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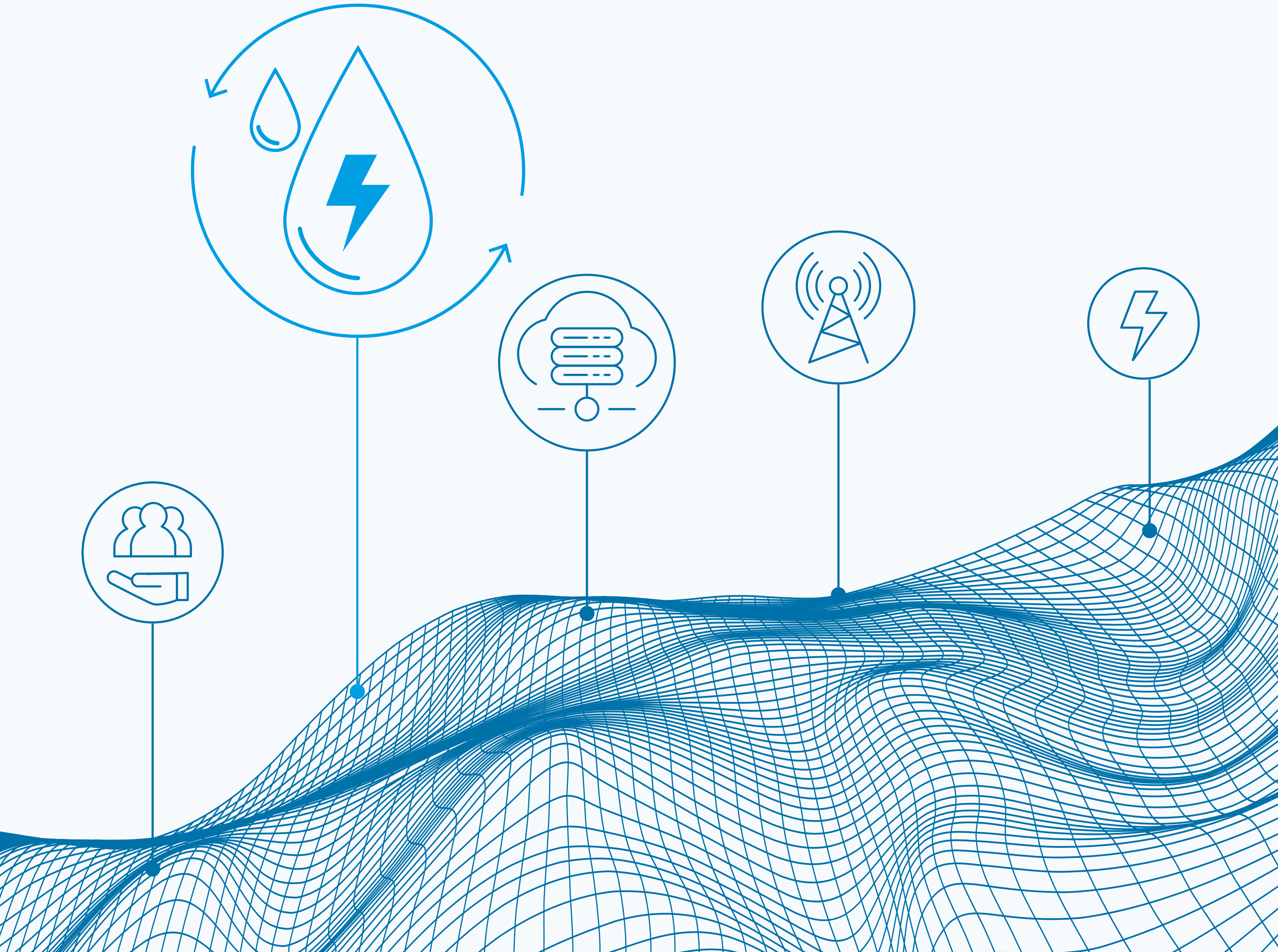
INNOVATIVE OPERATION OF PUMPED HYDROPOWER STORAGE

INNOVATION LANDSCAPE BRIEF



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ABOUT IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

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1 BENEFITS

Pumped hydropower storage (PHS) ranges from instantaneous operation to the scale of minutes and days, providing corresponding services to the whole power system.

Innovative PHS operation

- Load shifting and reduction of variable renewable energy (VRE) curtailment
- Frequency regulation
- Fast and flexible ramping
- Black start

PHS coupled with VRE

- Capacity firming

2 KEY ENABLING FACTORS

- Regulatory framework incentivising flexible operation
- Digitalisation of PHS systems
- Retrofitting PHS facilities
- Public-private research, development and demonstration (RD&D) projects

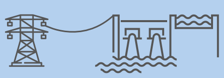
3 SNAPSHOT

- ➜ Installed PHS capacity reached 161 gigawatts (GW) by 2018
- ➜ PHS capacity is set to double by 2050
- ➜ A wind-hydropower hybrid project with PHS supported 100% renewable power generation for 24 days on El Hierro in Spain's Canary Islands in mid-2019
- ➜ Dinorwig power station in Wales, UK, (1.8 gigawatt generation capacity and 11 gigawatt-hours storage) is Europe's largest PHS system, sufficient to cover peak load.

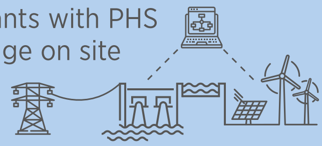
STORAGE TO ENHANCE SOLAR AND WIND POWER

Different PHS configurations to optimise VRE integration:

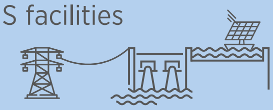
Conventional PHS balancing systems with VRE



VRE plants with PHS as storage on site



VRE technologies integrated into PHS facilities



INNOVATIVE OPERATION OF PUMPED HYDROPOWER STORAGE

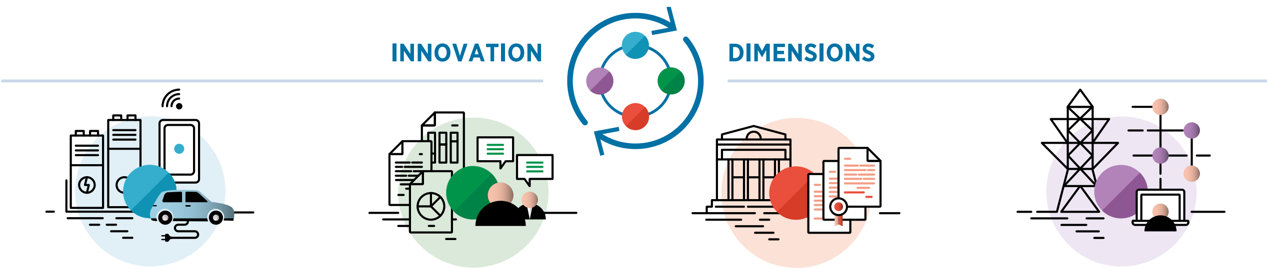
Pumped Hydropower Storage (PHS) serves as a giant water-based "battery", helping to manage the variability of solar and wind power

ABOUT THIS BRIEF

This brief forms part of the IRENA project "Innovation landscape for a renewable-powered future", which maps the relevant innovations, identifies the synergies and formulates solutions for integrating high shares of variable renewable energy (VRE) into power systems.

The synthesis report, "*Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables*" (IRENA, 2019a), illustrates the need for synergies between different innovations to create actual solutions. Solutions to drive the uptake of solar and wind power span four broad dimensions of innovation: enabling technologies, business models, market design and system operation.

Along with the synthesis report, the project includes a series of briefs, each covering one of 30 key innovations identified across those four dimensions. The 30 innovations are listed in the figure below.



ENABLING TECHNOLOGIES

1 Utility scale batteries
2 Behind-the-meter batteries

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4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of Things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
10 Supergrids

11 Flexibility in conventional power plants

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12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service

15 Community-ownership models
16 Pay-as-you-go models

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17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets

22 Time-of-use tariffs
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24 Net billing schemes

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26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

29 Virtual power lines
30 Dynamic line rating

This brief provides an overview of new ways to operate pumped hydropower storage (PHS) to provide greater flexibility to the power sector and integrate larger shares of VRE in power systems. The innovative operation of PHS and its complementarity with other power generating technologies offer plenty of opportunities for VRE integration. PHS represents over 10% of the total hydropower capacity worldwide and 94% of the global installed energy storage capacity (IHA, 2018).

