Pumped Storage
Hydropower
International Forum

Capabilities,
Costs & Innovation
Working Group

Pumped Storage Hydropower Capabilities and Costs

Capabilities, Costs & Innovation Working Group

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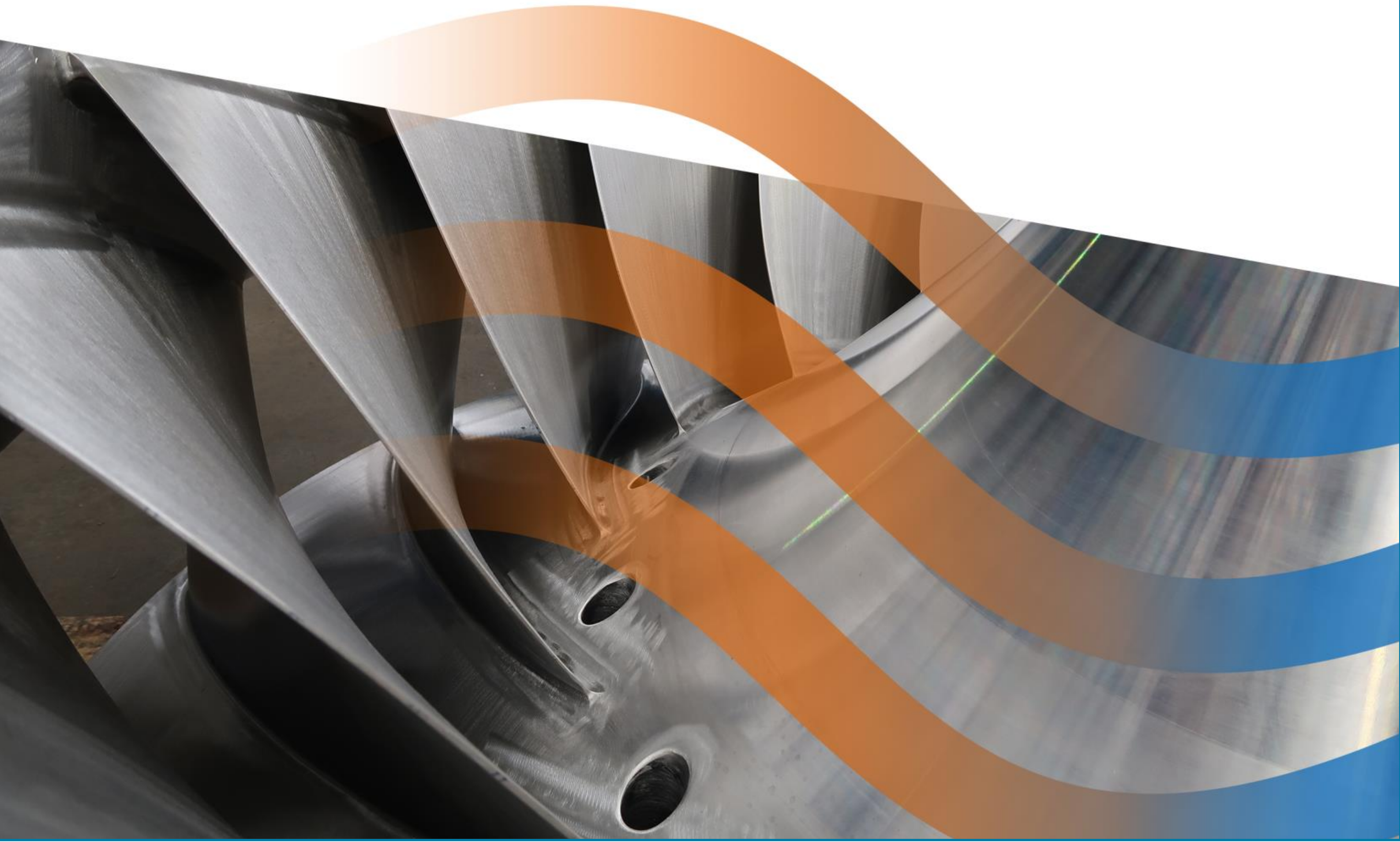

About the International Forum on Pumped Storage Hydropower

Launched in 2020 and jointly chaired by the U.S. Department of Energy and the International Hydropower Association (IHA), the International Forum on Pumped Storage Hydropower (IFPSH) is a multi-stakeholder platform that brings together expertise from governments, the hydropower industry, financial institutions, academia and NGOs to shape and enhance the role of pumped storage hydropower (PSH) in future power systems.

The Steering Committee of the IFPSH, comprised of governments, intergovernmental organisations and multilateral development banks, established three Working Groups (WG) covering 'Policy and Market Frameworks', 'Sustainability', and 'Capabilities, Costs and Innovation' to help address the common challenges facing PSH development.

The Policy & Market Frameworks WG, led by GE Renewable Energy, developed a global position paper to identify the current market and investment barriers and opportunities for PSH development, as well as recommendations to de-risk investment. With thanks to over 20 supporting organisations, country and region-specific recommendations were developed for the U.S., the U.K., Africa, Australia, Brazil, Latin-America and the Caribbean, Europe, Southeast Asia, India and China.

The Sustainability WG, led by EDF, aims to provide guidance and recommendations on mitigating adverse impacts that may occur in the development of PSH to ensure that it can best support the clean energy transition in the most sustainable way.

The Costs, Capabilities and Innovation WG, led by Voith Hydro, seeks to raise awareness on the role of PSH in addressing the needs of future power systems and deepen understanding about its potential, capabilities, costs, and innovation.

Disclaimer

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Executive Summary

- The need for energy storage and flexibility is growing with increasing shares of variable renewable energy (VRE) and phasing out of fossil power plants.

- Grid stability, grid resilience, and sufficient flexibility options for load-generation balancing will be central to planning for low carbon electricity grids of the future.

- Pumped storage hydropower (PSH) is a proven and low-cost solution for high capacity, long duration energy storage. PSH can support large penetration of VRE, such as wind and solar, into the power system by compensating for their variability and provides a range of grid services such as mechanical inertia, frequency regulation and voltage control, operating reserves and black start, which will be increasingly important in ensuring grid reliability.

- A range of flexibility options are available and they should be assessed based on system characteristics and priorities. Policymakers should assess the long-term storage needs of their future power system now, so that the most efficient options, although they may take longer to build, are not lost. Comparisons between energy storage and flexibility options must follow a consistent, technology neutral approach that considers all impacts and benefits.

- Simplistic capital expenditures (CAPEX) comparisons can be misleading without taking replacement life cycles and maintenance costs into consideration. For example, the total cost of PSH is significantly cheaper than of lithium-ion battery systems when accounting for PSH's full lifespan of 80 years and considering storage capacity in the GWh class.

- Given their different response characteristics and round-trip cycle efficiencies, PSH and battery systems can complement each other in a cost-effective and reliable power system.

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Introduction

Pumped storage hydropower (PSH) operates by storing electricity in the form of gravitational potential energy through pumping water from a lower to an upper reservoir (Figure 1). There are two principal categories of pumped storage projects:

- Pure or closed-loop: these projects produce power only from water that has been previously pumped to an upper reservoir and there is no significant natural inflow of water.
- Combined, mixed or open-loop: combined projects harness both pumped water and natural inflows to produce power. In a closed-loop development, the upper reservoir is located off-stream, while in an open-loop system the upper reservoir is generally located on-stream and has natural inflows. Thus, in an open-loop system, there is always a share of electricity that may be generated without the requirement for pumping, as in a conventional hydropower facility.

