaru has been built in Japan and operated from 1999 to 2015 to gain knowledge on different challenges regarding sea water impact^{4,5,6}. In the EU research project ALPHEUS an innovative dam design for a low-head seawater pumped hydropower storage in the North Sea has been studied^{7,8}. The Atoll like PSH consists of a basin created by a ring dam in shallow sea from which the water is pumped out into the sea and then turbinised again back into the basin having a lower water level.

In many coastal regions worldwide there have been serious forest fires over the last years. In such situation a kind of a multi-purpose PSH would be of interest where the upper basin can serve as pond for extinguishing water reserve with preinstalled supply pipes bringing water to critical locations besides serving as a fill place for fire-fighting helicopters or aircrafts.

The selected installed capacity of a new PSH is normally based on grid requirements. Then the required storage volumes of the upper and lower basins are given by the desired cycle duration. Nowadays the trend is to build PSH which allow cycles in the range of 24 hours up to 48 hours.

The best cycle efficiency of any PSH is obtained by an arrangement of upper and lower basin which give the lowest ratio between length of the waterways and the operational head difference between the two basins.



Figure 2 | Left: Raise-boring equipment at the top of the vertical pressure shaft of Nant de Drance pumped storage powerplant in Switzerland. Right: View into the concrete lined vertical pressure shaft from the bottom. [Courtesy Anton J. Schleiss].

Tendencies in alignments of PSH waterways with not steel-lined vertical shafts

Parallel to the development of the efficient raise-boring method vertical pressure shafts have been used for about 30 years for the alignment of waterway systems of hydropower power plants (Figure 2.) Such concept has now been used on many hydropower schemes⁸. Above all for new underground pumped storage power plants, there is nowadays a tendency to select a deep alignment of the waterway system which is favorable from the economical and safety points of view (Figure 3). In fact, compared to inclined and steel-lined pressure shafts, vertical shafts have advantages regarding construction time, working safety during excavation, quality of concrete lining due to better compaction as well as ease of maintenance. With the raise-boring method, vertical pressure shafts can nowadays be drilled up to 800 m in one step¹⁰. If the vertical shaft is deep in the rock mass, near the upper basin, hydraulic jacking is prevented without needing a steel liner, provided rock permeability is moderate. Then a reinforced concrete lining is sufficient which is designed in order to limit crack widths and thus keep water losses below acceptable values¹¹. In view of highly increasing steel prices, such a concept result in economic and competitive PSH projects. The cost savings could amount to approximately 100 million dollars or more, depending on the prevailing pressure head in the waterway system. Furthermore, placing the underground powerhouse close to the bottom of the vertical shaft, the headrace system length with high water pressure can be limited to a minimum which allows also to omit an upper surge tank (Figure 4). However, depending on the total length of the waterway system a surge tank may be required downstream of the powerhouse at the beginning of the tailrace tunnel.

Some design challenges

Based on my experience gained through the involvement as an expert in several new PSH project, some design challenges are highlighted in the following.

Sediment and flow dynamics in unlined basins and turbidity risk

New PSH are often planned in the upper part of hilly catchments with a lower basin created by a dam at a favorable location regarding available storage volume. The lower basin is then

supplied with a very moderate inflow from small river creeks which allows a timely first filling of the PSH and the compensation of evaporation losses. The upper basin is mostly a hilltop arrangement with in a favorable topographic depression allowing to create a basin with a main dam and eventually a certain number of required smaller saddle dams. Such basins having an irregular shape according to the prevailing topography and are normally left unlined even if their bottom consists of loose soil or rock covered by vegetation. Besides the mandatory removal of trees and wooden material the question arises if there are dispersive sediments (like lateritic soils) in the basin area which may be diluted even into stagnant water below the minimum operation level (MOL) of the basin. Furthermore, it should be checked if fine sediments along the shores can be washed out into the basin due to water level oscillations during pumped storage operation or due to wave impact and/or rain erosion after the protective vegetation cover has disappeared. There is also the question if sediments covering the bottom of the basins can be put into suspension by the internal currents and gyres occurring during pumped storage operation. Of course, the areas very close to the intakes and outlets have to be protected against erosion with a lining and/or protecting riprap layers. Finally, the concentration of suspended sediments in the water which is transported by the small rivers, gullies and creeks mainly into the lower basins during rain events every year must be assessed carefully over the lifetime of the project. Sediment management strategies have to be implemented, for example by the venting of turbid water with low level outlets during floods instead of operating surface spillways only. These issues have to be managed to avoid an increase in the turbidity in both basins with time due pumped storage operation which may have not only an environmental impact but also risk of abrasion of hydraulic machinery and clogging of its cooling systems.

