# Underground Cavities in Pumped Hydro Energy Storage and Other Alternate Solutions

**Alessandro Morabito**, Aero-Thermo-Mechanics Department, Université Libre de Bruxelles, Brussels, Belgium





## Introduction

The production of electricity from renewable sources is generally intermittent, especially as wind and solar energy, and weather and climate conditions have also a significant influence on hydropower. Among the different energy storage technologies, Pumped Hydro Energy Storage (PHES) accounts for more than 94% of the installed grid connected electricity storage capacity worldwide, with about 160 GW across over 300 medium-large sites (International Energy Agency, 2021). Key advantages in having large sites include lower costs per MWh, higher reliability and the strength to provide high levels of power for many hours. The remaining energy storage capacity is via other technologies such as compressed air and electrochemical storage (International Energy Agency, 2021).

PHES requires two linked reservoirs located at different elevations. When electricity is needed, gates are opened and water flows through, driving the turbines, which are coupled to electricity generators. When demand decreases during off-peak periods, the energy surplus from energy sources that continue to produce power (e.g., wind turbines, PV, nuclear plants) can be stored using PHES. Powered by this surplus electricity, a pump, alternatively a reversible turbine, can refill the upper reservoir. Fundamentally, the system is recharging the upper reservoir to have it ready to be used again when needed: pumps use the available surplus of energy for storing water in the upper reservoir and turbines operate when needed.

PHES preserves most of the advantages of hydropower plants, even if PHES is not considered a renewable energy source as such. Especially for closed-loop configurations, which consist of two reservoirs that are isolated from a free-flowing water source, the generated energy comes solely from the storage of a second energy source that is not necessarily renewable. On the other hand, closed-loop systems have fewer environmental impacts because, after the initial replenishment of the reservoir, there is almost no transfer of water from a free-flowing source, thereby greatly reducing environmental impacts (fish passage, sediment migration, etc.).

Relevant and unconventional design decisions can be taken to implement a PHES plant besides its traditional concept or to reduce costs. Section "Underground pumped storage hydroelectricity" (UPSH) overviews the energy storage power plants that, based on the mature PHES technology, use pre-existing underground cavities to cope with the expenses of building reservoirs from scratch or the lack of hilly areas suitable for pumped hydro storage (Pujades et al., 2017). This category of energy storage facilities includes Energy Membrane (EM) that consists in bury an inflatable cavity underground filled with water. As such, the weight of the soil above the membrane provides an exploitable hydrostatic pressure.

Another different PHES design is based on using seawater instead of freshwater: the Seawater Pump Storage (SPS) plants. SPS systems can pump seawater directly from the sea, thus the construction of a lower reservoir is avoided, which further implies less land use and lower construction costs (Ioakimidis and Genikomsakis, 2018). However, the use of seawater results in increased costs related to corrosion protection and the prevention of ground contamination from salt water (Katsaprakakis et al., 2013). Therefore, SPS systems comprise a solution for areas characterized by a lack of abundant natural fresh water and in the proximity of the seashore (Ioakimidis and Genikomsakis, 2018).

Following the concept of "think globally, act locally", micro and small pumped hydropower plants could help to ease the future electric energy provision for buildings or remote communities. Section "Micro-scale PHES units" provides an analysis of these applications and their perspectives. Finally, another innovative approach is emerging in proposing unusual PHES facilities. Instead

 https://doi.org/10.1016/B978-0-12-819723-3.00145-1 

of storing energy using reservoirs at different elevations, Hydraulic Gravity Storage systems (HGSs) pump water to lift a heavy piston. Allowing the piston to fall pushes water through a turbine to generate electricity. The concept and some of its variations are shown in Section "Hydraulic gravity storage (HGS)". In Section "Conclusions" final remarks on the different alternate solutions for PHES are presented.

## Underground pumped storage hydroelectricity

UPSH facilities represent a valuable solution in increasing the electrical energy storage capacity in those regions where, because of their geomorphology conditions, there are no promising sites for conventional PHES with sufficient head and surface (Martin, 2011). In these systems, the hydropower head is obtained by exploiting the depth of an underground cavity instead of elevated reservoirs (Fig. 1). However, the use of underground cavities as lower reservoirs for hydropower applications is not widespread and its technology has not yet passed the research and development phase (Pickard, 2011; Pujades et al., 2018).

### The development of UPSH

The patent for underground energy storage applied to hydropower is to R. Fessenden, being the first to record the idea of "placing the lower reservoir, not on the surface of the earth, but subterraneously, so as to have a high negative gravitation potential with reference to the earth's surface" (Fessenden, 1917). Nowadays, there is no evidence of an operating UPSH but a few projects worldwide in the attempt to use a subterranean pass-through hydro system or to re-evaluate abandoned quarries as water reservoirs. In the 1970s new research articles, especially from the United States, were proposing underground hydroelectric pumped storage as a practical option and they were prospecting the future needs in additional energy storage facilities. The first questions arose on which type of turbo-machinery to be used (Tam and Clinch, 1979), the power station arrangement and equipment (Scott, 1977), and if UPSH could compete with compressed air energy storage in the use of underground cavities (Chiu et al., 1979). Already, concerns were addressed for better techniques to determine underground geology during site exploration and possibly minimize cost overruns during construction (Chiu et al., 1979). Later in New Jersey, an iron mine was proposed as the lower reservoir for a UPSH (US Army Corps of Engineers, 1981) but the Mount Hope project never went further. In Minnesota, United States, 10 sites are analyzed and explained to produce caverns that could be used as the lower reservoir in a PHES (Martin, 2011; Zillmann and Perau, 2015).

In the early 1980s, a preliminary geological investigation has been conducted to find a suitable site in The Netherlands, pointing to the limestone rock of South Limburg to a reservoir at about 1000 m depth (Min, 1984). About 20 years later, the investigation on this site resumed to match with the actual Dutch energy policy that foresees a considerable role for renewable variable electricity sources. The O-PAC project (Ondergrondse Pomp Accumulatie Centrale) will be able to generate 8.4 GWh per cycle by exploiting an underground cavity at 1400 m depth. According to its business plan, it will be able to generate a societal benefit to the Netherlands and its citizens of 140 million EUR per annum (O-PAC Ontwikkelingsmij, 2021).

In the late 1990s in Singapore, the Bukit Timah granite quarry has been evaluated as the lower reservoir for a UPSH because of the lack of topographical reliefs (Wong, 1996). The high cost of land in Singapore and the possible costs to the back-filling of the abandoned mine, that is considered potentially dangerous for unauthorized visitors, make a UPSH plant of 370 MW economically comparable to an oil-fired plant at the time (Wong, 1996).

