Pumped Storage Hydropower International Forum

Policy and Market Frameworks Working Group

Pump it up: Recommendations for urgent investment in pumped storage hydropower to back the clean energy transition

International Forum on Pumped Storage Hydropower Policy and Market Frameworks Working Group: Global Paper

September 2021

Pumped Storage Hydropower International Forum

Policy and Market Frameworks Working Group

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

Working Group Members:

The Working Group was led by GE Renewable Energy.

Acknowledgements, contributors, and credits

The report would not be possible without the drafting and editing support of the following

- Jerome Bridon, GE
- Debbie Mursch, GE
- Dhruv Bhatnagar, PNNL

The report benefited from extensive contributions and comments from members of the Policy and Markets Working Group of the International Forum on Pumped Storage Hydropower, they include (cited alphabetically by first name):

Aditya Prasad Das (POSOCO), Alex Slocum (MIT), Amitabh Tripathi (WAPCOS), André Makishi (Energy Research Office Brazil (EPE)), Aniruddha Kumar (MNRE), Arnaud Koehl (EDF), Arturo Alarcon (InterAmerican Development Bank), Brittney Elzarei (The European Association for Storage of Energy (EASE)), Bruno Trouille (Mott Macdonald), Chi-Jen Yang (MIT), Colin Wain (Hydro Tasmania), DI Peter Stettner, Head of Market Strategy (ANDRITZ HYDRO GmbH), Dr. Gundula Konrad, Maintenance and Asset Management (VERBUND Hydro Power GmbH), Dr Judith Plummer Braeckman (University of Cambridge Institute for Sustainability Leadership), Earl Hamil (Worley), Erfaneh Sharifi (US DOE), Francois Halgand (Tractebel Engie), Gabriel dos Santos Cruz Rocha (Worley), Garry Wilks (SSER), Ghislain Weisrock, Guilherme Arantes (Brazilian Development Bank (BNDES)), Heymi Bahar (IEA), Jamie Maxton (SSER), Jan-Louis Janse van Vuuren (REH Group), JC Sandberg (GE), Jean-Christophe Fueeg (Federal Office for Energy, Swiss Government), Jean-Jacques Fry (EDF), .Jean-Pierre Maurand (Meridiam), JS Bawa (CEA), K Ramanathan (The Energy Resources Institute (TERI)), Kaamil Ansar and Arsh Dhillon Sekhon (Ansar Law Firm), KVS Baba (POSOCO), Lucinda Tonge (CEC), Luke Middleton (Hydro Tasmania), Mark Wilson (ILI Energy), Martin Kennedy (GE), Matthias Haller (Federal Office for Energy, Swiss Government), Michael Manwaring (McMillen Jacobs Associates), Mikael Bergmark (Pumped Hydro Storage), Mike McWilliams (McWilliams Energy), Nicholas Trojas (SSER), Nick Miller (HickoryLedge LLC), Paulo Sospiro (University of Florence), Peter Bauhofer (TIWAG-Tiroler Wasserkraft AG), Phillip Hannam (World Bank), Probodh Mallick (Marubeni), Prof. Anton Schleiss (École Polytechnique Fédérale de Lausanne), Prof. Arun Kumar (Indian Institute of Technology, Roorkee), Professor Dimitar Kisliakov, Puguh Imanto (World Bank), Pyush Dogra (World Bank), PM Nanda (Grrenko), Akshita Gupta (IITR), Rajiv Vishnoi (THDC), Reju Reghuveeran (KSEBL), Richard Taylor (RMT Renewables Consulting Ltd.), Roberto Brandão (GESEL), S K Soonee (POSOCO), Sam Bockenhauer (US DOE), Sanna Markkanen (University of Cambridge Institute for Sustainability Leadership), Santiago Rivas Navarro (Alpiq), Sean Kelly (SSER), Simon Bailey (Jacobs), Sofia Siachou (Greek Public Power Corporation), Sourav Mandal (POSOCO), SR Narasimhan (POSOCO), Usayed Casewit (World Bank), VERBUND Hydro Power GmbH, Victor de Genot (AFRY), Vincent Clausse (GE), VK Singh (NEEPCO), Yuetao Xie (CREEI)

The International Hydropower Association Staff who contributed to the report include:

- Eddie Rich, CEO
- Alex Campbell, Head of Research and Policy
- Rebecca Ellis, Energy Policy Manager
- Samuel Law, Analyst
- David Samuel, Senior Analyst
- Olivia McCue, Research and Policy Intern
- Cheng Cheng Wu, Research and Policy Intern

Table of Contents

Tables and Figures

Executive Summary

Pumped storage hydropower (PSH) works on a simple principle. At times of low demand when electricity prices tend to be lower water is pumped from a lower reservoir to an upper reservoir, and then released at times of high demand to drive a turbine and generate electricity. Today, in 2021, it is the dominant form of energy storage on electricity grids across the globe, providing daily, weekly, and seasonal storage, with over 160GW of installed generating capacity and around 9,000GWh of energy stored.

As the world relies more and more on variable sources of electricity like solar PV and wind, the demand for energy storage will grow. Even conservative estimates of the level of variable renewable deployment predict a ten-fold increase. To keep global warming below 1.5 degrees Celsius, many international organisations foresee significantly more deployment[1].

However, variable generation places new demands on grids.

Periods of excess supply of VRE will need to be curtailed unless there is flexible demand to absorb the surplus; conversely, prolonged periods when the sun does not shine, or the wind does not blow will mean system operators will need to turn to other sources of electricity to keep the lights on. Over much shorter time frames, variable renewables cannot provide the many ancillary services such as spinning and contingency reserves that are vital for keeping electricity grids stable.

In these circumstances, there is a role for shorter duration storage technologies such as batteries which perform well for up to four hours - but of course weather does not always accommodate these timeframes. Low carbon, long duration storage is, and will be, essential to maintain security of supply and avoid wasted energy in a renewables' dominated grid.

Historically PSH was built to take advantage of excess generation, usually at night, from relatively inflexible sources of baseload generation such as nuclear power and coal. However, the conditions that supported the development of PSH are changing. Baseload resources are retiring, many energy markets are no longer dominated by vertically integrated entities, and price fluctuations are no longer easy to model based on a simple difference between predicted day and night prices.

There is a real risk that without appropriate policy frameworks, PSH as a highly cost-effective, low impact technology will not be deployed at the scale needed to support an efficient and reliable energy transition.

The reasons for this are multiple. In common with other large low carbon infrastructure, much of the lifetime cost of PSH is incurred during construction, with a high capital cost; this means that without a degree of long-term revenue certainty, investors are unwilling to invest *even if* the technology is highly cost effective and sustainable. Historically developers were governments, government owned businesses or vertically integrated utilities, and as such were able to consider the wide range of benefits provided by PSH in a holistic, system-wide manner, with some certainty as to revenues generated by long duration storage projects. But now, in liberalized markets in particular, it is difficult for investors to judge what sources of revenue will be available over the long lifetime of PSH assets.

