CHAPTER 9

Lessons for pumped hydro energy storage systems uptake

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9.1 Introduction

The upscaling of energy storage systems (ESS) has become crucial in recent years, primarily due to the increasing interest in renewable energy (RE) and energy systems decarbonization as a result of climate

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change and its impacts. Some renewable and clean energy sources such as solar and wind are intermittent and so cannot deliver nameplate and continuous power capacity. The wind is a very changeable meteorological component that changes hourly, daily, weekly, monthly, and annually. Radiation from the sun, on the other hand, is less changeable yet only operates during the day.

The variable and intermittent nature of these renewables tend to introduce a wave of challenges such as grid system instability and irregular power supply. ESS are therefore needed to link these RE technologies to the grid to deliver continuous and high-quality power.

Well-known ESS in the electricity generation portfolio include compressed air energy storage, hydrogen storage systems, lead batteries, flywheels, supercapacitors, and others. But among these ESS options, pumped hydro energy storage (PHES) is recognized as the most promising technology for managing large energy networks.

PHES consists of two interconnected reservoirs at different altitudes. It stores energy by pumping water from a lower to an upper reservoir tank during a period of low electricity demand when electricity prices are low (Hino & Lejeune, 2012). During the peak demand period, water stored at the upper reservoir tank is then released through the hydraulic turbines to generate electrical power (IRENA, 2020a). This implies that the operation of PHES requires the provision of a pump and generator to be situated between the two reservoirs (Kocaman & Modi, 2017).

Globally, PHES potential is estimated to be 23×10^6 GWh in over 600,000 plants (Lu, Stocks, Blakers, & Anderson, 2018). PHES is recognized as the most matured and utility-sized energy storage technology for addressing peak load demands in the electricity market (Díaz-González, Sumper, & Gomis-Bellmunt, 2016). Also being a clean source of energy, it contributes little to the carbon footprint in addition to providing an opportunity for the optimal use of water, energy, and land resources in both the short and long terms. In addition, it has an immediate start-up time which enables it to rapidly respond to varying energy demands. PHES also has a relatively lower capital cost per kWh of energy storage and usually has a longer lifespan.

According to Barbour, Wilson, Radcliffe, Ding, and Li (2016) and IHA (2020), PHES provides the following enormous ancillary services and advantages:

1. flexible start/stop and quick reaction time
2. capacity to watch load changes and adjust to dramatic load fluctuations
3. ability to vary the frequency while maintaining voltage stability

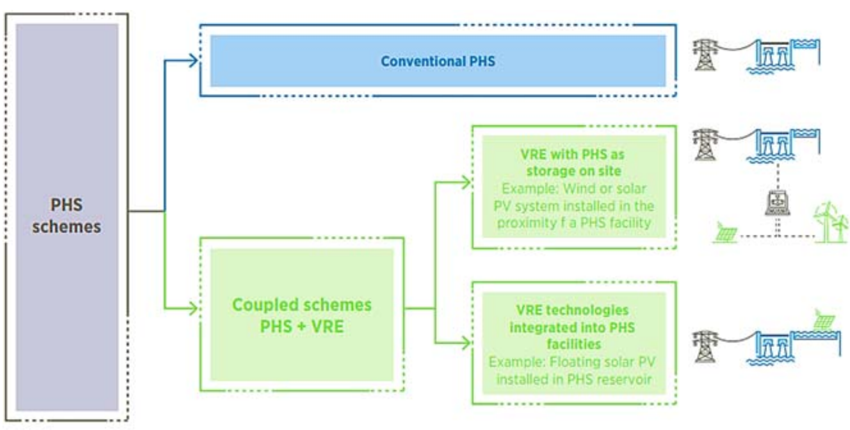
4. facilitating the increased deployment of low-carbon generation
5. increasing reliability for end users
6. facilitating a time of use energy management
7. increasing system flexibility
8. reducing the volatility of electricity prices
9. reducing the need for transmission upgrades/new transmission infrastructure
10. reducing overall pollutant emissions.

Notwithstanding these enormous advantages, PHES is often criticized as having relatively lower energy density as compared with some other ESS, higher construction cost and longer construction time compared to other energy generation plants, destruction or disruption of aquatic and terrestrial habitats as a result of the impoundment of water, etc.

9.2 Classifications of pumped hydro energy storage

According to Šćekić, Mujović, and Radulović (2020) and IRENA (2012), there are conventionally two main classifications of PHES (see Fig. 9.1):

1. Conventional river-based or open-loop PHES: Possesses two interconnected reservoirs at different elevations where the lower reservoir continuously receives its inflows from a river inflow. This continuous supply of river inflows provides additional flexibility to the scheme.



Note: PHS = pumped hydropower storage; VRE = variable renewable energy.

Figure 9.1 Configuration schemes for pumped hydro energy storage and renewables (IRENA, 2020a).