In Belgium, the Smart-water project had the objective of collecting the tools and information in socio-legal, economic, hydraulic, and hydro-geologic aspects to detect specific underground sites and unused quarries and mines in the Walloon region for EES use (Pujades et al., 2017; Morabito et al., 2020). Although this region does not have relevant differences in altitude, a preliminary mapping of the Walloon potential into new UPSH solutions using carrier sites is estimated to be about 4′896 MWh spread on

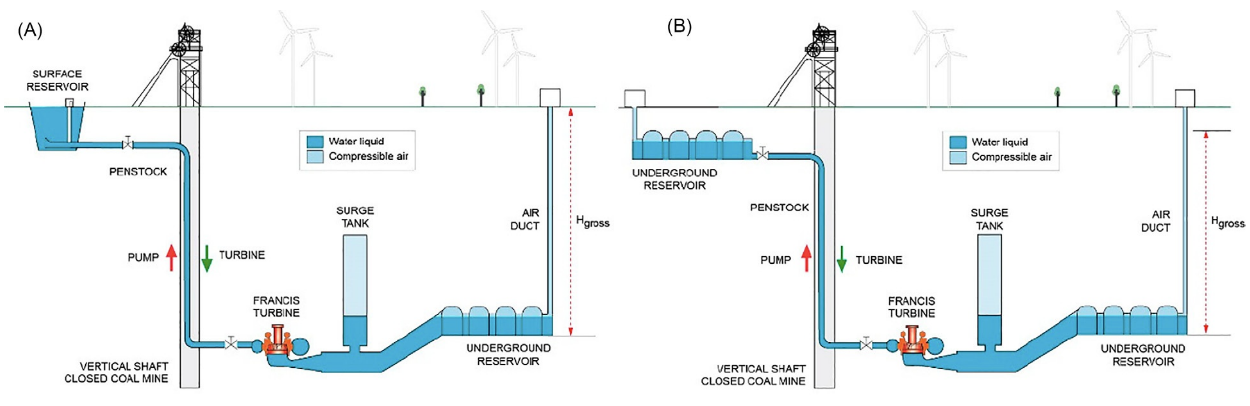


**Fig. 1** UPSH schemes in a closed deep mine with the upper reservoir at ground level (A) and subterranean (B) (Menéndez et al., 2020).

76 sites. The study has been conducted on the totality of about 300 underground cavities and 1500 quarries on surface. The two main obstacles to the development of PHES on the Walloon territory have been identified under the legal and socio-environmental aspect: the complexity of the procedures and the costs generated by the current taxation. Financial incentives could nevertheless be envisaged to facilitate their development. Other risks are also individuated by the hydro-geologic analysis (Pujades et al., 2017).

The Victorian Government and City of Greater Bendigo, Australia, co-founded a pre-feasibility study into UPSH using existing mining infrastructure in Bendigo (Bendigo Sustainability Group, 2021). The final report found that the project has the potential to be technically feasible and economically viable. The concept proposed for further development is an inter-reef pumped hydro system with a capacity of up to 30 MW which can store up to 180 MWh of energy. A Pelton turbine is supposed to exploit an available head of approximately 720 m from the two underground reservoirs. A group of pumps, located 150 m beneath the powerhouse, would store the water back in the upper cavity (Bendigo Sustainability Group, 2021).

In Germany, the coal mine of Prosper-Haniel has been studied as the lower reservoir for a closed-loop UPSH or in an open system, presenting the challenges of the rock stability, its porosity, and the composition of the used water (Wong, 1996; Alvarado and Niemann, 2015). The project foresees the use of infrastructures of an existing mine site and a new underground ring structure used as the lower reservoir. The new storage ring, long about 15 km, is located at a 500-m depth and provides 750 MWh capacity to the energy storage system.

In Estonia, a 500 MW PHES is an ongoing project that will generate electricity (6 GWh per cycle) using previously accumulated renewable energy. The power system is planned to become operational near Tallinn in Paldiski in 2028 and it will offer flexibility services to the Nord Pool Spot power market. This PHES will generate power by three Francis type pump-turbine units, installed at 730 m below sea level, exploiting a nominal water discharge of 96 $m^3/s$ (Energiasalv, 2021). The project has a unique hybrid business model of combining power storage services and deep granite mining which remarkably improves the initial revenue sources. The project financial viability is supported by the remarkable revenues generated from the sale of the crystalline bedrock that will be excavated to create the underground caverns. The mining of this material will allow for loans to be serviced before commissioning. Moreover, the upper reservoir consists of the sea. This fact introduces other requirements and constraints for the hydraulic system, but it dispenses with building an upper reservoir. The projected revenues of 150 million EUR equal about 25% of the project's current estimated total capital expenditures (620 Mio EUR) (Burdett, 2021).

## UPSH potential and risks

The most significant obstacles for PHES are the location of suitable sites and capital investment. Benefiting from an existing underground cavity, natural or unused mine, UPSH is characterized by lower civil construction costs for constructing the water reservoirs. Moreover, concerning the reservoir placement, the use of the lower reservoir located directly beneath the upper one (or sufficiently close) minimize the hydropower design parameter of pipeline length and available head (L/H) (Wong, 1996). Because the most relevant parameter in the cost of constructing underground is the excavated volume for the lower reservoir, powerhouse and accessories, there are economic incentives to set the water reservoir as deep as possible to increase the available head meeting the targeted capacity with the minimum volume of water required, thus with the minimum of excavation (Wong, 1996). However, a deeper underground reservoir calls for longer excavation for the access shaft and because the rubble must be lifted to the surface (Pickard, 2011); a trade-off design solution is needed.

In the framework of UPSH plants, not all types of soil have adequate characteristics. The geology is of course critical to the feasibility of UPSH projects, and the selected sites require very high compressed strength rock. Soft sediments and friable rocks cannot withstand the erosion created by the generating-pumping cycles and porous rocks are thus unsuitable as underground water reservoir (Bear and Cheng, 2010). Salt caverns for storage have typical geometrical volumes from several $10^5$ $m^3$ to $10^6$ $m^3$ but everything placed between the insides of the cavern wall needs to be able to withstand the geostatic pressure (approximately 22 MPa per kilometer depth) or cavern shrinkage would happen without a protective casing. Furthermore, a substance that dissolves salt cannot be used inside these caverns without separation from the walls. On the other side, coal and metalliferous mines as slate and black marble quarries could be taken into account for their rock stability.

Groundwater interactions and oscillations in piezometric heads by the influence of hydraulic conductivity of the surrounding aquifer are possible but are limited (Bodeux et al., 2017), as the head variation depends heavily on the discharge pumped from or injected in the cavity. Pujades et al. have estimated the groundwater exchanges positively as they mitigate the head variation due to regular operation of the turbomachinery (Pujades et al., 2017).

