The world's water battery:

Pumped hydropower storage and the clean energy transition

IHA working paper

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Key messages and findings

- Pumped hydropower storage (PHS), the world's 'water battery', accounts for over 94 per cent of installed global energy storage capacity and retains several advantages such as lifetime cost, levels of sustainability and scale. The existing 161,000 megawatts (MW) of pumped storage capacity supports power grid stability, reducing overall system costs and sector emissions.

- A bottom up analysis of energy stored in the world's pumped storage reservoirs using IHA's stations database estimates total storage to be up to 9,000 gigawatt hours (GWh).

- PHS operations and technology are adapting to the changing power system requirements incurred by variable renewable energy (VRE) sources. Variable-speed and ternary PHS systems allow for faster and wider operating ranges, providing additional flexibility at all timescales, enabling higher penetrations of VRE at lower system costs.

- As traditional revenue streams become more unpredictable and markets are slow to appropriately reward flexibility, PHS needs to secure new sources of reliable and long term revenue in order to attract investment, particularly in liberalised energy markets.

- Driven by the increasing penetration of wind and solar, reduced dispatchable generation and the need for greater grid flexibility, an additional 78,000 MW or an increase of nearly 50 per cent of PHS capacity is expected to be commissioned by 2030. This could further increase with the right policy settings and market rules.

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About IHA

The International Hydropower Association (IHA) is a non-profit organisation that works with a vibrant network of members and partners active in more than 100 countries. Our mission is to advance sustainable hydropower by building and sharing knowledge on its role in renewable energy systems, responsible freshwater management and climate change solutions.

Formed under the auspices of UNESCO in 1995 as a forum to promote and disseminate good practice and further knowledge about hydropower, today IHA has a Central Office based in London and representative offices in South America and China. In addition, IHA has consultative and/or observer status with all United Nations agencies addressing water, energy and climate change.

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Cover photo: Guangzhou pumped storage plant, China. Credit: Voith.

Introduction

Energy storage will be a key component in accelerating global efforts to meet the ambitious climate mitigation and sustainable development goals set in 2015 in Paris and New York, respectively. In its recently published special report on the impacts of global warming of 1.5°C, the Intergovernmental Panel on Climate Change stated that reducing emissions to meet a 1.5°C limit will require "rapid and far-reaching transitions" across the global economy.[1] Many pathways exist to meeting this goal but they all share certain features: emissions falling to zero with renewables meeting the majority of future electricity supply, including the electrification of multiple energy end-use sectors. The report also emphasises grid flexibility resources such as storage as essential enablers for accelerated renewables development.

Energy storage in the form of pumped hydropower storage, the world's 'water battery', has provided flexible power services to grids since the beginning of the 20th century. Currently accounting for over 94 per cent of installed global energy storage capacity, and over 99 per cent in terms of energy stored, PHS has been used as a means of load-shifting and balancing inflexible sources of power generation.[2]

Last year witnessed the largest single-year growth in renewable power generating capacity, where wind and solar photovoltaic (PV) made up nearly 60 per cent of net additions to global power capacity, highlighting that a global transformation of energy systems is underway.[3] Wind and solar PV technologies have experienced rapid cost reductions and are now competitive with thermal power sources on the basis of generation cost per kilowatt hour (kWh) in a growing number of markets. The success of these technologies, supported by government policies, is driving changes to power systems worldwide and poses a variety of technical, regulatory and market challenges.

PHS succeeds in balancing the variable nature of wind and solar by providing reliable energy in bulk and on demand for sustained periods, while also avoiding the need for their curtailment during periods of excess supply, which further supports their increased deployment. As VRE sources continue to displace dispatchable fossil generation, power system flexibility becomes a crucial tool to prevent both interruptions to end-users and extreme levels of price volatility.

This working paper, prepared with assistance from IHA's members, is intended to help stimulate timely discussion among policy makers and energy system stakeholders about the increasingly important role of PHS in the clean energy transition. While much attention has been directed to new technologies such as battery storage in recent years, PHS is expected to grow in many parts of the world with up to 78,000 MW of additional capacity to be commissioned by 2030.

This paper provides an assessment of PHS's current status, highlighting its unique attributes, including technological and operational innovations that contribute to power system flexibility and how it can work in concert with other flexibility options such as batteries or long-distance interconnections. A description of the disruption to power systems incurred by higher penetrations of VRE is juxtaposed with how PHS technology and operations are adjusting to continue to support the clean energy transition.

While we are witnessing renewed interest and growth in PHS development, this paper also briefly examines its business model and the challenges faced. It pays particular attention to liberalised markets where traditional revenue streams are becoming more unpredictable and opportunities to provide more stable revenue are slow to materialise.

Finally, the paper outlines a number of policy areas or knowledge gaps which would benefit from further investigation, led by IHA and its members, to advance the role of PHS in clean energy systems.