2. Off-river PHES or closed-loop PHES: Though also composed of two interconnected reservoirs, the system does not receive any river inflows. The absence of a river inflow minimizes flood mitigation costs, ensures higher heads, eliminates the negative impacts of damming, and ensures speedy construction.

At present, PHES systems are being coupled with other forms of variable RE systems based on a variety of hybrid PHES designs for both grid and off-grid applications, and these include wind-PHES hybrid system (Pali & Vadhera, 2018), hybrid wind-solar-PHES-battery system (Javed, Zhong, Ma, Song, & Ahmed, 2020), hybrid solar-wind-PHES-diesel generator system (Kusakana, 2016), integrated fossil fuel-wind-PHES system (Segurado, Madeira, Costa, Duić, & Carvalho, 2016), and double storage PHES-battery powered by renewable energy sources (RES) (Abdelshafy, Jurasz, Hassan, & Mohamed, 2020).

9.3 Site considerations for pumped hydro energy storage development

To ensure optimal harnessing of the economic, social, and environmental benefits of a PHES project, there is the need for the careful selection of an appropriate site for the project. Key among the site considerations for PHES development is the availability of a suitable geographical location with a desirable head and the availability of water (Kocaman & Modi, 2017).

Economic factors considered during site consideration for a PHES project include nearness to power lines, access to a road network, geological condition of the site, head-distance ratio, the complexity of the civil works involved, as well as seismic considerations. On the social aspects, the following factors are taken into consideration: nearness to an urban area, settlement, potential for a new latent fault, as well as land use. Alteration to either the daily water level or the water flow rate or both, sealed ground surface, local solar irradiation, and wind speed in addition to landcover form part of a group of environmental factors considered during the site selection process (Nzotcha, Kenfack, & Blanche Manjia, 2019).

Due to the complexity of the multiple social, techno-economic, and environmental factors considered during the site selection of PHES, a multi-criteria decision-making (MCDA) tool is often used. A typical MCDA for PHES site selection encompasses three (3) main stages: (1) defining the problem, (2) decision-making, and (3) recommendation.

9.4 Climate change impact on pumped hydro energy storage

PHES projects are impacted by climate change through the modification of rainfall patterns, water availability, and significant variation in temperature regimes. Though PHES is known to have a long project lifespan, this on the other hand also exposes its operations to the severe impact of climatic and hydrological uncertainties. Particularly, small-scale hydropower projects, in general, appear to be more vulnerable to climate change impacts. However, PHES is generally less vulnerable, due to its efficient capture and re-use of stored water, which offers added flexibility to the system.

Thus, there is an urgent need to consciously integrate climate adaptation, mitigation, and risk assessment into the design and planning of PHES.

9.5 Drivers and barriers to pumped hydro energy storage

The drivers and barriers associated with PHES can be categorized broadly into socio-economic and techno-environmental factors. The socio-economic factors look at both the positive and negative influence of the deployment of PHES on social and economic dimensions, for example, resettlement issues, job opportunities, revenue mobilization, etc. The techno-environmental factors also look at both the positive and negative impact of the utilization of PHES on technical and environmental dimensions, for example, land use, topography, clearing of vegetation, clean energy, etc. (Ali, Stewart, & Sahin, 2021).

9.5.1 Classification of pumped hydro energy storage drivers

9.5.1.1 Socio-economic drivers

Energy arbitrage: This technique works by pumping water to the upper reservoir during off-peak periods where electricity prices are low and then turbining at peak demand hours where electricity prices are high. The opportunities associated with energy arbitrage trading, therefore, appeal to investors to invest in this technology. Due to technological advancement, the cost of generating electricity from renewables has been reducing over the years and these sources are opinionated to be competitive and even cheaper than fossil fuels (Ram et al., 2018). This is indeed true for PHES whose capital costs remain high, but its low cost in running and maintenance makes it commercially lucrative in the long run while delivering low-cost electricity.

Rural development: Various job and business opportunities are often created for the local inhabitants during the construction and operation phase of PHES projects, especially in developing countries. Commercial opportunities such as fish farming, tourism and recreational activities, property rentals around the project site, etc., serve as a critical societal motivator for rural development. Further, local contractors may be adequately rewarded for delivering materials and other critical services during the construction process. Since large PHES are usually located in isolated places that lack basic and essential amenities such as hospitals, roads, schools, and infrastructure, PHES development naturally delivers such facilities in addition to revenue sharing and local tax payment which enhance the socio-economic development of the rural inhabitants (Ali et al., 2021).