Sediment behavior and flow dynamics in unlined basins and turbidity risk are strongly influenced by the choice of MOL. The required minimum dead storage respectively the feasible MOL can be determined by a 3D hydrodynamic numerical model of the two reservoirs simulating pumping and turbine operation. When approaching MOL, the velocity and turbulence of the water entering from the intake/outlet (Figure 5) into the reservoir can be determined. To avoid significant resuspension,

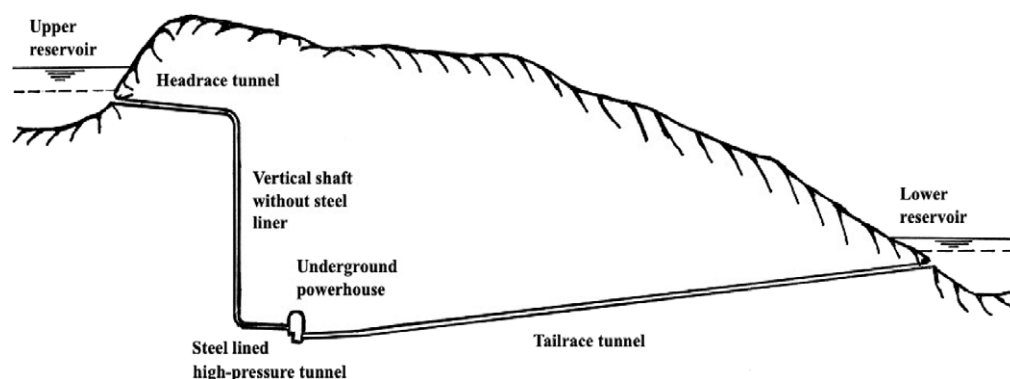


Figure 3 | Schematic longitudinal profile of a typical waterway system of a PSH with a vertical shaft between the two basins located close to the upper basin.



Figure 4 | Excavation of main machine hall of the underground powerhouse of Limmern pumped storage powerplant in Switzerland. [Courtesy Anton J. Schleiss].

the velocities of flow and gyres should be limited below about 0.1 to maximum 0.2 m/s everywhere in the basin outside of the erosion-protected area near the intakes/outlets. This gives a criterion for the minimum required dead storage and respectively the feasible lowest MOL. With the same numerical simulation, the drawdown velocities at the shores can be analyzed when emptying the reservoirs to MOL, which may also give an additional criterion for the minimum required reservoir surface, i.e. the feasible MOL. Furthermore, the numerical 3D simulations of the two reservoirs will give valuable information on the adequate choice of the geometry and orientation of the intakes which create favorable internal currents in the two reservoirs during pumped-storage operation. Stagnant water zones in the reservoir with fine sediment deposition should be avoided as well as high velocities near the bottom and along the shores which risk whirling up already deposited fine sediments. In the case of multiple intakes/outlets the interaction of crossing jets and its potential oscillation may be an issue too. Finally, the numerical 3D simulations of the two reservoirs can be combined with water quality models.

Following such numerical analysis, hydraulic model tests are recommended for the final verification of the intake geometry including vortex formation. The higher the intake/outlet velocity is the higher is the turbulence rate introduced in the basins and the risk of turbidity and vortex formation. Intake velocities close to 1 m/s have proven to be economical regarding head losses over the project's lifetime and potential vortex formation can be better avoided or handled with mitigation measures.

Bifurcation design considering short circuit-operation

The water from the headrace tunnel and shaft is normally branched to two up to four pump turbines in the underground powerhouse. A symmetrical manifold should be avoided since the discharge between the branches having the same friction characteristics, may oscillate significantly due to vortex shedding at the bifurcation creating problems with machine regulation. A non-symmetrical manifold is also more favorable for short circuit operation, that means with a unit pumping and the neighboring unit turbinning at the same time to give rotating mass

inertia in the grid as well as fast response. From the point of view of structural design of the steel manifold non-symmetrical bifurcations are also more favorable.

Implications for dam design considering daily significant reservoir fluctuations

For frequent high reservoir fluctuations concrete faced rockfill dams (CFRD) and gravity dams by conventional or roller compacted concrete (RCC) are most adequate. Another, potentially more cost competitive, option would be the new concept of Faced Symmetrical Hardfill Dam (FSHD) built with cemented soil rock material with low cement content. Such RCC dam types, conventional RCC with an upstream slope or FSHD with lean cemented soil-rock material, are more suitable for unfavorable geological conditions since the loading of the foundation is an almost uniform compression for full and empty lake conditions. Thus, also less creeping of the foundation with frequent significant reservoir level fluctuations has to be expected as it would occur in a conventional triangular gravity dam profile having high stresses at the upstream and downstream toe for empty and full reservoir respectively.