Still in respect to the groundwater flow impact, if the mine is isolated with respect to the surface, it appears that the pressure inside the chambers will increase as they are filled by water, and it could influence the water exchanges between the underground reservoir and the surrounding medium (Pujades et al., 2018). In any case, old mine rehabilitation tasks should be undertaken to adapt abandoned mines as underground reservoirs for UPSH (Morabito et al., 2020). Thus, additional works might be required to strengthen the rock stability. Special attention must be given to the effects of increasing the connectivity between all the mine chambers or cavities. For instance, to damp oscillations or eliminate disruptive water flows in the underground cavities, galleries homogeneously distributed between them could be drilled.

The hydraulic cycles of pumping and generating will involve significant and rapid changes in the pressure on the rocks, which can affect their stability. Erosion effects could be significant when the rock is friable (chalk, limestone) and altered: more suspended sediment in the water raises the risks of sedimentation and corrosion of the pipes and turbomachines.

In case the underground reservoir is not strictly built for UPSH applications but obtained from an existing mine (or quarry), the geology-related issues can be summarized in the thermal/physical/mechanical rock properties and conditions of the site in question. Multiple boreholes must be drilled to a comparable depth to obtain reliable information on the ground soil. Moreover, other issues emerge for mines with a complex system of galleries due to possible fracked rock or trapped compressed air.

Although the environmental effects of a UPSH plant vary specifically by the selected site, all locations are subject to certain generic alterations, such as the disposal of excavated material, water contamination, and the disruption of the natural habitat (Tam and Clinch, 1979). Wildlife and environmental disturbances are similar to traditional hydropower plant or PHES but they can be reduced if the reservoirs are entirely artificial. Furthermore, social factors need to be assessed for pondering the possible dissension of the local community and the district advantages such as employment, new infrastructures, and additional business activities. Whereas the social acceptance can be deemed like other large construction projects, exploiting hidden water reservoirs strikes a blow for UPSH plants.

The turbomachinery selection in a UPSH, as in all conventional hydropower plants, is critical for the correct functioning and financial availability. The available differences of the water levels in the reservoirs and the rated discharge define the design of the pumps and turbines. Difficulties arise in case the volume of the reservoirs develop vertically, as for deep mine shafts, such that the operating conditions differ whether the reservoir is empty or filled with water (Morabito et al., 2020). Other design choices are affecting the turbomachinery selection. For instance, the Pelton turbine must operate in free air and is normally situated above the highest tailwater. Pump-turbines are commonly used for PHES and they can change the rotational direction. However, to cope with irregular fluctuating regimes, variable rotational speed driver needs to be added to the regulation system but it requires a larger investment. The use of variable geometry pump-turbines (such as Kaplan and Deriaz turbines) (Morabito et al., 2019a) offers alternatives to tackle shifty operating conditions. Finally, it's worth adding that to preserve the mine rock stability a discharge threshold must be set. Small discharge and high-head pump-turbines call for multistage units, rare but potentially effective (Doujak, 2015).

### Energy membrane

Energy membrane (EM) is a novel concept of an energy storage system to apply to underground pumped hydro storage. In EM-UPSH, energy is stored by lifting a mass of soil through the pumping of water into two impermeable membranes welded along the edges (Olsen et al., 2015). This inflatable cavity between the membranes is filled with water which is pumped in through a connecting pipe from a near water reservoir. The inflation of the cavity lifts the soil placed on top of the upper membrane. The amount of energy stored is roughly proportional to the lift height and the lifted mass of soil. Finally, the flow is released from the cavity and propels a turbine that generates electricity. The results of a laboratory set-up of $5 \times 5$ m dimensions allowed the realization of a case study of $50 \times 50$ m for the study of visco-elastic and plastic effects for the cyclic loading of the soil. The research outcomes combined with the theoretical modelling done on a 30 MW power and 200 MWh capacity system are indicating that the efficiency by the visco-elastic energy loss (on average 99.24%) is greater than to usual hydraulic efficiency of traditional PHES pipeline (Olsen et al., 2015). The economic and performance analysis show that EM-UPSH can compete with other PHES technologies (Fig. 2).

## Seawater pump storage

Seawater pump storage (SPS) plants are characterized using seawater as liquid and the sea as low reservoir and very exceptionally as high reservoir (as it will be in Paldiski UPSH, Estonia). These systems have the possibility of settling outside mountainous areas but in the proximity of the seashores. The location of the upper reservoir would be saved by more stringent topographical constraints, and it is usually possible to shorten the hydraulic circuits. However, the use of the sea as the lower reservoir impacts the construction time and costs (McLean and Kearney, 2014). SPS must take into account the risk of corrosion of materials in contact with seawater and the risk of efficiency drop by gluing marine organisms (Fujihara et al., 1998). On land, the reservoir must adopt measures to

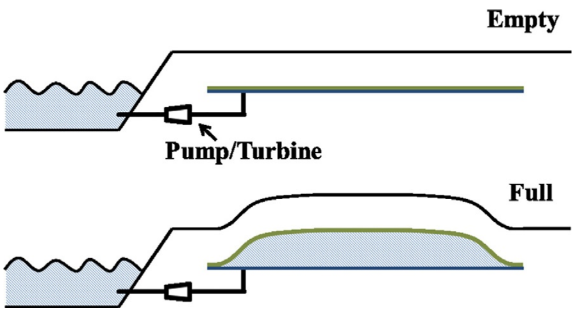


**Fig. 2** Representation of an EM-PHES system at empty and filled with water membrane (Olsen et al., 2015).

**Fig. 3** Overview of the SPS power plant in Okinawa, Japan (Fujihara et al., 1998).

avoid seawater pollution of soils and freshwater groundwater. Moreover, additional infrastructure would be required to provide calm water at the seaside to stabilize production and facilitate the pumps suctioning, always with respect for the marine environment. The 30 MW Yanbaru project in Okinawa, Japan, was the first demonstration of SPS (Fig. 3) (Hiratsuka et al., 1993). Another 300 MW seawater-based pumped storage project has been proposed on Lanai, Hawaii (Kroposki et al., 2012). Further case studies are investigated for the island of Rhodes (Katsaprakakis and Christakis, 2014), on the island of Sao Miguel (Azores) (Ioakimidis and Genikomsakis, 2018), the Cultana project in Australia (Hendriks et al., 2018), in Southern California (Scorza, 2019), for the Guadeloupe Island (Brun et al., 2015), and in west-Ireland (Hughes, 2010) (Fig. 3).

### Sea/land PHES plant

The first recorded SPS was completed in 1999 in the Kunigami district of Okinawa Island, Japan, but the investigation and verification tests for seawater machinery and operative techniques started already in 1981 (Fujihara et al., 1998). The SPS provides 180 MWh for 31.4 MW of maximum power output exploiting an upper reservoir located 500 m away from the seashore at the elevation of 150 m. After the successful realization, it was monitored in detail for 5 years before the commercial approval, granted only in 2004 (Hino and Lejeune, 2012). This procedure made it possible to verify, before the operation, the effectiveness of the various measures taken to abide by the constraints mentioned above. A special committee conducted an environmental impact assessment (Hino and Lejeune, 2012), that included studies of SPS impacts on air and water quality, noise, vibration, offensive odor, soil contamination and settlement, marine phenomena, plant vegetation, terrestrial and aquatic animals.

