CHAPTER 9
PUMPED HYDROELECTRIC STORAGE

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Abstract

Pumped hydroelectric storage (PHS) is the most widely used electrical energy storage technology in the world today. It can offer a wide range of services to the modern-day power grid, especially assisting the large-scale integration of variable energy resources. It has gained a renewed interest among investors, utilities, and regulators alike because of its environmental benefits. This chapter discusses the evolution of PHS in the United States and the world, the current state of technology, and its applications and benefits. Some key challenges faced by PHS and their potential solutions are also discussed.

Key Terms

Adjustable speed (AS), arbitrage, black start, fixed speed (FS), frequency regulation, hydropower, inertia, inertial response, inertial support, pumped hydroelectric storage (PHS), pump-turbine, ramping support, reactive power, renewable energy resources (RERs), run-of-the-river (RoR), valuation, variable energy resources (VERs), variable speed (VS).

1. Introduction

Pumped hydroelectric storage (PHS) is the oldest, most commercially mature, and most widely used utility-scale electrical energy storage technology in the world. According to the International Hydropower Association's 2021 Hydropower Status Report [1], the globally installed capacity of PHS reached about 160 GW in 2020, with 1.5 GW of capacity added in 2020 alone. PHS currently accounts for over 90% of the world's grid-scale energy storage applications. PHS has similar representation in the United States as well, with 43 plants and a total installed capacity of 22 GW, making up about 94% of utility-scale electrical energy storage capacity in the country at the end of 2019 [2].

PHS facilities have been around for more than a century, with the oldest known facilities dating back to the 1890s in Italy and Switzerland [3]. However, notwithstanding the old age of its technology, PHS has achieved newfound relevance because of the global movement toward replacing fossil fuels with variable energy resources (VERs, which are intermittent renewable energy sources such as wind and solar). PHS uses the gravitational potential energy of water to store electrical energy. This involves connecting two reservoirs with a head difference through a water conductor, such as a pipe, as shown in Figure 1. Water is pumped through the conductor from the lower to the upper reservoir, typically when demand, and therefore electricity prices, are low. When demand and consequently electricity prices are high, water is released back to the lower reservoir through a turbine, which generates electricity. Round-trip efficiencies for PHS facilities often exceed 80% [4] and do not degrade over the lifetime of the equipment, providing it with an advantage over other energy storage technologies.

As power system planners and grid operators aim to build and operate a more environment-friendly grid with low-to-zero carbon emission within the next few decades, an increasing amount of VERs are being integrated into the power grid. Although VERs contribute to a great extent toward reducing emissions, integrating such resources degrades the reliability and resilience of the grid because of the uncertainties and intermittencies associated with these resources. In addition, as VERs replace conventional generation, they reduce options for base load generation and reduce overall system inertia, thus compromising the frequency stability of the system.

PHS facilities offer a dependable solution to these problems and have been providing reliability and resilience services to the grid for decades. Moreover, PHS offers a considerable amount of flexibility in the operation of power systems by balancing load and supply. Besides the benefits related to electricity generation, PHS and hydropower offer other benefits to society as well, for example, providing flood control, irrigation support, and clean drinking water.

The many advantages of the PHS technology mentioned above, coupled with its relatively straightforward design, have propelled it back to relevance in at a time when large-scale integration of VERs demands vast amounts of electrical energy storage. The International Hydropower Association estimates that the global PHS capacity will increase from 160 GW in 2020 by almost 50% to 240 GW by 2030, and is predicted to solidify its position as the largest electrical energy storage technology even with the massive increase in the number of stationary batteries in the power grid [1]. While most of the new PHS plants are expected to be developed in Asia and Africa over the next decade, a considerable amount of effort is also expected to be spent on modernizing the aging plants in advanced economies like North America and Europe [1].

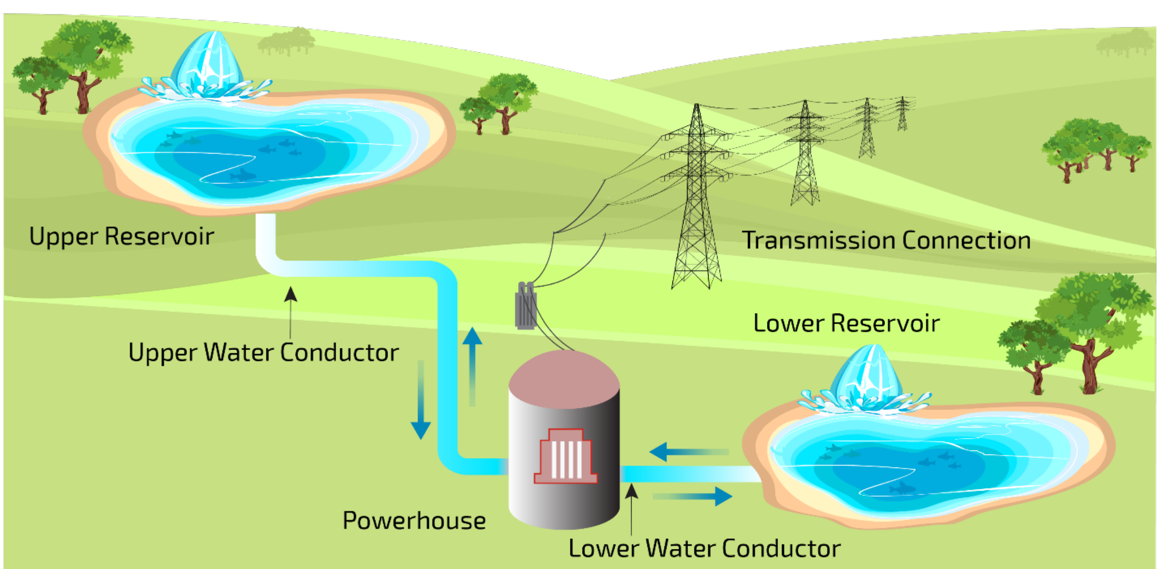

Figure 1. A typical pumped hydroelectric storage system

1.1 PHS in the United States

The United States has one of the largest shares of PHS capacity in the world, after Japan and China [5]. The first PHS facility in the United States was the Rocky River project on the Housatonic River in Connecticut and was constructed by the Connecticut Light and Power Company. Beginning operations in 1929, it comprised one 24 MW conventional unit, two 3.5 MW motor generator units, and two pumps [6]. This PHS facility was initially designed to support large thermal base load generation into the grid by providing flexibility and allowing these large thermal generation plants to operate more efficiently.

After the Rocky River project, the development of PHS facilities in the United States was slow until the 1950s, when growth of PHS surged, mainly due to technological advancements. First, the utilization of the reversible Francis turbine for PHS was a big contributor toward its growth [6]. Second, the surge could be attributed to the population increase after World War II, which led to economic growth and reshaped the electric demand pattern.

However, the biggest acceleration in the planning and construction of PHS facilities in the United States took place during the 1960s and 1970s, leading to the development of nearly half of the PHS capacity in operation today. The largest facilities built during this time were Northfield Mountain in Massachusetts (1972), Ludington in Michigan (1973), and Blenheim-Gilboa in New York (1973). During this period, the average electric power load in the United States was continuing to grow quickly, doubling approximately every 10 years. This presented a challenge for utilities to develop sufficient generating capacity to supply electric loads in an efficient and reliable manner. PHS offered a solution to this challenge as a resource that could be operated economically and efficiently in large electric power systems. In addition, the optimistic outlook for nuclear power with its relatively inexpensive off-peak pumping power also helped the growth of PHS. More than 40 PHS plants exist in the United States today, with an installed capacity of almost 22 GW. Figures 2 and 3, developed with data from the U.S. Energy Information Association's "Annual Electric Generator Report" [7], show the PHS facilities in the United States by initial operating year and state-wise capacity distribution, respectively.