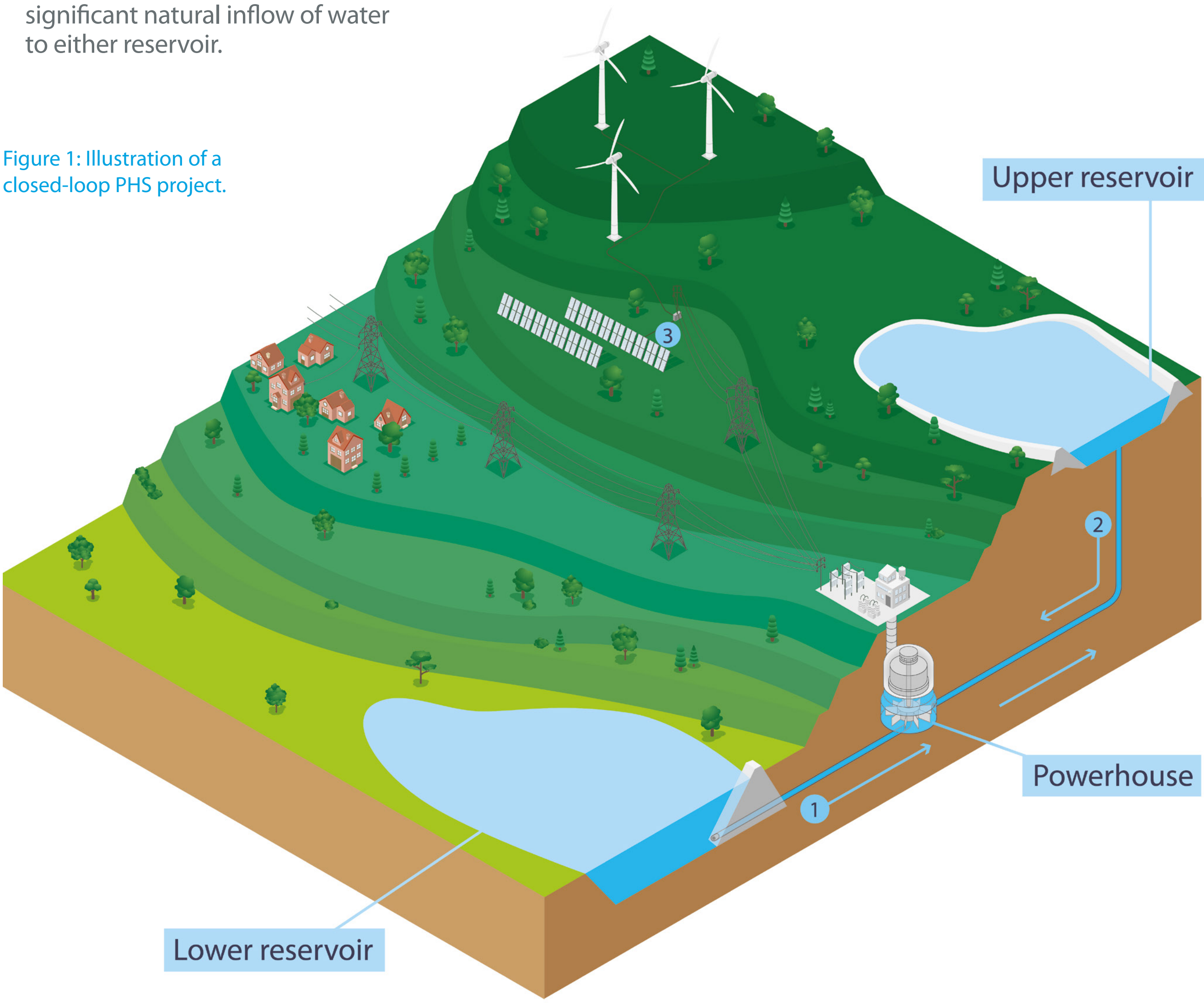
Defining pumped hydropower storage

A pumped hydropower storage project is a hydroelectric development that generates electric energy by using water that has previously been pumped from a lower source to an upper reservoir. There are two principal categories of pumped storage projects:

- **Closed-loop:** these projects produce power only from water that has been previously pumped to an upper reservoir. There is no significant natural inflow of water to either reservoir.
- **Open-loop:** these projects have either an upper or lower reservoir that is continuously connected to a naturally flowing water feature. Some open-loop projects can have significant natural inflows to the upper reservoir, meaning that electricity may be generated without the requirement for pumping, as in a storage hydropower facility without pumping ability.

The power generated by a PHS project is linked to the turbine size and the energy storage capacity depends on the size of the reservoir. For example, with two Olympic swimming pools and a 500 metre height difference between them, a capacity of 3 MW storing up to 3.5 megawatt hours (MWh) can be provided.

Figure 1: Illustration of a closed-loop PHS project.



1. During periods of low demand reflected by lower prices, renewable energy such as wind and solar is used to pump water uphill.
2. When demand increases, water from the upper reservoir runs downhill through the turbines to produce electricity.
3. Pumped storage combined with variable renewable energy can provide reliable, dispatchable and low carbon electricity to domestic and industrial consumers.

Brief history of pumped hydropower storage

Pumped hydropower storage technology was first developed at the turn of the 20th century, however, the planning and construction of PHS projects began in earnest after the end of the Second World War. Significant post-war population increases and rapid economic growth reshaped demand curves by increasing the peak-to-baseload ratio and creating more distinct seasonal peaks. PHS also became increasingly attractive as part of multipurpose projects, where it enhanced the economics of each objective. For example, the Lewiston project on the border between the USA and Canada guarantees minimum daytime flows over the Niagara Falls during the tourist season.

By the 1960s, most new thermal generators coming online were large-capacity, high temperature and high pressure units, with little prospect for significant improvements in efficiency. These generators were best suited for constant high output in order to reduce equipment stress and maintenance costs while optimising operating efficiencies. PHS plants were ideally placed to absorb surplus power and generate peaking capacity and were almost exclusively built by state-owned utilities. Many of these projects were also designed to offer water management co-benefits, with PHS in California and later South Africa being used for significant water transfer and supply schemes to major demand centres. At this time the operation of most PHS was relatively simple: surplus night-time power was used to pump water to elevation and stored for release and generation during peak demand hours during the daytime.