Because of the positive results obtained by the Okinawa plant, other possible seawater projects have been considered and implemented. Dead Sea Power Project would connect the Dead Sea and the Mediterranean Sea by a 72 km tunnel implementing a unique SPS system. Among other energetic and economic benefits of the application, the system will replenish and revitalize the Dead Sea that continues to shrink at a very rapid rate (Dead Sea Vision LLC, 2021). Valhalla's project in Chile is expected to store intermittent renewable energy from the 600 MW Cielos de Tarapacá solar PV farm in the 300 MW Espejo de Tarapacá pumped hydro plant, where three 100 MW reversible turbines will be installed. There is also an ongoing development study of the 30 MW South Maui SPS project on the south coast of Maui Island, Hawaii and other seawater-based case studies have been analyzed in Ireland (480 MW), in Saudi Arabia (1000 MW) and in Egypt (Ioakimidis and Genikomsakis, 2018; Kim et al., 2017; Kotiuga et al., 2013; Sultan et al., 2018).

Finally, the Integrated Pumped Hydro Reverse Osmosis (IPHRO) system is a promising solution to merge an osmosis desalination plant, built to generate freshwater, with a PHES technology that would soften the large energy expenses for the process (Slocum et al., 2016). The synergy of these two technologies aims to reduce the capital investment and facilitate the disposal of brine from the reverse osmosis system with the hydraulic turbine discharge. An example of this study is conducted on the shores of California, United States (Slocum et al., 2016). Seawater is pumped up into a close mountaintop reservoir and only about 5% of the reservoir water is processed into the reverse osmosis unit. Low-pressure brine leaving the treatment unit combines with seawater into the pump/turbine for reaching the upper reservoir or released in the ocean.

### Low head and tidal PHES

Marine and tidal energy generation could represent in their normal application an opportunity to contribute to the research of storage capacity. Scope exists to alter the generation phase by holding water for a limited period, and by pumping into or out of the system. The new operating schedule would meet different economic constraints by the need to allow the basin to empty or fill for the next cycle (Neill et al., 2018). A different business plan than traditional tidal hydropower would be required for running turbines during periods of high demand and pumping during periods of low demand. The consequent optimization of the schedule should resolve issues related to temporal variability and tidal elevations or streams that can be mostly predictable but doubtless not synced with the energy market nor under comparable timescales.

An example of off-shore low head PHES is the notorious Energy Island of the "Plan Lievense" (Zwemmer et al., 2007), a dike that encloses a 10- by 6-km section of the North Sea off the Dutch coast. Hydraulic pump-turbines move water in and out of the sea in this internal artificial lake that lies between 32 and 40 m below sea level. One of the key advantages of an offshore SPS plant is that there is no potential serious harm from flood risk. In case of accidental flooding of the storage facility, the only possible damage is on the dam and the temporary loss of revenues in filling up the lake. Since the energy storage functioning does not need a human presence on-site, there is low risk for operators and the demand for safety factor is significantly reduced. The "Plan Lievense" has never been built but has brought inspirations to the academic and professional communities (Fig. 4).

In Belgium, the Energy Atoll project would have stored surplus energy from offshore wind turbines that are expected to increase, in sight of the Belgian nuclear phase-out. However, the project was dropped as not viable but, in the future, the strategic importance of the plan for international energy connections could be high enough to justify the cost.

On land, other SPSs are conceived to work possibly with other scopes. This is the case of the DELTA21 plan that tackles the problem of energy storage, flood protection and recovering fish migration. The infrastructure at Rhine-Meuse delta in The Netherlands is meant to allow for the simultaneous closure of the storm-surge barriers on the Dutch coast, while actively discharging river water that would normally be pilling up behind the closed barriers (Buijs, 2021). The storage system would be able to deliver at its maximum 1.8 GW at head differences of 23 m. The capital investment, estimated at 5 billion euro, would be significantly mitigated (60% by 2050) by cost savings in the unavoidable flood safety measures that are expected to grow with the rise of the sea level (Buijs, 2021).

## Submerged PHES

Storing electricity at the bottom of the ocean is a recent concept that exploits the different pressure between a hollow submerged sphere and the surrounding sea. The first conception was elaborated in support of floating wind turbines and to reduce the impact of intermittent energy production of diurnal wind patterns. Moreover, such a system, called Ocean Renewable Energy Storage (ORES), could also act as moorings for floating wind turbines (Slocum et al., 2013). When needed, a valve opens and the water flows into a robust concrete sphere anchored at the bottom of the ocean driving the hydraulic turbines (Fig. 5). To store energy pumps empty the sphere enough and let expand the minimum of air left in the vessel at the designed pressure. To avoid cavitation phenomena the main pump is supported by an auxiliary pump that fills a cylinder which then feeds water into the pump-turbine. Besides the installation costs and exclusive maintenance, this technology does not require upper reservoir, land, pipeline (Puchta et al., 2017)


**Fig. 4** Artistic representation of the Plan Lievense, an offshore low head PHES (Zwemmer et al., 2007).

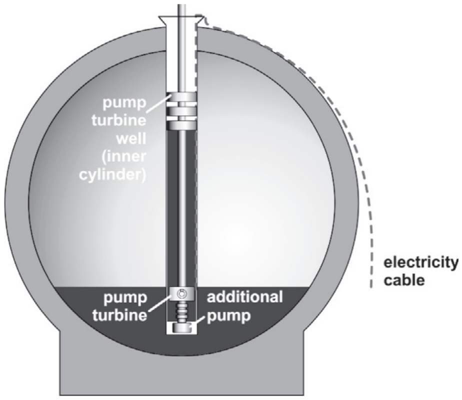


**Fig. 5** Schematic cross section of the submerged concrete sphere (Puchta et al., 2017).

and it would be completely hidden from the human eye, such to overcome the social acceptance barrier. Moreover, the structures are minimized, and the danger of dam collapse and harm are crossed out.

A developed study of this energy storage system, entitled Storing Energy at Sea (StEnSea), produced a demonstrator pilot case (Puchta et al., 2017). The scaled model of an outer diameter of 3 m and an inner volume of approximately 8 $m^3$ has been built and successfully tested in Lake Constance at a depth of 100 m. Further tests are ongoing for spheres with a diameter of 30 m at a depth of 700 m, giving 18.3 MWh storage capacity with a peak power output of 5 MW. This system could be very effective with a hydraulic round trip efficiency of around 80% (Puchta et al., 2017). To economic viability analysis for StEnSea shows that for a break in the market without subsidies, the energy arbitrage, or difference between purchase and sale price, would need to reach at least 0.04 EUR/kWh and potentially as high as 0.20 EUR/kWh, depending on the annual operation hours (Puchta et al., 2017).