With a total installed capacity of over 160 GW, pumped storage currently accounts for more than 90 percent of grid scale energy storage capacity globally. It is a mature and reliable technology capable of storing energy for daily or weekly cycles and up to months, as well as seasonal applications, depending on project scale and configurations.

First built since the end of 19th century, PSH has continuously evolved to suit the needs of changing power systems, providing a suite of essential flexibility services to support the changing needs of power systems. PSH can provide a range of services including:

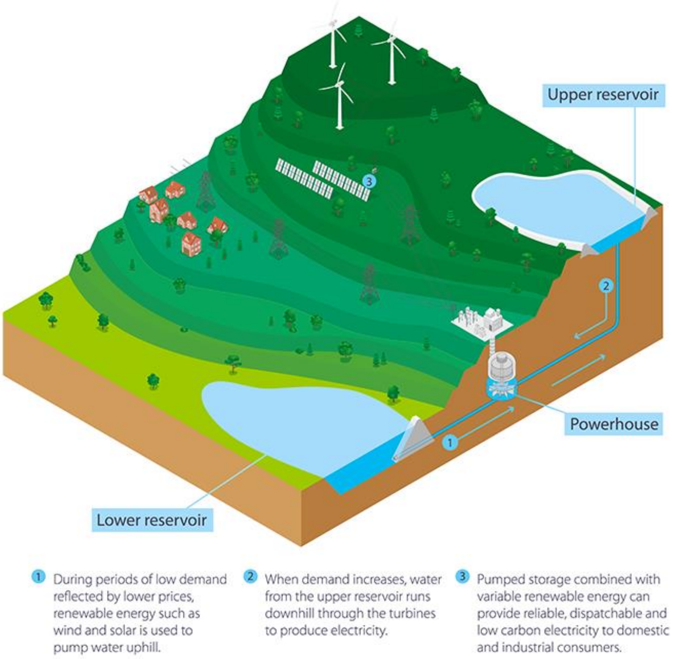


Figure 1. Illustration of a pumped storage hydropower plant

- support large penetration of variable renewable energy (VRE), such as wind and solar, into the power system by compensating for their variability and by providing many ancillary services necessary for power system operations;
- provide large energy storage capacity for storing, or shifting large amounts of energy from one period to another, thus contributing to stable, economical, and reliable operation of the power system;
- help avoid or reduce the curtailments of VRE in case of over generation, or provide the needed energy in case of under generation due to weather forecast errors or during times of low VRE supply;
- firm up the variable generation of wind and solar into firm power output;
- offer rotating inertia to stabilize the power system during disturbances such as in case of generator or transmission outages;
- reduce the needs for operating reserves from conventional thermal power plants;
- reduce the ramping, starts/stops, and partial load operation of existing conventional generation fleet, thus making the operation of these units more efficient and reducing their wear and tear; and
- provide black start service to restore the power system after a blackout.

However, PSH is often absent in discussions concerning the need and deployment of energy storage due to lack of understanding about its capabilities, costs, and potential.

This report aims to improve understanding on the role of PSH in the clean energy transition and compare PSH capabilities and costs with other sources of energy storage and system flexibility options.

Enormous growth opportunity for energy storage

Summary

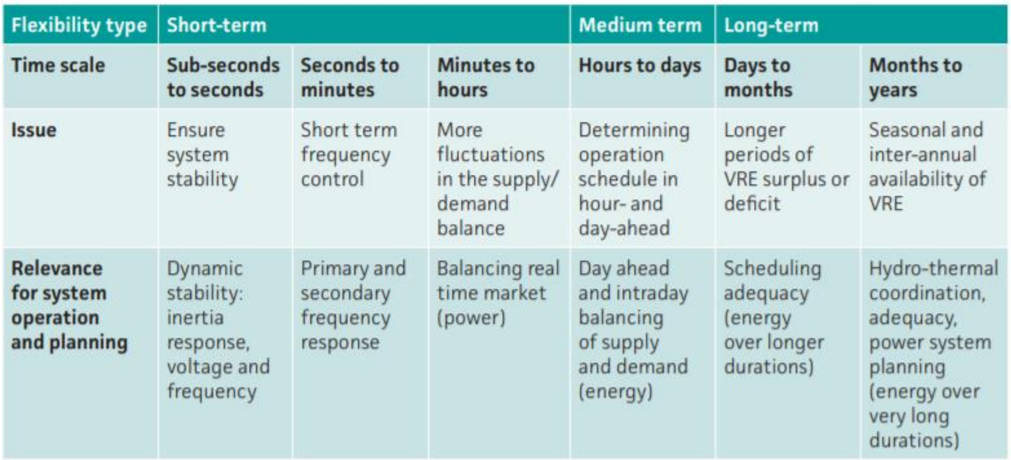
- Electricity supply from variable renewable energy (VRE) is detached from demand and it becomes necessary to store surplus VRE energy and to compensate under-production of VRE.
- Energy storage options are available to correct for imbalances in electricity supply and demand across different timescales, such as daily, weekly or even seasonal storage.
- It is estimated that future energy consumption and storage requirements will reach 500 TWh and 20 TW, which is more than an order of magnitude larger than at present.

In the majority of today's power systems, fossil fuels and nuclear power are the primary energy sources for electricity generation. Energy storage was inherently provided by nature in the form of gas, oil, coal or uranium and electricity was generated according to demand, meaning that generation always had to match the demand. In the past energy storage took place before production.

As major economies commit to reach zero emissions by 2050, the world is transitioning to renewable energy sources. However, electricity generation from variable renewable energy (VRE) such as wind and solar photovoltaics (PV) is detached from demand and it becomes necessary to store surplus energy from VRE sources at times when the generation exceeds the demand for electricity and vice versa. This changes the sequence of storage and generation.

Energy storage will be essential to correct for imbalances in electricity supply and demand across different timescales, and a range of storage options are available such as daily, weekly or even seasonal energy storage services to help manage changes in supply and demand. Table 1 gives a brief overview of flexibility services, as defined by IEA. (1)

Table 1. Different timescales of power system flexibility (IEA, 2018)



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

A simple estimation could provide an idea on the prospective scale of future energy consumption and storage requirements. Currently, per capita electricity consumption in advanced economies is in the range of 5 to 15 MWh per person per year. The complete elimination of fossil fuels from the economy entails doubling or tripling of electricity production. (2) Thus, global electricity production may reach 20 MWh per person per year. With global population expected to reach about 10 billion by 2050 and developing countries catch up to per capita energy consumption in today's advanced economies, then global electricity production of about 200,000 TWh per year will be required. If we assume that one day of energy storage is required, with sufficient storage power capacity to be delivered over 24 hours, then storage energy and power of about 500 TWh and 20 TW will be needed, which is more than an order of magnitude larger than at present. (3)

Greater flexibility needs with higher shares of VRE

Summary

- The increasing need for essential grid service has become important to ensure the stability and reliability of the power system.
- Mechanical inertia provides an important stabilising effect to the grid.
- While thermal power plants that provide inertia are gradually phasing out, maintaining a minimal amount of mechanical inertia will be crucial in higher VRE scenarios.

With the rapid rollout of variable renewables such as wind and solar, there is an increasing need for essential grid services (i.e. ancillary services) to balance the grid and ensure power system stability and reliability. Some of the key services include:

- **Reactive power control** – management of voltage levels on the grid and is an ancillary service that units can provide either automatically or manually.

- **Frequency control** – when technologies adjust their power output in response to an imbalance in supply and demand on the grid. Typically, the market requires primary and secondary frequency services, and in some cases, very fast frequency response (within 1 or 2 seconds) is emerging as a service.