The majority of PHS projects were built between the 1960s and 1980s, driven by energy security concerns and nuclear energy development after the oil crises in the 1970s. Fewer projects, especially in the more mature markets of Europe, Japan and the USA, were developed in the 1990s; the main reason for the reduction was a result of energy market deregulation and a decline in nuclear growth. However, there were some exceptions. Austria, with no nuclear generation but a rich hydropower resource, developed PHS to enhance the operation and efficiency of its large-scale hydropower fleet and balancing services to neighbouring grids Meanwhile, Norwegian PHS was developed for seasonal balancing i.e. pumping in summer during snow-melt driven flows and generating in winter.

Since the turn of the century, there has been a renewed interest in PHS in a number of countries, most notably China, but also in Europe and virgin markets. As VRE sources increasingly penetrate grids, PHS is viewed as a key renewable integration tool. At the end of 2017, the global installed capacity stood at 161,000 MW.[4] China has contributed to much of the recent growth, having added nearly 15,000 MW of capacity since 2010, driven by ambitious government targets for renewables (see Figure 2).

IHA estimates the total energy stored within the world's PHS projects to be up to 9,000 GWh.[5] This is the result of a bottom-up analysis using IHA's global hydropower database and is similar to Uruguay's total annual electricity consumption.[6] In comparison, the total energy stored within utility scale batteries is estimated at just 7 GWh.[7]

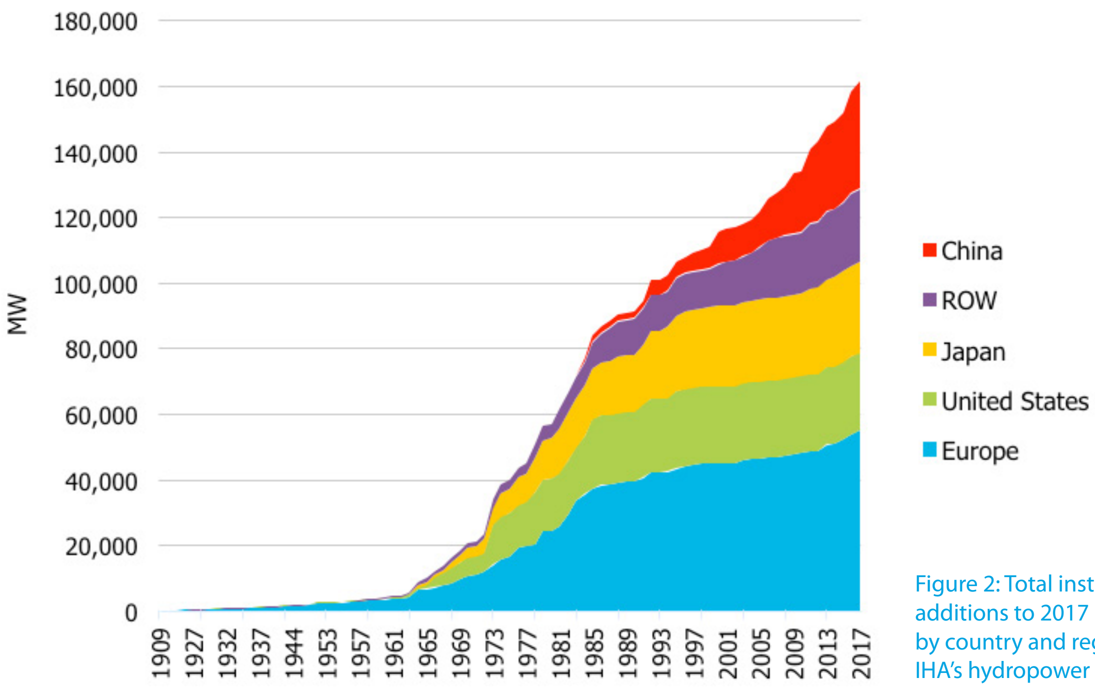


Figure 2: Total installed capacity additions to 2017 broken down by country and region. Source: IHA's hydropower database.

Pumped hydropower's changing role in an evolving electricity market

The success of VRE sources is driving change in power systems around the world. At low levels of VRE penetration, fluctuations in supply can be managed with low impact and existing conventional generators are able to provide the necessary system balancing services. However, as VRE continues to grow and, in some systems, begins to displace conventional generators, system operators are faced with the challenge of effectively managing increasing uncertainty and variability. As a result, power system planning and operations are being adapted and upgraded to add 'flexibility' to the system.

Flexibility is one of the terms used to refer to a power system's capability to maintain uninterrupted service when encountering often large and rapid swings in supply or demand, whatever the cause. Flexibility in electricity systems can be provided by four main pillars:

- Flexible power supply - such as gas turbines and hydropower that are capable of rapid start-ups and dispatching adjustable output;
- Flexible power demand - where consumers are incentivised to adjust their demand according to system requirements such as demand-side response;
- Interconnections to adjacent power systems - essentially expanding the area over which supply and demand can be balanced, while linking distant flexible generators; and
- Energy storage - to balance supply and demand.

These flexibility tools can protect the security of the electricity grid by ensuring that demand is always met.

Conventional hydropower has traditionally provided flexible power generation as well as the overwhelming majority of large-scale energy storage by storing water in reservoirs. Hydropower facilities that incorporate reservoirs (without pumping capability) have always provided significant flexibility to the power grid by modulating output in line with fluctuations in demand and other generation. When output is reduced to accommodate surplus VRE, a hydropower reservoir functions as virtual storage as natural water flows into the reservoir raise its energy potential in proportion to reduced output. Overall, hydropower has a great potential for providing flexibility, with rapid ramping potential and very low minimum operating levels.