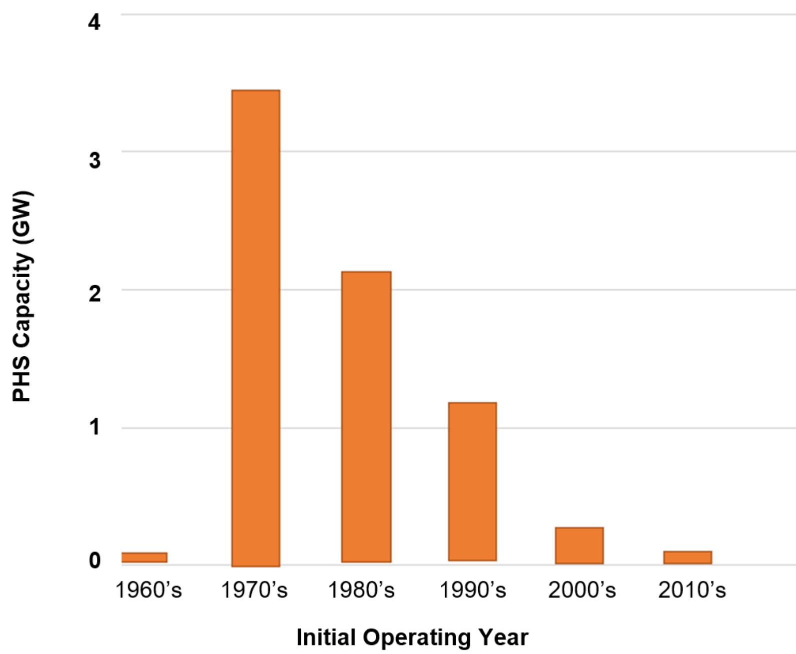

Figure 2. PHS plants in the United States by initial operating year

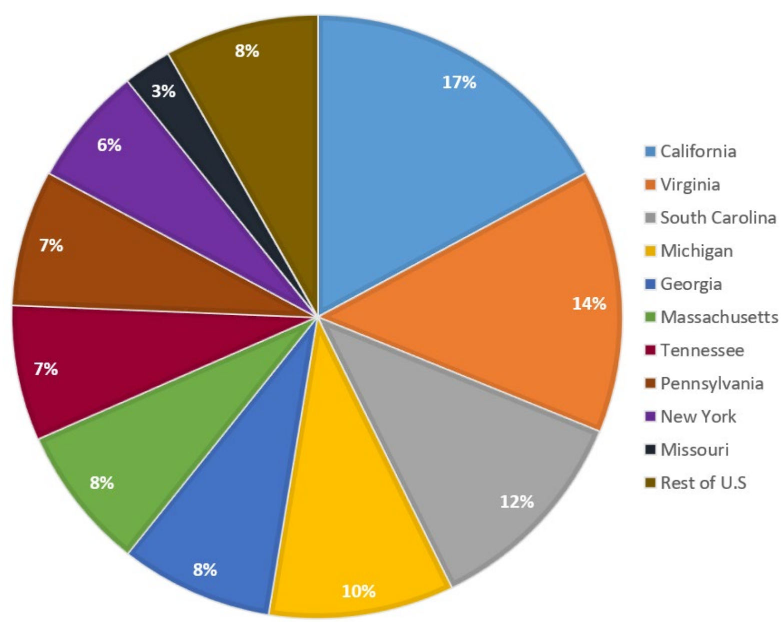

Figure 3. Share of PHS by states in the United States

Although new PHS facilities have not been commissioned in the United States since 2012, 1,333 MW of capacity was added between 2010 and 2019 by upgrading existing facilities [2]. It is estimated that 16.2 GW of PHS capacity will be added by 2030 and another 35.5 GW by 2050 in the United States. There are currently 67 new PHS projects across 21 states in the country, representing over 50 GW of new long duration storage [4]. Owners of existing PHS facilities are already experiencing increased utilization of their assets in some markets, especially in regions with a high penetration of VERs. This includes increased pumping during the day, more starts and stops, increased ramping for evening load, and condensing operations [4].

2. Applications and Valuation of PHS

As mentioned before, many new PHS projects are underway across the world today. Several existing PHS facilities are being rejuvenated and developers are also investigating dozens of new project opportunities due to the environmental and grid reliability benefits that PHS offers. The following sections describe some of the most common PHS applications.

2.1 Grid-Scale Applications

Energy Arbitrage: This is one of the oldest applications of PHS facilities. PHS can perform energy arbitrage by generating electricity when demand and/or prices are high and consuming electricity by pumping when demand and/or prices are low. This application of the PHS helps to reduce the need for expensive generation during peak load periods and capacity commitments from other resources. Besides this, the PHS can also earn revenues from the price difference of electricity by performing this service.

Inertial Support: The high penetration of renewable energy resources (RERs) poses significant challenges to the stability of the power grid because of their low-inertia characteristics. In the event of an imbalance in the system, the rotational kinetic energy stored in the rotor of the conventional synchronous generators is used to provide inertial support to the grid, thus restoring frequency stability. However, RERs like wind or solar are interfaced with the grid through power electronic devices like inverters, thus limiting their capabilities of providing inertial support. Several studies have shown that the replacement of conventional generators with RERs reduces system inertia, which leads to an increased rate of change of frequency and lower frequency nadirs [8], [9]. Independent system operators like Electric Reliability Council of Texas (ERCOT) [10] and regulatory bodies like North American Electric Reliability Corporation (NERC) [11] have also reported a reduction in frequency response because of the increasing penetration of RERs. Under these circumstances, PHS facilities can help in providing inertial support since they possess rotating masses. Fixed speed (FS) PHS units can provide inertial response through rotating synchronous generators while adjustable speed (AS) PHS units can do the same using power electronic converters [12].

Frequency Regulation: The frequency of a power system may deviate from the nominal value (60 Hz in the United States) if there is an unforeseen imbalance between generation and load. Several generator actions are needed during an imbalance to restore the frequency back to the normal operating range. These include primary, secondary, and tertiary frequency controls that may range from a few seconds to several minutes. Some PHS units are well-suited to provide frequency regulation services to the grid. While conventional FS PHS units are incapable of providing regulation services while pumping and idle, they can do so while in generating mode. In contrast, AS PHS units can perform regulation services during generation, pumping, and idle modes. Recent technological advances in AS pump-turbines allow a greater range of frequency regulation services in both pumping and generation modes [4]. AS PHS can operate across many speed segments to replace reduced generation or absorb generation spikes from RERs, making it an especially useful resource for regulation services.

Ramping Support: PHS facilities offer flexibility in the operation of power systems since it can switch quickly between pumping and generation modes, effectively capable of providing twice its capacity to meet system ramping requirements. The ability of PHS to provide ramping services has recently been especially useful with the high penetration of RERs and the uncertainty that accompanies RERs.

Voltage support: System voltages need to remain within a specified limit for all equipment and devices to function properly and can be managed with the help of reactive power. FS PHS units have reactive power generation capabilities similar to conventional synchronous generators, while AS PHS units use power electronics to provide voltage support.

Black start capability: In the event of a system-wide blackout, restoration of power must begin with resources that have the ability to start themselves. These resources are known as black-start units and are used for bootstrapping the restoration process, beginning at the transmission connected to the resource itself and subsequently moving outward toward critical system loads. FS PHS units are well-suited to provide this service while AS PHS units are not equipped for this application because of their use of power electronics, which require an external source of power that is unlikely to be available during a blackout.

Transmission upgrade deferral: A PHS can help in the deferral of transmission system upgrades. Transmission equipment can get overburdened during peak demand periods. These events usually occur for a noticeably short duration during the year, when the demand exceeds the load-carrying capacity of the transmission equipment, usually during the hottest days. Instead of upgrading the transmission equipment, which can be expensive, PHS can provide a portion of the peak load as long as it is located downstream from the overburdened equipment. By providing a portion of the peak load, PHS can reduce the stress on the transmission equipment and thus extend their lifetime. PHS can also help in reducing transmission congestion by absorbing excess generation, reducing the need for investments in new transmission equipment.

Environmental benefits: Systems with a high penetration of renewable energy will see reduced emissions if the PHS uses electricity generated from renewable energy for pumping while displacing electricity generated from conventional and gas-fired plants during the peak demand period. In addition, the flexibility of operation offered by PHS will help integrate more renewable energy into the grid, thus reducing emissions.