- **Spinning and fast ramping reserve** – when units are held in a ready-state so that they can be ramped up or down in minutes to support grid balancing.

- **Black start** – involves restarting a power generation system, from a complete shutdown and island-operating state, without any power feed from the grid. The service is intended to restore the grid after a blackout event.

- **Inertia** – offers instantaneous support to grid frequency variations, traditionally through large rotating mechanical generators. The total rotating mechanical inertia is a huge kinetic energy storage system, and it is provided by synchronous electrical machines directly connected to the power grid, such as PSH units; whereas electronic-interfaced energy sources, such as batteries, can provide synthetic inertia, which is almost instantaneous.

Across the world, we mainly rely on flexible fossil generation, hydropower (hydropower with reservoir storage and PSH) and curtailment of VRE to balance the grid. Hydropower plants are a primary contributor to power system flexibility, being relied on to balance timely power demand changes. Hydropower contributes to most grid services and provide flexible power generation. Hydropower plants can ramp up and down and be restarted and stopped quickly and smoothly. This flexibility makes reservoir storage hydropower and pumped-storage hydropower extremely valuable for electricity security.

According to the IEA Hydropower Special Market Report, coal, gas, and oil account for over half of the world's flexible supply capacity, while hydropower (including pumped storage hydropower, storage hydropower and run-of-river hydropower) contribute about one-third of global flexibility based on hour-to-hour ramping needs (see Figure 2). (4)

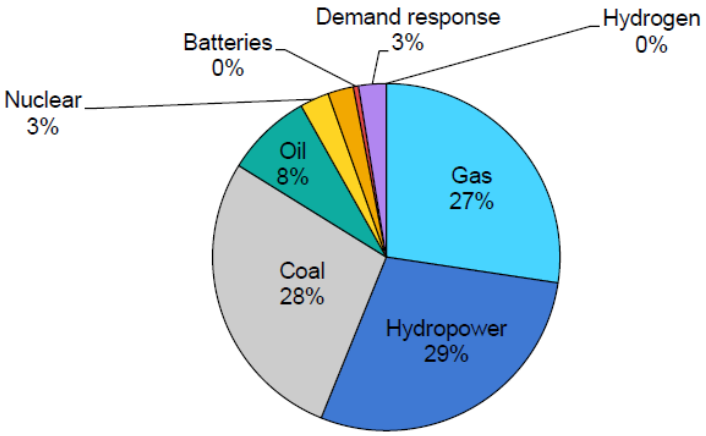


Figure 2. Global electricity system flexibility by source (IEA, 2021)

As the world transitions away from carbon intensive fossil fuel generation, low carbon and dispatchable flexibility options, such as pumped storage hydropower, will be required to ensure grid reliability and security of supply. Without the appropriate policy and market frameworks, the investors have been reluctant despite the cost effectiveness of many low-carbon long duration storage technologies. Electricity grids around the world risk being unnecessarily locked into high-carbon sources for backup and flexibility provisions.

India - Increased ramping needs with higher shares of VRE

IEA estimated that India would require fast and very steep ramping reserves by 2030, which could be provided by additional PSH. Over the next decade, wind and solar VRE is expected to increase in India from 7% in 2019 to almost 25% in 2030. (5)

This dramatic increase in VRE will lead to exponential ramping needs, from 16 GW maximum hourly ramps in 2020 to 68 GW (an increase of 7% to 19% of daily peak net load), and the 3-hour ramps might increase from 40 GW to 342 GW (an increase of 18% to 40% of daily peak net load).

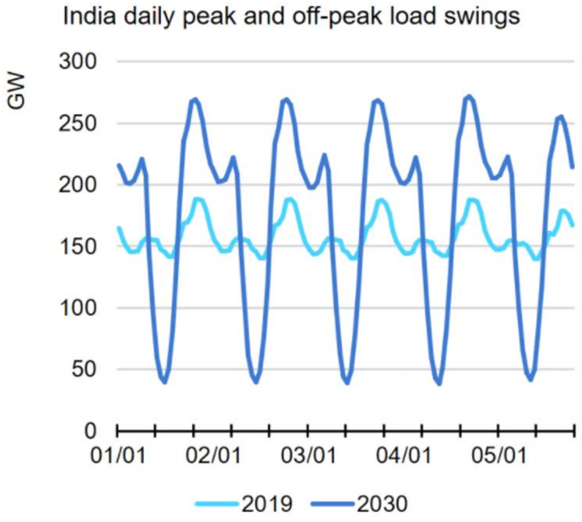


Figure 3. India load swings and load duration curves, 1-5 January 2019 and 2030 (IEA World Energy Outlook STEPS scenario). The net load duration curve represents the net demand profile of the entire year from highest value to lowest, with the x-axis representing the number of periods in the year in which net demand exceeds that value.

Reduced system inertia due to higher shares of VRE

With the ongoing transformation towards low carbon energy systems, thermal power plants are gradually being phased out and power systems with high shares of VRE will lose a substantial part of their mechanical inertia. Figure 4 shows the decline in system-level inertia in India between 2014 and 2018, as the share of renewable energy increases. (6)

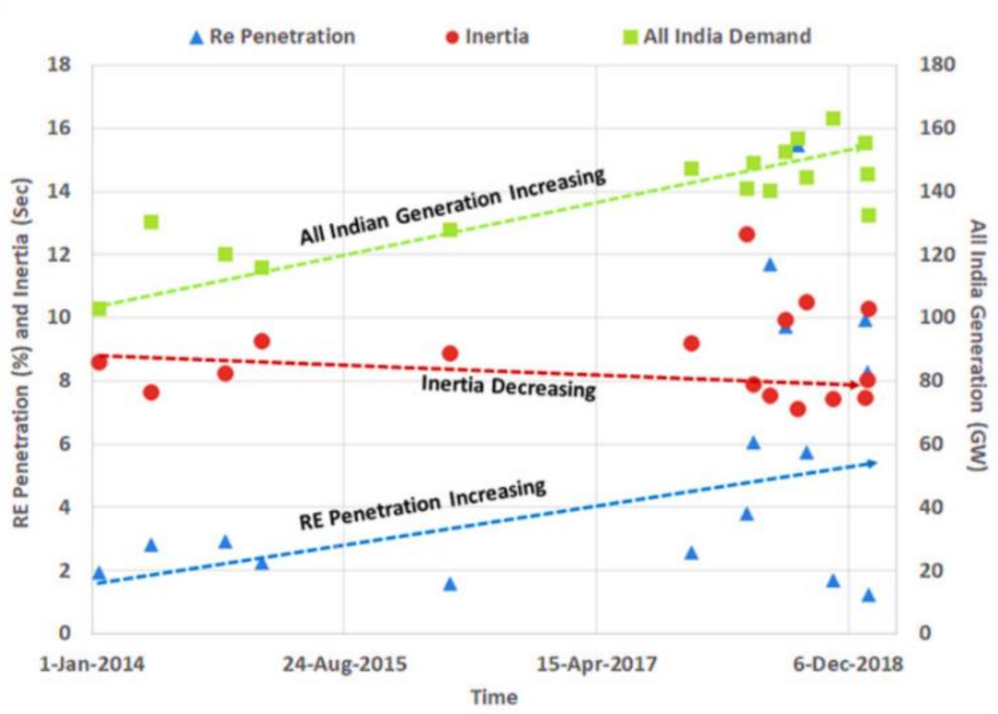


Figure 4. Inertia and renewables penetration in India, 2014-2018 (IEA, Renewables Integration in India 2021)

Mechanical inertia provides an important "self-healing" stabilisation effect to the grid: spinning generators resist drops in frequency when a power plant or transmission fails, and this mechanical inertia, or stored kinetic energy, limits the gradient and the total drop of the grid frequency.