PHS has the additional ability to absorb surplus power. While PHS was initially developed to balance inflexible baseload thermal generation starting in the 1960s, PHS technology and operations are adapting to the evolving energy system, offering a wider range of balancing and ancillary services with occasional co-benefits for other flexibility solutions (see page 8).

Variable speed pump-turbines and ternary systems offer additional network flexibility by enabling power regulation and load following when pumping as opposed to more conventional fixed-speed units, which operate at a constant speed and input power for pumping. The advantage of variable speed over fixed speed pump-turbines is that variable speed PHS projects can operate at a wider range, higher efficiency and quicker response time. Moreover, variable speed PHS can also adjust their power consumption while pumping, allowing for improved frequency control.

Variable speed pump-turbines have been in use since the early 1990s in Japan, where they were implemented to reduce fossil-fuel consumption by shifting the responsibility for frequency regulation to pumped storage facilities.[8] Variable speed pump-turbines are well suited to the integration of VRE into systems, but do not necessarily supplant fixed-speed turbines, as both types offer unique grid services.

Ternary pumped storage machines are a unit configuration where pumps and turbines are separate machines connected to the same shaft. This means that these units do not need to reverse their rotational direction to switch between pumping and generation, which allows for the turbine and pump to operate in parallel, also known as a 'hydraulic short-circuit.' This offers quicker response times and additional flexible operations in terms of faster mode times i.e. the time it takes to switch from pumping to generating modes.[9] Operating under hydraulic short-circuits can also be possible with both variable and fixed-speed reversible pump-turbines and essentially reduces the time necessary to bring the system back to optimal frequency.[10]

Power system flexibility has always been a necessity even before the rise of VRE; however, before low-cost VRE, the main sources of variability were changes in demand patterns and unexpected failures by generators or Transmission & Distribution (T&D) infrastructure. Dispatchable and synchronous generation were traditionally the dominant sources of flexibility. As the transformation of power systems progresses, centralised thermal synchronous generators are being displaced by asynchronous VRE sources, putting a heightened focus on power system flexibility. A lack of flexibility can reduce the resilience of power systems or lead to significant losses of clean electricity via curtailments.

Electricity systems are complex and the dynamics between the various components vary in time, from microseconds to inter-annual variability in rainfall. There are different sources of variability that affect the supply/demand balance and, appropriately, different options to cope with the imbalances.

Traditionally, when balancing inflexible thermal generation, PHS projects followed a simple diurnal cycle that involved pumping at night and generating during peak daytime hours. With increasing shares of solar PV, daytime peak demand is depressed, which shifts the peaking requirements towards the 'duck-neck', (i.e. in the early morning, before solar has ramped up and early evening as solar PV is ramping down). On top of this phenomenon, short-term variability e.g. from gusts of wind or passing clouds, increase the need for flexible ancillary services. As a result, many PHS projects constructed 30-40 years ago have adjusted their operations accordingly, exhibiting more cycles, with shorter operating times but higher and more intensive ramps.

Ensuring reliable, stable and constant power grid operation requires maintaining a narrow band of alternating current frequency. In traditional centralised power systems grid frequency was supplied by the synchronised rotation of thermal and hydroelectric turbines. Grid system frequency is a continuously changing variable that is governed by the real-time balance between supply and demand, that is, if demand exceeds supply, frequency falls and vice-versa.

With respect to very short timescales, an important property of VRE sources is the manner in which they connect to the grid. Whereas synchronous generators are directly and electromechanically coupled to the power grid, modern VRE sources use software-controlled power electronics to connect to the grid. VRE sources are generally deployed asynchronously, and their displacement of synchronous generators can have an impact on the very short-term (sub-second) stability of the grid. Synchronous generators, by virtue of their physical spinning mass, provide a natural mechanical inertia that resists sudden changes to the grid. Thus, systems with less inertia will exhibit faster rates of frequency change during a perturbation.[11] Fixed-speed and ternary PHS units provide mechanical inertial response directly through their rotating generators.

The short timescale, from milliseconds to minutes, includes the actions that are required to compensate for a system imbalance and to return the grid frequency and voltage to its optimal range. This can include automated responses at the individual turbine scale, but also include active responses by rapidly dispatchable and adjustable generators. Variable-speed and ternary units offer faster and wider ranges of response in both generating and pumping mode and contribute to better frequency regulation.

The medium scale ranges from hours to days and refers to the ability to use alternative modes of production to respond to a transient shock such as the unexpected outage of a generator. It is often referred to as peaking support or system reserves. Reserve is called upon after automatic frequency response has been used, and covers unexpected losses or forecasting errors on the system. This timescale is often dependent on the technical availability and redundancy of alternative options, as well as having the relevant market conditions in place. PHS systems tend to hold large volumes of water and have very high energy-to-power ratios and are thus also well suited to provide long-term services.

Frades II (780 MW), a Portuguese pumped storage project commissioned in 2017, installed variable speed turbines to provide dynamic grid support for Portugal's high injection of wind power (accounting for around 20 per cent of the country's electricity generation). Credit: Voith.

The long timescale extends from days to weeks and is driven primarily by weather system patterns. For example, this includes week-long periods of low-wind or weather-driven heating or cooling demands.