This is compounded by the fact that in many markets a number of the vital grid services that PSH can, and does provide, are not fully remunerated. For example, storage solutions charged from renewable resources and able to provide energy over long durations in case of unfavourable climatic conditions (a sustained lack of wind or cloudy days) are not rewarded for delivering this low carbon electricity. Instead, they are compensated on par with carbon fuelled resources in both energy and capacity markets. Other services, such as inertia, are often a requirement of grid interconnection and receive no remuneration at all.

The services that PSH provides can be considered transmission services as well as generation services. In the past this was not a problem for vertically integrated utilities, as they could assess the benefits of PSH to the

[1] The IEA in their *Net Zero by 2050 – A Roadmap for the Global Energy Sector* report, indicated that global generation from renewables needs to triple by 2030 and grow eightfold by 2050 (based on 2020 figures). They anticipate that solar and wind will generate over 23,000 TWh by 2050. To meet 1.5°C scenarios with no or limited overshoot, IPCC *Special Report 15* states renewables will increase across all 1.5° scenarios, and renewables (including hydro) shall makeup 38–88% of primary energy.

whole system to guarantee the continuity of electricity supply, but it poses a challenge in liberalized markets. Rules designed to protect consumers by limiting the activities of transmission system operators inadvertently restrict access to more cost-effective ways of managing grids. For example, it may be cheaper to procure a PSH project to ease congestion than to build new transmission cable infrastructure, while at the same time delivering generation services, but transmission system operators are often not able to procure PSH in this manner.

Any significant new infrastructure requires appropriate planning and permitting; however, it is important that these are timely and proportionate, avoid complex regulatory approval processes, and legislative uncertainty does not disincentivise investment in the most efficient low carbon solutions. Planning authorities can learn from the best practices in other regimes to ensure issues are addressed in good time, and take advantage of the availability of internationally recognised assessment mechanisms, such as the IHA Sustainability's tools[2], which can further provide reassurance that good practice is being met in the development of PSH.

More generally, many energy system planning authorities lack targets for long duration storage and the models used do not fully reflect the system-wide benefits that long-duration storage can deliver, particularly in facilitating an effective and cost-efficient integration of higher shares of VRE on their grids. Up to now, the successful deployment of wind and solar PV globally has been a result of clear goals and policy interventions to systematically support the deployment of those technologies, despite the high upfront costs. As this deployment continues, it will be more and more difficult to ensure system reliability while meeting clean energy goals without resources like long duration storage to support renewable integration.

No two electricity markets are identical – different mixes of energy resources, regulatory frameworks, market structures and historical characteristics mean that there is no 'one size fits all' approach to securing the place of long duration storage technologies like PSH. However, this report identifies key **recommendations** that are applicable in many contexts.

[2] IHA Sustainability Ltd (IHAS), a not-for-profit corporate entity created to carry out the sustainability work programme of International Hydropower Association, manages the Hydropower Sustainability Tools on behalf of the multistakeholder Hydropower Sustainability Council and its Governance Committee. This Council includes representatives of social, community and environmental organisations, governments, commercial and development banks, and the hydropower sector. The Hydropower Sustainability Tools include the Hydropower Sustainability Guidelines on Good International Industry Practice (HGIIP), Hydropower Sustainability Assessment Protocol (HSAP) and Hydropower Sustainability ESG Gap Analysis Tool (HESG). More recently, the tools have been developed into a new global Standard for hydropower and provided the basis for additional How-to Guides.

Summary of what we need to do now:

1) Policymakers should assess the long-term storage needs of their future power system now, so that the most efficient options, which may take longer to build, are not lost.

2) Comparisons between energy storage and flexibility options must follow a consistent, technology neutral approach that considers all impacts and benefits.

3) Providers of essential electricity grid, storage, and flexibility services should be remunerated for all services that they provide.

4) Licensing and permitting arrangements must be timely, proportionate and take advantage of the range of internationally recognised sustainability tools.

5) Investors in long lasting assets, such as PSH, must have long-term visibility of revenues, with risk that is shared fairly to deliver the lowest overall cost to society in the long-term.

6) Existing hydropower assets and prospective sites should be assessed and mapped for their potential to provide the most efficient long duration storage.

7) Green recovery programmes should include and support PSH, and green finance mechanisms should incentivise PSH.

Modelling and System planning

In order to avoid unnecessary future costs as more and more variable renewables come onto the system, policymakers need to *assess the long-term storage needs of their future power system now*. This is a low cost, no regrets option.

These *assessments should follow a consistent, technology neutral approach* to evaluating storage and other flexibility options that accounts for the full spectrum of grid needs including deep storage, grid services, and environmental impacts, including land use and decommissioning.

Opportunities for *sharing assets such as PSH across regional borders* should be given full consideration, including coordination with transmission expansion and augmentation strategies.

Prospective PSH sites should be mapped to understand the full development potential, including the potential from existing mines.

Existing hydropower assets should be assessed for their potential to be converted to PSH or modernized to make better use of existing energy storage operations.

Existing PSH assets should be assessed for their potential to be upgraded to the latest technology to enhance the benefits they bring to the system.

Licensing and permitting

Licensing and permitting arrangements must be timely and proportionate and take advantage of the range of internationally recognised tools[3] for assessing the environmental and social impact of hydropower (including conventional and new technology based pumped storage hydropower). These tools can be deployed by policymakers with confidence.

Electricity market design

In designing market products, policymakers must ensure that those products *provide enough long-term revenue visibility* to stimulate investment in the most efficient low carbon technologies. There are many options to do so, including ensuring appropriate contract lengths, allowing for 'bundled' grid services products and introducing income floor mechanisms.

Providers of ancillary services such as frequency control, inertial response and voltage control should be *remunerated for those services* as well as providers of transmission congestion solutions.

Where PSH can participate in ancillary services markets, those *market rules should be stress tested* to ensure they are not inadvertently excluding the most efficient technologies, and low carbon solutions should be prioritized.

Transmission system operators should be allowed and encouraged to *procure* PSH services for which they are responsible, and where that would be the most efficient way of managing grids.

Market rules should be reformed to allow participation of technologies, such as PSH, across transmission and generation markets, if necessary, through the creation of a new storage asset category.

Green Recovery

PSH should be included in green recovery programmes and be part of a sustainable approach to build back better and strengthen grid resilience while helping to meet 2050 net zero targets.

Finance

PSH should be permitted and encouraged to actively participate in finance mechanisms like green bonds or impact bonds.

Governments should consider *recoverable grants* that allow the sharing of project risks between Government and developers to support private investment and development.

[3] As noted above the IHA Sustainability has a range of tools internationally recognised. For further information on international tools, please see International Forum on Pumped Storage Hydropower's (IFPSH) WG.2 paper on Sustainability.