2.2 Valuation

Pumped hydro is a technologically mature approach for achieving long- and short-term energy storage goals. The economic opportunities for pumped hydro energy storage are a function of its technical capabilities. There are two main categories of pumped hydro energy storage:

- Fixed speed (FS) pump-turbines
- Adjustable speed (AS) pump-turbines

FS pump-turbines are not capable of providing frequency regulation while pumping. In addition, AS pump-turbines can operate at higher efficiencies over a larger portion of their operating range. Keeping these limitations in mind, a similar approach for energy storage technoeconomic evaluation can be applied to pumped hydro energy storage systems. An energy flow model is typically employed for energy storage evaluation,

$$S_t = S_{t-1}\gamma_s + q_t^r \gamma_c - q_t^d \quad (1)$$

where S_t is the state of charge at time period t (MWh), S_{t-1} is the state of charge at time period $t-1$, γ_s is the storage efficiency (e.g., percent of state of charge kept over each time period), q_t^r is the quantity of energy from charging at time period t, γ_c is the conversion efficiency (e.g., percent of charge kept after losses), and q_t^d is the quantity of energy discharged at time period t. Charge/discharge terms can be added to the model to incorporate additional grid services. The model assumes that all losses occur on charging so that the state of charge is the available state of charge. Losses occur during charging and discharging. Mathematically, it is equivalent to model the losses during charging and discharging or lump them together as a round trip efficiency [13]. The efficiency in Equation (1) is modeled as a constant. Efficiency can be a function of operating conditions. Using a constant efficiency makes the optimization problem simpler and faster to solve because it can be formulated as a linear program. A time varying efficiency requires solving an optimization using a dynamic programming formulation. Therefore, if the efficiency varies in a relatively narrow range, it is preferable to employ an energy flow model with a constant efficiency.

The storage efficiency of a pumped hydro system can be affected by evaporation, seepage, or runoff. These can be modeled by adjusting the γ_s term to reflect the fraction of stored energy remaining after one time period. The quantity of energy that may be charged or discharged at each time period can be subject to additional constraints depending on the type of pumped hydro system. Open loop systems are continuously connected to a naturally flowing water feature. Activities like irrigation, recreation, and conventional hydro power generation can limit the operation of the pumped hydro energy storage system. For closed-loop systems that are not continuously connected to a naturally flowing water feature, operational constraints can still exist.

The technoeconomic modeling approach for a pumped hydro energy storage system is a function of its location. In a market area, the system can only be remunerated for services associated with market products. In a vertically integrated utility, the pumped hydro system is typically operated to minimize the overall cost of electricity. For market areas, a price taker model is only accurate for small systems relative to the size of the market. Since pumped hydro systems are often large, a more accurate approach in a market area is to employ production cost modeling to estimate both the potential revenue of the energy storage system as well as the cost savings to market participants. In a vertically integrated utility production cost modeling is typically employed to identify the optimal dispatch that results in the lowest energy costs. The cost savings achieved from deploying a pumped hydro energy storage system are the value to the power system.

A value-based decision process, which selects the option with the largest net present value, is typically employed for expansion planning decision making. Societal impacts from a pumped hydro energy storage system can often be significant. Examples include creation of new jobs and economic development; water management services; and reduced greenhouse gases when integrated with renewables. It is preferable to assign a monetary value to societal impacts and incorporate them directly into the benefit cost analysis. Typical benefits achieved from the operation of a pumped hydro energy storage system include:

- Energy arbitrage – charging with inexpensive energy and then discharging when demand and prices are higher. In a market area, systems are remunerated through energy sales and purchases in the market. For a vertically integrated utility, this reflects cost savings achieved from improvements in overall generation efficiency.
- Energy capacity – the value of providing energy during periods of peak demand. In market areas, capacity payments are often determined through a capacity market.
- Frequency regulation – an ancillary service used to maintain grid frequency. The pumped hydro facility must be capable of meeting the market performance requirements, which favors adjustable speed pump-turbines for this application.
- Transmission and distribution upgrade deferral – the deployment of the pumped hydro energy storage system defers a large investment, resulting in cost savings.
- Power system stability – pumped hydro systems can provide system inertia and governor response which improve the dynamic performance of a power system.

An extensive list of potential benefits from pumped hydro energy storage, as well as valuation methodologies are listed in the *Pumped Storage Hydropower Valuation Guidebook* [14].

3. State of Current Technology

PHS is the oldest electrical energy storage technology in the world, in use for over 100 years. PHS has evolved extensively during this lengthy period of existence. Initially built for providing energy shifting services, advances in technology now enable PHS to include a multitude of applications, such as frequency regulation and integration of VERs. This section discusses the working principle of PHS facilities, evolution of the PHS technology over the years, the current state-of-the-art, and some future improvements.

3.1 Working Principles

PHS works by converting electrical energy to potential energy and storing it for future use. This concept is similar to a battery which converts electrical energy and stores it in the form of chemical energy. For this reason, PHS systems are also referred to as *water batteries*. PHS facilities achieve this by first using electricity from the grid to pump water to a higher elevation and later using the stored potential energy in the pumped water to generate electricity. Pumping is usually performed during periods of low electricity demand and generating during periods of high demand. The pumping and generating modes of the PHS are illustrated in Figure 4. Although they were primarily constructed for these energy shifting services, modern PHS facilities can provide many other services, some of which are discussed in Section 2.1 Grid-Scale Applications.

The power available from a stream of water can be represented by the following expression [15].

$$P = \eta . \rho . g . h . q'$$

where P is the available power in Watts, η is the turbine efficiency, ρ is the density of water in kg/m^3, g is the acceleration due to gravity (9.81m/s^2) h is the water head, and q' is the flow rate (m^3/s).

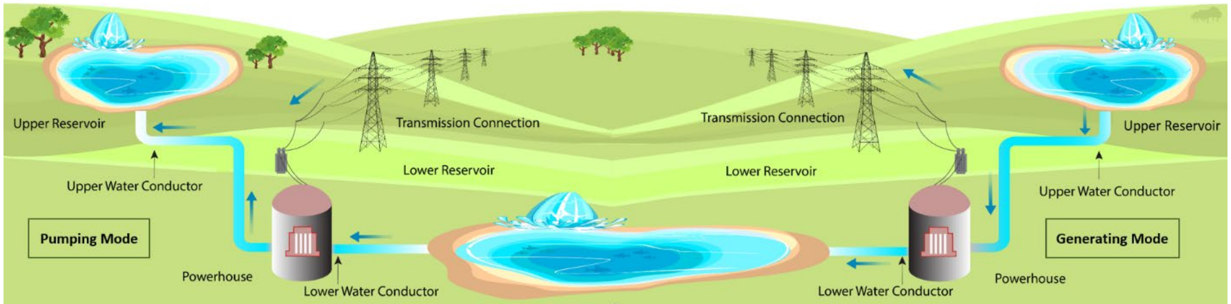

Figure 4. Pumping (left) mode and generation (right) mode operations of a PHS facility

A typical PHS facility comprises two reservoirs of water at different elevations, which are connected using conduits or water tunnels. A motor/pump system is used to move water from the lower reservoir to the upper reservoir, while a generator/turbine system is used to generate electricity from the stored water. PHS projects can be categorized into *pure* or *combined* projects depending on the source of pumped water [6]. *Pure* PHS projects only use water that has been previously pumped to an upper reservoir to generate electricity. This upper reservoir is not connected to any natural water stream. In contrast, *combined* plants use both pumped water and water from a natural stream to generate electricity. In this case, the upper reservoir is connected to a natural stream and electricity can be generated without the pumping requirements, similar to a conventional hydroelectric facility. The lower reservoir can be located on or off-stream for either facility.

PHS systems can be further classified into open and closed-loop systems (Figure 5). An open-loop system integrates PHS directly into a naturally flowing water source, such as a river. A closed-loop system comprises two reservoirs that are interconnected but otherwise separated from a natural water source. Closed-loop systems have the advantage of limiting impact on the natural aquatic environment. In either case, PHS systems are sized based on the required storage duty and operating cycle.