Finally, the very long timescale encompasses intra- and inter-seasonal variability in both energy demand and resource availability. VRE sources, and also hydropower, exhibit strong seasonal patterns that can result in a mismatch with demand. The challenge then is to schedule energy resources that can cope with long term variability, such as during protracted low-wind periods, long-term drought or simply seasonal dry and wet periods. Both VRE and hydropower can also have significant inter-annual variations, for example as a result of the El Niño phenomenon. Seasonal pumped storage has been proposed in Brazil to balance seasonal variations and to increase total storage efficiency by coupling with conventional cascade systems. In cases where seasonal pumped storage projects decrease spillage or evaporation in cascade systems, it may result in an overall energy gain rather than loss to the system.[12,13]

Apart from the technical aspects, the increasing penetration of VRE in power systems also has the potential to significantly affect spot-market prices and hourly price profiles, which can reduce opportunities for PHS assets to access their traditional energy arbitrage based revenue stream. PHS owners are thus looking for additional revenue sources, often by employing the technical and operational adjustments described above, which is further explored in the 'Challenges and emerging opportunities of PHS financing' section.

The mutual benefits of PHS and interconnectors

High voltage (HV) interconnectors and transmission lines can link together separate grid networks and connect clean energy resources in remote locations to distant markets. However, operating high capacity and cross-regional power lines can be challenging. For example, variable renewable power flows can affect power quality and transfer efficiency across the line. Furthermore, sudden changes on one side of the interconnector can propagate network problems and fault risk to the other side. PHS stations located nearby interconnectors can provide an effective means of mitigating these risks and manage technical conditions across the lines. The following case studies give some examples:

Kruonis, Lithuania: In 2016, the high voltage direct current (HVDC) NordBalt interconnector was commissioned, connecting Lithuania to Sweden through a submarine cable link.[14] Cable malfunctions occurred a number of times during 2017 and 2018, causing NordBalt to disconnect, which, if importing, takes up to 700 MW of supply off Lithuania's system. Lithuania's Kruonis PHS station has provided critical back-up during these events, with its quick response and reserves to cover demand and stabilise the network.[15] There are also possible plans to install a fifth generating unit at the Kruonis site, which would make the local grid even more robust and further support progress towards synchronising the Baltic and Continental European grids (via Lithuanian-Poland AC grid links).[16,17]

Tasmania, Australia: Tasmania is an island state just south of the Australian mainland, with rich hydropower resources and significant PHS development opportunities to further benefit the national market. The island is currently connected to the mainland via the HVDC Basslink interconnector, which already provides back-up imports, as well as export options for Tasmanian hydropower.[18] Under the 'Battery of the Nation' initiative, Hydro Tasmania has shown that with increased interconnection capacity, new pumped hydropower sites totalling 2,500 MW could be developed, more than doubling the existing traditional hydropower capacity and providing extremely competitive firming capacity for Australia's National Electricity Market (NEM).[19] In addition, the initiative would create billions of dollars of investment and thousands of jobs across the state.

How PHS compares to and complements battery storage

PHS represents over 94 per cent of global electricity storage by capacity, however there are a range of other technologies on the market at various stages of development. Most notable is Lithium-ion (Li-ion) battery storage which continues to gain the lion's share of publicity following the commissioning of the world's biggest battery, the 100 MW project in South Australia last year. While innovation is seeing marked improvements in performance and costs of Li-ion battery storage, PHS retains several distinct advantages.

PHS stands out in the wide range of power (MW) and energy (MWh) capacity offered by existing facilities across the world. Large utility-scale PHS projects benefit from the high energy-to-power ratios i.e. from the huge volumes of energy that can be stored in raised reservoirs and released through powerful turbines, with the largest facility, Bath County (closed-loop) in the USA, sized at 3,060 MW / 24,000 MWh. Current open-loop systems can also go beyond 100 GWh in energy stored such as the Vilarinho das Furnas project in Portugal.[20,21] The 3,600 MW Fengning pumped storage project under construction in China will be the largest in the world once completed in 2025. Li-ion batteries and other rapid response systems are traditionally suited to smaller scale localised grids in the kW to MW range.

In terms of discharge time, referring to how long power output can be maintained while releasing stored energy, PHS projects can typically generate for up to 12 hours (or more in some cases) if the plant is being charged and discharged over a 24 hour period for example (diurnal cycling).[22] In comparison, batteries typically provide short duration storage, meaning charge and discharge cycling over small timescales rather than extended periods. For example, the 100 MW Li-ion project in South Australia can store 129 MWh of energy so, if used at full capacity, it would only be able to provide output for little more than an hour.

While PHS projects can take several years from construction commencing to commissioning, they last the longest in terms of project lifetimes of all storage technologies, from 60 to 100 years. For example, the 360 MW Ffestiniog pumped storage project in the UK was commissioned in 1963 and is moving ahead with major refurbishment of two of its four generating units in 2018, which will extend their operational life for at least a further 20 years. In addition, the 324 MW Cabin Creek project in the USA, originally commissioned in 1967, has recently launched the refurbishment of its two units, extending the project's flexibility and output thanks to the new design of the turbines. Even if the construction of a battery system is much quicker, a limitation of batteries is that they degrade quickly (their round-trip efficiency can fall from 85 per cent to below 70 per cent), with a lifetime of up to 10 years depending on the conditions of operation such as cycling frequency, depth of discharge and temperature.[23,24]

On both a capital cost per unit of energy storage (kWh) and a levelised cost of storage basis, PHS remains one of the most competitive energy storage options thanks to its economies of scale and long lifetime. According to Lazard, on a capital cost basis per kilowatt hour PHS can fall in the range of USD 200 to USD 300, while on the same basis the value range of Li-ion batteries is USD 400 to USD 900.[25] On a levelised basis, PHS is between USD 150 and USD 200 per MWh, while using the same methodology, Li-ion batteries range from USD 250 to USD 550 per MWh.[26] This reflects, for example, that batteries have a much shorter life and the need for regular replacement. In addition, given the ability of PHS to store days and potentially weeks of available storage at very low costs, even with the potential for further battery cost reductions, PHS will remain by far the most cost-effective solution for large quantity and duration of stored energy.