9.5.1.2 Techno-environmental drivers

Utility-scale storage: PHES could be used in power networks for daily and seasonal storage of renewable and non-RE to address fluctuation in the power system since it provides flexibility to seasonal variations and is easy to dispatch (Kear & Chapman, 2013). For intra-day balancing, excess power from baseload technologies such as nuclear and coal is mostly used for pumping water to the upper reservoir at night and is used to enhance required generation during peak demand periods. Some PHES, on the other hand, maybe used as weekly or monthly storage if it is economically justified. Overall, both daily and seasonal storage choices for utility-scale applications are driving forces behind global PHES growth (Ali et al., 2021).

Grid resilience: The progress of PHES is crucial to the present power networks as it supports the transition to RE systems (Ghorbani, Makian, & Breyer, 2019). By distributing electricity when demand is high and storing it when supply is high, PHES can provide energy time-shifting and grid balancing of variable RE sources. Additionally, as shown in Fig. 9.2, PHES provides auxiliary support like frequency and voltage modulation, detection and response to high load variations, reduction of renewables curtailment, capacity firming, fast and flexible ramping, and black start to relieve grid congestions. Due to its extraordinary operational mobility, PHES is frequently used as a backup powerhouse, quickly regulating unanticipated changes caused by either demand or generation. PHES can move from zero to full power in minutes, which is crucial for

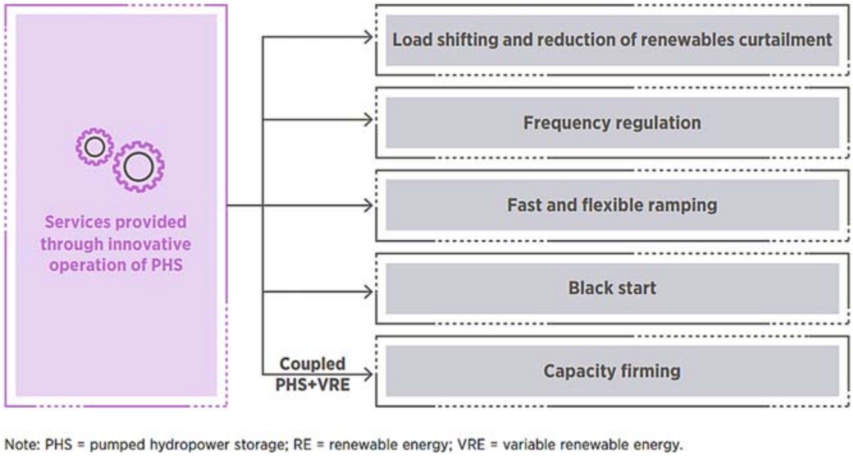


Figure 9.2 Contribution of pumped hydro energy storage to the power sector (IRENA, 2020a).

averting system-wide mishaps and recovering from disasters and catastrophes. In addition to their role in local grids, PHES plays a significant supplementary role in regional grids and cross-regional interconnected grids (Ali et al., 2021).

Sustainability: The development and utilization of PHES enhance the penetration of RE and directly lower reliance on non-RE sources such as coal power. Furthermore, substituting these high carbon sources with PHES integrated with renewable sources can substantially reduce anthropogenic emissions such as carbon monoxide, nitrogen oxides, sulfides, particulates, etc (Ming et al., 2013). Carbon dioxide (CO_2) is the major contributor to greenhouse gases, which causes global warming. As a result, implementing PHES and cutting CO_2 emissions entails attaining low-carbon economic development while also implementing the Paris Climate Agreement. PHES has a life expectancy of 40 to 80 years, with some studies estimating a life expectancy of up to 100 years (Deane, Ó Gallachóir, & McKeogh, 2010), meaning that it is a dependable and one-time investment that is attractive to investors and governments searching for commercial prospects.

Auxiliary services: A few of the auxiliary services linked with PHES include sediment and flood control, breeding sites for amphibians, groundwater recharge and replenishment, etc. PHES can reduce floods and silt that normally occur as a result of natural land degradation and the establishment of settlements upstream. This is because the reservoir holds water to decrease the impact of floods and sediments and prevent them from reaching vulnerable downstream settlements (Munthali, Irvine, & Murayama, 2011). Further, a comprehensive PHES system may support the existence of amphibians and water-related insects and it can also positively influence the microclimate and enhance the landscape. PHES could be good for the environment since it allows for groundwater recharge and replenishment, which is an important step in sustainable groundwater management (Ali et al., 2021).

9.5.2 Classification of pumped hydro energy storage barriers

9.5.2.1 Socio-economic barriers

The socio-economic barriers capture key factors such as public opposition, market failures, institutional challenges and political interference, project investment and financing, etc.

Public opposition: Public disputes, arguments and not in my backyard (NIMBY) syndrome are usually common with the development of PHES and hydro projects. There is usually a notion of breeding mosquitos which causes diseases, bad smell, and risk of explosion when earthquakes occur. The issues of potential dispersion of existing communal values, habitat, and livelihood due to resettlement or relocation of local people also create opposition. Further, the potential disturbance to the fishing population and other linked benefits for downstream settlers are major factors for public outcry in hydro developments. At times lack of information on financial and ecological benefits also creates this dispute, which can create delays in the approval and construction of these projects (Ali et al., 2021).