Another economic study on submerged PHES is carried out for Subsea Pumped Hydro Storage (SPHS) systems in Almén and Falk (2013), that implements the aforementioned theory. Revenues and costs have been estimated and additional considerations are given on maintenance: underwater operations are very costly and deep-water support represents a techno-economic barrier for SPHS. It was concluded that, at that time, the SPHS concept (with an LCOE of 0.21–0.37 EUR/kWh) needs to be developed further to be competitive from a cost point of view (Almén and Falk, 2013) (Fig. 5).

## Micro-scale PHES units

According to the rated power of PHES, these systems can be classified into large (above 10 MW), small (between 100 kW and 10 MW), micro (between 5 kW and 100 kW), and pico (below 5 kW), although there is no such clear standard definition for PHES yet. While large-scale systems are still today the most known and used way to store energy, the growing interest in micro prototypes (μ-PHES) has reached a worldwide level and the development of innovative concepts is a clear example. These systems can be implemented to provide continuous electrical power to off-grid and remote small communities when RES systems cannot meet demand.

### Existing installation

The interest in this topic is recently increasing with the actual demand for robust energy storage for decentralized renewable power supply systems. Manolakos et al. (2004) illustrate a μ-PHES on Donoussa Island, Greece, coupled with an 18 kW-peak (kWp) photovoltaic power system. The micro-hydraulic system consists of a pump and a hydraulic turbine of 7.5 kW and two identical water reservoirs of 150 $m^3$ capacity each with a height differential of about 100 m. Another hybrid system with PV and a co-generative internal combustion engine is coupled with lead-acid batteries and thermal and water storage, to satisfy the energy and water needs of a small isolated touristic resort in Northern Italy (Stoppato et al., 2016). PHES technical feasibility and its economic comparison with other promising storage technologies are discussed for buildings by Oliveira e Silva and Hendrick (2016). It appears that high cost and low efficiency compromise the competitiveness of PHES on small scales (Oliveira e Silva and Hendrick, 2016).

Another μ-PHES is installed in a smart grid in the industrial area of Froyennes, Belgium. Fig. 6 shows the interconnection scheme of the smart grid for renewable energy sources, the μ-PHES, an electrochemical battery linked to an electric vehicle charging station, and the programmable logic controller that manages the PHES operation. Energy storage and energy recovery are achieved both via a single industrial centrifugal pump that can run as a turbine too (PaT) (Morabito and Hendrick, 2019). PaT at variable rotational speed is demonstrated to be a valid turbomachinery alternative to conventional micro-turbines in exploiting fluctuating loads in distributed storage solutions. The PHES requires a calibrated evaluation of the hydraulic system performance taking into account energy fluctuation and the turbomachinery operating conditions. The use of the same machine for pumping and generating

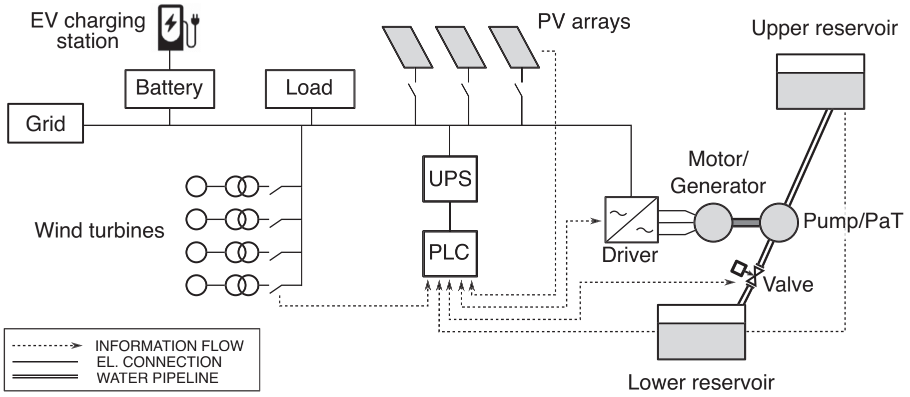


**Fig. 6** Interconnection scheme of μ-PHES implemented in the smart grid in Froyennes (Morabito and Hendrick, 2019).

is related to the objective of saving the cost of energy, space, and maintenance for a micro installation. The PaT hydraulic efficiency recorded experimentally in the case study (about 72%) may be smaller than with regular micro turbines but it is still very competitive and attractive for users (Morabito and Hendrick, 2019). About simplifying the control operations, if it were not for the working condition variations, a gearbox would only set two rotational speeds on the shaft: one suitable for pumping and the second applied for generating mode. In these circumstances, the expenses would drop considerably, but any speed adjustment would be possible for the adaptation of the fluctuating head, nor for responding to an intermittent injection of renewable energy into the smart grid.

## Analysis and perspectives

The problems associated with micro-scale units (μ-PHES) are different than in large PHES units. The issues related to operation, maintenance and repair technologies are critical for the micro-scale that benefits fewer resources than larger scales. In the urban environment and the context of energy decentralization, the push in innovation unbalances the traditional business model for renewable energy sources which is focused on indirect revenues by self-consumption. Nowadays, in some countries, prosumers are allowed to sell their energy production directly under the regional and federal bills. The local legislation would quickly need to be adapted to enable small prosumers to participate in more complex energy market dynamics, where they could sell their production and their flexibility too (namely when to produce or consume). This fervent market opportunity for small players calls for functional analysis of the micro energy storage system as an assisting tool to flexibility.

In this regard, a comprehensive comparison between the energy storage technologies for decentralized energy storage would be needed per case study in order to better propose the most sustainable and beneficial solution for the matter. Table 1 helps in this quest by gathering design key points on μ-PHES about its strength, weakness, opportunities, and threats (SWOT). μ-PHES represents a robust energy storage alternative for rural and remote areas where technical expertise might hard to find. Complex maintenance

**Table 1** SWOT analysis of μ-PHES.

| *Strengths* | *Weakness* |
|---|---|
| - Although the land-take might be an issue, μ-PHES is environmentally friendly. Furthermore, it has minor disruptive effects on ecosystem than large scale PHES.<br>- Robust and reliable back-up system of total grid-loss for vital function of industries of small communities.<br>- Low operating costs, long lifetime and simple maintenance and refurbishment.<br>- Increase self-sufficiency and flexibility in smart-grids, especially with variable speed control. | - Low energy density and electrical round-trip efficiency (<50%) smaller than common lead-acid batteries (75–80%) and lithium-ion batteries (95%).<br>- Time from zero to full-load is at least >30 s. Longer period from the opposite operation regime.<br>- Strong design dependence on the site space and elevation.<br>- Micro power-size limits the involvement in ancillary services. |
| Opportunities | Threats |
| - Effective synergies with other complementary systems such as water distribution, stormwater capacity, waterways, and others.<br>- Easy access to the growing market opportunity of electrical demand-response (for time-base retribution or other financial incentives).<br>- The micro scale helps to reduce the geological constraints and it eases integration in small smart grid and buildings. | - In case of μ-PHES equipped with PaTs, there are uncertainties linked to the performance prediction of the turbomachine.<br>- A limited number of cycles penalizes the LCOE of μ-PHES to grid parity and its competitiveness with other electrical energy storage systems.<br>- A rapid economic growth of competitive electrical energy storage technologies such as electrochemical batteries. |

and high installation expertise, typical for other electrical energy storage technologies, could jeopardize the electricity provision stability in such remote regions.