There are various methodologies and assumptions required when calculating levelised cost. For example, the referenced methodology assumes one charge/discharge storage cycle per day which will not always be the case, especially for batteries. Another approach can be to analyse the levelised cost of storage in system-scale models, which consider how much energy should be stored across the grid in different scenarios.

With respect to the sustainability of both technologies, there are many variables to consider. For PHS it is often a site-specific proposition while batteries can be modularly deployed close to the demand or generation centre. Many of the environmental impacts of constructing and operating a PHS facility can be mitigated, although they have associated cost implications. Utilising existing reservoirs or using off-river closed-loop systems can further reduce impacts, as can employing other innovative configurations including using oceans/seawater as the lower reservoir or underground reservoirs.[27] Detailed and comprehensive lifecycle analysis of battery storage is still in its early stages, but recent research indicates that the global warming potential of battery storage over a lifetime of 100 years could be twice that of PHS.[28] Much of this is down to the emissions associated with the large quantities of raw materials such as lithium, graphite, cobalt and nickel (i.e. mining, refining and manufacturing) needed due to the technology's capacity deterioration and relative short lifetime.

Theoretically, both PHS and battery storage can provide similar balancing and ancillary services, but ultimately due to their technical characteristics they are deployed and used differently. PHS's advantage is in cost-effectively storing and releasing large amounts of energy, while batteries are more suited to short-term incremental balancing due to their ability to dispatch stored energy in milliseconds. This highlights their complementarity and both technologies will have a part to play with increasing demand for electricity and achieving the best solution for a system will depend on its particular circumstances.

Coupling PHS plants with batteries is also a future avenue of potential growth. Multi-national utility, Engie, unveiled a combined project earlier this year in Bavaria, Germany.[29] As part of upgrading one of its existing PHS facilities, which already plays a significant role in grid-balancing, Engie commissioned a 12.5 MW Li-ion storage facility to utilise its short reaction time to further aid the integration of VRE in the country.

Challenges and emerging opportunities of PHS financing

Much like the development of conventional hydropower, securing favourable financing arrangements for PHS is a challenging and complex task, which needs to be specifically tailored for each project. While a mature and proven technology, projects face a long gestation and payback period with high upfront capital costs. Specific to PHS though, it can be difficult to accurately forecast revenues derived from energy arbitrage and a lot of the ancillary services provided are still not adequately remunerated, if at all, in many markets. This can restrict the ability of developers to secure additional revenue streams.

The vast majority of PHS projects currently in operation were commissioned and financed under public ownership, often by vertically integrated utilities that enjoyed a monopoly status due to owning and operating all the generation, transmission and distribution assets.[30] Under such market conditions, vertically integrated utilities have been able to benefit from both the project's generating ability and their ancillary services through improved efficiency and avoided costs to other parts of their business, notably their transmission and distribution operations. Many of the projects under development today are still being carried out under similar market structures which points to deficiencies in how liberalised markets are incentivising development and rewarding their services. The failure to provide the required certainty and clarity in policies and regulations in markets can increase borrowing costs and deter investment in new projects.

There are considered to be three broad classes of revenue models for PHS projects: 'cost-of-service', 'direct participation' and 'behind-the-meter'.[31] In some circumstances, a mixture of models can be employed to optimise revenue streams.

Cost-of-service is a model where a facility is compensated via a regulated arrangement, whereby it is able to recoup its operating cost plus an agreed rate of return on its capital costs. This is commonly used by monopoly operators overseen by a state regulator. Variations of the model are used in China as payment or tariff mechanisms for PHS facilities (the majority owned by transmission and distribution companies) which reflect their value across the power system. In unbundled liberalised markets, regulators have tended to restrict bulk energy storage facilities such as PHS from benefiting from this model for fear that they would also seek revenue from the competitive part of the market and therefore gain an unfair advantage.

Direct-participation is the competitive part of a liberalised market in which PHS operators compete with other market participants. Revenue can be generated in several ways specific to each market and they often need to be combined, known as 'revenue stacking', to make a project financially viable. However, this can be challenging due to the differing operating demands required for each revenue stream.

- Energy arbitrage: daily arbitrage is the main source of revenue for many PHS projects and involves using electricity to pump water during periods of low demand and off-peak prices and generating when there is high demand into the spot market reflected by higher peak prices (i.e. shortage in supply to meet demand). The spread or difference in price between pumping and generating also needs to take into consideration the project's round-trip efficiency and other costs such as grid charges.

Forecasting revenue for arbitrage can be particularly difficult given the lifespan of projects. It requires detailed modelling which needs to try to account for potential changes in market dynamics and the regulatory environment, all of which impact market prices. For example, Germany's renewable energy policies have brought online large amounts of subsidised solar and wind, which has significantly reduced price differentials.[32] In turn, this has negatively affected the profitability of existing plants and reportedly diminished the prospects of new investments. PHS developers must also assess to what extent their own project will smooth prices and therefore impact their revenue derived from arbitrage. In today's markets, energy arbitrage alone is generally considered to be insufficient to warrant investment.

- Long-term contracted revenue: developers enter into Power Purchase Agreements (PPAs) or similar contracted arrangements with credit worthy off-takers (i.e. energy retailers, industrial customers or governments) and the nature of such agreements can determine the operating model of the facility.