Known as the oldest technology for large-scale energy storage, PHS can be used to balance the grid, complement other renewable energy infrastructure and facilitate effective supply shifts.

PHS has the ability to actively absorb surplus power from the grid, making it a more cost-effective flexibility option than technologies such as batteries, interconnections or Power-to-X.

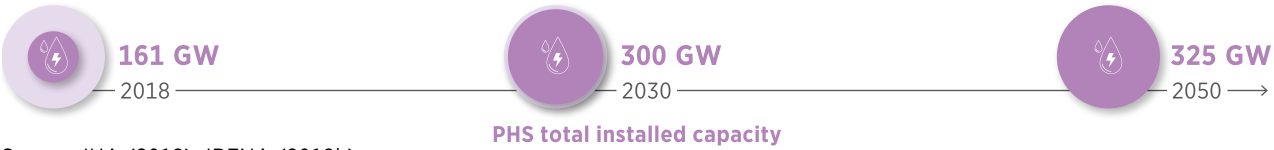
The brief is structured as follows:

I. DESCRIPTION

Traditionally, a pumped hydro storage (PHS) facility pumps water uphill into a reservoir, consuming electricity when demand and electricity prices are low, and then allows water to flow downhill through turbines, generating electricity when demand increases and electricity prices are higher (GE Power, 2017). Currently, PHS systems are the primary technology used to provide electricity storage services to the grid, accounting for 161 gigawatts (GW) of installed global storage capacity (IHA, 2018).

IRENA's global roadmap calls for a two-thirds increase in hydropower installed capacity, to 2 147 GW, by 2050. In other words, around 850 GW of new installed capacity is required in the next 30 years. As part of that target, PHS would need to double, reaching 325 GW (Figure 1) (IRENA, 2019b).

Figure 1 Growth in PHS installed capacity by 2050



Source: IHA (2018); IRENA (2019b).
Note: PHS = pumped hydropower storage.

The transition to renewable energy sources, particularly wind and solar, requires increased flexibility in power systems. Wind and solar generation are intermittent and have seasonal variations, resulting in increased need for storage to guarantee that the demand can be met at any time.

Short-term energy storage solutions with batteries are being used to resolve intermittency issues. However, the alternative for long-term energy storage that is usually considered to resolve seasonal variations in electricity generation is hydrogen, which is not yet economically competitive (IIASA, 2020). PHS can provide long-term energy storage at a relatively low cost and co-benefits in the form of freshwater storage capacity. A study shows that, for PHS plants, water storage costs vary from 0.007 to 0.2 USD per cubic metre, long-term energy storage costs vary from 1.8 to 50 USD per megawatt-hour (MWh) and short-term energy storage costs vary from 370 to 600 USD per kilowatt (kW) of installed power generation capacity when dam, tunnel, turbine, generator, excavation and land costs are considered (Hunt *et al.*, 2020).

Innovation has driven development in the operation of PHS stations, both in mechanical and digital operation. Digitalisation, for instance, is playing a prominent role in the improvement of PHS facilities. Innovations in the design, operation and maintenance of PHS; remote monitoring; and predictive maintenance have reduced the capital and operational costs of PHS systems, raising their attractiveness to potential investors. Furthermore, with increasing shares of VRE in the system, PHS can be a valuable enabler of increased flexibility.

Pumped hydropower storage systems

PHS systems can be divided into two main categories according to their operational design: **open-loop systems**, where the PHS facility is continuously connected to a naturally flowing water source, and **closed-loop systems**, where the PHS facility is isolated from any naturally flowing water source.

PHS systems can be integrated with battery storage; irrigation projects; or systems where the ocean, a lake or a river is used as the lower reservoir.

A variety of configuration schemes enable PHS to integrate more VRE into power systems:

CONVENTIONAL PHS: This type of system guarantees rapid start-up and adjustable power output, depending on demand. It also absorbs surplus VRE generation in the system, while minimising losses. Existing conventional hydropower plants can be retrofitted with pumping systems to integrate PHS capabilities. Currently, PHS can be considered a very versatile energy storage solution owing to its functionality over a wide range of timescales.

COUPLED SCHEMES (PHS + VRE): A VRE generation plant coupled with a PHS plant can pump water to the upper reservoir(s) of the PHS plant to minimise curtailment. The PHS would be then effectively acting as a behind-the-meter battery.

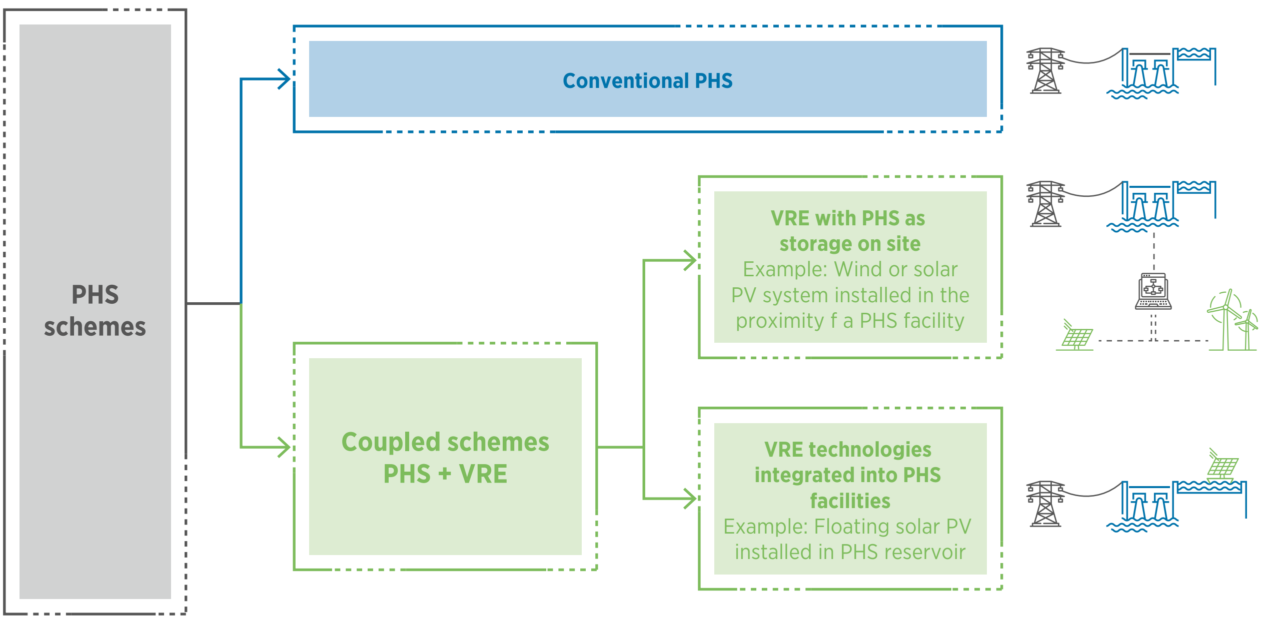
- **VRE with PHS as storage on site:** In this type of system, a wind or solar power plant would be installed in proximity to a PHS plant. The PHS will serve as on-site storage for the VRE plant, firming its intermittent supply.

- **VRE technologies integrated into PHS facilities:** Floating photovoltaic (PV) systems can be installed in the upper and lower reservoirs of a PHS facility, creating a hybrid model that can take advantage of existing high-voltage grid connections. Schemes with floating PV, where PV panels are installed on the water rather than on land, can provide other potential advantages, such as:

  - ➜ increasing the efficiency and productivity of land and water usage
  - ➜ reducing evaporation losses, especially in the case of floating solar, by shading the water
  - ➜ increasing solar cell efficiency through water cooling (World Bank Group, ESMAP and SERIS, 2019)
  - ➜ taking advantage of existing transmission infrastructure and readily combining with storage capabilities to provide dispatchable, uninterruptable and flexible power generation.

The schemes mentioned are summarised in Figure 2.