Grid-connected buildings or communities could also take advantage of pre-existing infrastructure to install a cost-effective μ-PHES. The experimental results and data obtained from the few existing operational μ-PHES site allow for Levelized Cost of Energy (LCOE) calculation and cost-saving recommendations (Oliveira e Silva and Hendrick, 2016; Morabito and Hendrick, 2019). A cost-benefit analysis proves that the installed μ-PHES have not reached parity to other small scales electrical energy storage (Oliveira e Silva and Hendrick, 2016), but, yet the results are promising for an improved and proposed case study (LCOE reduction by 40%) (Morabito and Hendrick, 2019).

The key concept for spreading μ-PHESs is to detect possible synergies with other appliances. These explorations would unveil new market scenarios and their possible evolution with stormwater basins (Morabito et al., 2019b), or irrigation appliances (Mousavi et al., 2020), or waterways locks (de Andrade Furtado et al., 2020) or rainwater harvesting systems that today are more often implemented for sustainable drainage practices. Fire-safety systems are often located on rooftops of high buildings, and they could offer appealing water reservoirs for energy storage, but they are highly regulated and hard to adapt.

However, it is true PHES is a mature technology in which it is not expected any disruptive evolution that could make it more competitive to other storage growing technologies (e.g., electrochemical batteries or hydrogen). For instance, different kinds of batteries are present in today's market according to charging and discharging efficiency (or round-trip efficiency), lifetime cycle, weight, and peak voltage output (Palizban and Kauhaniemi, 2016). In the last decade, battery costs are falling quickly for the new growing market in electric vehicles and the global trend toward energy self-sufficiency.

On the other hand, the battery industry generates considerable amounts of environmental pollutants (e.g., hazardous waste, greenhouse gas emissions, and toxic gases) during different processes including mining, manufacturing, use, transportation, collection, storage, treatment, disposal, and recycling (Poullikkas, 2013; Dehghani-Sanij et al., 2019). Battery use will have significant social and environmental impacts; hence, it must be compared carefully with alternatives in terms of sustainability, while focusing on research to quantify externalities and reduce risk (Dehghani-Sanij et al., 2019). Alternatives like pumped hydro must be encouraged because of their low environmental impact compared to different types of batteries.

## Hydraulic gravity storage

Another concept based on the well-established PHES technology is the Hydraulic Gravity Storage (HGS) that offers efficiency as high as the conventional pumped storage plants (Grid-Scale Energy Storage, 2018; Heindl-Energy, 2020). The hydrostatic head of HGS in generation mode is caused by the weight of a piston in a vertical shaft above the water tank. To store energy, the piston is lifted by pumping water underneath it. These systems are suitable in areas where the traditional alternative PHES is not feasible due to a lack of local elevation difference. The weight of the piston can be obtained by detaching the cylinder from the surrounding bedrock or from produced by the rubble of the construction site. Both surfaces of the piston and cylinder are sealed against water loss and preserve the geometries in motion. Waterproof sealing represents one of the most technical challenges in HGS installations. The sealing apparatus must be able to adapt at various heights of the piston, bear high water pressure, and resist abrasion.

There are several variations of this energy storage concept. It is worth mentioning the closed-loop solution in which water is located in both parts of the cylinder: under and above the piston, respectively for high and low-pressure water tanks (Aufleger et al., 2015). In order to store energy, water is pumped from the upper part of the cylinder to the lower reservoir by external conduct (Fig. 7). The highest position of the piston corresponds to a fully charged system. Regardless of the position of the piston, the pressure at the bottom of the cylinder is constant and it always counts the weight of the piston and the column of water. When required, the HGS releases the flow that drives a turbine before reaching the upper part of the cylinder. Among the close-loop HGS systems, a prototype is designed with the pump-turbine integrated into the piston that is equipped with a connection between the lower and upper part of the cylinder. This alternative is a more compact solution, and it records a reduction in energy losses and costs (Aufleger et al., 2015).

Finally, the buoyant energy principle uses weights over a floating reservoir, located in a larger basin (a lake or the sea) to ensure different water levels between the two reservoirs. To store energy, water is pumped out from the floating reservoir into the larger. As a result, the floating structure that encloses the smaller reservoir loses load and the reservoir rises. To release the energy, the structure is lowered and the inflow into the smaller reservoir powers a turbine (turbine mode) (Hydraulic Engineering Department University of Innsbruck, 2021).

## Conclusions

Large-scale PHES plants have made significant efforts toward higher capacity and flexibility to accommodate grid frequency stability despite the growing share of intermittent renewable energy sources. To escape usual topographical restrictions, UPSH facilities provide an alternative to traditional PHES. Past and ongoing research projects show the hidden potential of UPSH, but further investigations are needed to assess its business model and technical feasibility, especially in re-evaluating abandoned mines. The common lack of precise information on old mines would render extensive vulnerabilities in setting up a PHES in such deep

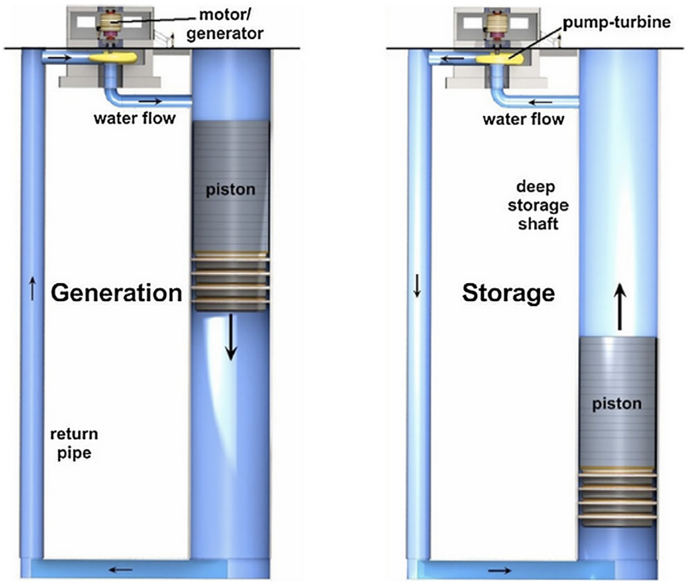


**Fig. 7** Schematic hydraulic gravity storage facility in generation and storing phases (Grid-Scale Energy Storage, 2018).

underground cavities. On the other hand, the implementation of a PHES in a former underground slate quarry could be considered and case-by-case checks could be carried out to appraise its economic viability.