Pumped Storage Hydropower International Forum

Policy and Market Frameworks Working Group

Chapter 1

Pumped storage hydropower’s place in the global energy transition

Summary

- The global energy transition from fossil fuels to renewable energy will require large quantities of long duration storage.
- Pumped storage hydropower is a proven storage technology that offers a cost-effective way to provide reliable large-scale balancing and grid services.
- Countries and regions are developing storage targets, estimated requirements, and need to ensure PSH is included as part of critical infrastructure planning.

1.1 Introduction

As the world relies more and more on variable renewable sources of energy like solar photovoltaic (PV) and wind, the demand for energy storage is only going to grow as variable generation places demands on grids. Without flexible demand to absorb the surplus, periods of excess supply will need to be curtailed, and prolonged periods when weather conditions are not right will mean system operators have to turn to other sources of electricity to keep the lights on.

Pumped storage hydropower (PSH) works on a simple principle. At times of low demand (and low electricity prices), water is pumped from a lower reservoir to upper reservoir, and then released at times of high demand (and high prices) to drive a turbine and generate electricity. Today it is the dominant form of energy storage on electricity grids across the globe with over 160GW installed and around 9,000GWh of energy storage.

While some markets have begun to assess storage needs, there is a real risk that without appropriate policy frameworks, this highly cost-effective, low impact technology will not be deployed at the scale needed to support an efficient and reliable energy transition.

This International Forum on Pumped Storage Hydropower (IFPSH) report on policy and markets identifies key **recommendations** that are applicable in many contexts to enable a global energy transition.
In addition to the main report, supplementary regional and country-specific reports have been written to provide detailed contexts and recommendations on the potential for pumped storage hydropower. These are available at https://pumped-storage-forum.hydropower.org and include the following:

- Africa
- Australia
- Brazil
- China
- European regional paper, as well as annexes for:
    - Austria
    - Greece
    - Italy
    - Portugal
    - Switzerland
- India
- Latin American countries
- South East Asia
- United Kingdom
- United States

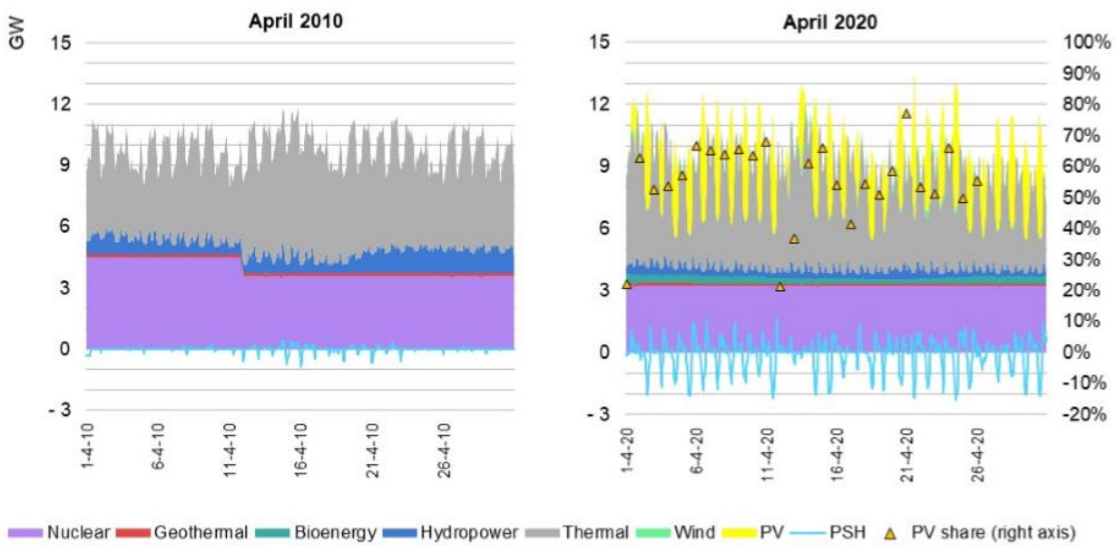
1.2 Global energy transition

Tackling climate change is one of the most challenging issues facing the world today. Central to solving climate change is the need for a rapid transition of the energy sector from fossil fuels to decarbonised production and renewable sources. The energy transition has become a reality globally, in every single region, and is accelerating as more and more countries place renewables at the core of their post-pandemic recovery plans. In addition to post-pandemic targets, over 40 nations are in the process of introducing legislative targets to achieve net zero emissions by 2050.

Today, hydropower is the most significant provider of renewable electricity (over 15% of the total global electricity generation), however, the share from variable renewables is expected to continue increasing. With strong government support, global installed capacity has grown from approximately 1 GW of solar PV and 17 GW of wind in 2000 to approximately 650 GW of each today (1). Under IRENA's Transforming Energy Scenario for 2050, 86% of electricity generation will be renewable, and 60% would come from solar and wind, with installed capacities of over 6,000 GW (wind) and 8,500 GW (solar), in 2050 (2).

This huge increase in variable renewables will radically change how electricity grids are planned and operated (see Figure 1 for an example of Kyushu Japan's grid is already impacted by the increase in VRE). To compensate for periods of low supply – for example during prolonged spells of cloudy weather and / or low wind – there must be reliable, low carbon alternatives. Conversely, to avoid curtailment (i.e., wasting energy from solar or wind when there is excess supply relative to demand) there must be flexible sources of demand. According to the IEA, over 250 TWh of variable renewable electricity was curtailed in 2020 – nearly the equivalent of Spain's annual electricity demand. If this wasted clean generation could have been stored for later use, 180 million MT CO2 emissions could have been avoided (3). Moreover, avoiding curtailment also improves the utilization of renewables and contributes to higher investment returns for such projects.

Figure 1 – Example of increased variant renewable generation for hourly electricity generation in Kyushu, Japan, April 2010 and 2020.



Source: IEA, 2021 (4)

And over much shorter timeframes – seconds and minutes – ancillary grid services such as frequency control will continue to be needed on electricity grids; however, solar and wind are rarely able to provide these services due to their variability and/or their innate technical characteristics.

The need for energy storage is not new. Indeed, for years, PSH has offered a cost-effective way to provide reliable large-scale balancing and grid services, and today accounts for more than 95% of the global storage capacity on electricity grids with a huge installed base of more than 160 GW and an estimated 9,000 TWh of storage. What is new is the likely demand to meet the challenges described above.

In some markets an early assessment of storage needs – including long term storage – has begun, but there is a very mixed picture globally, with a lack of consistent methodological approaches that may or may not consider all relevant factors. Table 1 highlights some examples of existing targets or estimated needs in different electricity markets around the world.