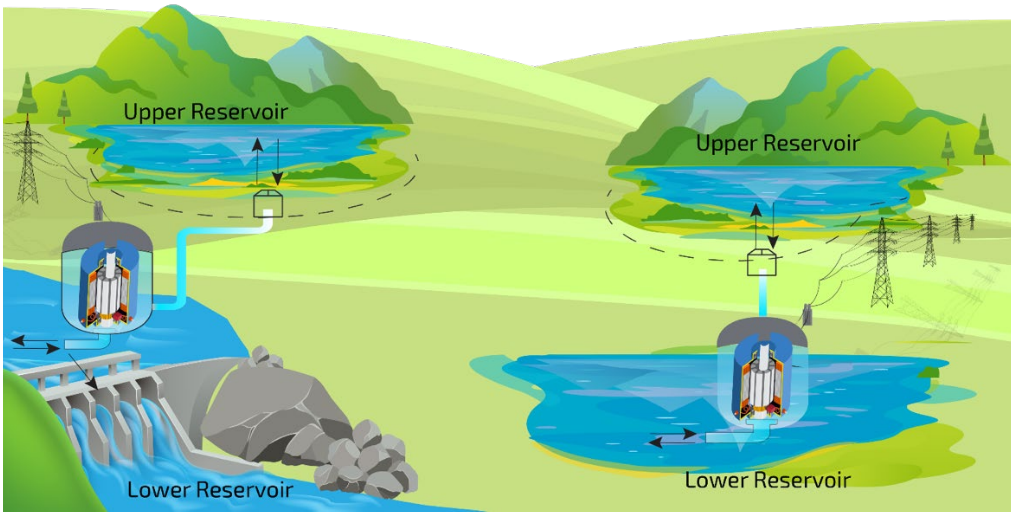

Figure 5. Open-loop (left) and closed loop (right) PHS plants

3.2 Evolution of PHS Technology

PHS facilities were originally built with separate pumps and generating units. For instance, the Rocky River project (1929) was built with one conventional 24 MW unit, two 3.5 MW motor generator units, and two pumps. These units usually had a motor and pump on one shaft and the generator and turbine on another shaft. Further developments led to a single vertical shaft being used with a motor and generator on the top above a pump and a turbine at the bottom of the shaft [16]. Subsequently, the reversible pump/turbine was developed in the 1940s, which considerably extended the scope of PHS applications at reduced costs [6]. The first reversible unit (8.5 MW) in the United States was installed in the Flatiron Project (1954). The Tennessee Valley Authority's Hiwassee Plant (1956) also installed a 60 MW reversible unit, which was larger than any earlier installation.

Besides the development of reversible pump/turbines, the increase in the height of the operational heads (vertical distance between the upper and lower reservoirs) also led to the construction of bigger PHS projects with lower costs. The Taum Sauk plant (1963) in Missouri with a head of 764 feet was the first project to see a significant increase in the operational head in the United States. Advances were also taking place in Europe and Japan with the Ohira project in Japan (1780-foot head), surpassing all previously held records for operating heads. This advancement was significant, since the power output of the plant is directly proportional to the head under which the turbines operate – the higher the head, the higher the power output. Also, the per unit cost of development of the project decreases since longer penstocks (conduits carrying water from the upper reservoir to the turbines) make up only a small percentage of the overall project costs, while significantly increasing the power output of the plant.

Another major milestone for PHS technology was the development of adjustable speed units instead of fixed speed ones. The first facility to use this technology was the Yagisawa pumped storage plant, where one 87 MW unit was converted from FS to AS in 1990. Prior to this, AS control of large generators and motors was not practicable for commercial application in hydroelectric plants. Further, developments in power electronics led to the advent of high ampacity thyristor devices along with the required control systems, which in turn enabled the development of AS PHS units. This development has created more opportunities for PHS plants in terms of offering a wider range of grid-services since these units can operate across a large number of speed segments and can also pump at part load.

3.3 State-of-the-art Technology

Currently, both FS and AS units are used in PHS projects. A detailed description of these units is provided in this section.

Fixed Speed (FS) PHS: FS PHS units can be based on synchronous or induction generators. These units are directly connected to the grid. An FS PHS unit based on a synchronous generator is illustrated in Figure 6. The excitation for synchronous generators is performed by feeding DC current to the field winding in the rotor. The excitation can be controlled efficiently to vary the reactive power generated and can operate without capacitor compensation. In generation mode, the power output can be varied by the operation of wicket gates[1] and governor control, although this method is not very efficient. In pumping mode, the wicket gate position is fixed at a point where the best efficiency can be achieved. Hence, the unit can only operate at rated pump power and cannot perform regulation services in pump mode.

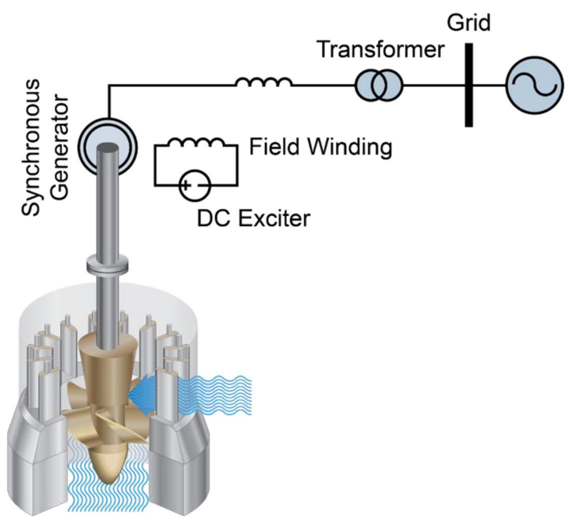

Figure 6. FS PHS based on synchronous generator

While synchronous generators are more commonly used for PHS facilities, induction generators are sometimes used in micro-hydro turbines [15], generally employing a squirrel-cage induction motor. An FS PHS based on an induction generator is illustrated in Figure 7. Although the operating speed of induction generators varies, the range of variation is sufficiently narrow (1-2%) and is still considered to be fixed-speed operation. Reactive power in this case is mostly provided by capacitors that are connected to the terminals of the generator. Despite being less

[1] Wicket gates are adjustable vanes or louvers in a hydroelectric turbine that control the flow of water entering the turbine. By adjusting the position of these gates, the flow rate and the power output of the turbine can be precisely managed.

efficient than synchronous generators, induction motors are less expensive, rugged, and require practically no maintenance. They are also used extensively as the motors that drive the pump.

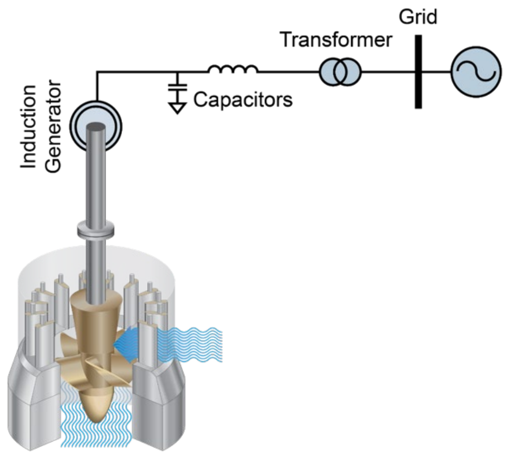

Figure 7. FS PHS based on induction generator

Adjustable Speed (AS) PHS: As the name suggests, AS PHS units allow operation across a greater generating range and greater pumping power inputs. AS speed control is made possible by the use of power electronic converters. The power electronic converters (PECs) can adjust the frequency of the supply and can provide rotor excitation at different frequencies. The frequency of the rotor voltage and current can be adjusted using the PECs to control the rotor speed, and that is how AS operation is achieved. Thus, by optimizing the speed and power, AS units can be operated at a high efficiency over a large head range. A comparison between the efficiency and operating range of FS and AS PHS units are provided in Figure 9 [16]. Since the PECs used in such units are robust, have high-capacity, and use high-speed computer controls, the unit can exchange energy rapidly with the bulk power system and provide fast frequency response services.