Figure 2 Configuration schemes for pumped hydropower storage and renewables



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

II. CONTRIBUTION TO POWER SECTOR TRANSFORMATION

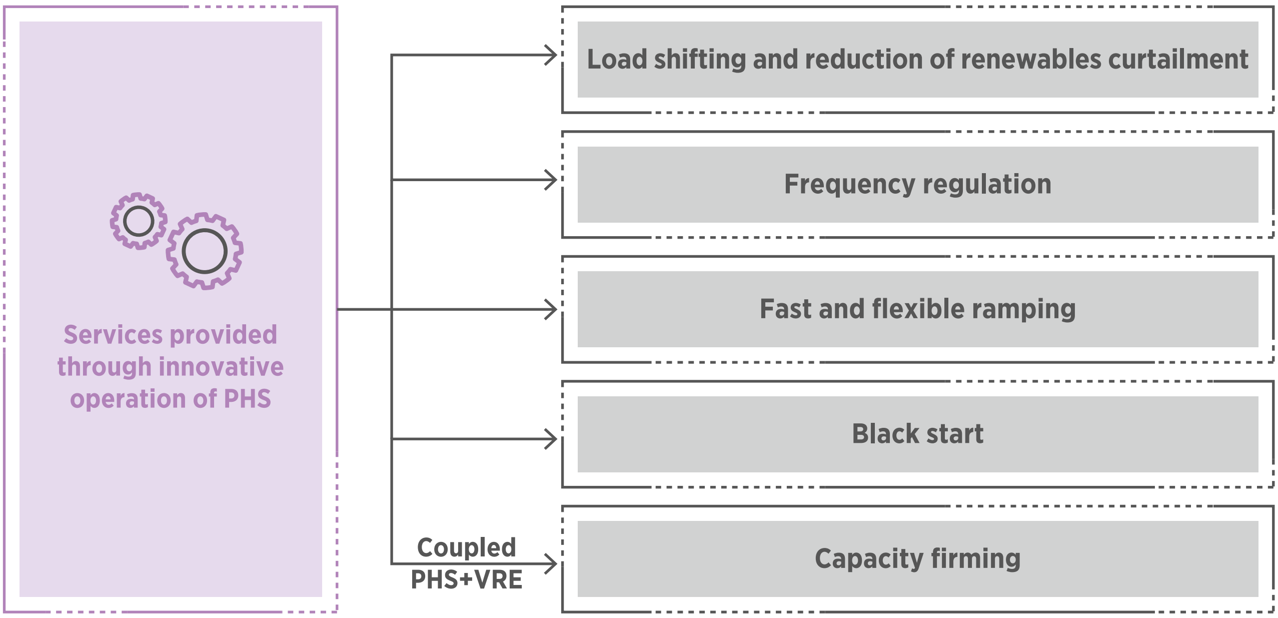
Overall, in its different forms and applications, PHS is providing new flexibility options for the operation of power systems, balancing the variability of other renewable sources – such as wind and solar – and maintaining grid stability. PHS can operate from the instantaneous scale (using synchronous rotational inertia provided by fixed-speed turbines), to minutes and hours, up to the seasonal scale for long-term storage.

The complementarity between hydropower and VRE sources can range from daily to seasonal (yearly) generation patterns.

The synergies between hydropower and other renewable energy technologies in system operation have potential benefit for (i) the cost-effectiveness of using hydropower to counteract the short-term variability of wind and solar generation and (ii) seasonal complementarities in resource patterns.

Figure 3 shows the contribution of the innovative operation of PHS in power systems.

Figure 3 Services to power systems enabled by innovative operation of hydropower plants



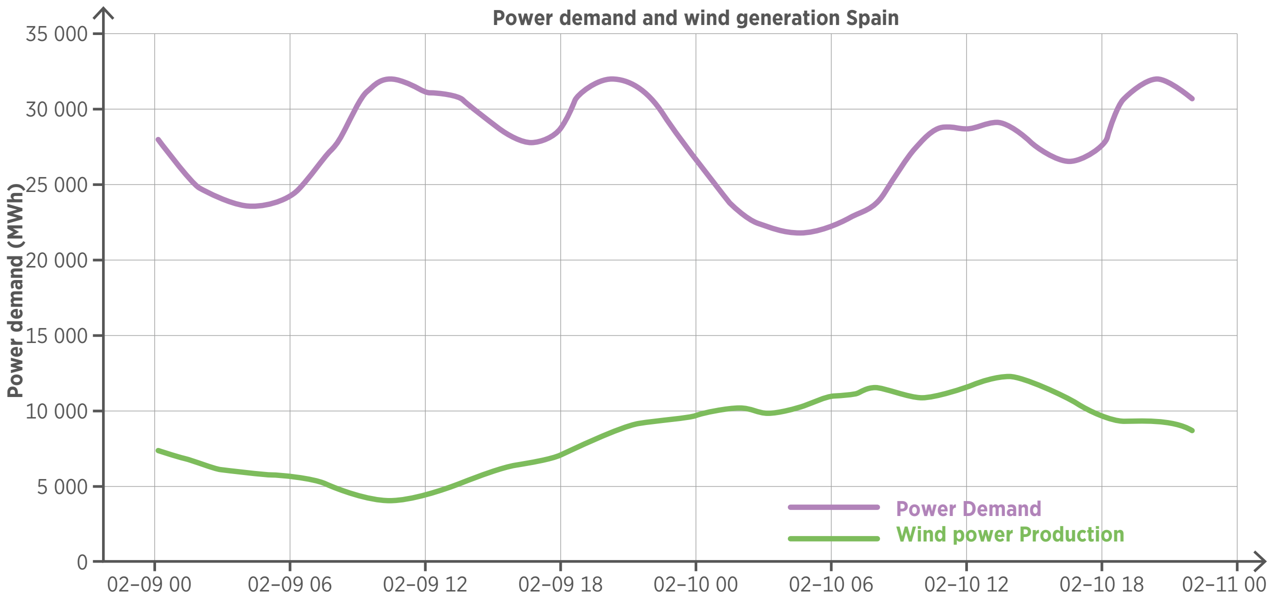
Note: PHS = pumped hydropower storage; RE = renewable energy; VRE = variable renewable energy.

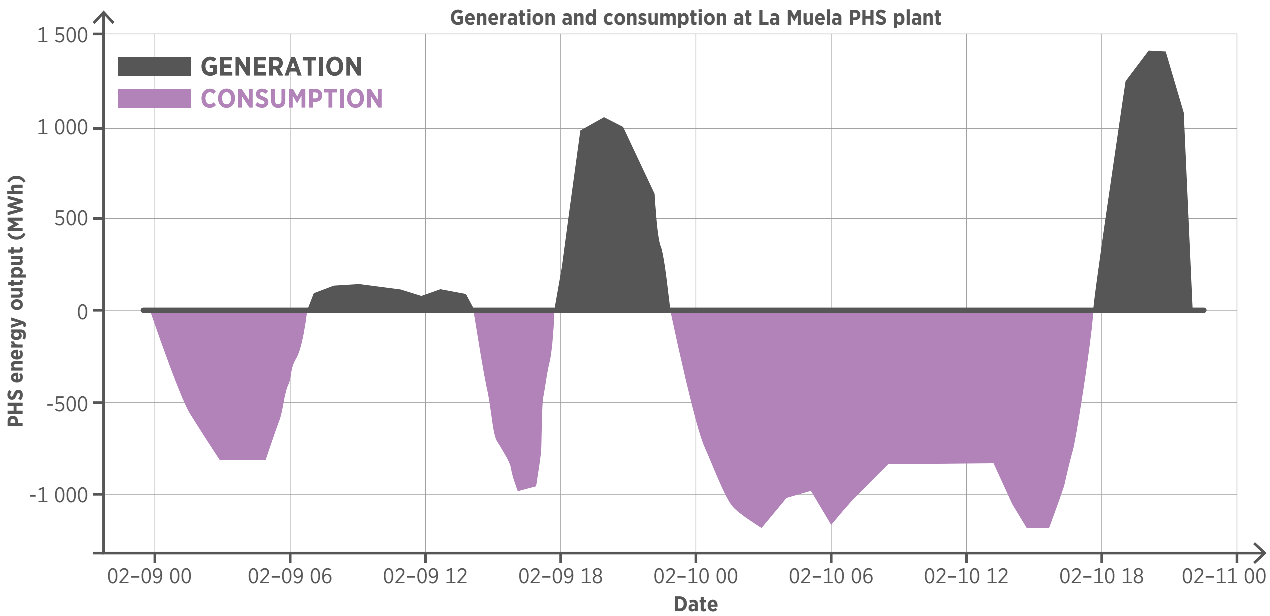
Load shifting and reduction of renewable energy curtailment

Load shifting provided by PHS is a key service for system operators. For example, during the daytime, solar electricity can be used to pump water to the dam, which will then provide power capacity in the evening or during cloudy periods. In this way, curtailment can be mitigated by storing any surplus of electricity, which can then be used during periods of high demand. By increasing flexibility, the overall efficiency of the system is also positively impacted.