To date, rotating mechanical inertia was provided by conventional fossil, nuclear and hydropower synchronous generators driven by giant steam turbines. The abundance of these power sources meant that in the planning and operations of electrical grids, the provision of mechanical inertia were taken for granted in the past.

As power systems around the world evolve with increasing penetrations of inverter-based resources, e.g. wind, solar photovoltaics (PV) and battery storage, that do not inherently provide mechanical rotating inertia, questions have emerged about the minimum necessary amount of mechanical or synthetic inertia for grid stability and resilience.

Comparing PSH with other energy storage technologies

Summary

- Comparing the technical capabilities of PSH with other energy storage technologies, PSH is one of the most mature technologies and has a high round trip efficiency.
- PSH also has a greater number of storage cycles and a longer total lifetime compared to chemical batteries.
- In general, PSH achieves economies of scale for high capacity, long-duration energy storage

While PSH is by far the largest source of grid-connected energy storage globally, there exists a range of other technologies on the market. Innovation continues to improve performance and costs in electricity storage both for mature and emerging systems, hence this section aims to evaluate PSH against an array of options available.

The U.S. Department of Energy's 2020 Grid Energy Storage Technology Cost and Performance Assessment provided a comprehensive evaluation of commercially available energy storage technologies with respect to system size and duration capabilities. Cost and performance characteristics were analysed for the state of technology development in 2020 and projected characteristics in 2030. (7)

Drawing on latest data from US DOE's Assessment, this paper compiled cost and performance characteristics of energy storage technologies for 100 MW and 4-hour duration systems and for 1,000/100 MW and 10-hour duration systems in shown in Table 2 and Table 3, respectively.[1]

Table 2 compares energy storage technologies with system size of 100 MW and 4-hour storage duration, which includes pumped storage hydropower (PSH), lithium-ion phosphate (LFP) batteries, lead-acid batteries, vanadium redox flow batteries, compressed-air energy storage (CAES) and hydrogen energy storage systems (bidirectional).[2] These technologies, with the exception of hydrogen, have commercially operating references that are more than 10-years old.

Table 3 compares characteristics of energy storage technologies providing 10 hours of storage. The size of most energy storage systems in Table 3 are the same as in Table 2 (100 MW), except for PSH and CAES, for which it was deemed that a larger 1,000 MW size would be more representative for 10-hour storage systems.

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[1] In their assessment, the authors have included grid energy storage technologies with at least 2-hour storage capabilities, therefore the scope did not cover flywheels, ultra-capacitors, and other energy storage technologies with shorter duration of storage.

[2] In 2020 Grid Energy Storage Technology Cost and Performance Assessment, hydrogen energy storage was only evaluated based on 10-hour storage duration, therefore it is for comparison purposes in both Tables 2 and 3 shown with 10-hour storage.

Table 2. Comparison of energy storage technologies for 100 MW and 4-hour duration in 2020 and 2030

Comparison metrics	Type of energy storage	Pumped Storage Hydro	Li-Ion Battery Storage (LFP)	Lead Acid Battery Storage	Vanadium RF Battery Storage	CAES compressed air	Hydrogen bidirect. with fuel cells
		100 MW / 4hr	100 MW / 4hr	100 MW / 4hr	100 MW / 4hr	100 MW / 4hr	100 MW / 10hr
Technical Capabilities	Technical readiness level (TRL)	9	9	9	7	7	6
	Inertia for grid resilience	Mechanical	Synthetic	Synthetic	Synthetic	Mechanical	no reference
	Reactive power control	Yes	Yes	Yes	Yes	Yes	Yes
	Black start capability	Yes	Yes	Yes	Yes	Yes	Yes
Performance Metrics	Round trip efficiency (%*)	80%	86%	79%	68%	52%	35%
	Response time from standstill to full generation / load (s*)	65...120 / 80...360	1...4	1...4	1...4	600 / 240	< 1
	Number of storage cycles (#*)	13,870	2,000	739	5,201	10,403	10.403
	Calendar lifetime (yrs*)	40	10	12	15	30	30
Costs 2020	avg. power CAPEX (USD/kW*)	2,046	1,541	1,544	2,070	1,168	3.117
	avg. energy CAPEX (USD/kWh*)	511	385	386	517	292	312
	avg. fixed O & M (USD/kW/yr*)	30	3.79	5	5.9	16.2	28.5
	effective CAPEX (USD/kW based on PSH life of 80 years and 6% discount rate**)	2,710	4,570	5,070	8,370	3,340	8,900
Estimated costs 2030	avg. power CAPEX (USD/kW*)	2,046	1,081	1,322	1,656	1,168	1.612
	avg. energy CAPEX (USD/kWh*)	511	270	330	414	292	161
	avg. fixed O & M (USD/kW/yr*)	30	3.1	4.19	4.83	16.2	28.5
	effective CAPEX (USD/kW based on PSH life of 80 years and 6% discount rate**)	2,710	3,210	3,920	4,910	3,340	4,620

Table 3. Comparison of energy storage technologies for 1,000/100 MW and 10-hour duration in 2020 and 2030

Comparison metrics	**Type of energy storage**	**Pumped Storage Hydro**	**Li-Ion Battery Storage (LFP)**	**Lead Acid Battery Storage**	**Vanadium RF Battery Storage**	**CAES compressed air**	**Hydrogen bidirect. with fuel cells**
		1000 MW / 10hr	100 MW / 10hr	100 MW / 10hr	100 MW / 10hr	1000 MW / 10hr	100 MW / 10hr
Costs 2020	avg. power CAPEX (USD/kW*)	2,202	3,565	3,558	3,994	1,089	3.117
	avg. energy CAPEX (USD/kWh*)	220	356	356	399	109	312
	avg. fixed O & M (USD/kW/yr*)	30	8.82	12.04	11.3	8.74	28.5
	effective CAPEX (USD/kW based on PSH life of 80 years and 6% discount rate**)	2,910	10,570	11,720	16,170	3,110	8,890
Estimated costs 2030	avg. power CAPEX (USD/kW*)	2,202	2,471	3,050	3,187	1,089	1.612
	avg. energy CAPEX (USD/kWh*)	220	247	305	319	109	161
	av. fixed O & M (USD/kW/yr*)	30	7.23	9.87	9.26	8.74	28.5
	effective CAPEX (USD/kW based on PSH life of 80 years and 6% discount rate**)	2,910	8,130	9,050	9,450	3,110	4,600

* Source: US DOE, 2020 Grid Energy Storage Technology Cost and Performance Assessment
** Estimation based on the value of initial investment at end of lifetime including the replacement cost at every end of life period.

Comparing the technical capabilities of PSH with other energy storage technologies, some of the key observations and conclusions that can be derived based on data presented in Tables 2 and 3 include the following:

Response time

Response time is the time taken for a storage device to respond after receiving a dispatch signal from the grid. All of the presented energy storage technologies are very flexible with fast ramping capabilities, which makes them highly suitable to provide operational flexibility to power systems with high penetration of variable renewables.

Batteries are fast response systems that can dispatch stored energy in milliseconds. These systems which are coupled to the grid via power electronics (inverters) can serve very rapid, enhanced frequency response; providing synthetic inertia to the grid, as opposed to instantaneous physical inertia.

PSH can reach full load in a few minutes from turbine stand-still, or less than 60 seconds from turbine spinning state. Advanced installations can be even quicker: for example, units at UK’s Dinorwig pumped storage station can be pre-synchronised to the grid and kept spinning-in-air, and ramped from this ready-state to full load in 12 seconds. It is also worth noting that variable speed turbine-generator systems can now enable PSH for enhanced responses in case of frequency deviations and grid faults.