  For example, a project could act as an insurance product (known as 'cap contracts') for off-takers to guard against high price events.[33] An extension of this is the capacity market mechanism which is designed to ensure sufficient and reliable supply is available across an entire market by providing payments (whether or not they are dispatched) to encourage investment in new capacity or for existing capacity to remain operational. Several governments around the world, including the United Kingdom, have established this mechanism resulting in mixed success for PHS due to the policy's preference for less-capital intensive projects and its inability to provide sufficiently long contracts. Capacity markets can also minimise energy price volatility which further reduces the ability of PHS to profit from arbitrage.[34] Finally, innovative new products in some markets are seeing flexible technologies generate revenue for their firming function. These 'firming products' could involve wind or solar generators purchasing the dispatch rights to a PHS facility to firm up their supply in order to always meet their contracted obligations such as through PPAs. There are many variations on this that are also possible.[35,36]

  Securing such arrangements can allow projects to be bankable with project finance (a non-recourse or limited recourse financing structure), thus satisfying lending requirements provided they deliver stable, long-term cash flows.

- Ancillary services: these non-energy services such as frequency control and system restart can be provided and contracted to system operators, commonly via a tendering process. While some electricity markets around the world are offering opportunities for these services due to the need to integrate increasing VRE, for certain services such as inertia their true monetary value and contribution to the system is not yet fully understood and rewarded. Inertia will be vital for grid stability into the future as the share of coal and gas-fired generation decreases in a number of markets as they have traditionally provided this service for free. It should be noted though that as greater PHS and other forms of flexibility enter the grid, all offering similar ancillary services, it's expected that competition in this market will drive down prices.

Behind-the-meter generation is when a project is located on the generator's, consumer's or end user's side of the electricity meter and is undertaken for a variety of reasons e.g. to improve their supply reliability and to avoid peak electricity prices and grid charges. A hybrid model can involve the PHS facility being used for internal purposes while also offering services into the competitive electricity market to improve its viability.

The proposed 250 MW Kidston PHS project in north Queensland, Australia, is looking to employ a similar model as it will be co-located with a 270 MW solar PV installation.[37] Considered a world-leading integrated solar pumped hydropower project, the developer Genex Power is to utilise two abandoned gold mines as the upper and lower reservoirs, which will provide energy storage of up to 2,000 MWh (250 MW of peaking power generation over an 8-hour period). The closed-loop system will benefit from being able to use the electricity generated by the nearby solar project to pump water uphill during the day before dispatching firm and flexible energy at periods of peak demand such as in the evening.

Pumped hydropower storage and the green bond market

The Climate Bonds Initiative (CBI), a not-for-profit organisation which develops certification standards for green bond issuances, is soon to publish its proposed hydropower criteria that will include PHS.[38]

In 2017, over USD 160bn of labelled green bonds were issued, nearly doubling the previous year. Expectations are that 2018 could see issuances up to USD 200bn.[39] Green bonds fund projects that have positive environmental and climate benefits and the market has experienced significant growth since the first bond was issued in 2007. Until now, however, a lack of clarity over eligibility for hydropower, particularly PHS, has meant that many green bond issuers have either excluded the technology or limited investments to small-scale projects.

The proposed criteria recognises PHS projects as key supporting infrastructure for the deployment of VRE sources and vital for grid stability. The green bond market could prove to be an important source of financing and re-financing, providing developers with a diversified investor base. The criteria are expected to be available for market use in the first half of 2019.

Global growth projections

Looking forward to 2030, PHS installed capacity is expected to increase by some 78,000 MW, with much of the expansion still taking place in China (up to 50,000 MW, see Figure 3).[40] The main driver for PHS expansion in China is the increased need for system flexibility, particularly the need to reduce wind and solar PV curtailment. Regulatory changes in 2015 have placed the responsibility for PHS under the transmission operators rather than with generating companies. As such, PHS growth will be overseen by China's two major grid companies, State Grid Corporation of China and China Southern Grid.

In Europe, PHS capacity is expected to grow modestly, between 8,000-11,000 MW by 2030, driven by the need for increased flexibility due to VRE growth. In many regions, however, barriers to PHS growth are the uncertain revenue streams, as the long-term business case for energy arbitrage remains challenging and alternative revenue streams from capacity, balancing and ancillary service markets develop slowly. Most additions in Europe are expected in Switzerland, Austria, UK, Portugal and France, while some prospective projects in Romania, Ireland and Ukraine may also go ahead.