Table 1 – Examples of existing targets or estimated needs in different electricity markets

National/ regional entity	Storage target/ identified need
Australia	Australia's market operator identifies that 6-19GW of dispatchable generation and storage (dependent on modelled scenario) will be needed by 2040 to support VRE integration. Most early investment focussing on PSH and utility-scale batteries. In the state of New South Wales, they have indicated they need 2 GW by 2030 with a focus on PSH.
China	Draft 14th Five-Year Plan (2021-2025) highlights energy storage as a priority to enhance consuming and storing renewable energy. Currently 52 GW of PSH is under construction, and the NEA plan includes 62 GW to be constructed by 2030 and 120 GW by 2035 and modernising PSH industry system with advanced technology (5).
France	French "Programmation Pluriannuelle de l'Énergie" forecasts an additional +1.5 GW of PSH before 2035 (6).
Germany	German "Netzentwiklungsplan 2021" forecasts, in 2035, an additional +0.4 GW of PSH, +3.4 GW of grid batteries and +13.5 GW of PV-associated batteries (7)
Great Britain (note that the GB electricity market is separate from Northern Ireland's)	Estimates that GB could need at least 13 GW by 2030 and 60 GW of flexible capacity to meet 2050 climate goals – fifteen times current energy storage capacity (8)
India	375 GW needed by 2030, focus on batteries (27 GW) and PSH (10 GW).
United States	As of March 2020, 67 new PSH projects with a total potential capacity of 52.48 GW are in various stages of permitting and development. California's Regulator, California Public Utilities Commission (CPUC), has identified the need for 1 GW of PSH, or other long-duration storage with similar attributes, by 2026. Studies suggest up to 55 GW will be needed by 2045. Other states that have outlined energy storage mandates include: Oregon, New York. States with energy storage targets include: Massachusetts, Nevada, New Jersey, and Virginia (9)

1.3 Long duration storage and PSH as a key enabler

The value of long duration storage capacity from PSH or conventional hydropower resources has been well established in many countries. For example, Costa Rica, with a heavy reliance on hydropower, in the order of 90% of the country's total installed capacity, uses reservoir storage on its system to manage seasonal dry periods of lower flow on its run-of-river hydropower plants, and both short-term and longer-term seasonal droughts from its wind generation fleet.

PSH is today the most competitive bulk energy storage solution. As with any large infrastructure project the initial capital expenditure (CAPEX) is high, yet PSH has one of the lowest costs of production and storage in terms of cost/kWh, thanks to its long lifetime, scale, and in many instances utilisation of pre-existing infrastructure. Additionally, PSH has an 'economy of duration' which makes pumped hydro inherently competitive at longer durations for energy storage (e.g., 6-24 hours+), and explains the significant cost differential observed when PSH is compared with chemical batteries, for which CAPEX scales more linearly with duration, and that are best suited for more limited scale storage. But it is not simply a question of a straightforward comparison of the levelized cost of electricity (LCOE) often used in energy policy making. PSH brings superior energy services to the grid including peak generation capability, demand management, and significant storage over a long duration. It also provides a wide range of ancillary services including inertia services, frequency regulation and black start capabilities[4].

Box 1. The demand for grid flexibility today

The need for flexible sources of electricity has also been demonstrated by recent events on grids across the globe. Historically, The European Blackout of November 2006 saw an increase in French hydroelectric production of 4 GW in 40 minutes, and elsewhere in Europe 1.6 GW of PHS in pump mode stopped, giving a net system improvement of around 6 GW to help restore generation and load balance (36).

More recently, in January 2021, an event caused the Continental Europe synchronous area to separate into two areas to avoid a major black-out across Europe with PSH playing a significant role in maintaining the system. Extreme weather events in Texas in 2021 have demonstrated the impact of a lack of system flexibility which PSH can provide. In India in 2020 a nationwide "lights out" to show solidarity with frontline workers tackling COVID led to a huge drop in system demand and then subsequent ramping up (37).

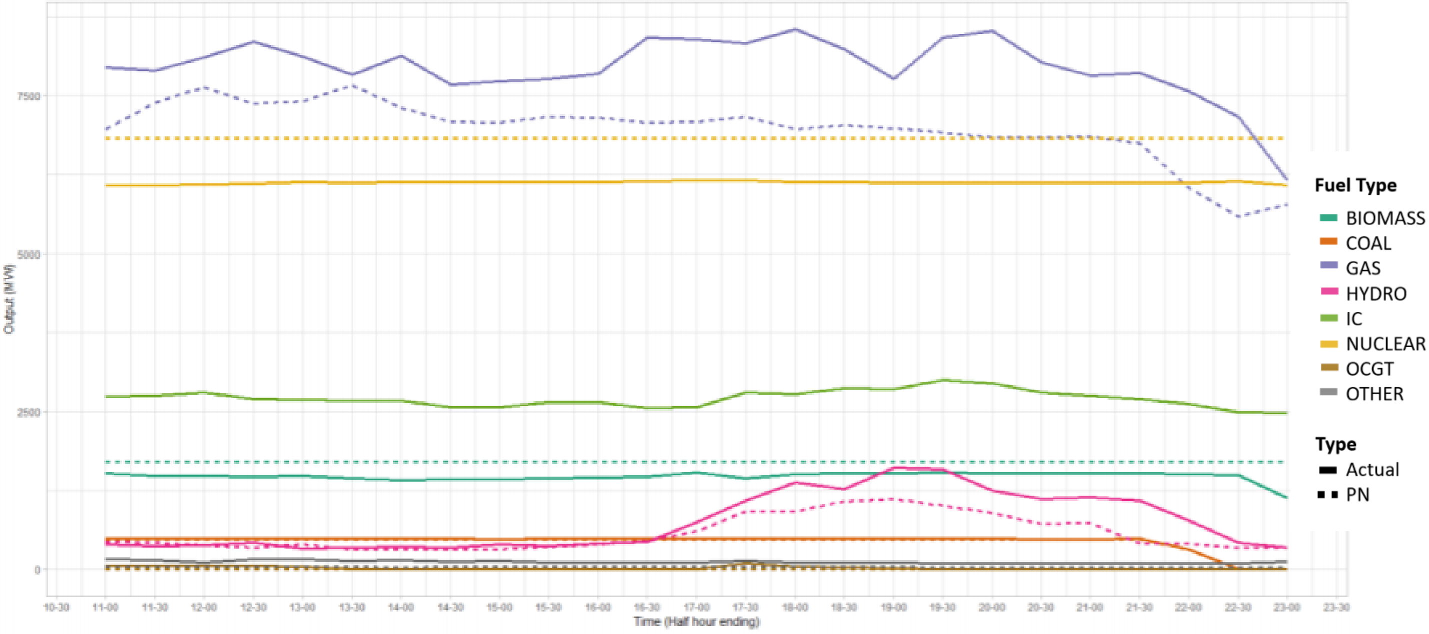
In August 2019, the UK electric grid saw a power outage with interruption to more than 1 million customers as a result of a fault caused by a lightning strike on a transmission line that led to simultaneous power-loss at an offshore windfarm and combine cycle gas turbine (CCGT) site. The event resulted in two large generators experiencing technical frequency issues and going offline (~1,000 MW). All of this led to a significant drop in overall system frequency and drops of 350MW embedded generation further exacerbated the issue. This required significant load shedding, or demand disconnection (38). Reserve providers, like hydro plants were able to help restore the system frequency and loads. Figure 2 provides the output in MW over time, showing an increase in hydro output at 16:53 as the energy system operator (ESO) instructed hydro plants to help stabilise the frequency and replace missing energy. The output was a significant increase to the estimated (dotted) transmission.