Roundtrip efficiency

Roundtrip efficiency is electrical energy output from the storage device compared to energy input, whereby a high efficiency means lower energy losses during a storage cycle. Most energy storage technologies have a very high estimated round-trip efficiency (RTE), ranging from 68% to 86%, except for CAES (52%) and bidirectional hydrogen energy storage systems (35%). PSH has high operating efficiency in the range of 70-85%, meaning most of the energy used during pumping (charging) is returned to the grid in turbine mode (discharging).

Lifetime and number of storage cycles

PSH has the highest estimated value for the number of storage cycles during its lifetime, estimated at about 14,000. PSH is followed by CAES and hydrogen energy storage with estimated 10,000 cycles. Of battery technologies, vanadium redox flow batteries have the highest number of cycles (about 5,200), followed by lithium-ion batteries (about 2,000) and lead-acid batteries (about 750 cycles).

The lifetime of battery storage technologies is estimated to be in the 10-15 years range, while for the CAES and hydrogen energy systems it is projected to be about 30 years. The estimated lifetime of PSH plants is the longest and ranges from 40 to 80 years.

The majority of today’s PSH stations were built some forty years ago. Yet, they are still providing vital services to our power systems today. With occasional refurbishment, these long-term assets can last for many decades to come.

Cost

Capital expenditure (CAPEX) represents the upfront investment costs to develop a storage facility; often quoted as cost per unit of power capacity (kW) installed (typically for rapid response systems), or cost per unit of energy storage (kWh) installed (for diurnal / bulk scale systems).

The total capital expenditures (CAPEX) for PSH and CAES systems are about the same in $/kW for both 4- and 10-hour storage systems, while the energy CAPEX, expressed in $/kWh, are much lower for 10-hour systems. On the other hand, for battery systems, the CAPEX in $/kW is much higher for 10-hour systems, while the CAPEX in $/kWh is about the same for both 4- and 10-hour systems.

Extended discussion
While not directly covered in the above comparison tables, there are other important attributes to consider in the comparison of capabilities and costs:

Effective lifecycle costs

As PSH has a much longer life than many technologies, simplistic capital expenditures (CAPEX) comparisons can be misleading as any comparisons need to take account of replacement life-cycles. When total life cycle costs of storage including replacement, are included, even with cost predictions looking ahead to 2030, PSH is highly competitive as battery systems degrade and periodically need replacing after around 10 years.
The total cost of PSH is significantly cheaper than of lithium-ion battery systems when accounting for PSH's full lifespan of 80 years and considering storage capacity in the GWh class. With a weighted average cost of capital of 6% and an 80-year time horizon, which is a realistic lifetime for PSH, the net present cost of PSH could be 43% lower than lithium-ion batteries for 100 MW and 4h storage duration and 63.5% less for a 1,000W and 10-hour storage system.[3]

The cost of PSH remains below the estimated price of lithium-ion, in 2030, even after taking account of anticipated cost reductions for chemical batteries. The chart below shows PSH's long-term cost advantage over other sources of energy storage technologies.

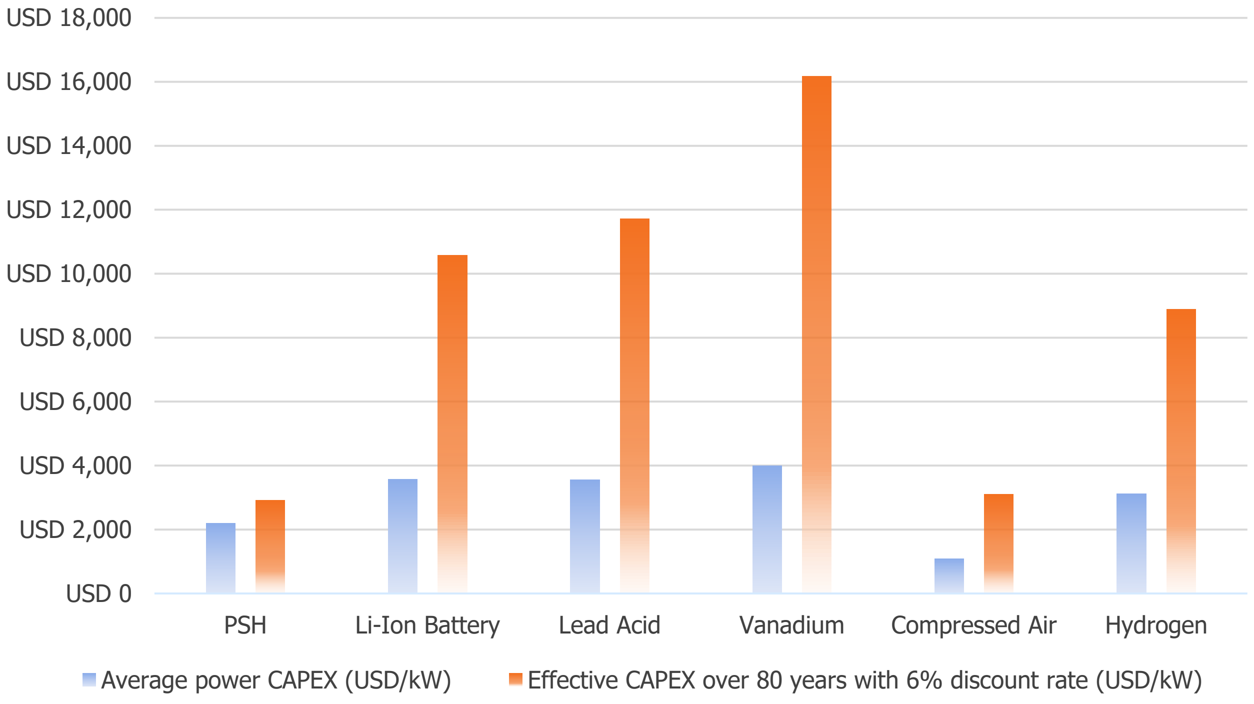

Figure 5. Comparison of effective lifetime costs of energy storage technologies over 80 years (10-hour duration, 2020)

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[3] The Weighted Average Cost of Capital serves as the discount rate for calculating the Net Present Value (NPV) to evaluate investment opportunities, often used as a proxy for discount rate.

Discharge duration

Discharge duration refers to the amount of time the energy storage system can provide output at its full power before depleting its energy capacity. In general, PSH achieves economies of scale for high capacity, long duration energy storage.[3] Bulk scale systems can be used for long duration storage, with PSH in many cases able to generate for up to 12 hours, if the plant is being charged and discharged over a 24-hour period for example (diurnal cycling).

Battery systems typically provide short duration storage, meaning charge and discharge cycling over short timescales rather than extended periods, i.e. they are well-suited to handle the intra-day variability of wind and solar and changes in demand profile during the day. Battery systems also have advantage in small-scale, modular installations that are quick to implement and are suitable for household/community scale applications. With reduction of battery costs, more utility-scale facilities are being built such as the 100 MW / 129 MWh Li-Ion project in South Australia by Tesla.

Comparing with battery systems, PSH typically has much higher installed power (MW) and stored energy (MWh) capacity due to economies of scale. With low energy capacity costs, PSH excels at long-duration energy storage, which will be useful to cope with long periods of supply profile change, such as the seasonality of wind and solar generation in high renewables systems.

Technological maturity and innovations

PSH is by far the most established and proven form of grid-scale energy storage. The Engeweiher pumped storage plant in Switzerland was built in 1907 and is still providing service today.