La Muela PHS facility in Spain is one of the largest PHS facilities in Europe. Figure 3 shows the demand and wind generation on 2 February 2019 in Spain, together with the PHS plant activity. The plant pumps water to the upper reservoir when demand is lower and wind production is relatively high and it generates power in the evening when demand is higher and wind production decreases. Figure 3 shows the daily complementarity of the PHS operation and wind energy generation; more benefits could be reaped from the complementarity of these resources on a longer-term basis (weeks, months).

Figure 4 Use of the flexibility provided by a PHS





Source: Iberdrola.

The southernmost island of Japan, Kyushu, is home to three PHS plants, operated by the Kyushu Electric Power Company. With 8.07 GW of installed solar capacity, Kyushu has one of the highest VRE shares in Japan. On 3 May 2018, PV output reached 6.21 GW (81% of peak demand on that day) at around 13:00. The surplus of solar energy generated was used to pump water to the upper reservoirs in the island's PHS plants, and thermal power generation was curtailed to accommodate the large amount of solar energy.

In this case, PHS helped to avoid complete shutdown of the thermal power stations by absorbing the surplus solar energy. This helped maintain their efficiency and response times, as thermal power stations can take anywhere from 2 to 8 hours to start, depending on the technology used. Moreover, PHS hydropower generation was used during times of lower PV output to meet demand peaks. Figure 5 shows the power supply and demand balance in Kyushu on that day.

One of the plants in Kyushu, the Omarugawa PHS power plant, featured variable speed generation systems with speeds of 576 to 624 revolutions per minute and a pump head of over 700 metres. This was an unprecedented installation for its time among PHS plants and supported the integration of a high share of VRE on the island of Kyushu (Nagura *et al.*, 2010).

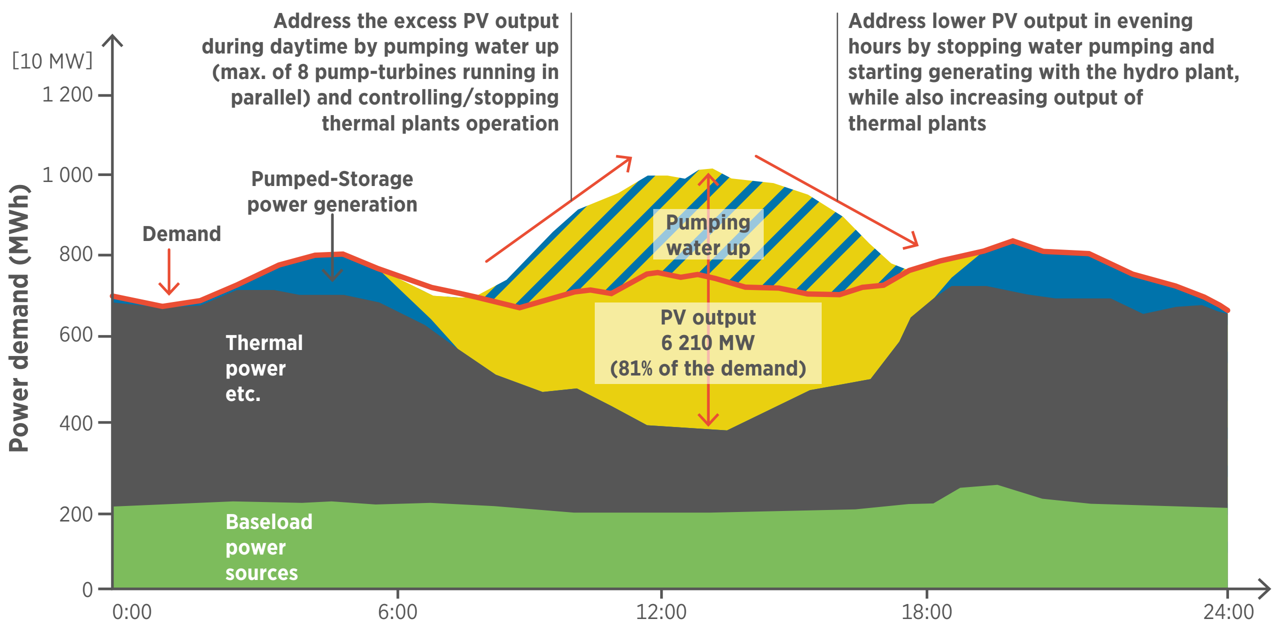
Frequency regulation

PHS is characterised by its fast response to balance variations between electricity supply and demand, keeping the balance between active power load and generation in the system to prevent frequency problems (IRENA, 2016). Also, PHS provides reactive power control as support to keep voltages in the system at acceptable levels.

The latest innovations in PHS technology, such as variable speed turbines and ternary systems, have further unlocked frequency control services. Variable speed turbines, as alternatives to traditional fixed-speed turbines, allow for power regulation during both pumping and generation modes, which increases system efficiency and flexibility. Ternary systems, which consist of a motor-generator and a separate turbine-and-pump set, allow for generation and pumping modes to operate in parallel, which leads to finer frequency control.

These innovations offer increased grid flexibility through load following and power regulation. Variable speed pump-turbines provide several advantages over fixed-speed pump-turbines to PHS projects, such as a wider range of operation, quicker response time and higher efficiency. They also allow for adjustable power consumption while pumping, hence allowing

Figure 5 Power supply and demand balance from Kyushu, 3 May 2018



Source: Kyushu Electric Power Company.
Note: PS = pumped storage; PV = photovoltaic.

for refined frequency control. Ternary systems permit the simultaneous operation of the turbine and the pump. This eliminates the time needed to switch between pumping and generation, which allows for additional flexibility and a quicker response time. Furthermore, owing to the nature of fixed-speed pump-turbines and ternary systems, mechanical inertial response can suffice to resist rapid changes in the grid (IHA, 2018).

The Frades II PHS facility in Portugal, a 780 megawatt (MW) project, is one of the few PHS facilities to use variable speed turbines (XFLEX Hydro, 2019a). The station contributes to frequency regulation in a grid with around 20% wind electricity generation (IHA, 2018). Variable speed turbines also allow the power plant to stay stable for 600 milliseconds: four times longer than fixed-speed turbines. This can help system operators prevent large-scale outages (XFLEX Hydro, 2019a).

Alternatively, coupling battery storage to a conventional PHS system would result in valuable services for system operation that could enhance frequency regulation of the plant. Battery storage can provide an instantaneous response time, while PHS can provide significantly larger amounts of energy than other storage systems. Such as system was implemented at the Kraftwerksgruppe Pfreimd power plant in Bavaria, Germany, when a 12.5 MW lithium battery storage system was installed to complement the existing PHS facilities (combined 137 MW capacity) at the site (Energy Storage, 2018). This system contributes to a secure energy supply by providing primary and secondary control power and reserve capacity to the grid.

Fast and flexible ramping

Advancements such as variable speed turbines have provided flexible ramping capacities, which refers to a generator's ability to rapidly increase or decrease its output, according to changes in the forecasted net load. Moreover, they have allowed PHS facilities to reach full output in less than 30 seconds when already connected to the network.

Challenges caused by VRE intermittency from resource fluctuation or weather events could be counteracted by the rapid ramping response provided by PHS.

System operators can take advantage of PHS facilities with second scale ranges to reach full output, maintaining a reliable and stable system while integrating higher shares of VRE. PHS is also being used to balance the so-called duck curve, where the difference between electricity demand and solar energy production around sunset reaches a maximum.

For example, the Kops II PHS facility in Austria, which features variable speed turbines, can reach a maximum output of 180 MW in 20 seconds. Another example is the Dinorwig PHS facility in Wales, the largest PHS facility in Europe, which can reach a full load of 1.8 GW in 16 seconds.

Kruonis PHS facility in Lithuania supported the Lithuanian grid efficiently with over 400 MWh when the NordBalt interconnector between Lithuania and Sweden failed on 18 May 2016 (LT Daily, 2016). In another example, the Fengning 2 Pumped Storage Power Station in China, with a planned capacity of 1.8 GW, plays an essential role in balancing generation from wind and solar energy projects to supply the Beijing-Tianjin-North Hebei grid (Hopf, 2020).