Market failures: This could include market rule unpredictabilities, scarcity of skilled labor, state-controlled energy industry, and others (Ali et al., 2021). The availability of skilled labor like technicians, engineers, policy experts, etc. is needed for hydro development and their availability locally is mostly governed by the country's educational system. Due to the grappling economy, developing countries usually lack local specialists who can do feasibility studies or aid in the construction of hydro projects. Hiring the services of expatriates could increase the entire project cost due to their expensive salaries and incentives. The liberalization of electricity markets accelerates the development of PHES projects, whilst failure to do so has negative implications (Deane et al., 2010). Uncertain market regulations are a major reason for limited project investment; hence this is also seen as a barrier.

Furthermore, the usual operation of a PHES project is for the plant to operate during a short period to meet the peak energy demand. Thus, in the implementation of a PHES project, special attention must be paid to the prevailing market pricing and regulations scheme to ensure value for money (Abdellatif, AbdelHady, Ibrahim, & El-Zahab, 2018). The following are the major market infrastructures under which a typical PHES may operate:

Liberalized: Also known as a "deregulated" market, this type of market infrastructure promotes competition and reduces price hikes by opening its avenue to all prospective energy service providers (Dragoon, 2010; Esmaeili Aliabadi, Çelebi, Elhüseyni, & Şahin, 2021).

Regional monopoly: This option of market infrastructure makes provision for each region to be served by a sole utility firm while all the regions remain interconnected (Shen & Yang, 2012).

Regional monopoly open to independent power producers (IPPs): This type of market infrastructure is synonymous with the Regional Monopoly only that IPPs are allowed to take part in the provision of energy services (Shen & Yang, 2012).

National monopoly: Under this category, a sole state-owned utility company is put in charge of the generation, transmission, distribution, and retail of energy services to consumers (Shen & Yang, 2012).

According to Barbour et al. (2016), more than 95% of PHES plants investigated in their study were commissioned under the three categories of monopoly market structures: national, regional, and regional monopoly that is open to IPPs. Also, a detailed survey of available literature revealed that the liberalized market environment generally provides a congenial atmosphere for the growth of PHES. However, it may reduce the prices of electricity and hence the returns on PHES investment. In the nutshell, the need for robust, transparent, as well as detailed market regulations without any ambiguity is crucial for the sustainability of a PHES under any market scheme or infrastructure.

Institutional challenges and political interference: Corruption, lack of proper institutional coordination, and legal frameworks could be major barriers to the development of PHES. The delays and bureaucracy associated with appropriate authorities granting licenses to potential developers can aggravate this issue while dissipating social resources.

Project investment and financing: The extent of capital and operational expenditure, payback length, and other economic factors could create barriers to PHES development. The capital expenditure for PHES projects is frequently site-specific, with some studies predicting a €600−3000/kW range (Deane et al., 2010) and there could be an additional cost in securing financing for all capital costs. The costs of operating and maintaining the facility, as well as pumping water to the upper reservoir, may be included in the costs of operation and maintenance (Ali et al., 2021). This cost, of course, may vary depending on the specific time electricity is borrowed from the grid to power the pumping equipment. Furthermore, open-loop PHES plants that draw water from a river or lake may attract a water usage tax. Wages and compensation for employees are among the other expenses. Additional costs would be paid to compensate businesses in the flooded public downstream including the agriculture and fishing sectors. Another hurdle to the growth of PHES is the payback period needed to repay loans, which is predicted to be at least 2.5−5.5 years (Connolly, MacLaughlin, & Leahy, 2010).

The development of a new PHES is dependent on the availability of funds from sources such as the government, Multilateral Development Banks (MDBs), private developers or mixed funding sources, and usually, this could be a daunting and complex process. At times, due to the long payback duration and licensing time unpredictabilities, not many organizations or private investors are willing to support such long-term ventures (Ali et al., 2021). According to studies, the public sector now funds the vast majority of PHES systems in existence, which is unsustainable in the long-term financing of PHES projects.

9.5.2.2 Techno-environmental barriers

The techno-environmental barriers capture key factors such as biodiversity loss, water issues, land acquisition challenges, landscape topology, lack of infrastructure support, etc.

Biodiversity loss: Depending on the nature of the site for construction, PHES has the potential of causing serious environmental impediments including perceived effects of climate change on fisheries and birds, as well as temperature changes, and soil erosion.