Likewise, SPSs support a more reliable power provision and facilitating grid integration of intermittent renewable energy sources. Therefore, seawater PHES systems can provide prompt and nearby storage to complement offshore wind energy farms or support decentralized communities by the sea. Furthermore, with their submerged design, they can also serve as anchor points for floating wind turbines.

In micro scales PHES plants, the target is to improve the energy efficiency of decentralized energy systems, which are currently growing rapidly at residential and industrial levels. The major difficulties for the feasibility of decentralized μ-PHES are the low energy density of the system, limited by the maximum available height differential of the reservoirs, and the high costs involved. Also, the global efficiency and economic viability are importantly affected by the response of pumps and turbines to load fluctuations. To face the frequent constraints linked to the site location and load variation, innovative options must be analyzed and tested to better evaluate the potential of μ-PHES.

In conclusion, this text shows that professional and academic communities are progressively focused on innovative PHES designs to meet the compelling need for energy storage capacity. Unfortunately, to date, some of these technologies are still under development and are still expensive. The high risk of investment envisaged for such unique energy storage systems could dissuade possible investors. However, societies concerned about climate change and pollution may be inclined to invest in alternative storage options like these as they recognize the gravity of the crisis.

## References


Almén J and Falk J (2013) *Subsea Pumped Hydro Storage.* Master thesis, Göteborg, Sweden.

Alvarado R and Niemann A (2015) Underground pumped-storage hydroelectricity using exisiting coal mining infrastructure. In: *36th IAHR World Congress* 1–8.

Aufleger M, Neisch V, Robert Klar R, and Lumassegger S (2015) Comprehensive hydraulic gravity energy storage system–both for offshore and onshore applications. In: *E-proceedings of the 36th IAHR World Congress*.

Bear J and Cheng AH-D (2010) Modeling groundwater flow and contaminant transport. In: *Modeling Groundwater Flow and Contaminant Transport*. Springer Science & Business Media.

Bendigo Sustainability Group (2021) *Bendigo Mines Pumped Hydro Project*. https://www.bsg.org.au/bendigo-pumped-hydro-project/ (Accessed 21 April, 2021).

Bodeux S, Pujades E, Orban P, Brouy`ere S, and Dassargues A (2017) Interactions between groundwater and the cavity of an old slate mine used as lower reservoir of an UPSH (Underground Pumped Storage Hydroelectricity): A modelling approach. *Engineering Geology* 217: 71–80.

Brun P, Mahiou B, and Ayoub M (2015) The petit canal sea water pumped storage plant in Guadeloupe island: A tool to allow the intermittent renewable energy development. *Houille Blanche* 7–13.

Buijs M (2021) Optimizing the Use of Delta21 for Flood Prone Areas Not Protected by Flood Defenses at Dordrecht: A Study On the Operation Strategy and Reliability of a New Flood Protection System. https://www.delta21.nl.

Burdett M (2021) Pioneering 500 mw pumped storage scheme advances in Estonia. *Hydropower & Dams* 28(2).

Chiu H, Rodgers L, Saleem Z, Ahluwalia R, Kartsounes G, and Ahrens F (1979) Mechanical energy storage systems: Compressed air and underground pumped hydro. *Journal of Energy* 3(3): 131–139.

de Andrade Furtado GC, Amarante Mesquita AL, Morabito A, Hendrick P, and Hunt JD (2020) Using hydropower waterway locks for energy storage and renewable energies integration. *Applied Energy* 275: 115361.

Dead Sea Vision LLC (2021) Med-dead/Lake Shalom Project—A Vision for Economic Development and Peace. http://deadseapower.com/projectreview/. Accessed 21 April 2021.