Black start

Hydropower plants are well suited to providing black start services, as long as the reservoirs store enough water to power turbines without any special preparation for black start operation. Minimal station power is needed, since fuel preparation and cooling are not required. Moreover, hydropower generators have significant inertia and high enough ramp rates (for changing power output) to help stabilise system frequency. Many hydropower generators are large enough to supply adequate power to energise the transmission system, provide station power to start up other generating plants, and pick up loads.

PHS units have almost all the advantages of conventional hydro units. However, economical dispatch may deplete the upper ponds of PHS systems, so PHS units are adequate for black start only if some water is always held in reserve for it (Garcia *et al.*, 2019).

The Cruachan PHS plant in Scotland, with a capacity of 440 MW, can achieve full load in 30 seconds and can maintain that level of production for over 16 hours if needed, guaranteeing a stable supply feed for system operation. Besides balancing services, the plant can also provide black start capability to the National Grid, the system operator (Drax, 2019).

Capacity firming (when connected to an on-site VRE generator)

Coupling VRE power plants and PHS systems permits them to provide a firm generation, turning the plant into a dispatchable power plant. This increases the reliability and efficiency of system operation, and, as a result, balance energy generation and complements different renewable energy generation sources for a stable energy supply.

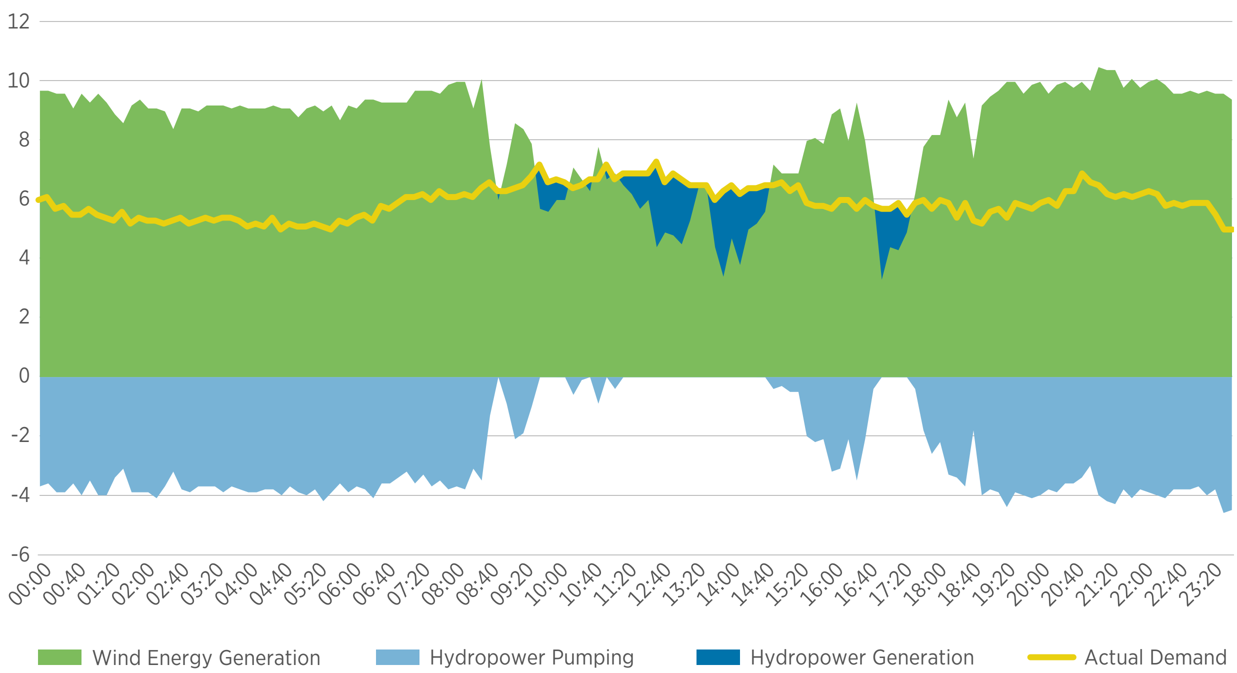
An innovative form that is under development, such as in the pilot project in Gaildorf, Germany, places smaller PHS reservoirs at the base of wind turbines to provide each turbine with its own storage capabilities. The reservoirs are connected via an underground penstock to a pumped-storage power station in the valley that can provide up to 16 MW in power. The electrical storage capacity of the power plant is designed for a total of 70 MWh (Max Bögl, 2018).

The Gorona del Viento wind-PHS hybrid power plant, located at El Hierro, Canary Islands, Spain, has reduced the small island's dependency on diesel generators.

This has been done by pumping water using surplus wind energy generation to the upper reservoir in the PHS facility and then using the PHS facility to meet the energy demand when wind speeds are too low to provide sufficient production levels. El Hierro was able to reach 4 800 consecutive hours (24 days) of 100% renewable energy generation in 2019, showing the potential for PHS to integrate renewables into system operation (Gorona del Viento, 2019).

Figure 6 shows the energy demand and generation data of a full day on El Hierro (5 September 2018) when the supply was successfully met with electricity generated from wind and PHS. The figure displays how wind energy curtailment is avoided; for instance, excess electricity generated from wind energy in the first 8 hours of the day is used to pump water into the upper reservoir. The operation of the energy system on El Hierro benefits directly from PHS, while mitigating curtailment and eliminating the need to cover energy demand with diesel generators.

Figure 6 Gorona del Viento demand and generation, 5 September 2018

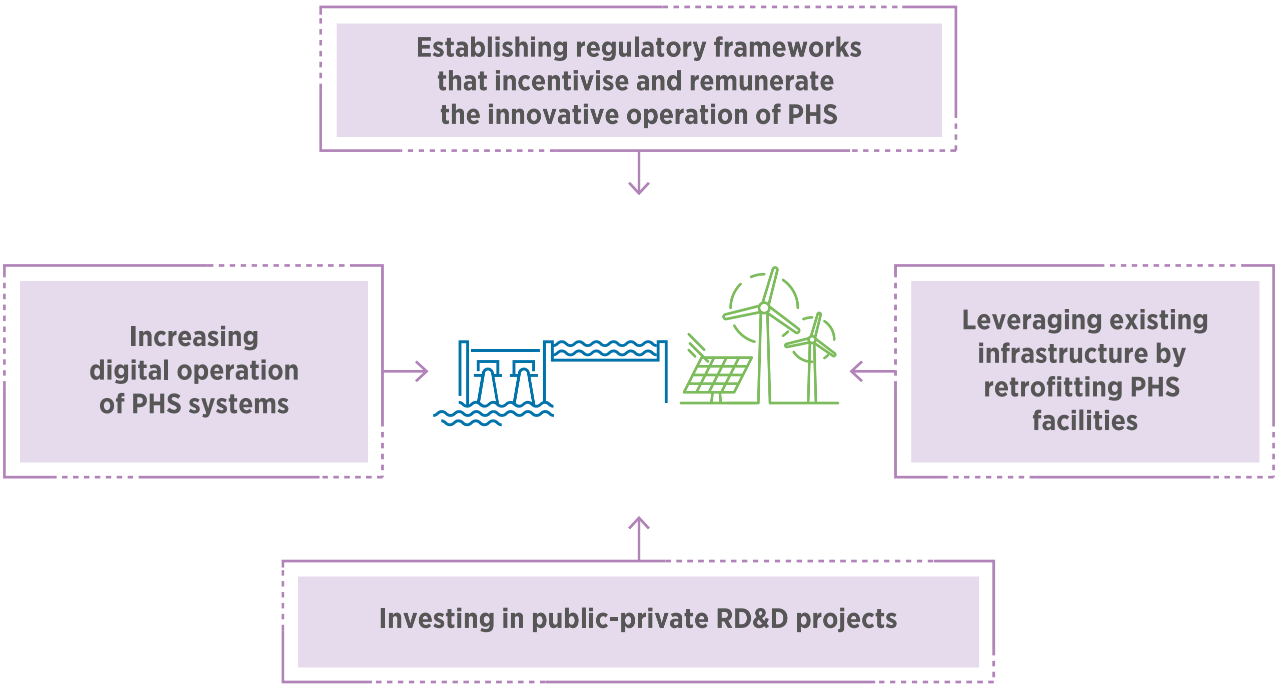


Based on data from Red Eléctrica de España.