The other bulk storage systems, such as CAES, and hydrogen, are less established, mainly at demonstration stage with some commercial projects.

Batteries, particularly lead-acid, have been used for many years for small-scale, mostly for non-grid applications; and commercial utility-scale projects using other types of battery storage are now emerging.

While PSH is a mature technology, new advanced technologies and operating strategies are continuously being developed to enhance PSH's performance, for example, PSH turbines synchronised to the grid can provide stable generation and fast ramping services for network stability, including 'instantaneous' physical inertia, as well as variable speed options for enhanced frequency response.

The U.S. Department of Energy's HydroWIRES (Water Innovation for a Resilient Electricity System) Initiative is conducting R&D for a range of innovative technology solutions, and the European Commission's XFLEX HYDRO project will demonstrate innovations such as ternary units, variable speed units, hydraulic short circuit and units spinning in air.[5,6] Further information could be found in "Innovative PSH Configurations and Uses" report under this Working Group.

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[3] While the costs of CAES systems were comparable to PSH, it is important to note that there are only two CAES plants in operation around the world (290-MW Huntorf in Germany, commissioned in 1978, and 110-MW McIntosh plant in Alabama, commissioned in early 1991) and there are currently no new planned CAES projects due to concerns of carbon emissions, rock cavern's limited fatigue cycling capabilities, relatively low efficiency and long start up times.

[5] https://www.energy.gov/eere/water/hydrowires-initiative

[6] https://xflexhydro.net/

Scale-up potential

The modular design and compact spatial requirements of battery systems offer the advantage of modular, easy-to-site installations, and often relatively short construction periods.

PSH is often dismissed in the discussion of growth potential due to being geographically constrained, however, research by the Australian National University highlighted over 600,000 potential sites for low-impact off-river pumped storage development. (8) There is also growing interest in retrofitting pumped storage at disused mines, underground caverns, non-powered dams and reservoir hydropower stations.[7]

Sustainability

With respect to the sustainability considerations, each energy storage technology has its own sustainability challenges in terms of on-site impacts as well as life cycle impacts across production and end-of-life treatment. Kruger at all. performed a detailed comparison of battery and PSH in terms of raw material cost, land requirement, annual lifetime investment cost and carbon emission. (9)

For battery systems, the extraction of raw materials entails sustainability concerns includes, for example, child labour, health and safety hazards in informal work, poverty and pollution. End of life treatment of battery systems will become a recycling challenge especially for developing countries, with few systems in place to enable reuse and recycling in a circular economy for batteries. (10) For example, PSH can have significant impacts on local landscape, including: flooding of land to form the reservoirs; construction of a infrastructure including dam, pipework, power station and electricity transmission lines. Further discussion on sustainability considerations are discussed in the Working Paper on Sustainability of Pumped Storage Hydropower, developed by the Sustainability Working Group of the Forum.

Conclusion

To conclude, for long duration, bulk energy storage systems, PSH offers the highest lifetime roundtrip efficiency, longest lifetime and effective reaction times. While CAPEX for new large-scale projects can be relatively high, the unit energy costs are among the most competitive. Battery projects above 100 MW are becoming viable too, as costs improve for grid-scale applications, and their modular design allows flexibility in project location and construction, although degradation of components mean that replacement costs have to be factored in. Coupling PSH plants with batteries, either physically at the same site or through transmission lines, is also an important future avenue.

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[7] Further information could be found in "Innovative PSH Configurations and Uses" report under this Working Group.

Discussion on PSH and other flexibility options

Summary

- There are four major categories of flexibility in the energy system to ensure load-generation balance, they include flexible generation, electricity networks, energy storage and distributed energy options
- These options should be considered in the comprehensive modelling and planning for future power grids
- Curtailment may prevent system-wide oversupply but it could be costly
- The continued use of flexible thermal power generation for is at odds with the goal to transition to low carbon electricity grids.
- Retrofitting and modernising existing assets is a major opportunity for increasing power system flexibility.

In addition to energy storage technologies, there are other power system flexibility options that should be considered in the comprehensive modelling and planning for future power grids. The imbalance between supply and demand, also known as "residual load", is actively controlled by four main categories of power system flexibility:

- **Flexible generation** (including conventional and renewable generation as well as curtailment);
- **Electricity networks** (such as electricity import and export, grid extension and reinforcements);
- **Energy storage** (such as PSH, chemical batteries and hydrogen) and
- **Distributed energy options** (including demand side management).

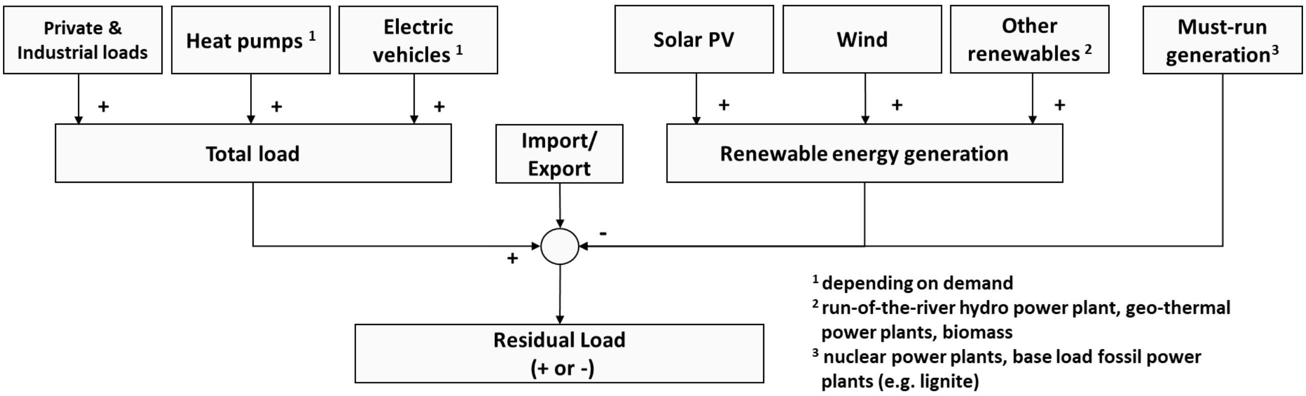

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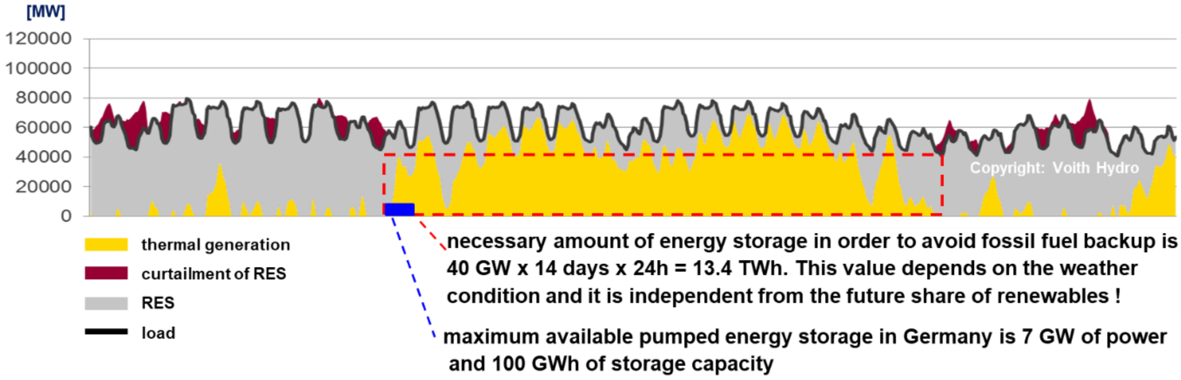
Figure 6. Definition of residual load (11)

The residual load can be positive or negative, and is actively controlled by flexible thermal power plants, by energy storage systems, by electricity import and export options, by curtailments of renewables, or by managing the electricity demand. (11)

This chapter will discuss how a mix of flexibility options and strategies have been deployed in real world applications.