Water issues: This could be a major hindrance to the development of PHES and may take any of the following forms: water availability and quality issues, water loss, oxygen loss, conflict of interest with local water supply, especially for open-loop PHES systems, and other hydrological issues such as huge water volumes needed to fill up the reservoir. The development of PHES could have less potential in countries where water scarcity is more common, such as Jordan, Iran, Cameroon, etc. (Droogers et al., 2012). Another source of worry is leakage and water evaporation loss, which is mitigated to some extent by rainfall and occasional water replenishment. A group of environmental activists in Hudson Highlands in the United States prevented the development of a PHES project that posed a danger to the local water supply (Yang & Jackson, 2011). Water oxygen loss has also been observed in a hydro station in South Carolina, United States, where a system for oxygen injection was installed to resolve the challenge (Ali et al., 2021).

Land acquisition challenges: Site acquisition challenges comprise issues of land ownership, land use, vegetation clearing, etc. which are inherent in some of the environmental challenges of PHES. Disruption to forests, rivers, protected lands, historically or culturally significant areas, etc. should be avoided. Infringement of these principles is typically in contrast to the environmental and social viewpoint, which ultimately impedes PHES development. Land ownership is a major barrier as locals may claim ownership of empty areas, or purposefully migrate into planned project areas by erecting temporary structures before construction begins in order to receive compensation money (Ali et al., 2021).

Landscape topology: Site topology determines the type, slope and shape of the dam, elevation, head to length (H/L) ratios, and the amount of earthwork needed to construct the PHES. Usually, a high head indicates less needed construction and relatively lower equipment costs. The time and cost of cutting and filling the surface when establishing an artificial reservoir are reduced with a mild slope surface. Sites with more than a 10% slope, for instance, are a stumbling barrier. The H/L ratio is the gross head divided by the horizontal distance between the two reservoirs of a PHES, and it is generally 10/2 for most PHES projects (Ali et al., 2021). A greater H/L ratio suggests more hydraulic losses and higher excavation and building costs, hence landscape topology affects both the economic and technical aspects of PHES projects. A H/L of 10/2 is generally used for most PHES projects (Ali et al., 2021).

Lack of infrastructure support: The nonexistence of transmission lines and access roads creates both technical and financial impediments to the development of PHES. This is because having a road and electrical transmission system nearby is beneficial as it allows for easy access to the materials supply required during the construction and maintenance stages; without this infrastructure, creating new highways would increase the project's initial cost. Again, to transmit power, it must be connected to adjacent transmission lines or a power utility grid. When there is excess electricity in a grid, it can be used to pump water, and when power is needed for load balance, generation can be done by using the stored water. However, the plant in certain instances can be rendered unusable due to a shortage of surplus power, especially if electricity for pumping is available during midnight and early morning (Ali et al., 2021).

Notwithstanding these environmental impacts and concerns, modern PHES projects are being designed and implemented to address these challenges through the use of new approaches and technologies such as the use of off-stream systems, abandoned quarries, and mines, underground reservoirs, and groundwater systems in addition to the proposed use of wastewater for off-stream PHES projects (Yang & Jackson, 2011).

9.6 Market overview and future trends of pumped hydro energy storage

Presently, over 340 PHES projects have been implemented globally and across over 14 countries with China, the United States, and Japan having the largest capacities (Vasudevan, Ramachandaramurthy, Venugopal, Ekanayake, & Tiong, 2021). Though many countries and regions such as the EU, China, and the United States are igniting initiatives toward expanding the PHES capacity, very little can be said about this in the African continent where it appears that only South Africa and Morocco have shown interest in PHES though RE projects on the African continent are continuously increasing. As a result of the growing need to increase the world's energy storage capacity, the PHES market is expected to see a compound annual growth rate of more than 2% from 2020 to 2025 (Modor Intelligence, 2021). In most regions and countries such as China, Asia Pacific, the United States, Australia, and Europe, the drive towards deployment of more PHES is being fueled by governmental policies aimed at minimizing variable renewable energy (VRE) curtailment (IEA, 2021).

9.6.1 Financial and economic assessment indices of pumped hydro energy storage projects

Various financial and economic indices are used in assessing PHES projects and these include the net present cost, net present value, levelized cost of energy or electricity, pay back period, internal rate of return, avoided cost of energy, benefit—cost ratio, etc.

These metrics in most instances determine the viability of any PHES project, especially at the project inception and selection stages where cost-effective tools and techniques are often used in selecting a project from several available alternatives (Gupta, Bhattacharya, Barabady, & Kumar, 2013).

After the selection of an appropriate PHES, several installation cost components will be encountered in the implementation and these include costs related to the following: storage-balance of system, power equipment, controls & communication, Grid Integration, Engineering, Procurement, and Construction (EPC), and Project Development (IRENA, 2020b). There is also the need to take into account the cost associated with the operation and decommissioning of the project.

9.6.2 Pumped hydro energy storage financing models

A detailed overview of factors that influence PHES project financing has been discussed by Head (2008), whereas a PHES project finance structure was also presented by (IHA, 2017b). In summary, a typical PHES project may be financed through any of the following models: EPC, build operate transfer, design-build-operate, finance, engineer, lease, and transfer, and climate financing (Eberhard, Gratwick, Morella, & Antmann, 2016; Marquard & Bahls, 2021; World Bank Group, 2020).