These events are demonstrating the value of long-duration storage and flexible system services as in all of these instances, the broad capability of PSH was, or could have been, utilised to help manage these events.

[4] Many authors have noted the critical role of PSH for grid flexibility, including the IEA and UN Sustainable Water and Energy Solutions Network. The IEA Hydropower working Group published in July 2021 Annex IX " Valuing Flexibility in Evolving Energy Markets: Current Status and Future Outlook for Hydropower" and a Whitepaper in October 2019 "Flexible Hydropower providing value to renewable energy integration". The UN Sustainable Water & Energy Solutions Network published in July 2021 a "Report on Sustainable Water and Energy Solutions Addressing Climate Change", which notes the critical role hydropower already plays in energy storage.

Figure 2 – Balancing Mechanism Conventional Forecast submitted by the generators (dotted) and estimated outturn of conventional transmission generation (solid line) by fuel type at the 4-hour ahead stage.

SOURCE: National Grid ESO Appendices to the Technical Report on the events of 9 August 2019 (56 p. 76)



PSH further contributes to reducing overall system costs through avoiding variable renewable energy (VRE) curtailment, avoiding the CAPEX from other generation solutions options (e.g., nuclear, hydrogen, gas CCS) that would otherwise be needed. It can reduce transmission congestion, avoiding CAPEX of additional transmission (deferring transmission network investment) and can displace investment in carbon intensive flexible assets such as CCGTs avoiding the costs of related greenhouse gas (GHG) emissions.

To put this into context, according to Bill Gates' *How to Avoid a Climate Disaster*, if Tokyo were to get all its electricity from wind power and a storm causes the wind turbines to shut down, 14 million batteries would be required to keep the lights on for three days. The purchase price would be USD $400 billion for the capital cost of the batteries alone, without including installation and maintenance costs (10). If Tokyo were to rely on PSH, the required investment in PSH assets would be between 2 and 10 times lower than the costs of batteries.[5] Furthermore, while batteries have a shorter lifespan and need to be replaced every ten years, PSH electromechanical equipment is typically refurbished after 40 years, and dams can last for over a century. Beyond the lifespan and costs, PSH brings additional grid services such as inertia or black start capability on a large scale[6].

Lastly, beyond power generation, some PSH can also provide many additional benefits (such as water management, irrigation control for agriculture, water distribution and water waste control).

Therefore, a holistic approach that considers the overall system benefits of PSH over the longer-term will help minimise cost and make energy production more reliable than ever. These holistic benefits for the system are rarely valued; whereas, if valued appropriately, they justify the development of new PSH projects. One such example that holistically assesses market-wide benefits is the Australian Integrated System Plan (ISP) which communicates the system operator's view of a least-cost resource mix over the next twenty years. The ISP indicates that Australia will need 6-19 GW of new dispatchable resources (energy storage including PSH), to support increasing shares of VRE. The ISP also assesses the emerging need for short, and long duration storage assets, demonstrating a clear and critical role for long-duration storages in a high renewables future.

[5] These estimates vary depending on the assumptions taken as a reference for the $ / kWh from different projects.
[6] For more information on the additional grid services that PSH can provide, please see International Forum on Pumped Storage Hydropower's (IFPSH) WG.3 paper on Costs, Capabilities and Innovation.

A further Australian example is the New South Wales's Electricity Infrastructure Roadmap which promotes the development of Renewable Energy Zones combined with long duration energy storage (specifically PSH) and found that this initiative would benefit the end user by reducing retail electricity prices by 8% compared to no action, representing savings of several billion dollars per year.

Another recent study by Imperial College London estimated the whole-system value of long-duration energy storage in a net zero emission energy system. The study stated that the total gross electricity system cost savings from an additional 4.5 GW or 90 GWh of new PSH were estimated to be up to US$950m per year in 2050, with more savings made when the energy storage volume is higher, and system flexibility is lower (11).

The IFPSH's Capabilities, Costs and Innovation Working Group has prepared a comparative analysis of different type of storage technologies and a detailed assessment of the capabilities of PSH. Table 2 summarises this comparative analysis, visually showing PSH's unique properties in comparison with other existing storage technologies, including Mechanical inertia, Reactive power and Black start capabilities, as well as its long lifetime, high storage cycles, and very high technical readiness level[7]. When looking at the effective capex costs of PSH's long lifetime, in comparison to other technologies which may need replacing, PSH is the most cost-effective energy storage choice in the long term.

Table 2 – Comparison of different electricity storage technologies for 1000/100 MW and 10h duration

Source: provisional information extracted from IFPSH WG.3 reports

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
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	av. power CAPEX (USD/kW*)	2,202	3,565	3,558	3,994	1,089	3.117
	av. energy CAPEX (USD/kWh*)	220	356	356	399	109	312
	av. 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	av. power CAPEX (USD/kW*)	2,202	2,471	3,050	3,187	1,089	1.612
	av. 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.

PSH, like all infrastructure, has local environmental impacts and it is important that these are properly assessed and appropriately mitigated. The Forum's Sustainability working group's report sets out how this can be achieved through the deployment of a wide range of globally recognized tools and practices.

[7] For more information on the additional grid services that PSH can provide, please see International Forum on Pumped Storage Hydropower's (IFPSH) WG.3 paper on Costs, Capabilities and Innovation.

1.4 Recent PSH development worldwide and looking ahead

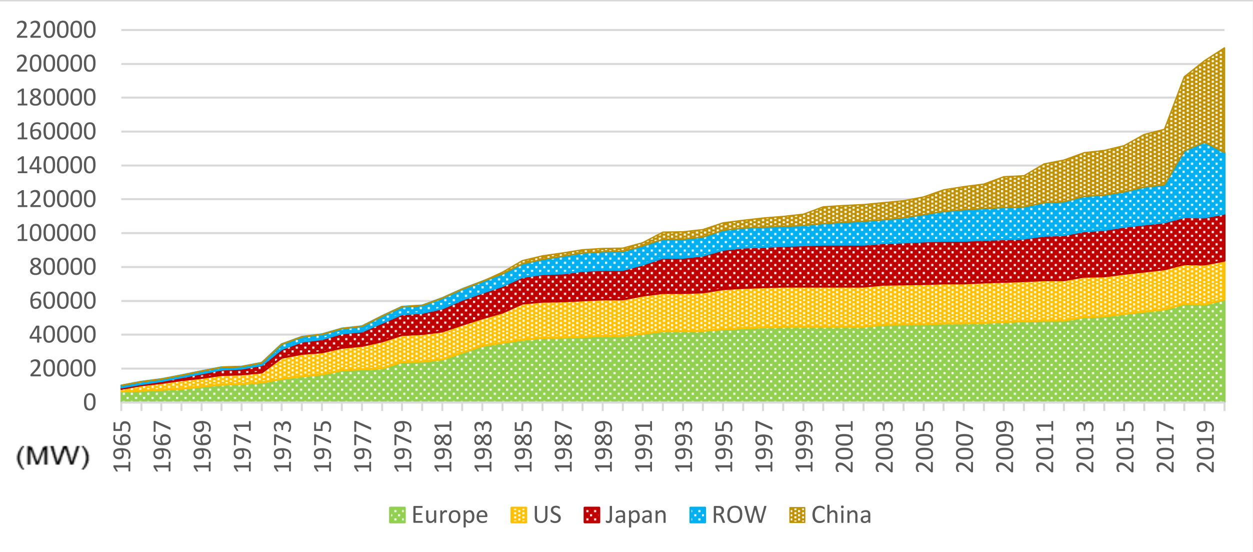
Pumped storage technology was first developed at the turn of the 20th century, however, the planning and construction of PSH projects began in earnest after the end of the Second World War (see Figure 3). By the 1960s, most of the new thermal generators coming online were of large-capacity and high temperature and pressure units, with little prospect for significant improvements in efficiency. These generators were best suited for constant high output to reduce equipment stress and maintenance cost while optimizing operating efficiencies. PSH plants were ideally placed to absorb surplus power and generate peaking capacity and were almost exclusively built by state-owned utilities.