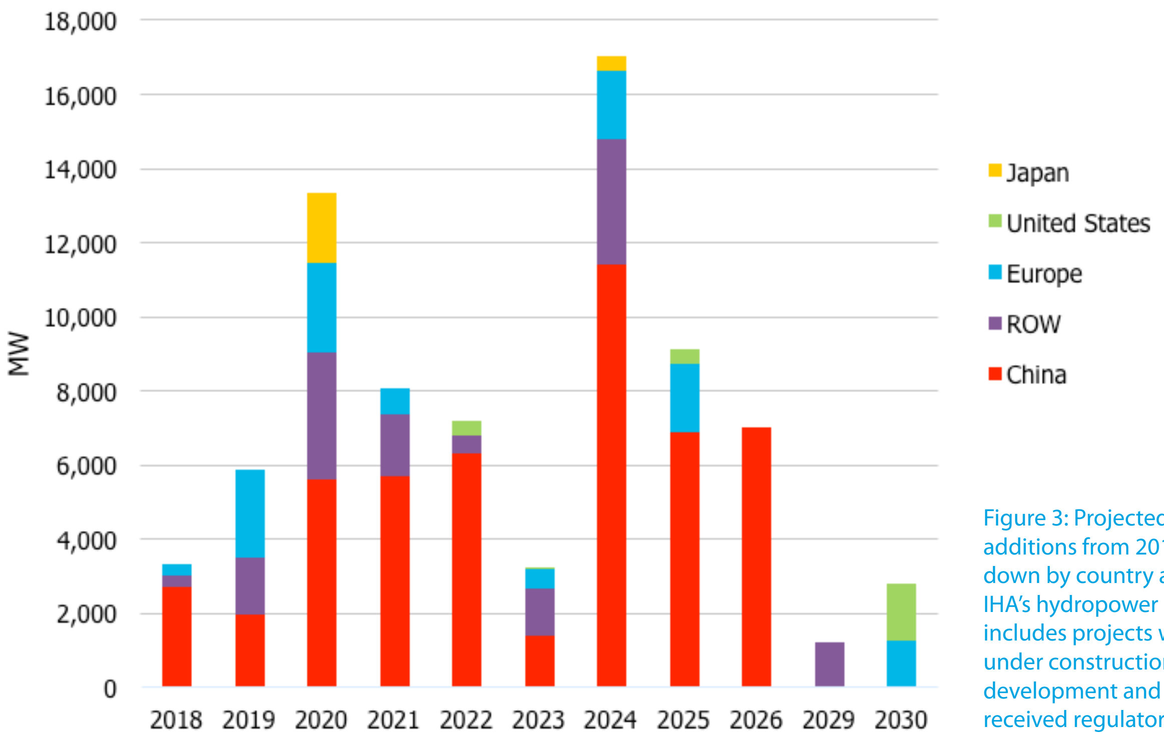


Figure 3: Projected installed capacity additions from 2018 to 2030 broken down by country and region. Source: IHA's hydropower database and includes projects which are either under construction or planned for development and have sought or received regulatory approval.

Outside China and Europe, the majority of PHS additions are expected to occur in the Asia-Pacific region, with some notable additions in non-traditional PHS markets in the Middle East. India, Indonesia, the Philippines and Thailand all have projects in the pipeline. These projects are not only driven by increasing VRE, but also the optimisation of expanding power systems in general. In Australia, the federal government has announced support for numerous PHS schemes, notably the 2 gigwatts (GW) Snowy 2.0 project, in order to balance higher shares of VRE and the expected retirement of existing baseload coal generation. Projects under construction in Israel, Morocco and Iran are expected to add nearly 1,000 MW, while the UAE and Egypt have also recently announced plans to add PHS to their grids.

Further information on existing and planned projects can be found on IHA's Hydropower Pumped Storage Tracking Tool, which was launched in November 2017. It is the most comprehensive and up-to-date online resource on the world's water batteries.

A vast potential for further PHS development across the world exists, especially given the ability to construct closed-loop off-river projects. A number of countries have mapped this potential, most notably in Australia where a recent study identified 22,000 potential sites with a storage potential of 67 terawatt hours (TWh). The vast majority of these sites were off-river and the study concluded that in order for the country to transition to a 100 per cent renewable electricity grid, only the best 20 sites would need to be developed.[41,42]

Non-powered dams also represent great untapped potential. It is estimated that 12,000 MW of capacity could be added from this source in the USA, some of which could be used for PHS. It would allow developing projects at lower cost, with less risk and in a shorter timeframe. This kind of conversion also works with conventional hydropower plants. The Los Angeles Department of Water and Power is considering equipping the Hoover Dam with a pipeline and a pump station that would help regulate the water flow through the dam's generators, sending water back to the top to help manage electricity at times of peak demand.[43]

Conclusion and areas of further investigation

Energy storage, especially in the form of PHS, has a crucial role in enabling higher levels of variable wind and solar penetration, by adding wide ranging flexibility services across multiple timescales. The level of carbon-free generation needed to meet the ambitious climate goals means that PHS will be required to work together with other energy storage technologies, especially batteries, as well as other grid flexibility resources.

While electricity systems of the future will require greater flexibility, many markets have been slow to react and provide the price signals needed to secure private sector investment as the dynamics of energy arbitrage change. PHS is a cost-effective and technically proven technology with strong environmental benefits, the challenge for industry and policy-makers is to develop the market and regulatory frameworks which will help ensure its full contribution to the clean energy transition is realised. Work being undertaken by the likes of the U.S. Department of Energy will be critical in this respect as they seek to support PHS developers, owners and operators to better understand and assess the changing economic and financial value of existing and planned projects.[44]

Areas which would benefit from further investigation and discussion, led by IHA together with our member organisations, leading up to and during the 2019 World Hydropower Congress include:

- Identifying what policies, regulatory frameworks, permitting regimes and grid charging structures have proven to be most successful in incentivising and adequately rewarding private sector PHS development. This could also involve exploring whether more targeted and interventionist mechanisms are needed and how they could be structured. Developing an understanding from the system operator's perspective on how available flexibility can be best utilised and procured will be critical in this respect.
- Developing case studies which highlight the complementary roles that PHS and batteries can provide in the clean energy transition. How can batteries and PHS best work together in concert to ensure stable, reliable and affordable energy services?
- Further research and analysis on how much energy is currently stored in PHS reservoirs around the world.
- Evaluating the system scale greenhouse gas benefits of PHS at increasing levels of VRE penetrations and how that compares to other electricity storage options.

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5 This bottom-up analysis used IHA's global database of hydropower and pumped hydropower stations. Estimations use max head, and maximum usable storage volume. Where such information is not available, best case assumptions using averages based on PHS type and classification are applied. For open-loop projects, the smaller reservoir was used to limit storage, so this number is likely a conservative underestimation. For more information, see our Pumped Storage Tracking Tool. http://www.hydropower.org/hydropower-pumped-storage-tool

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