9.7 Key factors for pumped hydro energy storage uptake

Considering some of the constraints and challenges linked to the smooth operation of PHES, certain key factors presented in Fig. 9.3 are required to motivate the deployment of PHES projects, especially in combination with other VRE sources and these include the following:

9.7.1 Investing in public-private research, development and deployment

To fully harness the full potential and benefits associated with PHES combined with VRE and/or batteries, there will be the need for a massive investment of resources into Research, Development and Deployment (RD&D). This initiative will go a long way to minimize the associated project risk in addition to maximizing the investors' confidence in PHES projects. Furthermore, a key ingredient for the success of this initiative will be a well-coordinated partnership between the public and the private sector (IRENA, 2020a).

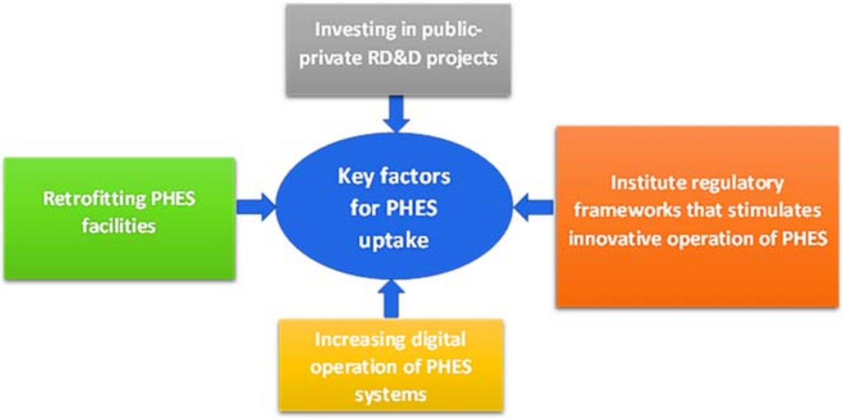


Figure 9.3 Key factors to stimulate pumped hydro energy storage uptake (IRENA, 2020a).

9.7.2 Instituting regulatory frameworks that stimulate innovative operation of pumped hydro energy storage

Since PHES plants are often used to complement VRE as well as other inflexible generation plants, there is the need to ensure the provision of a conducive market and regulatory climate that fosters innovation as well as inverter confidence in supporting and investing in PHES projects. These provisions could be channeled through any of the following means: provision of ancillary services, energy arbitrage, and capacity payments among others (IRENA, 2020a).

9.7.3 Increasing digital operation of pumped hydro energy storage systems

Most innovative and optimization interventions in PHES are being driven by the rapid digitization of the operations of PHES. These digitization breakthroughs include power generation prediction using machine learning, remote equipment, monitoring, predictive maintenance, and smart coupling with batteries or with VRE plants (IHA, 2017a; IRENA, 2020a). Digital operation improves efficiency while reducing operational and maintenance costs since it could incorporate and support activities and applications such as virtual reality training for staff, maintenance robots, remote control maintenance technologies, etc (IRENA, 2020a).

9.7.4 Retrofitting pumped hydro energy storage facilities

One of the main strategies used to enhance system operations and maximize the benefits of PHES is by retrofitting the system with modernized and innovative components. Such state-of-the-art components and interventions may include the use of variable speed turbines to enhance response time and widen the operational range, thus maximizing economic returns. Also, the combination of existing PHES with other VRE systems such as floating PV minimizes capital expenditure costs (IRENA, 2020a).

9.8 Conclusion

The global transition to more RE sources implies that flexible ESS such as PHES is crucial in the energy generation mix to address the intermittent and variable nature of the VRE sources. This flexible energy storage provision offered by PHES occurs at a relatively low cost and within an appreciably longer term compared to other energy storage solutions. Factors that motivate the deployment of PHES projects may include investing in Public-Private RD&D, instituting regulatory frameworks that stimulate innovative operation of PHES, increasing digital operation of PHES systems, and retrofitting PHES facilities. The liberalized market environment has been found to generally provide a congenial atmosphere for the growth of PHES. However, it may reduce the prices of electricity and hence the returns on PHES investment. There is therefore the need for robust, transparent, as well as detailed market regulations, without any ambiguity for the sustainability of a PHES under any market scheme or infrastructure.

References

Abdellatif, D., AbdelHady, R., Ibrahim, A. M., & El-Zahab, E. A. (2018). Conditions for economic competitiveness of pumped storage hydroelectric power plants in Egypt. *Renewables: Wind, Water, and Solar*, *5*(1), 1−14. Available from https://doi.org/10.1186/S40807-018-0048-1.