This process can be achieved by using either a *cycloconverter* or a *static frequency converter*. The cycloconverter is a direct-conversion device (i.e., the energy does not appear in any other form than AC input or AC output). This differs from a static frequency converter, which first converts the AC to DC and then converts the DC back to AC. It should be noted that static frequency converters are most commonly used with synchronous generators instead of doubly fed induction generators (DFIGs). A DFIG is more commonly used in AS PHS units, but synchronous generators can be used as well [17].

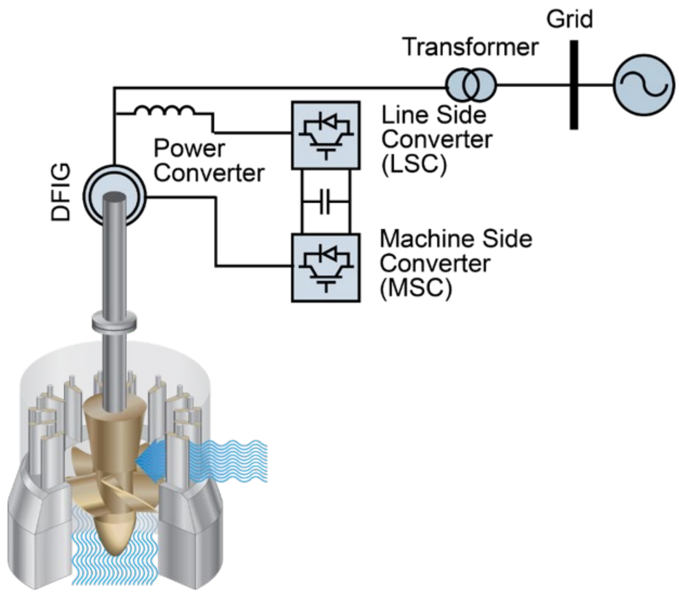

Figure 8. AS PHS units with DFIG and power electronic converters

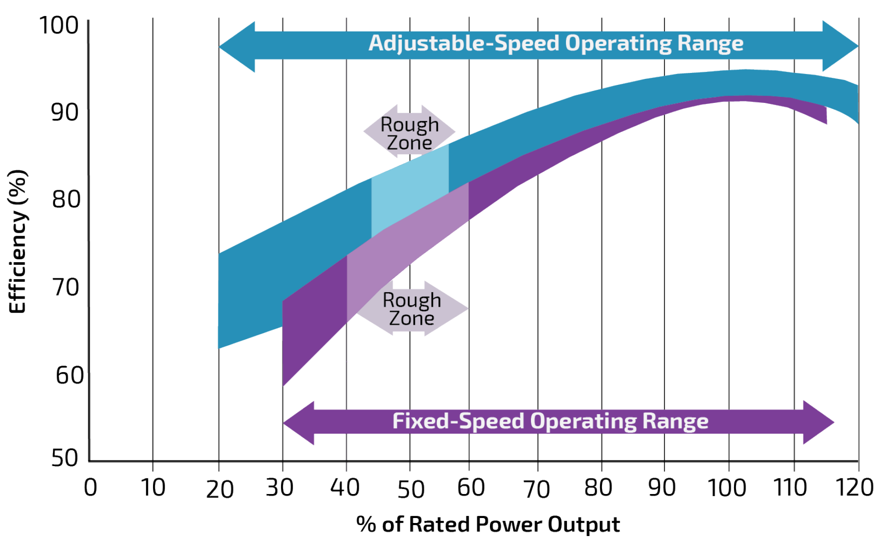

Figure 9. Efficiencies and operating ranges of FS and AS units.

3.4 Upgrading Existing PHS Facilities

Creating a new pumped-storage facility necessitates finding a suitable location, a substantial financial commitment, and a timeline of 8-10 years. An alternative method to boost capacity and flexibility of PHS involves upgrading FS units to AS units. Upgrading traditional synchronous pump-turbine units can provide added network adaptability to traditional pumped-storage plants, enabling them to regulate power and frequency even in pumping mode. For instance, a utility that has no frequency regulation capability can benefit by installing an AS unit in its PHS facility. Similarly, a PHS plant having a significant head variation can upgrade its FS unit to an AS unit to achieve improved operation over a greater head range [17].

Converting an FS unit to an AS one involves several critical factors, each with its own set of considerations and challenges. Some key factors include:

- **Technical feasibility and system compatibility:** The existing infrastructure should be examined to make sure that it can support the transition. This includes evaluating the mechanical integrity of turbines and generators, as well as the compatibility of electrical components with variable speed operations. Some facilities may require significant upgrades or even complete replacement of some components to handle the new operational modes, which can be expensive and technically challenging.

- **Control system upgrades:** AS units require advanced control systems for efficient operation. These systems must be capable of handling the dynamic changes in speed and load, ensuring stable and efficient operation under varying conditions. Upgrading control systems involves integrating new hardware and software with existing infrastructure to ensure system compatibility.

- **Power electronics upgrades:** Converting to AS operation often involves the installation of power electronics to control the speed of the pump-turbine units. Additionally, the integration of these units into the grid must be managed to maintain power quality and reliability. Power electronics can be expensive, and their integration into the existing grid infrastructure must be carefully planned to avoid harmonic distortion and other power quality issues.

- **Economic viability:** The conversion must be economically viable, with the benefits outweighing the costs. This includes not only the initial investment in hardware and software but also ongoing maintenance costs. Estimating the true cost of conversion and the expected return on investment can be complex, considering the potential for unforeseen expenses and the variability in energy market prices. Also, such analyses are site-specific, and a comprehensive cost-benefit analysis should be performed to ensure that an upgrade is feasible and beneficial for a particular site.

- **Environment and regulatory considerations:** Any modification to the plant, including conversion to AS, must comply with environmental regulations and the necessary permits must be obtained. This might include assessments of potential impacts on local ecosystems and water quality. Navigating the regulatory landscape can be time-consuming and may impose additional requirements or limitations on the project.

Because of these factors, successful conversion projects require detailed planning, expertise in a range of engineering disciplines, and a clear understanding of the expected benefits and challenges.

4. Operation of PHS: Coordination and Optimization

This section describes several operational and planning aspects associated with PHS including scheduling approaches for short- and long-term operations, market-based planning, and coordination with traditional thermal generation as well as renewable resources.

4.1 Hydro-thermal coordination: concept and evolution

The coordinated operation of hydroelectric plants, including PHS, with thermal plants is known as hydro-thermal coordination. Traditionally this consisted of an extended form of the economic dispatch that took into account energy availability constraints over short and long horizons, as well as hydraulic coupling between the hydroelectric plants, and tended to be quite complex [18]. The electrical coupling between hydro and thermal plants resulting from their serving the same system load subject to transmission constraints is complex enough to model. The hydraulic coupling, i.e., the relationship between the outflow of upstream plants with the inflow of downstream plants, adds a further layer of complexity.

Scheduling hydro for hydro-thermal coordination comprises both short-term operational optimization as well as long-term projections. The short-term optimization (days to weeks) focuses on minimizing the production costs. The objective is to determine an hourly schedule over the short-term horizon that minimizes production costs subject to the constraints described above, while also considering long-range water-release schedules.

Long-term scheduling (normally annual) focuses on water availability and seasonal variations. The objective of such scheduling is to ensure water availability over the long-term horizon, taking into account uncertainties such as:

- hydrological conditions and inflows
- resource availabilities of both hydro and thermal resources
    - including maintenance and forced outages (random failures)
- load stochasticity

Different utilities use varied methods to reach their assumptions regarding hydrological conditions. Some use a combination of forecasts and statistical expectation while others are more conservative, basing their long-term schedules on worst-case scenarios derived from their forecasts.

Traditional hydro-thermal scheduling is a complex, stochastic optimization problem. Solution methods employed by utilities predominantly fell into two categories:

1. Dynamic programming or stochastic dynamic programming, seeking optimal paths (schedules) over the entire long-term horizon
2. Statistical production simulation over the long-term horizon.

With the transition in many regions from pool operation to competitive markets, and the increasing integration of renewable generation (the availability of which is also largely stochastic), the traditional approaches have been gradually evolving. In competitive markets, the nature of dependencies between hydro and thermal resources has changed since the operation of thermal resources is determined by auctions rather than schedules. Stochastic generation has also impacted the solution methods. What has remained the same is that all methods still seek optimal schedules for pumped hydro operation, with the objective of minimizing production costs in pool operations or maximizing social welfare in competitive markets.