Yet, after the 1980s, fewer projects, especially in the more mature markets of Europe, Japan and the United States, were developed; the main reason for the reduction was a result of energy market deregulation and a decline in nuclear growth. However, there were some exceptions, notably Austria. With no nuclear generation, but a rich hydropower resource, Austria developed PSH to enhance the operation and efficiency of its large-scale hydropower fleet and provide balancing services to neighbouring grids. Since the turn of the century, there has been a renewed interest in PSH in numerous countries, most notably in China but also in Europe and virgin markets. As VRE sources increasingly penetrate grids, PSH has begun to be viewed by some as a key renewable integration tool.[8] At the end of 2020, the global installed capacity stood at 160GW with over 9,000 GWh of storage capacity. China has accounted for much of the recent growth, having added over 15 GW of capacity alone since 2010, driven by ambitious government targets for renewables. For PSH in China, 31.5 GW has already commissioned, a further 53.7 GW is under construction, with the aim of 62 GW installed by2025, for a total installed capacity of 120 GW by 2030 (5).

Over the last decade, new PSH installed capacity in Europe was almost +8 GW, with the biggest growths in Switzerland, Austria, Portugal, Spain, and France.

Figure 3 – Total installed capacity additions between 1965 and 2020 broken down by country and region.

Source: IHA's hydropower database.

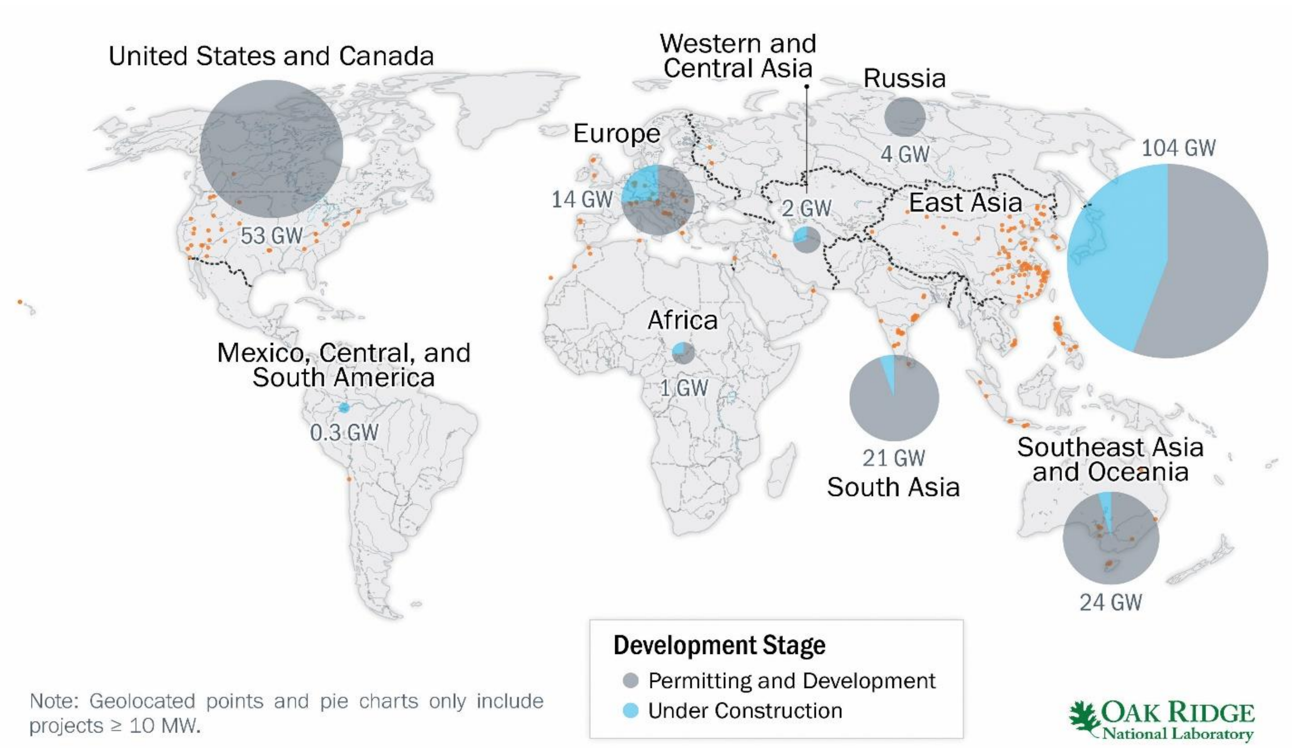


[8] The International Energy Agency recently released a report on the challenges associated with integrating variable renewable energy sources and the potential of hydropower (traditional and PSH) to deliver system services to meet these challenges. *See* Botterud et al. (2021) "Valuing Flexibility in Evolving Electricity Markets: Current Status and Future Outlook for Hydropower."

Despite this renewed interest and market need, PSH capacity growth has slowed in recent years to below 3% (see Figure 3 and a map of the pipeline for PSH development in Figure 4). Indeed, despite all the potential benefits and value, the maturity of the technology and its costs, outside China, year-on-year installed capacity growth has been just 1.5 per cent since 2014. This has been due to a combination of factors, most notably policy and market frameworks which in many countries fail to provide appropriate market signals to de-risk development.

Figure 4 – Map of pumped storage hydropower project development pipeline by region and development stage.

SOURCE: US DOE - U.S. Hydropower Market Report January 2021 (9)



Lack of appropriate policy and market frameworks have also contributed to limited private-sector-led or financed PSH capacity being added: of the estimated 60 GW expected to be commissioned by 2030, less than 10% is being developed by the private sector. Given the growing need for long-duration storage as highlighted by several country and regional targets, and estimated requirements (see Table 1), the level of private-sector-led development will need to rapidly accelerate supported by a viable route to market.