Dehghani-Sanij A, Tharumalingam E, Dusseault M, and Fraser R (2019) Study of energy storage systems and environmental challenges of batteries. *Renewable and Sustainable Energy Reviews* 104: 192–208.
Doujak E (2015) Draft tube design and multistage performance of a pump turbine. *WasserWirtschaft* 105(1): 38–42.
Energiasalv (2021) *Project of the Estonian Pumped-Hydro Energy Storage*. https://energiasalv.ee/project/ (Accessed 21 April, 2021).
Fessenden RA (1917) *System of Storing Power*. Patent US1247520A.
Fujihara T, Imano H, and Oshima K (1998) Development of pump turbine for seawater pumped-storage power plant. *Hitachi Review* 47(5): 199–202.
Grid-Scale Energy Storage (2018) Gravity Power Module—Energy Storage. http://www.gravitypower.net. Accessed 21 April 2021.
Heindl-Energy (2020) A New Solution for Large Scale Energy Storage. https://heindl-energy.com. Accessed 21 April 2021.
Hendriks M, et al. (2018) South Australia leads the way in energy storage integration. *Energy News* 36(1): 15.
Hino T and Lejeune A (2012) 6.15: Pumped storage hydropower developments. In: Sayigh A (ed.) *Comprehensive Renewable Energy*, pp. 405–434. Oxford: Elsevier.
Hiratsuka A, Arai T, and Yoshimura T (1993) Seawater pumped-storage power plant in Okinawa island, japan. *Engineering Geology* 35(3-4): 237–246.
Hughes D (2010) *Investigation Into the Feasibility of a West of Ireland Pumped Storage System*. GMIT.
Hydraulic Engineering Department University of Innsbruck (2021) Buoyant Energy, Smart Concept for Energy Storage. http://www.buoyant-energy.com/. Accessed 21 April 2021.
International Energy Agency (2021) Renewable Information: Database Documentation 2020. https://www.iea.org.
Ioakimidis CS and Genikomsakis KN (2018) Integration of seawater pumped-storage in the energy system of the island of Sao Miguel (Azores). *Sustainability* 10(10): 3438.
Katsaprakakis DA and Christakis DG (2014) Seawater pumped storage systems and offshore wind parks in islands with low onshore wind potential: A fundamental case study. *Energy* 66: 470–486.
Katsaprakakis DA, Christakis DG, Stefanakis I, Spanos P, and Stefanakis N (2013) Technical details regarding the design, the construction and the operation of seawater pumped storage systems. *Energy* 55: 619–630.
Kim J, Suharto Y, and Daim TU (2017) Evaluation of electrical energy storage (EES) technologies for renewable energy: A case from the us pacific northwest. *Journal of Energy Storage* 11: 25–54.
Kotiuga W, Hadjian S, King M, Al-Hadhrami L, Arif M, and Al-Soufi KY (2013) Pre-feasibility study of a 1000 MW pumped storage plant in Saudi Arabia. *HydroVision International* 5.
Kroposki B, Burman K, Keller J, Kandt A, Glassmire J, and Lilienthal P (2012) *Integrating High Levels of Renewables in to the Lanai Electric Grid*. *Tech. Rep* Golden, CO: National Renewable Energy Lab (NREL).
Manolakos D, Papadakis G, Papantonis D, and Kyritsis S (2004) A stand-alone photovoltaic power system for remote villages using pumped water energy storage. *Energy* 29(1): 57–69.
Martin GG (2011) *Underground pumped hydroelectric energy storage*. Tech. Rep. Richland, WA: Pacific Northwest Lab.
McLean E and Kearney D (2014) An evaluation of seawater pumped hydro storage for regulating the export of renewable energy to the national grid. *Energy Procedia* 46: 152–160.
Menéndez J, Fernández-Oro JM, and Loredo J (2020) Economic feasibility of underground pumped storage hydropower plants providing ancillary services. *Applied Sciences* 10(11): 3947.
Min APN (1984) *Ondergrondse Pomp Accumulatie Centrale: E_ectiviteitsverbetering dmv Verschillende Pomp-Turbinevermogens*. Master thesis TU-Delft.
Morabito A and Hendrick P (2019) Pump as turbine applied to micro energy storage and smart water grids: A case study. *Applied Energy* 241: 567–579.
Morabito A, de Oliveira e Silva G, and Hendrick P (2019a) Deriaz pump-turbine for pumped hydro energy storage and micro applications. *Journal of Energy Storage* 24: 100788.
Morabito A, Furtado GCA, Amarante Mesquita AL, and Hendrick P (2019b) Variable speed regulation for pump as turbine in a micro pumped hydro energy storage application. In: *38th IAHR World Congress—"Water: Connecting the World", (Panama City)* 4039–4046.
Morabito A, Spriet J, Vagnoni E, and Hendrick P (2020) Underground pumped storage hydropower case studies in Belgium: Perspectives and challenges. *Energies* 13(15): 4000.
Mousavi N, Kothapalli G, Habibi D, Lachowicz SW, and Moghaddam V (2020) A real-time energy management strategy for pumped hydro storage systems in farmhouses. *Journal of Energy Storage* 32: 101928.
Neill SP, Angeloudis A, Robins PE, Walkington I, Ward SL, Masters I, Lewis MJ, Piano M, Avdis A, Piggott MD, et al. (2018) Tidal range energy resource and optimization–past perspectives and future challenges. *Renewable Energy* 127: 763–778.
Oliveira e Silva G and Hendrick P (2016) Pumped hydro energy storage in buildings. *Applied Energy* 179: 1242–1250.
Olsen J, Paasch K, Lassen B, and Veje CT (2015) A new principle for underground pumped hydroelectric storage. *Journal of Energy Storage* 2: 54–63.
O-PAC Ontwikkelingsmij (2021) *O-PAC, the Sustainable Solution*. https://o-pac.nl (Accessed 21 April, 2021).
Palizban O and Kauhaniemi K (2016) Energy storage systems in modern grids—matrix of technologies and applications. *Journal of Energy Storage* 248–259.
Pickard WF (2011) The history, present state, and future prospects of underground pumped hydro for massive energy storage. *Proceedings of the IEEE* 100(2): 473–483.
Poullikkas A (2013) A comparative overview of large-scale battery systems for electricity storage. *Renewable and Sustainable Energy Reviews* 27: 778–788.
Puchta M, Bard J, Dick C, Hau D, Krautkremer B, Thalemann F, and Hahn H (2017) Development and testing of a novel offshore pumped storage concept for storing energy at sea—Stensea. *Journal of Energy Storage* 14: 271–275.
Pujades E, Orban P, Bodeux S, Archambeau P, Erpicum S, and Dassargues A (2017) Underground pumped storage hydropower plants using open pit mines: How do groundwater exchanges influence the efficiency ? *Applied Energy* 190: 135–146.
Pujades E, Orban P, Archambeau P, Erpicum S, and Dassargues A (2018) Numerical study of the Martelange mine to be used as underground reservoir for constructing an underground pumped storage hydropower plant. *Advances in Geosciences* 45: 51–56.
Scorza D (2019) *Stranded Nuclear Asset Provides Opportunity for Seawater Pumped Storage*. http:www.powermag.com/solving-renewable-transmission-constraints-with-water-infrastructure. (Accessed 21 December, 2020).
Scott F (1977) Underground hydroelectric pumped storage-a practical option. *Energy* 2: 20–22.
Slocum AH, Fennell GE, Dundar G, Hodder BG, Meredith JD, and Sager MA (2013) Ocean renewable energy storage (ORES) system: Analysis of an undersea energy storage concept. *Proceedings of the IEEE* 101(4): 906–924.
Slocum AH, Haji MN, Trimble AZ, Ferrara M, and Ghaemsaidi SJ (2016) Integrated pumped hydro reverse osmosis systems. *Sustainable Energy Technologies and Assessments* 18: 80–99.
Stoppato A, Benato A, Destro N, and Mirandola A (2016) A model for the optimal design and management of a cogeneration system with energy storage. *Energy and Buildings* 124: 241–247.
Sultan HM, Diab AAZ, Oleg NK, and Irina SZ (2018) Design and evaluation of PV-wind hybrid system with hydroelectric pumped storage on the national power system of Egypt. *Global Energy Interconnection* 1(3): 301–311.
Tam SW and Clinch J (1979) *Study of Certain Economic Aspects of Turbomachinery for Underground Pumped Hydroelectric Storage Plants*. *Tech. Rep* Illinois: Argonne National Lab.
US Army Corps of Engineers (1981) An Assessment of Hydroelectric Pumped Storage. In: *Tech. Rep., National Hydroelectric Power Resources Study*. The U.S. Army Engineer Institute for Water Resources.
Wong IH (1996) An underground pumped storage scheme in the Bukit Timah granite of Singapore. *Tunnelling and Underground Space Technology* 11(4): 485–489.
Zillmann A and Perau E (2015) A conceptual analysis for an underground pumped storage plant in rock mass of the Ruhr region. *Proceedings of the XVI European Conference on Soil Mechanics and Geotechnical Engineering, ECSMGE* vol. 7, 3789–3794.
Zwemmer D, de Boer W, Verheij F, and Das R (2007) The Energy Island–An Inverse Pump Accumulation Station. https://www.energythic.com/usercontent/3/PaperEnergyIslandEWEC2007.pdf. Accessed 21 April 2021.