Abdelshafy, A. M., Jurasz, J., Hassan, H., & Mohamed, A. M. (2020). Optimized energy management strategy for grid connected double storage (pumped storage-battery) system powered by renewable energy resources. *Energy*, *192*. Available from https://doi.org/10.1016/J.ENERGY.2019.116615.

Ali, S., Stewart, R. A., & Sahin, O. (2021). Drivers and barriers to the deployment of pumped hydro energy storage applications: Systematic literature review. *Cleaner Engineering and Technology*, *5*, 2666−7908. Available from https://doi.org/10.1016/j.clet.2021.100281.

Barbour, E., Wilson, I. A. G., Radcliffe, J., Ding, Y., & Li, Y. (2016). A review of pumped hydro energy storage development in significant international electricity markets. *Renewable and Sustainable Energy Reviews*, *61*, 421−432. Available from https://doi.org/10.1016/j.rser.2016.04.019.

Connolly, D., MacLaughlin, S., & Leahy, M. (2010). Development of a computer program to locate potential sites for pumped hydroelectric energy storage. *Energy*, *35*(1), 375−381. Available from https://doi.org/10.1016/J.ENERGY.2009.10.004.

Deane, J. P., Ó Gallachóir, B. P., & McKeogh, E. J. (2010). Techno-economic review of existing and new pumped hydro energy storage plant. *Renewable and Sustainable Energy Reviews*, *14*(4), 1293−1302. Available from https://doi.org/10.1016/j.rser.2009.11.015.

Díaz-González, F., Sumper, A., & Gomis-Bellmunt, O. (2016). *Energy storage in power systems*. John Wiley & Sons Ltd.

Dragoon, K. (2010). *Enhancing wind energy value. Valuing wind generation on integrated power systems*. Elsevier Inc.

Droogers, P., Immerzeel, W. W., Terink, W., Hoogeveen, J., Bierkens, M. F. P., Van Beek, L. P. H., & Debele, B. (2012). Water resources trends in middle East and North Africa towards 2050. *Hydrology and Earth System Sciences*, *16*(9), 3101−3114. Available from https://doi.org/10.5194/HESS-16-3101-2012.

Eberhard, A., Gratwick, K., Morella, E., & Antmann, P. (2016). *Independent power projects in Sub-Saharan Africa—Lessons from five key countries*. <https://www.worldbank.org/en/topic/energy/publication/independent-power-projects-in-sub-saharan-africa>.

Esmaeili Aliabadi, D., Çelebi, E., Elhüseyni, M., & Şahin, G. (2021). *Modeling, simulation, and decision support. Local electricity markets* (pp. 177−197). Academic Press. Available from https://doi.org/10.1016/B978-0-12-820074-2.00017-4.

Ghorbani, N., Makian, H., & Breyer, C. (2019). A GIS-based method to identify potential sites for pumped hydro energy storage—Case of Iran. *Energy*, *169*, 854−867. Available from https://doi.org/10.1016/J.ENERGY.2018.12.073.

Gupta, S., Bhattacharya, J., Barabady, J., & Kumar, U. (2013). Cost-effective importance measure: A new approach for resource prioritization in a production plant. *International Journal of Quality and Reliability Management*, *30*(4), 379−386. Available from https://doi.org/10.1108/02656711311308376.

Head, C. (2008). *The financing package. Hydro Finance Handbook,(prepared by the authors as a companion document for "Hydro Finance Tutorial," Session 1C of the New Development Track of the HydroVision 2008 Conference)*. Kansas City, MO: HCI Publications.

Hino, T., & Lejeune, A. (2012). Pumped storage hydropower developments. *Comprehensive Renewable Energy*, *6*, 405−434. Available from https://doi.org/10.1016/B978-0-08-087872-0.00616-8.

IEA. (2021). Hydropower special market report. In *Hydropower special market report*. Available from https://doi.org/10.1787/07a7bac8-en.

IHA. (2017a). *2017 Key trends in hydropower*. <https://www.hydropower.org/publications/2017-key-trends-in-hydropower>.

IHA. (2017b). Hydropower financing. *Asia clean energy forum deep-dive workshop, 5−8 June*.

IHA. (2020). *2020 Hydropower status report*. <https://www.hydropower.org/publications/2020-hydropower-status-report>.

IRENA. (2012). Renewable energy technologies: Cost analysis series. Hydropower Power Sector. In *Report No. 1(3/5)*. https://www.irena.org/documentdown-%0Aloads/publications/re_technologies_cost_analysis-hydropower.pdf.

IRENA. (2020a). *Innovation landscape brief: Innovative operation of pumped hydropower storage*. <http://www.irena.org>.

IRENA. (2020b). *Renewable power generation costs in 2019*. <https://www.irena.org/publications/2020/Jun/Renewable-Power-Costs-in-2019>.