Germany - “Dunkelflaute” renewable energy drought

Germany's Energiewende, the transition from fossil and nuclear to renewable energy sources was met with the problem of Dunkelflaute, i.e., solar and wind energy drought in the winter months which can last between one to three weeks. The figure below provides a real-world example from Germany during two weeks of renewable energy drought in December 2007.



necessary amount of energy storage in order to avoid fossil fuel backup is 40 GW x 14 days x 24h = 13.4 TWh. This value depends on the weather condition and it is independent from the future share of renewables !

maximum available pumped energy storage in Germany is 7 GW of power and 100 GWh of storage capacity

Figure 7. Projection of a one month of load-generation balance in Germany with 2-weeks of wind calms & low sunshine irradiation in 2050 assuming 80% of VRE (solar and wind).

The total energy storage capacity of PSH in Germany is around 100 GWh assuming all upper reservoirs were full (blue rectangle). However, in order to provide enough energy for a renewable energy drought of two weeks, a total of 13.4 TWh in energy storage would be needed to provide back-up power (red dotted rectangle), which would require seasonal storage systems.

Without seasonal storage capabilities, up to 80 GW of fossil or nuclear installed capacity were needed as a back-up in parallel with VRE, as seen today in 2021.

To compensate for the volatility of renewable energy, the main flexibility options in Germany today include:

1. **Enhancing flexibility of existing fossil generation:**
   The cheapest flexibility resource was to utilize existing flexible thermal power generation units and reduce their minimum load. Must-run and base load operated power plants could be converted to more flexible generation, which would allow daily start-ups and shut-downs of fossil fuel power plants and increase load gradients when possible. However, the continued use of fossil generation is at odds with the goal to transition to low carbon electricity grids.

2. **Renewables curtailment:**
   Curtailment of renewable energy generation and re-dispatch of thermal power plants can help ensure load-generation balance, but it can be very costly. [8] The Transmission System Operator (TSO) spent more than €1.4 billion for the re-dispatch of 20.4 TWh and 5.5 TWh curtailment of renewables in Germany in 2017. 5.5 TWh curtailment per year is equal to the annual production of 825 wind turbines with 2.5 MW each.

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[8] Re-dispatch measures could be the start or stop of fast reserves, e.g. conventional generation like gas turbines or storage facilities but also coal-fired plants in the strategic reserve.

3. **Demand Side Management:**
   Demand Side Management (DSM) includes load rejections (disconnecting consumers in the industrial and private sectors), peak shaving or load shifting. DSM was not widely deployed in Germany.

4. **Increase flexibility of existing combined heat and power plants (CHP):**
   Including new hot water storage tanks with electrical heaters in existing CHP can decouple the district heating demand from electricity generation for up to 16 hours. These flexibilized CHPs are perceived from the electrical grid operator (TSO) as an electricity storage system, similar to PSH or chemical batteries. The total potential of the existing CHP in Germany can reach a potential of 48 GWh_{el}. This is about 50% of the current total storage capacity of PSH (100 GWh). [5]

5. **Transmission expansion and new interconnectors:**
   Improve and increase the grid transfer capacity within the federal states and neighbouring countries. Connecting the high voltage grid of Germany with storage hydropower in Norway and Sweden using new HVDC cables are cross-border applications. For transmission expansion and new interconnectors in practice is the 625 km Nordlink between Germany and Norway. The CAPEX for this HVDC sea cable link with a transmission capacity up to 1,400 MW are around €2 billion.

6. **Seasonal energy storage:**
   Invest in new bulk energy storage systems (e.g. conventional storage hydropower, seasonal PSH, hydrogen storage or others). However, there has been no new investment in seasonal storage in Germany.

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[5] Example for a flexibilized CHP Nürnberg-Sandreuth, Germany (source: n-ergie.de, 2017):
CAPEX: 12mio€ for the heat storage system + 4mio€ for the electrical heaters,
Construction time: 1.5 years,
Hot water tank size: 70m high, approx. 26 m diameter,
Capacity of storage: 1,500 MWh,
Electrical heaters: 2 x 25MWel,
Hot water temperature range: 60°C to 113°C

Morocco - Load management with PSH and curtailment

Morocco's generation and storage load curves provide an example to understand how grid operators balance the grid with flexibility options such as flexible fossil generation (gas, LNG, diesel and coal), storage with PSH and curtailment of VREs.

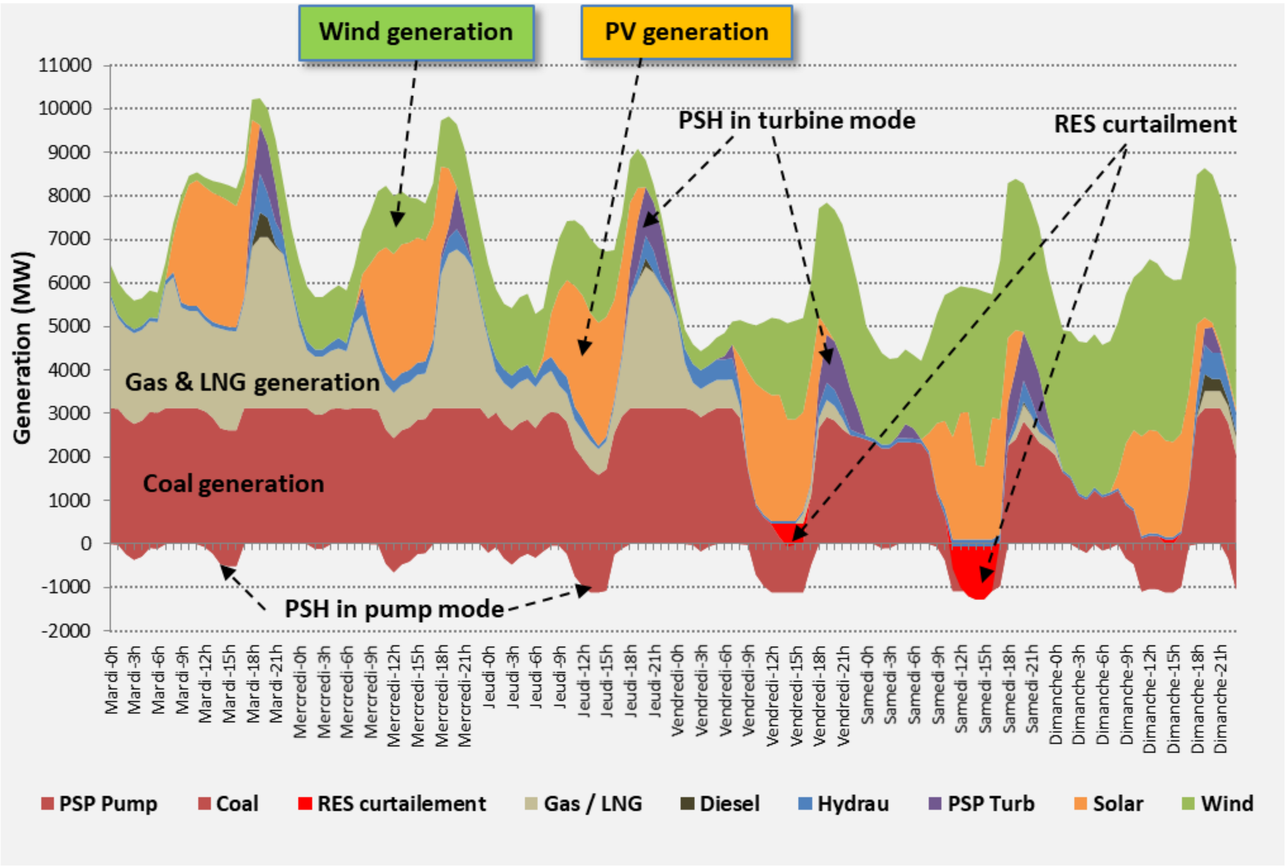

Figure 8. Projection of a 6-day load-generation balance in Morocco by 2025 assuming 30% of solar and wind penetration rate. "Hydrau" in the legend refers to hydro power not including PSH. (12)

The two red areas in the graph represents curtailment of VRE where the VRE generation is significantly higher than the load.