III. KEY FACTORS TO ENABLE DEPLOYMENT

A summary of the key factors to enable deployment is illustrated in Figure 7.

Figure 7 Key factors to incentivise innovative ways to operate pumped hydropower storage in combination with variable renewable energy



Note: PHS = pumped hydropower storage; RD&D = research, development and deployment.

Establishing regulatory frameworks that incentivise and remunerate the innovative operation of PHS

PHS stations have been in operation for decades. In the past, PHS was built to complement large, inflexible generation, such as nuclear plants, for arbitrage on a diurnal basis. However, the increased VRE share in the systems demands new ways to operate flexible power plants. To compensate for the increased variability of wind and solar generation, existing PHS systems tend to operate with increased start-stops and with decreased total hours of generation, resulting in a less predictable revenue regime and reduced bankability for future projects.

Therefore innovative policies and regulations must be tried and adopted to incentivise and remunerate such flexible facilities for the provision of ancillary services. For more about this, see *Innovation Landscape Brief: Innovative ancillary services* [IRENA, 2019c]).

In liberalised markets where vertical integrated utilities have been unbundled, enabling revenue stacking from the provision of different services can incentivise innovative operation of PHS systems. New revenue streams can result from ancillary service provision, energy arbitrage or capacity payments.

- **Ancillary services:** Where ancillary service markets or rules are in place, PHS facility owners could obtain revenue by offering ancillary services – such as frequency control, black start, active and reactive power regulation – to network operators to maintain the system in balance.
- **Energy arbitrage:** Where wholesale electricity markets are in place, PHS facility owners could obtain revenue by purchasing off-peak (cheaper) electricity to pump water when VRE generation is low and then sell back electricity at peak time (more expensive) when demand is high and VRE generation is still low. With further integration of VRE, this disparity is getting smaller and thus diminishing profits from arbitrage.
- **Capacity payments:** Where such regulations are in place, PHS could obtain revenue by providing services to system operators to ensure a certain supply level for a certain (predefined) period of time, thereby helping with system adequacy.

Different countries and contexts need to adopt different frameworks that can maximise the potential of PHS. One such example lies in Ireland. As the only PHS facility operating in the Irish Single Electricity Market, the Turlough Hill PHS station (292 MW capacity) uses all three revenue streams. It provides several ancillary services, such as black start, reactive power and operating reserve. The transmission system operator EirGrid recommended the addition of other services, such as synchronous inertial response and fast frequency response (Wänn and Leahy, 2014).

Another way to increase flexibility provided by generation plants, in addition to allowing revenue stacking and innovative ancillary services, is to increase the time granularity in electricity markets. This would lead to prices that better reflect the conditions on the market in shorter time intervals (see *the Innovation Landscape brief: Increased granularity in electricity markets* [IRENA, 2019d]).

In vertically integrated markets, the policy and regulation frameworks must be consistent with the country energy roadmap to guarantee the best use of renewable resources.

For example, several policies were issued in China in 2014 to facilitate the development of new PHS stations. A two-part feed-in tariff was implemented: the first part reflected the value of the ancillary services provided and the second reflected the value of the plant's power generation. This ensured remuneration for the different services that can be provided by a single PHS plant, which can encourage investment in the technology and its diverse uses in system operation (Zhang, Andrews-Speed and Perera, 2015).

Increasing digital operation of PHS systems

Innovative operation of energy systems has been and will continue to be positively influenced by digitalisation. In the case of PHS, many digital breakthroughs optimise the operation of the plant, such as smart coupling (with batteries or with VRE plants), operation monitoring equipment and generation forecasting through machine learning (IHA, 2017a) (for more information on digital technologies in the power sector see *Innovation Landscape brief: Artificial intelligence and big data* [IRENA, 2019e]; *Innovation Landscape brief: Internet of things* [IRENA, 2019f].

In addition to optimising the operation and increasing the efficiency of the PHS, the benefits of digital innovations include decreasing operation and maintenance costs. Such applications include maintenance robots, virtual reality training for operation personnel and remote-control maintenance technologies. For example, Hydro-Québec says its underwater monitoring and maintenance robot generates around USD 1.4 million (CAD 2 million) of savings annually (Lorinc, 2016). The robot has a positioning system to pinpoint its own location and that of anomalies, as well as cameras to display graphical data for the monitoring team. This makes inspections safer and quicker and thereby reduces operating downtime (Hydro-Québec, 2010).

Portugal's utility Energias de Portugal (EDP) has benefited from digital solutions (*i.e.* real-time measurements using big data and computational fluid dynamics) to determine the high- and low-stress zones of the turbines in the Alqueva II PHS plant (GE Renewable Energy, 2019). This analysis resulted in an increase of 50% in the operating range for its two-unit 260 MW PHS, enabling higher flexibility when operating the plant with other VRE. In addition, this enhancement provided EDP with additional revenue from the plant, which could be used to improve its ancillary services for the secondary reserve market (CAREC Program, *n.d.*).

Leveraging existing infrastructure by retrofitting PHS facilities

Retrofitting existing PHS plants with modernised and innovative components can improve their operation and add significant benefits to the system operation. Components such as variable speed turbines can improve response time and expand the operating range of the facility, giving it increased revenue streams, where applicable, and making PHS more attractive to investors, leading to further integration of new VRE plants.

Additionally, combining existing PHS projects with other VRE systems, such as floating PV, can decrease capital expenditure costs, first because of the technology's modular features, which can help reduce the construction times of floating PV and, second, through the use of already existent transmission and distribution grid connections.

A relevant case is the floating solar PV plant integrated into an existing PHS facility in Alto Rabagão, Portugal. This pilot project consists of 840 PV panels with a total of 220 kW power output and an estimated annual energy output of 300 MWh. This scheme proved to be a success in its first year of testing, producing 15 MWh more than previously estimated (EDP, 2017).

Investing in public-private research, development and deployment projects

More economic resources assigned to the research, development and deployment of PHS combined with VRE and/or batteries could showcase their benefits and complementarities. The overall enhancement of existing PHS and new synergies with other renewable energy technologies can, among others benefits, provide a lower-risk portfolio and raise the confidence of investors, who could therefore further invest in renewable technologies, leading to higher shares of VRE in power systems.

Enabling such projects calls for the establishment of more partnerships with the private sector and the involvement of those partners in the development or enhancement of PHS technologies. In this context, another prominent example is Hidrocaleras, a pilot project to be developed in the Spanish region of Cantabria. The project consists of a scalable PHS plant with seawater, equipped with 50 MW turbines. Several European-based actors are involved, including engineering companies, banks and research institutions, led by Cobra Infraestructuras Hidráulicas. The project was approved by the local and regional administration (Grupo Cobra, 2018).

IV. CURRENT CONTEXT AND ONGOING INITIATIVES

Table 1 contains some of the key insights into existent PHS facilities.

Table 1 Current status and examples of leading PHS initiatives

Indicator	Key facts
Geographies where the innovation is deployed	Argentina, Australia, Austria, Belgium, Bosnia and Herzegovina, Brazil, Bulgaria, China, Croatia, Czech Republic, France, Germany, India, Iran, Ireland, Italy, Japan, Lithuania, Morocco, Norway, Philippines, Poland, Portugal, Republic of Korea, Romania, Russian Federation, Serbia, Slovenia, South Africa, Spain, Sweden, Switzerland, Thailand, Ukraine, United Kingdom, United States of America[a]
Installed PHS capacity (GW)	161 in 2018[b]
Forecasted installed capacity	By 2030: 300 GW[c] By 2050: 325 GW[c]
Levelised cost of pumped storage (USD/MWh)	15-year lifetime: 150–200[d] 40-year lifetime: 186 (compared to 285 USD/MWh for Li-ion battery facility)[e] 100-year lifetime: 58[e]
Capital expenditure for PHS construction[f] (USD/kW)	Low end: 617
	Medium end: 1 412
	High end: 2 465

Note: PHS = pumped hydropower storage.

[a] IHA (2019).

[b] IHA (2018).

[c] IRENA (2019b).

[d] Lazard (2016).

[e] Giovinetto and Eller (2019).