When defining the required depth of the grout curtain, standard approaches, as those used for conventional reservoirs with moderate water level fluctuations, may not apply. For hilltop reservoir conditions an appropriate grout curtain depth should ensure that seepage from the reservoir, even if very limited, cannot reach the free surface at the hill slopes which in the long run may trigger landslides in the case of quite impermeable covering soils. For this purpose, 3D seepage analysis from the reservoir to the hill slopes as a function of the grout curtain depth is highly recommended. Finally, for CFRD dams, plinth width and contact grouting design should also account for high water level fluctuations changing the seepage below the plinth daily.

First filling of PSH waterways

During excavation works of the waterway the natural groundwater level in the rock mass will be drawn down by the effect of drainage into the shaft and tunnel. Thus, the first filling of the water-

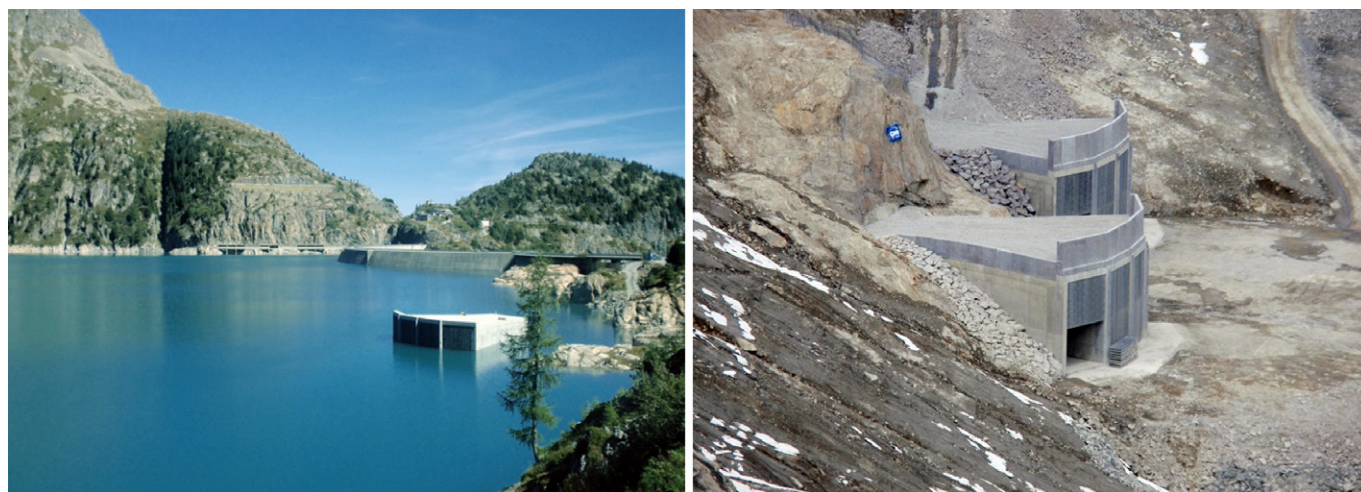


Figure 5 | Left: Pre-construction of intake/outlet of Nant de Drance pumped storage project in Switzerland at the shore in late summer of the lower Reservoir Emosson. Right: After floating of the intake structure, implementing it at the portal of the tailrace tunnel early spring when Emosson reservoir is empty. [Courtesy Anton J. Schleiss].

way has to be done with care in order to ensure that the rock mass can slowly and uniformly re-saturate, thereby avoiding overstressing of the concrete lining and the rock mass due to the high gradient of seepage flow^{12,13}. This could lead to uncontrolled cracking of the lining and even of the rock mass resulting in the widening of existing joints with the possibility of washing out the joint filling material and increasing the permeability around the tunnel. Furthermore, the sealing effect of a grouted rock zone could be reduced by crack propagation. Thus, the waterway should be filled slowly increasing the pressure with steps and saturation pauses in between. The gradient of the

seepage flow at the beginning of each new pressure step should not exceed the value of the maximum gradient during operation, which is defined as the ratio between maximum internal pressure head and shortest seepage path towards the rock surface. The pause between each pressure step is equal to the time needed to saturate the rock mass around the tunnel. After each pressure step the water level in the shaft should be kept constant until the water losses attain a nearly steady quantity indicating that the rock mass saturation is achieved. It may be concluded that the first filling of PSH waterways is a very critical phase which needs a carefully planning and monitoring.

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