4.2 Coordination with thermal and other renewable resources

Traditional coordination of PHS with thermal resources consisted of developing schedules based on dynamic programming, production simulation, or other algorithms, as stated in Section 4.1. Following the arrival of electricity markets, newer tools were developed based on the auction mechanisms employed in individual markets. Most of these tools consisted of estimating arbitrage patterns from day-ahead bids, determining a schedule based on price differentials, and making adjustments in the real-time market, along with other participating resources. As an example [19], PJM Interconnect performs PHS scheduling optimization over 24-hour periods based only on day-ahead bids, maximizing social welfare subject to system constraints including reservoir limits and end-of-day state-of-charge. Real-time deviations are permitted, incurring deviation charges. Other markets use similar approaches, as the penetration of other renewable resources such as solar and wind continue to rise and their prices increasingly affect arbitrage patterns.

Traditionally, PHS plants have operated in daily cycles, generating during the day when loads and prices are high, and pumping during the night when loads and prices are low. Although scheduling approaches have changed since the advent of markets and continue to change with the evolution of methods for valuation of different products, the day-night PHS arbitrage pattern has persisted, except in regions with high renewable penetration, such as in the California ISO (CAISO).

In CAISO, with increased renewable integration, spot prices during the day have steadily dropped, often becoming negative, and this has led to a different arbitrage pattern in many of the PHS plants in the region. In fact, since 2014, the daytime pumping energy of some PHS plants in California has exceeded the nighttime pumping energy [20]. In Midcontinent Independent System Operator (MISO), on the other hand, the nighttime pumping pattern has persisted. This is because in MISO, renewable energy production is not sufficient to alter the day-night arbitrage pattern, which is still the fundamental determinant of PHS scheduling operations for most other regions in the United States.

In many US markets, notably MISO and Pennsylvania-New Jersey-Maryland (PJM), revenues from energy and ancillary services have been declining. This has reduced arbitrage price spreads, and consequently the revenues of PHS facilities, and, often, that of conventional hydro as well. Most hydro resources in the United States derive their revenues predominantly from energy, and, to a very limited extent, from ancillary services. There is, therefore, strong interest in extending the capabilities of PHS plants to enable participation in ancillary and flexibility services. In the next two sections take a closer look at how markets have influenced PHS operation, and opportunities for PHS to participate in flexibility services.

4.3 Market-driven planning of pumped storage

Since revenues of PHS are still predominantly derived from energy services, it is important to understand the relationship between markets and energy planning. With increasing integration of renewables, it is imperative to be able to balance resources across several time scales ranging from sub-seconds to days, spanning entire seasons, to ensure reliable operation. Reliability issues arising from imbalances have manifested themselves in several forms across the United States, most recently in ERCOT. Several countermeasures are being evaluated and implemented. These include (i) overbuilding of variable resources based on their capacity value; (ii) use of storage to smooth temporal variations; (iii) building of new transmission; and (iv) development of demand response and other flexibility services to balance generation and load. Storage resources can assist directly by smoothing temporal variation, and indirectly through a variety of flexibility services.

It is important for balancing authorities to correctly interpret price signals to drive appropriate investment in the different countermeasures. The understanding of price signals is still evolving, and continues to be a challenge in competitive markets. Although methods for operation have evolved more rapidly, as discussed in section 4.2, accurate planning is much more challenging. Another area where gaps exist is in the understanding of the value of long-term storage such as PHS. For storage technologies that assist with balancing over shorter periods (e.g., batteries), the value proposition is simpler to evaluate and justify, and these have seen significant growth in recent times. But such evaluation and justification are much more complex for longer duration storage systems that also require much higher capital costs and lead times.

Where commercial motivation is insufficient, regulatory bodies and governmental entities can assist. In recent times, California and some other states have recognized the need for investing in long-duration storage and are exploring mechanisms to incentivize such investment. For instance, the CPUC (California Public Utilities Commission) has released a decision on long term planning frameworks that identified 1 GW of pumped storage by 2026 [21].

4.4 Flexibility services and operational considerations

From the foregoing discussions on balancing of resources, it is evident that several means of operating and managing the resources (generation, storage, transmission, and demand) must be implemented for reliable operation of the grid. Balancing ensures continuity of energy supply at stable frequency and acceptable power quality. These solutions are collectively called flexibility services. The table below gives a brief overview of flexibility services, as defined by IEA [22]. The purview of flexibility services encompasses not just operational practices, but also public policy, market design, forecasting methods, and optimization algorithms.

As described in section 2, PHS, particularly those equipped with adjustable speed pumps, and appropriate controls, can contribute to several of these services across all time scales. The manner in which these services are dispatched is based on a more complex form of the operational optimization outlined in section 4.1, utilizing the operational flexibility of PHS to counter temporal and spatial variations in availability of renewable resources, as well as scheduling to coordinate with thermal resources to minimize fuel costs.

Flexibility type	Short-term			Medium term	Long-term	
Time scale	Sub-seconds to seconds	Seconds to minutes	Minutes to hours	Hours to days	Days to months	Months to years
Issue	Ensure system stability	Short term frequency control	More fluctuations in the supply / demand balance	Determining operation schedule in hour- and day-ahead	Longer periods of VRE surplus or deficit	Seasonal and inter-annual availability of VRE
Relevance for system operation and planning	Dynamic stability: inertia response, voltage and frequency	Primary and secondary frequency response	Balancing real time market (power)	Day ahead and intraday balancing of supply and demand (energy)	Scheduling adequacy (energy over longer durations)	Hydro-thermal coordination, adequacy, power system planning (energy over very long durations)

As the understanding of the role of long-term storage in grid reliability continues to grow, and the regulatory authorities assist in illuminating the need for and incentivizing investments in such resources, PHS will play an increasing role in grid operations. In the long run, PHS controls will evolve, as will operating strategies to render them more responsive to increasing uncertainties in grid operations. Their impact on market operations will also be more dominant, affecting price formation as penetration of renewable resources continues to lower marginal costs.

5. Cost of PHS

PHS facilities entail a variety of costs over their lifetime. To the extent available, facts and figures below rely on data reported by US utility owners of PHS facilities reported via FERC Form 1, for the years 1976 to 2020 [23] [24]. Brief descriptions of different cost categories are provided as follows.

Initial Capital Cost: PHS facilities are capital-intensive investments. Due to economies of scale, power ratings of a gigawatt or larger are the most economical to construct [25]. Costs also vary widely according to site-specific conditions, such as local topography and the availability of an existing man-made lower reservoir. Overnight capital costs (OCC) constitute a significant portion of initial capital costs and include all initial capital costs, such as, engineering, procurement, construction, contingency, and owner's costs. Another aspect of capital costs of PHS is the operational project lifetime. While the initial capital cost can be quite large, the annualized capital costs—the amount owed a lender or investor on an annual basis to repay a loan or justify an investment—of a PHS facility can be quite low. This is due to exceptionally long lifetimes of PHS facilities, assuming appropriate maintenance & refurbishments. For the purposes of financial calculations during project development, the expiration date of the initial FERC license, which is granted for a term of fifty years, is a customary assumption for the end of the project. After accounting for possible delays in construction, a project lifetime of 40 years would be a conservative, defensible assumption [25].

Overall, cost estimates from the literature are highly diverse, and more information regarding capital costs can be found in [6], [27], [28], [25], [26].

Incremental Capital Expenditures: There are certain expenditures incurred after the completion of construction that are not sufficiently routine to be classified as operation & maintenance (O&M) expenses. These expenses are capital in nature as they provide benefits over a long-time horizon but are not associated with the initial capital cost. Hence, these are categorized as incremental capital cost. These include refurbishments of depreciated capital equipment and the replacement of turbines to increase power output, efficiency, or operational flexibility. It should be noted that these costs are incurred on a non-routine basis, typically once every ten or twenty years [25].