[f] Calculated using the average annual capital expenditure between 2003 and 2019 for 19 countries from IRENA database. Lower-end costs can be attributed to low labour and construction costs (*e.g.* China, Thailand) or large-scale installations. Higher-end costs can be attributed to high labour costs (*e.g.* Japan, Switzerland) or small-scale installations.

Table 2 provides a non-exhaustive sampling of current projects benefiting from the innovative operation of PHS plants.

Table 2 Current status and examples of leading PHS initiatives

PHS scheme	Location	Description	Value added
PHS coupled with floating PV system	Montalegre, Portugal	This is the world's first hybrid PV and hydroelectric dam power plant system and has a total capacity of 68 MWp. The dam adds an additional 220 kWp through the floating PV installation (Prouvost, 2017).	The panels generate during the day and save hydropower to use during the evening peak demand (Carr, 2017). After the first year of operation, the facility generated around 5% more than its initially projected annual generation target of 300 MWh (EDP, 2017).
PHS with ternary systems	Vorarlberg, Austria	The three ternary units installed in Kops II allow the parallel operation of the 180 MW turbine and the 150 MW pump (Pöyry, 2014).	This PHS facility is considered fast, as it reaches full load in 20–30 seconds, enabling it to provide a wider range of ancillary services.
PHS coupled with wind power plant and battery system	El Hierro, Canary Islands, Spain	In the Gorona del Viento project, five wind turbines with a generating capacity of 11.3 MW are connected to the PHS station, which is used to store surplus energy and generate power when wind speed is insufficient.	The project played a role in the island of El Hierro reaching 56% wind power in 2018 (Gorona del Viento, 2018). In August 2019, the island's demand was completely met by renewable energy sources for 24 consecutive days.
Conventional PHS systems	Kyushu, Japan	These three PHS stations on the Japanese island of Kyushu have a storage capacity of 2.3 GW and are operated by Kyushu Electric Power Co.	The use of PHS on the island assists the integration of over 8 GW of solar PV by reducing its curtailment. PHS also prevents the complete shutdown of the island's baseload sources, such as nuclear and thermal power. This reduces financial losses due to the slow start time for those technologies.
PHS with variable speed turbines (with doubly fed induction machine)	Frades II, Portugal	The 780 MW project is one of the few PHS facilities to use variable speed turbines (XFLEX HYDRO, 2019a).	The facility contributes to frequency regulation in a grid with around 20% wind generation (IHA, 2018). Variable speed machines enable wider operating range, faster response and higher efficiency in PHS plants (Voith, 2019).
Conventional PHS	Dinorwig, Wales, United Kingdom	This is the largest PHS facility in Europe, with an 11 GWh storage capacity. It consists of six 300 MW reversible turbines. It is able to reach full load in 16 seconds.	The facility supports the grid by providing peak load electricity. Owing to its fast response time, it also provides electricity in rapid changes in demand, for example during "TV pickup", where households simultaneously use electric kettles and other appliances during commercial breaks, and demand surges. Dinorwig is also able to provide black start services.
Conventional PHS	Cortes de Pallás reservoir, Spain	La Muela has a total generating capacity of 1 517 MW, with seven reversible turbines.	The facility's average annual output of around 1 625 GWh is enough to provide the electric consumption of close to 400 000 households. La Muela also dedicates 40% of its production to ancillary services for real-time system management.

Note: PHS = pumped hydropower storage; PV = photovoltaic.

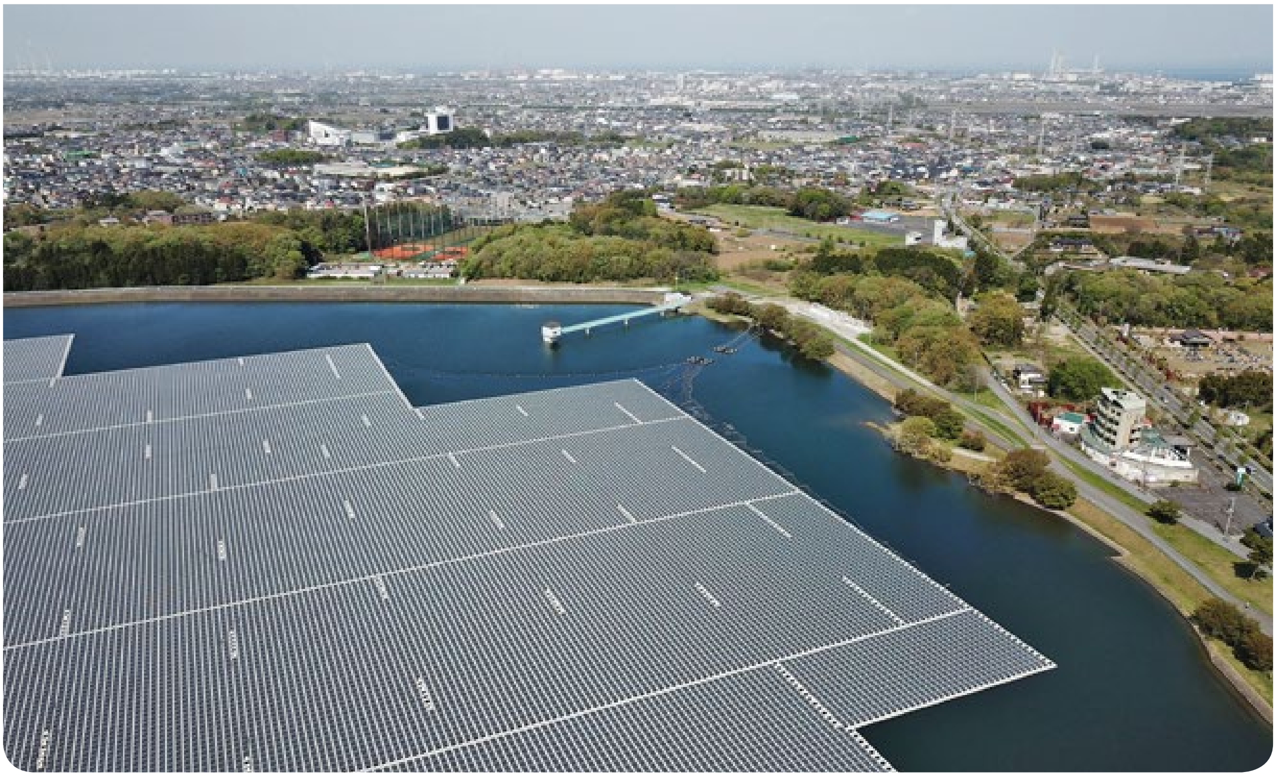
Table 3 provides a non-exhaustive sampling of future projects benefiting from the innovative operation of PHS plants.

Table 3 Future deployment PHS projects and schemes

PHS scheme	Location	Description	Value added
PHS coupled with floating solar PV technology	Kruonis, Lithuania	The pilot floating PV retrofit will consist of a 60 kW PV system. The floating PV system could have a capacity of 200–250 MW. It would be installed at the existing 900 MW Kruonis PHS facility.	The system would allow the utility to provide reliable frequency control and primary reserve services and improve its connectivity to the integrated pan-European market (Hydro Review, 2019).
PHS coupled with onshore wind project	Gaildorf, Germany	In this pilot project, the foundations of the wind turbines are used as upper reservoirs of a PHS facility. They are connected to a pumped-storage power station in the valley that can provide up to 16 MW in power. The electrical storage capacity of the power plant is designed for a total of 70 MWh (Max Bögl, 2018).	Surplus wind electricity is stored in the upper reservoirs and helps to smooth the wind generation output.
PHS coupled with wind and solar PV technology	Kidston, Australia	The projected large-scale hydro 250 MW PHS, with a total of 8–10 hours' storage, would combine a total capacity of 320 MW solar PV and 150 MW wind (Iannunzio, 2018).	The project is expected to provide dispatchable and reliable renewable energy at peak demand, being able to store solar energy during the day and release it during the morning and evening peak periods through the hydro system. It can reduce losses associated with importing electricity from the grid for the PHS scheme, as well as mitigate the risk associated with rising overnight electricity prices when PHS facilities are usually "recharging" (Energy Magazine, 2018).
PHS coupled with solar PV technology	Atacama Desert, Chile	The Valhalla project will send intermittent generation from the 600 MW Cielos de Tarapacá solar PV farm to the 300 MW Espejo de Tarapacá PHS plant to convert it into a dispatchable power plant.	The project plans to deliver continuous baseload power to fill about 5% of northern Chile's baseload demand. It would be the first to demonstrate that baseload power can be generated from a utility-scale PV plant (Andrews, 2017).
PHS coupled with solar PV technology	Hatta, United Arab Emirates	The Hatta PHS facility, with a generation capacity of 250 MW, will use surplus electricity from the world's largest planned solar PV installation, the 5 GW Mohammed bin Rashid Al Maktoum Solar Park.	The PHS facility is planned to reach 80% of peak capacity within 90 seconds, from zero. This fast response will prove very beneficial in balancing load within the power system in the United Arab Emirates and will be essential in reaching the country's target of 75% renewable power by 2050 (Gulf News, 2019).
PHS with variable speed turbines (with full size frequency converter)	Z'Mutt, Switzerland	A 5 MW variable speed pump-turbine will be installed with a full size frequency converter and optimisation software to enhance flexibility services.	The project will demonstrate optimum flexibility and power control at prototype scale. Service improvements will include fast power injection or absorption in pumping and generating modes, inertia emulation, and fast turbine starts, stops and transitions (XFLEX HYDRO, 2019b).