Box 2. How Israel is managing the energy transition in an island grid

The Israel Electric Corporation (IEC) - Israel's state grid operator - identified a need for the development of long-term reliable capacity to integrate variable renewables, specifically increasing developments of solar resources. The Israeli grid is fossil fuel heavy, as it is without any regional interconnections, limiting the system's flexibility to respond to long duration solar energy output shortages. IEC identified a need for 800 MW of energy storage (5% of demand of 18 GW). Recognizing this need on its system, the IEC undertook a concerted effort to develop this long-term capacity in the form of multiple PSH resources. At present, these are among the small number of PSH plants in the world of a significant size being actively built by private developers. These plants are discussed in further detail in section 4.3 *Capacity and availability payments*.

Pumped Storage Hydropower International Forum

Policy and Market Frameworks Working Group

Chapter 2

Barriers and Challenges to PSH development

Summary

- Many markets lack long term modelling or targets for long duration storage needs.
- Where models are used, they often have outdated assumptions about technical capabilities and may not take account of key discriminating factors.
- Long term electricity and ancillary services prices are difficult to forecast and subject to wider government policies. Without risk mitigation mechanisms investors are reluctant to invest in assets with long term pay back periods such as PSH.
- In many markets not all services provide by PSH are remunerated.
- In some markets existing PSH plant margins are being squeezed by carbon intensive gas.
- Rules on transmission assets can create barriers to efficient deployment of PSH. Hybrid assets that can serve both transmission and generation markets may lower overall system costs.
- Licensing and permitting requirements for PSH are often lengthy, where feasible these should be shortened, and best practice robust yet timely process introduced.

2.1 Planning and modelling

In many instances, decision makers and planners utilise models that are not robust enough to properly evaluate and distinguish different storage technologies. For example, many use data based on existing resources and technologies within their systems, which in the case of PSH, may be old technology (e.g., 30 years+ in some markets). These data and models are not representative of what new technology can achieve.

Like for like comparisons between technologies are important but can be conceptually difficult. Factors such as the timeframe on which comparisons are based can make a significant difference to a recommended option. For example, using a 5-year life to compare battery costs to PSH costs will skew the results to batteries; whereas, using a 40-80-year reference period is more reflective of the typical lifespan of PSH but would require many cycles of battery deployment. Lifecycle costing should include the costs of decommissioning and disposal including associated environmental impacts. In the previous example this would include the costs of multiple decommissioning of batteries, but only one PSH decommissioning exercise. Furthermore, projected costs for unproven technologies must be realistic and decision makers should be clear when they are being asked to take decisions based on estimates of future costs rather than technology that is understood and deployable today.

Planners must be clear on the services they are seeking to model when considering energy storage resources: modelling should not be limited to only generation or charging capacity (i.e., MW of capacity) but should consider storage of energy (i.e., MWh of energy) and the operational ranges capabilities of storage resources across capacity and energy. System models in use today have been designed for traditional energy systems dominated by dispatchable resources and accordingly do not adequately model operations in systems with significant deployments of variable renewable resources. Many models use average values for renewable generation, energy storage, and other asset characteristics, as well as for grid service requirements beyond energy. Importantly, most energy models used by planners and policymakers do not capture intra-hour operations, which can lead to potential underestimates of system flexibility requirements and the capability of resources that might be able deliver services to meet them.

Similarly, many models do not capture multi-day, weekly, monthly, or longer duration seasonal operations, and thus may not adequately model the need for long duration capacity needs, such as those that can be provided by PSH. Aligning electricity supply and demand and ensuring grid stability over a long period requires long duration large scale energy storage solutions that can provide not only capacity (MW) but also energy (MWh) to the network for several hours or days. Finally, in an environment of increasing weather severity, many models do not consider inputs from updated climate models, rather relying on historical data that does not include more recent extreme climate events such as those recently experienced in the U.S. or Australia.

Utilising models that consider the full benefits of PSH is critical for setting energy storage targets; however, very few countries have set targets for energy storage, and some of them only focus on batteries or hydrogen deployment.

As part of assessing and planning for sustainable long duration storage, WG3 on Sustainability, has noted three core requirements 1) System-level strategic assessment 2) Options Assessment 3) Project optimisation. Sustainable long duration storage planning requires a system-level strategic assessment to determine the electrical system service needs, characteristics of flexibility that may be needed, economic performance and life duration expectation to ultimately determine the storage and flexibility demonstrated need. Next, an options assessment to compare potential energy storage technologies should be carried out, and finally project optimisation to ensure that the most sustainable PSH projects will be delivered.

To prepare a smooth clean energy transition, and ensure grid stability in the near future, decisions on energy storage must be made today, require global action, national commitments, and consistent policy and regulatory frameworks for all storage technologies. However, planning considerations leave out long duration storage, and there are constraints around financing PSH projects and how services will be remunerated.

2.2 Financial considerations

The main challenges for PSH today are the profitability of existing plants and the need for stable economic signals to build the business case and attract institutional investors for new development. As with all large infrastructure projects it is necessary to mitigate investment risks as much as possible to improve attractiveness to developers and financiers. There are several reasons for this but at the core it results from two related considerations: the large capital outlay and lack of a secure revenue stream.

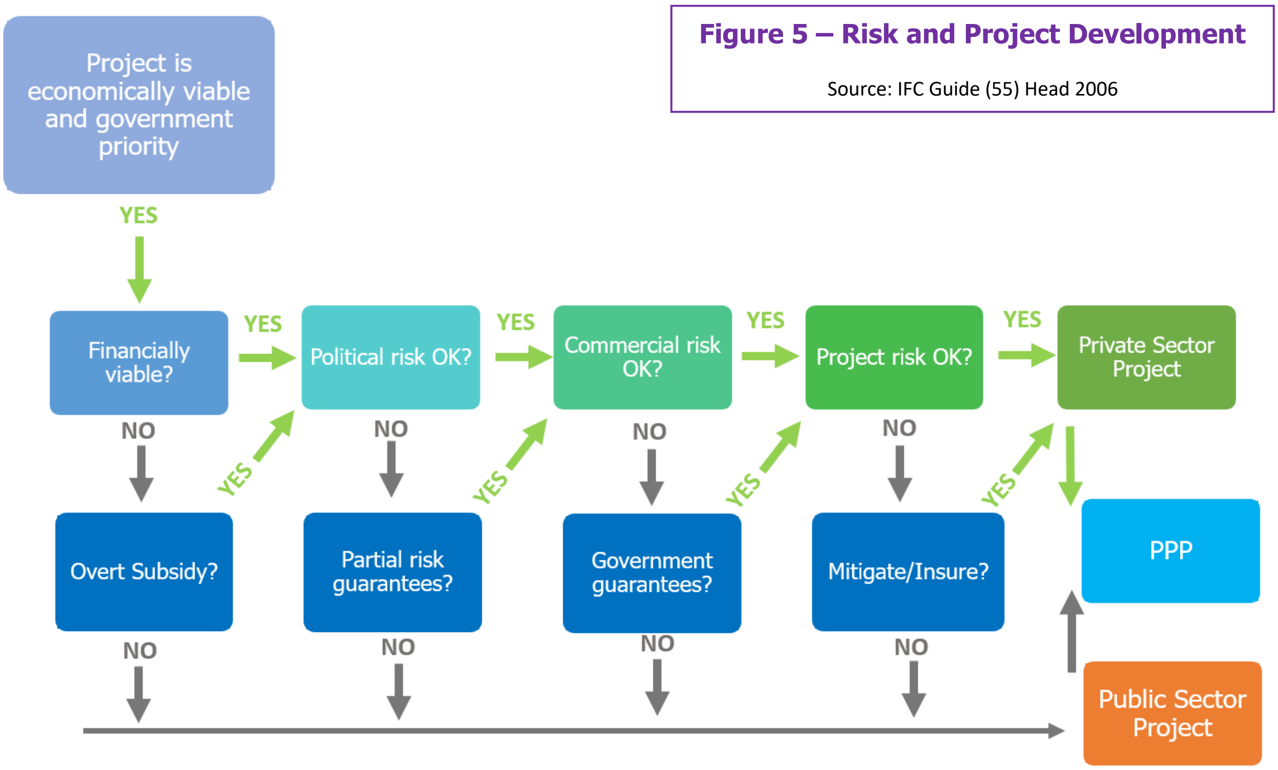
2.2.1 Large capital outlay – project finance risk