Operations & Maintenance (O&M) Costs: The operation and maintenance of a PHS facilities entails various routine costs, primarily labor, as well as material and parts used in upkeep and repair of the equipment. The single largest category of expense is associated with the electric plant. Other O&M costs include matters as diverse as grounds keeping, maintenance of roads, clerical work, environmental monitoring, and costs associated with making reservoirs available for recreation. PHS facilities exhibit very strong economies of scale in O&M, as shown in Figure 13.

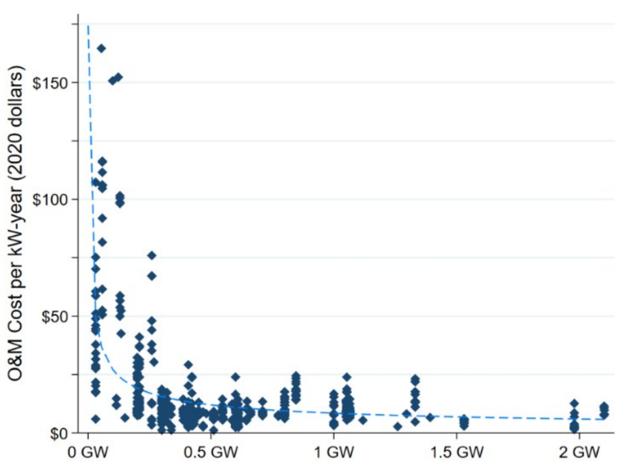

Figure 10. O&M Costs for PHS Facilities in the United States vs. Power Capacity

Energy Cost: The largest operational expense for a PHS facility is the cost of purchasing energy for pumping water into the upper reservoir. In the future, PHS facilities may be able to charge on lower-priced energy during periods of excess generation of variable renewables, which have zero marginal cost.

Regulatory Costs & Fees: A PHS facility faces two regulatory costs from FERC: (1) costs incurred by the project owner during licensing, and (2) "annual charges" collected by FERC to offset the costs of its operations. FERC annual charges are set by a regulatory-determined formula which can be found in (18 CFR 11.1).

Levelized Cost of Storage: "Levelized cost" conveys the notion of an average cost per unit of energy supplied to the grid that accounts for the net present value of when costs are incurred and revenues are generated. The concept of "levelized cost of storage" (LCOS) is analogous to the levelized cost of energy (LCOE). Estimates of LCOS from the DOE Energy Storage Grand Challenge for differently sized PHS can be found in [30]. It should be noted that LCOS is sensitive to assumptions about duty cycles, which reflect a storage system's application. Under historical conditions, PHS has been the least-cost storage-based solution for energy arbitrage, secondary response, tertiary response, black start, transmission investment deferral, and congestion management [31].

6. Industry Status

The PHS industry faces several challenges in developing new projects, including geographic barriers, high capital expenditure, and environmental impacts. Some of the most important issues are described here.

Geographic Barriers: The construction of a PHS facility requires two reservoirs with a significant elevation separating them. This requirement restricts PHS siting to terrains which can satisfy these conditions, including the presence of a significant amount of water resource. In addition, the construction of a PHS project demands massive land requirements. Some of these limitations can be overcome with the deployment of alternate PHS designs, which are discussed in the next section.

Environmental Impacts: The environmental impacts related to the development of a PHS facility are significant, especially for open-loop plants, which integrate PHS directly into a naturally flowing water source, such as a river. This is because the construction of a PHS projects involves building dams around the river, which leads to the blockage of natural waterways. This is turn can disrupt the local aquatic ecosystem, result is flooding, displace terrestrial wildlife, and ultimately change the landscape. Some of these impacts can be reduced by the use of closed-loop plants, where the reservoirs are physically separated from existing river systems. In addition, opportunities to locate PHS systems underground and in coastal settings provide greater opportunity for siting outside environmentally valuable and sensitive areas.

Policy Impacts: Several regulatory policies affect the development of new PHS projects. One of the primary regulatory challenges facing PHS project developers is the regulatory timeline for the development of new projects. All non-Federal PHS projects must obtain a FERC license, as well as multiple other state or Federal permits. Under the current FERC licensing process, obtaining a new project license to construct can take three to five years or longer [32]. With construction requiring six to ten years to complete, few financial institutions are willing to finance projects with such long lead times. In efforts to reduce some of this permitting burden, the Hydropower Regulatory Efficiency Act of 2013 directed FERC to investigate the feasibility of a 2-year licensing process for closed-loop PHS projects [33]. Other policy challenges include the non-existence of any investment tax credit for PHS, unlike some common storage technologies and the exclusion of PHS from renewable portfolio standards or energy storage procurement targets of most state procurement policies [4].

Valuation: In today's electric market, PHS has the potential to generate added value through ancillary services beyond time-shift of energy; in fact, as many as twenty PHS services and contributions have been identified [16], [34]. However, both competitive electricity markets and traditional regulated utilities lack established revenue streams to cover the full range of PHS services. In competitive electricity markets PHS operations can only receive revenues from energy production, certain ancillary services (typically for regulation, spinning, and non-spinning reserves), and capacity markets. Regulated utilities lack any established revenue streams for PHS services and are limited to optimizing PHS operations to minimize system-wide generation costs. Although FERC Orders 890 and 719 required ISOs to modify their tariffs and market rules so all non-generating resources, including PHS, can fully participate in established markets, these are typically real-time or day-ahead markets and there are no long-term value streams where a bulk storage project can attract investors seeking revenue certainty through long-term power purchase agreements or defined value streams [35].

Others: Other issues include supply chain issues like long lead time for critical PHS components and low diversity of suppliers [36], competition with natural gas when prices are low [5], etc.

7. Modular PHS

Due to the various challenges facing the development of traditional PHS, several new modular PHS configurations have been proposed in recent times. In addition to overcoming some of the shortcomings of traditional PHS, these modular units also have the potential to participate in grid applications beyond the load shifting and reliability services generally offered by traditional PHS. Some of these modular PHS designs are discussed in this section.

Aquifer PHS: The working principle of an aquifer PHS is similar to a traditional PHS with the lower reservoir being replaced by an underground aquifer and the upper reservoir being replaced by a water tower. The existing pumps, motors, and piping systems in municipal water systems can be used as the turbines and generators [37] thus reducing the need for investment in new equipment. The aquifer PHS concept could broadly extend the potential siting locations for PHS to areas with limited geographic relief. One such pilot aquifer PHS project currently under development aims to utilize the large number of underground wells in Central Valley, California [38]. The project developers plan to retrofit the existing wells in this region to generate power and back up critical loads like hospitals, nursing homes, and charging centers.

While this PHS configuration has potential, there are several challenges that must be overcome before these projects can be realized, including the aboveground water having sufficient excess capacity to supply the minimum required off-peak water volume, the aquifer having sufficient capacity to accommodate the required reverse flow volume, and the head difference between the water tower and the aquifer being sufficiently long for power to be generated.