PHS scheme	Location	Description	Value added
PHS with variable speed turbines and hydraulic short circuit	Frades II, Portugal	Two variable speed machines will be run in hydraulic short circuit mode for added flexibility from a PHS site.	The project will demonstrate pumping working simultaneously with generation, using variable speed machines for added flexibility. Benefits will include extending power range and response; emulating virtual inertia; and improving operations, maintenance and efficiency using condition monitoring and smart controls (XFLEX HYDRO, 2019a).
PHS with hydraulic short circuit using fixed-speed machines and optimised equipment	Grand Maison, France; Alqueva, Portugal	Fixed-speed pumping will be operated simultaneously with units in generation mode, together with optimisation software for improved flexibility.	The project will allow frequency response when consuming power from the grid. At Grand Maison, a new Pelton turbine will be used to regulate the load and improve generating efficiency. At Alqueva, extended unit operation of fixed-speed reversible turbines will be tested, targeting an almost continuous power output from zero to rated power. Both demonstrations will implement advanced software to optimise performance (XFLEX HYDRO, 2019c).

Note: PHS = pumped hydropower storage; PV = photovoltaic.



V. IMPLEMENTATION REQUIREMENTS: CHECKLIST

TECHNICAL REQUIREMENTS	**Hardware:** • PHS facilities that fulfil grid connection requirements • For coupled schemes, wind and (floating) solar PV power plants • Where applicable, upgraded PHS facilities with new pump and turbine technologies for improved frequency control and power regulation • Operation monitoring equipment
	Software: • Optimisation software for the operation of hybrid systems, including PHS, VRE and batteries • Advanced weather forecasting tools for improved power generation forecasting • Automation of various processes and information exchange related to system operation
POLICIES NEEDED	• Provision of an enabling environment supporting the deployment and scale-up of enhanced PHS with complementary VRE generation and/or storage systems • Policies that can help complement the seasonal variability and availability of various power generating resources
REGULATORY REQUIREMENTS	**Wholesale market:** • Incentives for flexible operation, such as remuneration mechanisms and stacking revenues from various flexibility services • Increased time granularity in electricity markets providing better price signals closer to the real-time delivery of power • Innovative ancillary services, incentivising the provision of flexible services to system operators
	Grid codes: • Development of technical standards for the deployment of hybrid systems that create dispatchable renewable power plants, such as PHS coupled with VRE and batteries
STAKEHOLDER ROLES AND RESPONSIBILITIES	**System operators:** • Together with regulators, define technical requirements for the provision of ancillary services needed for the integration of high shares of VRE into the system • Design and develop new dispatch strategies that consider the flexibility potential of PHS coupled with additional VRE and/or storage infrastructure
	Generators: • Participate in ancillary service markets, where established, providing flexibility options to system operators in addition to power supply and trade • Increase deployment of hybrid PHS-VRE schemes via the diversification of a power generation portfolio or via partnerships, such as co-operation with research and development institutes, equipment manufacturers, financial institutions, project developers

ABBREVIATIONS

EDP	Energias de Portugal
GW	gigawatt
GWh	gigawatt-hour
kW	kilowatt
MW	megawatt
MWh	megawatt-hour
PHS	pumped hydropower storage
PV	photovoltaic
VRE	variable renewable energy

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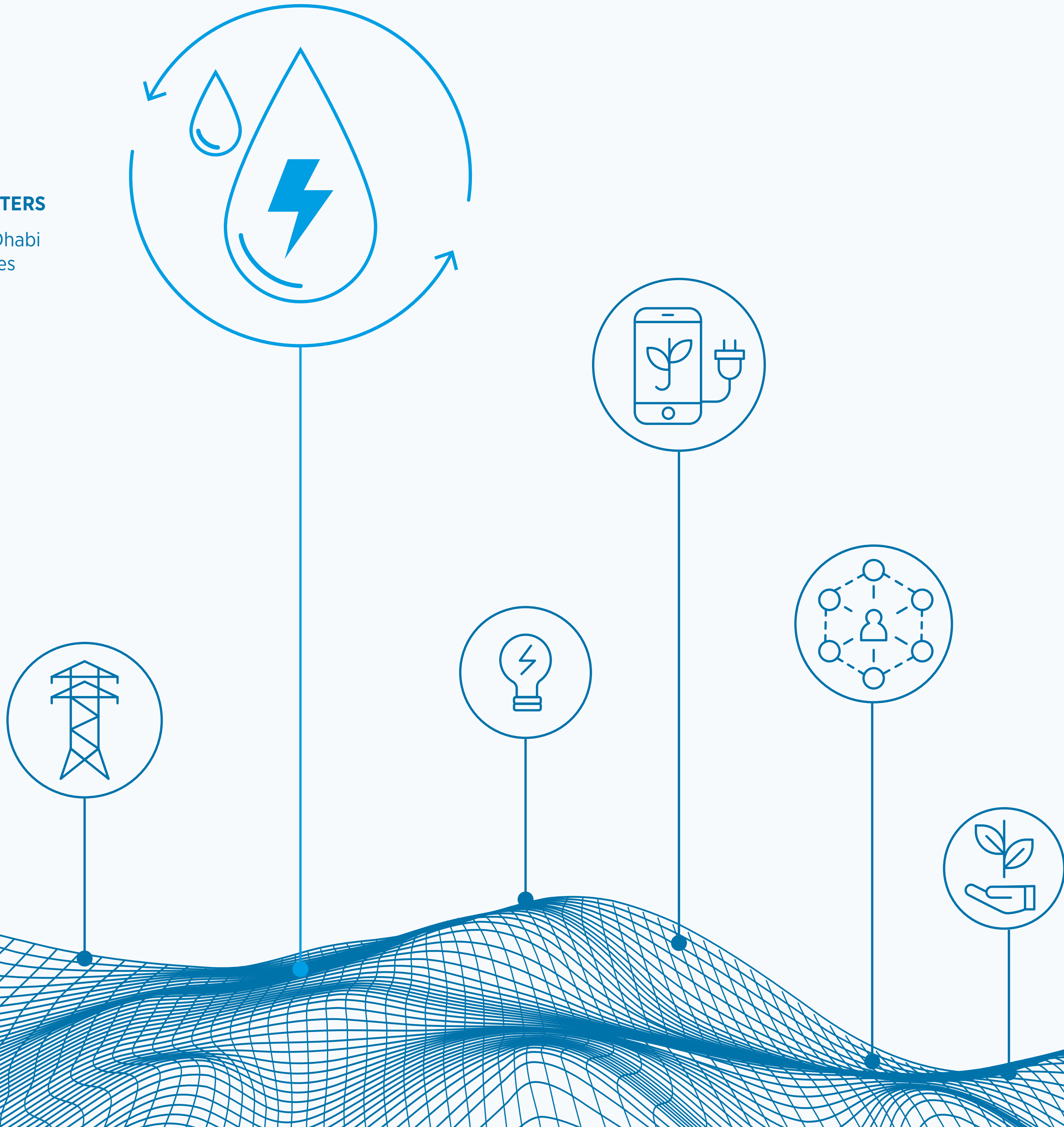
INNOVATIVE OPERATION OF PUMPED HYDROPOWER STORAGE
INNOVATION LANDSCAPE BRIEF



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