Javed, M. S., Zhong, D., Ma, T., Song, A., & Ahmed, S. (2020). Hybrid pumped hydro and battery storage for renewable energy based power supply system. *Applied Energy*, *257*, 114026. Available from https://doi.org/10.1016/J.APENERGY.2019.114026.

Kear, G., & Chapman, R. (2013). "Reserving judgement": Perceptions of pumped hydro and utility-scale batteries for electricity storage and reserve generation in New Zealand. *Renewable Energy*, *57*, 249–261. Available from https://doi.org/10.1016/J.RENENE.2013.01.015.

Kocaman, A. S., & Modi, V. (2017). Value of pumped hydro storage in a hybrid energy generation and allocation system. *Applied Energy*, *205*, 1202–1215. Available from https://doi.org/10.1016/J.APENERGY.2017.08.129.

Kusakana, K. (2016). Optimal scheduling for distributed hybrid system with pumped hydro storage. *Energy Conversion and Management*, *111*, 253–260. Available from https://doi.org/10.1016/J.ENCONMAN.2015.12.081.

Lu, B., Stocks, M., Blakers, A., & Anderson, K. (2018). Geographic information system algorithms to locate prospective sites for pumped hydro energy storage. *Applied Energy*, *222*, 300–312. Available from https://doi.org/10.1016/J.APENERGY.2018.03.177.

Marquard & Bahls AG. (2021). *EPC (Engineering, procurement and construction)*.

Ming, Z., Junjie, F., Song, X., Zhijie, W., Xiaoli, Z., & Yuejin, W. (2013). Development of China's pumped storage plant and related policy analysis. *Energy Policy*, *61*, 104–113. Available from https://doi.org/10.1016/J.ENPOL.2013.06.061.

Modor Intelligence. (2021). *Pumped hydro storage market | 2022–27 | Industry share, size, growth—Mordor intelligence*. <https://www.mordorintelligence.com/industry-reports/pumped-hydro-storage-market>.

Munthali, K. G., Irvine, B. J., & Murayama, Y. (2011). Reservoir sedimentation and flood control: Using a geographical information system to estimate sediment yield of the Songwe River watershed in Malawi. *Sustainability*, *3*(1), 254–269. Available from https://doi.org/10.3390/SU3010254.

Nzotcha, U., Kenfack, J., & Blanche Manjia, M. (2019). Integrated multi-criteria decision making methodology for pumped hydro-energy storage plant site selection from a sustainable development perspective with an application. *Renewable and Sustainable Energy Reviews*, *112*, 930–947. Available from https://doi.org/10.1016/J.RSER.2019.06.035.

Pali, B. S., & Vadhera, S. (2018). A novel pumped hydro-energy storage scheme with wind energy for power generation at constant voltage in rural areas. *Renewable Energy*, *127*, 802–810. Available from https://doi.org/10.1016/J.RENENE.2018.05.028.

Ram, M., Child, M., Aghahosseini, A., Bogdanov, D., Lohrmann, A., & Breyer, C. (2018). A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015–2030. *Journal of Cleaner Production*, *199*, 687–704. Available from https://doi.org/10.1016/J.JCLEPRO.2018.07.159.

Šćekić, L., Mujović, S., & Radulović, V. (2020). Pumped hydroelectric energy storage as a facilitator of renewable energy in liberalized electricity market. *Energies*, *13*(22), 6076. Available from https://doi.org/10.3390/EN13226076.

Segurado, R., Madeira, J. F. A., Costa, M., Duić, N., & Carvalho, M. G. (2016). Optimization of a wind powered desalination and pumped hydro storage system. *Applied Energy*, *177*, 487–499. Available from https://doi.org/10.1016/J.APENERGY.2016.05.125.

Shen, D., & Yang, Q. (2012). Electricity market regulatory reform and competition—Case study of the New Zealand electricity market. In Y. Wu, X. Shi, & F. Kimura (Eds.), Energy market integration in East Asia: Theories, electricity sector and subsidies

(Issue August (pp. 103−139). Jakarta: ERIA. Available from http://www.eria.org/Chapter6-Electricity, Market Regulatory Reform and Competition-Case Study of the New Zealand Electricity Market.pdf.
Vasudevan, K. R., Ramachandaramurthy, V. K., Venugopal, G., Ekanayake, J. B., & Tiong, S. K. (2021). Variable speed pumped hydro storage: A review of converters, controls and energy management strategies. *Renewable and Sustainable Energy Reviews*, *135*, 110156. Available from https://doi.org/10.1016/J.RSER.2020.110156.
World Bank Group. (2020). *Concessions build-operate-transfer (BOT) and design-build- operate (DBO) projects*.
Yang, C. J., & Jackson, R. B. (2011). Opportunities and barriers to pumped-hydro energy storage in the United States. *Renewable and Sustainable Energy Reviews*, *15*(1), 839−844. Available from https://doi.org/10.1016/J.RSER.2010.09.020.