Curtailment of VRE (i.e. purposeful reduction in renewable electricity output below the levels that could otherwise have been produced) is required to prevent system-wide oversupply as all flexible fossil generation is shut down and PSH serves as a demand-side response resource in pumping mode.

This example shows that the PSH is operating in a daily cycling mode as energy stored in pumping mode is released in the following day.

United States – PSH and new flexibility technologies

According to the U.S. Hydropower Market Report, in 2019, hydropower capacity (80.25 GW) accounted for 6.7% of installed electricity generation capacity in the U.S. and its generation (274 TWh) represented 6.6% of all electricity generated and 38% of generation from renewables domestically produced. (13)

Hydropower is extensively used in the United States for power system flexibility and resilience. In most states with installed hydropower plants, the hydropower provides more frequency regulation and reserves than its share of installed capacity. Hydropower represents less than 6.7% of U.S. electricity generation capacity but provides approximately 40% of black start resources.

In the United States, the operational flexibility in power systems is mostly provided by flexible generation and energy storage, with some flexibility also provided by demand response and other demand side management technologies.

Regarding energy storage technologies, about 94% of grid-scale energy storage capacity in the United States is provided by PSH (21.9 GW), with batteries providing most of the remaining 6%. Flexible generation mostly includes combustion turbines and hydropower plants with reservoirs.

In addition to combustion turbines, other thermal generation technologies with flexible operational characteristics can also contribute to system flexibility (e.g. combined cycle plants). There have been efforts in recent years to utilize variable renewables, such as wind power to provide a certain amount of flexibility in their operations. A few electricity markets in the United States are also introducing flexibility products as market mechanisms for maintaining the needed flexibility in power system operations.

Finally, hybrid energy storage systems are currently being considered as potential sources of operational flexibility in future power systems characterized by very high penetrations of variable renewables, such as wind and solar generation. For example, many new solar PV systems are being proposed as hybrid "solar plus storage" systems.

In addition, research is being conducted to investigate potential benefits of adding energy storage to other less flexible generation technologies, thus adding some flexibility to their operations. For example, the generation of "pure" run-of-river hydropower plants (those without any reservoir storage capabilities) depends on the water flows in the river and does not provide for flexibility in their operation. An energy storage technology added to the run-of-river hydropower plant may provide for a "virtual reservoir", thus enabling certain amount of operational flexibility and allow the hybrid system to provide ancillary services as well.

Australia - Retrofitting of existing hydropower and transmission expansion

In Australia, the need for flexible and dispatchable energy generation and storage has been steadily growing as higher shares of wind and solar connect to the grid, displacing ageing thermal generators.

At present, the main sources of system flexibility in the Australian National Electricity Market (NEM) come from the operation of open cycle gas turbines, various forms of conventional hydropower plant, and a growing number of grid-scale batteries. There are also three existing PSH storage plants in operation. Recently, there has been a growing curtailment of VRE and, during times of rare peak system stress events, out of market reserves can be called upon via the "Reliability and Emergency Reserve Trader" (RERT) mechanism. These reserves predominantly consist of demand response from major energy users involving short term load shedding, for example from aluminium smelters.

The inherent variability and uncertainty of the Australian energy system will continue to increase as Australia's clean energy transition continues. To manage the challenges associated with a more variable energy mix, Australia will require investment in new flexible generation and storage assets. Additional future flexibility is expected to be provided by a combination of modifications and changed operating roles for some existing hydropower, additional PSH and open cycle gas turbines, growth in grid-scale batteries and domestic battery applications (including the aggregation of domestic batteries and electric vehicles to form virtual power plants) and other sizeable demand-side response.

Australia's two largest hydropower schemes - in the Snowy Mountain region (NSW) and the island state of Tasmania - are poised to play a major role in enabling an efficient transition in the NEM towards a lower carbon future. The Snowy 2.0 PSH scheme is currently under construction, and when completed will provide 2,000MW of flexible capacity with 350,000 MWh of storage. The future role of the Tasmanian hydropower system in the national market is also expanding significantly, with the planned development of a 1,500MW Marinus Link HVDC subsea interconnector between Tasmania and mainland Australia. Known as the 'Battery of the Nation', this project will enable the Tasmanian hydropower system to play a greater role in providing flexibility services nationally. The project includes plans to develop a 750MW pumped storage hydro plant at Lake Cethana with 20 hours of storage and to upgrade some existing hydropower stations to increase their capacity by up to 300MW in total. Once completed, these major projects will provide over 3.5GW of new firming capabilities to underpin a deeper decarbonisation of Australia's energy sector.

Summary

The need for energy storage and flexibility is growing with increasing shares of variable renewable energy (VRE) and phasing out of fossil power plants. Grid stability, grid resilience, and sufficient flexibility options for load-generation balancing will be central to planning for low carbon electricity grids of the future. A range of flexibility options are available and they should be assessed based on system characteristics and priorities. Policymakers should assess the long-term storage needs of their future power system now, so that the most efficient options, although they may take longer to build, are not lost.

Pumped storage hydropower (PSH) is a proven and low-cost solution for high capacity, long duration energy storage. PSH has a higher round-trip efficiency compared to compressed air energy storage and hydrogen; and provides a range of grid services such as mechanical inertia, frequency regulation and voltage control, operating reserves and black start, which will be increasingly important in ensuring grid reliability.

Comparisons between energy storage and flexibility options must follow a consistent, technology neutral approach that considers all impacts and benefits. Simplistic capital expenditures (CAPEX) comparisons can be misleading without taking replacement life cycles and maintenance costs into consideration. For example, the total cost of PSH is significantly cheaper than of lithium-ion battery systems when accounting for PSH’s full lifespan of 80 years and considering storage capacity in the GWh class.

Overall there are merits and demerits of each energy storage and flexibility technology, and the best system will depend on the project. For each project considered, economic, environmental, and social cost accounting must be done in detail to enable proper decision-making decisions. With different characteristics and roundtrip efficiencies, chemical batteries and PSH can complement each other in the power system to support a balanced system that is both cost-effective and reliable.

Acronyms and Abbreviations

CAES	Compressed-Air Energy Storage
CHP	combined heat and power plants
DOE	U.S. Department of Energy
DSM	Demand Side Management
GW	GW gigawatt
HVDC	high-voltage direct current
IEA	International Energy Agency
LNG	Liquefied natural gas
MW	Megawatts
MWh	Megawatt-hour
NEM	National Electricity Market
NPV	Net Present Value
NSW	Snowy Mountains, New South Wales
PSH	Pumped Storage Hydropower
PSPP	Pumped-Storage Power Plant
PV	Photovoltaic
RERT	Reliability and Emergency Reserve Trader
RES	Renewable energy sources
TSO	Transmission System Operator
VRE	variable renewable energy

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