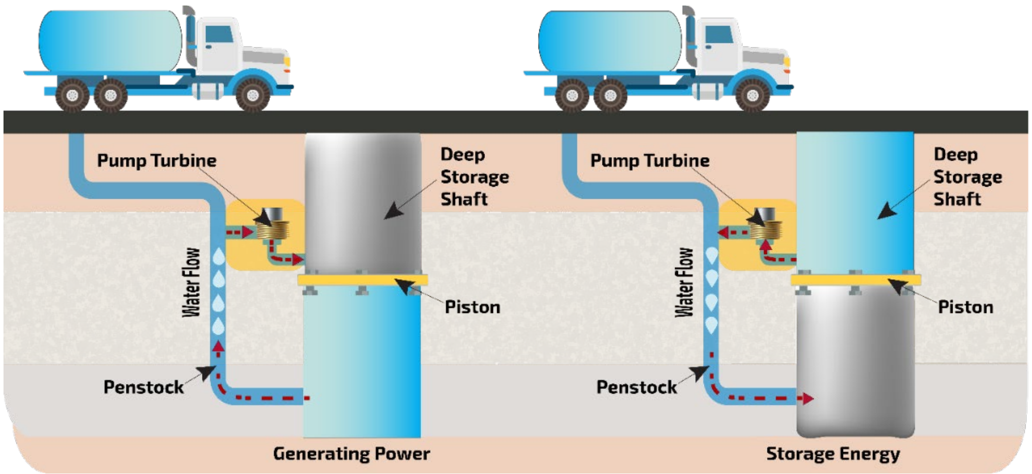

Figure 11. Implementation of an in-ground storage pipe PHS

Underground Reservoir PHS. The concept of underground reservoir PHS is similar to aquifer PHS. However, instead of aquifers for the lower reservoir, these PHS facilities use old mine shafts, depleted natural gas formations, wells and other underground man-made or naturally occurring features [39]. One such system is being developed by Quidnet Energy, funded by the U.S. Department of Energy's Water Power Technology Office, as an innovative geo-mechanical pumped-storage system and it uses the pressure in underground wells to generate electricity. Similar to aquifer PHS, these systems can be installed in flat areas—eliminating typical PHS geographical challenges in finding high and low elevations in close proximity. Underground PHS can also be implemented as an in-ground storage pipe PHS, as shown in Figure 10. The shaft is initially filled with water during the first operation and no additional water is required. As the piston drops, it forces water down the storage shaft, up the penstock and through the turbine, generating electricity. Power purchased during off-peak hours drives the pump-turbine in reverse, to force the water down the penstock and into the shaft, thus lifting the piston. A similar system called the Gravity Power Module is being developed by Gravity Power, LLC [40].

Energy Island PHS: This type of PHS can be especially useful for storing energy from renewable resources, like and solar. These designs usually include a ring-like dike encircling an internal lake or lagoon that could be 100 feet or more below the surrounding sea level [34], as shown in Figure 11. Sea water could be pumped out of the island's interior lake when excess renewable generation is available, thus creating an elevation difference between the sea water inside and outside the island. Sea water can be allowed to flow back in to generate electricity during peak demand periods. One implementation of this PHS also uses tidal energy. When high tides occur at off-peak hours, turbines can be used to pump more seawater than the high tide would have naturally achieved. The La Rance Power Plant in France, which has a capacity of 240MW, is a tidal powered facility with the option of employing PHS [41].

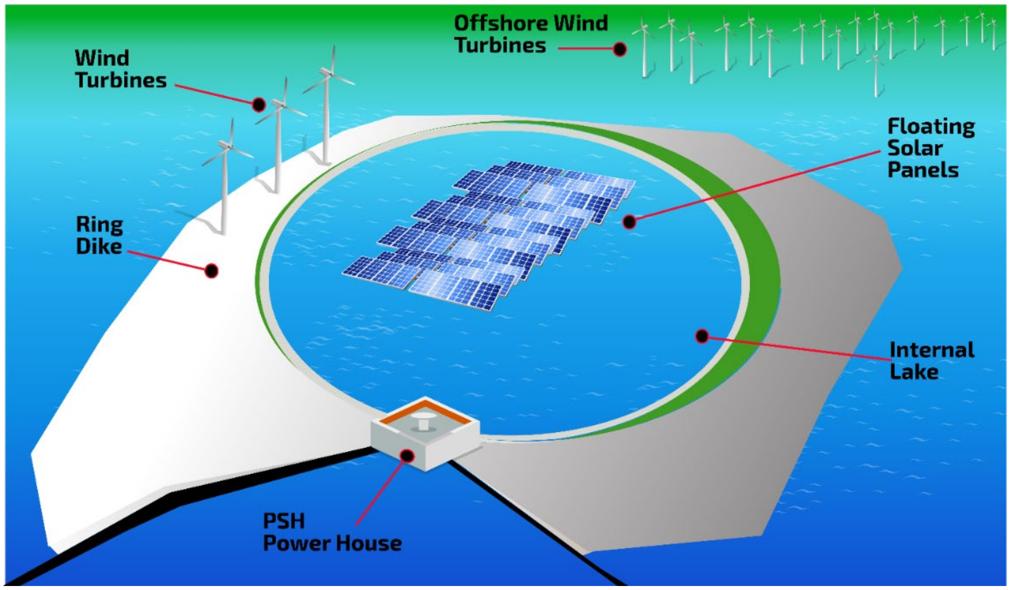

Figure 12. A concept for tidal lagoon PHS plant, adapted from *[34]*.

GLIDES: A modular PHS system called Ground-Level Integrated Diverse Energy Storage (GLIDES) has been recently developed at the Oak Ridge National Laboratory (ORNL) [42]. This low-cost, scalable system is a combination of PHS and Compressed Air Energy Storage technologies. It stores energy by compression and expansion of air using water as a liquid piston inside high-pressure chambers. During charging, a pump is used to push water into the pressurized reservoirs, compressing the air inside and increasing its pressure. Water is released from the reservoirs during discharging, letting the air inside expand. The released water turns a turbine, thus generating electricity. This system is scalable, with its size ranging from a few kWh to hundreds of MWh. The cost of these systems primarily depends on the vessel being used as the high-pressure reservoirs. A range of storage vessels have been modeled and tested by ORNL, ranging from steel tanks and carbon-fiber tanks to underground reservoirs and caverns. According to [42], the cost of GLIDES can be as low as $13/kWh if depleted oil or gas reservoirs are used as the high-pressure chambers. An illustration of the GLIDES system is provided in Figure 12.

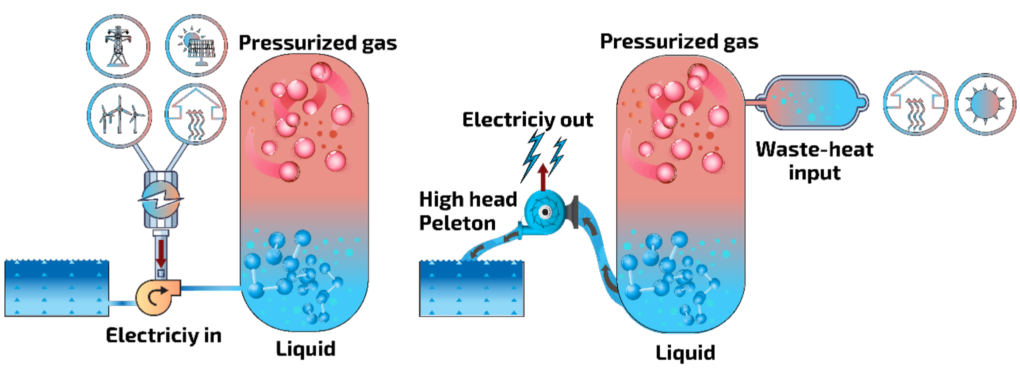

Figure 13. The GLIDES system.

8. Concluding Remarks

In conclusion, PHS is by far the most widely used electrical energy storage technologies, playing a pivotal role in modern power grids worldwide. It has the capability of providing numerous grid services, particularly in accommodating the integration of variable energy resources, underscoring its significance in today's energy landscape. While traditional PHS units predominantly operate at fixed speeds, the potential for conversion to variable speed operation opens up new possibilities for their applicability by enhancing their flexibility and efficiency. Despite its widespread adoption, the PHS industry faces formidable challenges in the development of new projects, ranging from geographical constraints to substantial capital investments and environmental considerations. However, innovative solutions such as modular PHS configurations offer promising alternatives, addressing some of the limitations of conventional projects while expanding the scope of grid applications beyond conventional load shifting and reliability services.

Author Biographies

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Ray Byrne is manager of the Energy Storage program at Sandia National Laboratories where he has been employed since 1989. Prior serving as manager, he was a Distinguished Member of the Technical Staff. He completed a B.S. in electrical engineering at the University of Virginia, an M.S. in electrical engineering at the University of Colorado, and a Ph.D. in electrical engineering at the University of New Mexico. He also completed an M.S. in financial mathematics (financial engineering) at the University of Chicago. He currently serves as team lead of the Equitable Regulatory Environment thrust area of the Sandia energy storage program. Awards include Time Magazine invention of the year in robotics in 2001, as well as the Prize paper award at the 2016 IEEE Power and Energy Society General Meeting for a paper on maximizing revenue from energy storage in grid applications. He is a member of Tau Beta Pi, Eta Kappa Nu, and Sigma Xi. He was elevated to IEEE Fellow in 2017 for contributions to miniature robotics and grid integration of energy storage.

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