Hydropower projects, including PSH, typically have large upfront civil works costs as well as a high-risk profile because investors are exposed to the full cost before revenues commence. Risks will impact whether a project is deemed bankable to the private sector[9]. Because of this required high upfront capital investment, this can directly add to increasing the financial risk, i.e., a project might be seen as nonviable financially, so even for those projects deemed low risk, public sector financial measures can be used to help mitigate risk. Financial nonviability can be mitigated through tax concessions, which provide early relief, as well as government subsidies. Risk profiles that are deemed "unacceptable" can be supported through credit enhancement guarantees or rearrangement of the risk between the project parties.

One common way that Hydropower Projects like PSH mitigate risks, is to set-up public private partnerships (PPPs) which can have a combination of public and private ownership of the asset, as well as combination of private or public financing; thereby enabling risk sharing across parties[10].

Figure 5 – Risk and Project Development

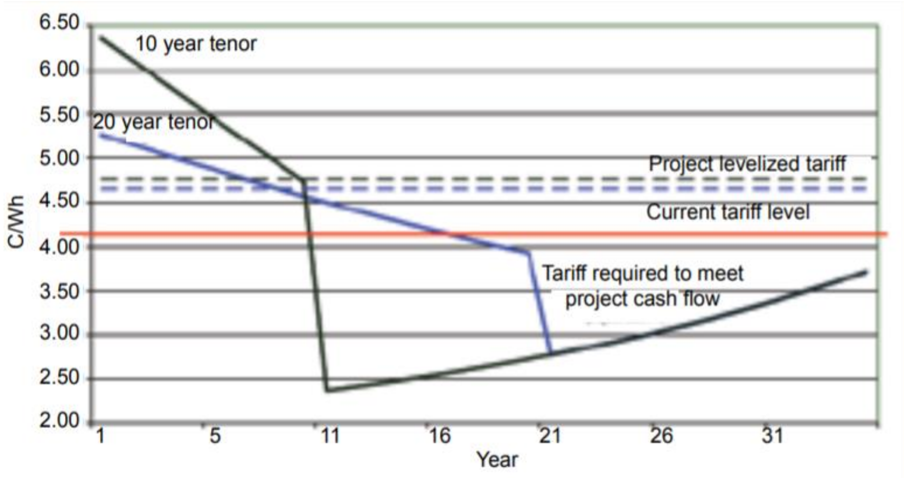
Source: IFC Guide (55) Head 2006



[9] For more on the risk profile of Hydropower projects, please see "Perceptions of risk in relation to large hydropower projects: a finance perspective" and for an interactive model of hydropower project risk see Future DAMS Risk Framework.
[10] The choice of financing model or structure of ownership is discussed in "The Financing of Water Infrastructure A Review of Case Studies 2006" and charts the chain of decisions for potential risks which then impact whether a project is funded and owned/operated via the public sector or private.

Figure 6 – Example of debt tenor and tariffs for hydropower project

Source: *(39)*



One example of risk sharing is the San Roque hydroelectric power project in the Philippines which was built through a consortium of Marubeni Corporation, Sithe Philippines Holdings Inc. and Italian Thai development public issuer under a BOT scheme and now provides peaking power, irrigation, flood control and water quality improvement to the area (12). The project was split between a lower risk private project for the power station and a higher risk public project for the dam, thereby sharing risk across the two split projects. The consortium formed the San Roque Power Corporation which will operate and own the power facilities for 25 years before transferring to the public sector National Power Corporation.

As part of determining the ownership and financing model, this process will also include an assessment of the length of time for debt repayment or 'tenor'. With high upfront costs for civil works creating a high risk, Figure 6 shows an example of how a longer debt tenor of 20 years allows the break-even tariff to be closer to the levelized tariff whilst servicing debt in early years, compared to shorter debt tenor of 10 years. Because projects have a long lifespan, debt repayments tend to be relatively short in comparison to the technical life span, and any PSH investment should be viewed as long-term. If projects are financed with short tenor debt, then they may need a much higher tariff in the short term or could be viewed as unattractive for investment. Thus, the level of tariff or remuneration can affect how projects are funded and it is therefore, critical to reduce financial risks by securing a revenue stream that will effectively remunerate PSH for all the services it provides, and thereby reduce revenue uncertainty.

2.2.2 Revenue uncertainty

Lack of a secure revenue stream uncertainty manifests in two primary ways: first the difficulty of predicting revenue streams over long timeframes due to market conditions and emerging technologies, and secondly the existing regulatory and market paradigms where storage assets are only remunerated for a fraction of the benefits they can provide to the system (13) (14) (15) (For a breakdown in remuneration services provided in different country's electricity markets, see Figure 7).

These revenue uncertainties do not allow potential developers or financiers to predict revenue over the time required to recover the pumped storage investment. Whereas, for example, energy and ancillary service market prices may be reasonably predicted in a short timeframe based on historical data, fuel forecasts, and market planning processes; predicting these same variables over the duration of a pumped storage asset's life (e.g., at least 40 years) is far more difficult. Further complicating this difficulty is that by their very nature and scale, pumped storage assets can alter system conditions by charging or discharging. While this is exactly what makes these plants valuable, their charging and discharging operation alters the market and the precise impact on pricing may be difficult to predict.

Another form of revenue uncertainty is that energy storage resources, including pumped hydro plants but also others, are subject to limiting and unclear market and regulatory rules. Pumped storage plants are not compensated for all the benefits that they can provide to electricity systems that are impacted by the higher penetration of VRE; this includes their uncompensated delivery of system inertia and primary frequency response, which are not currently market products in most electricity markets. It also includes the value they provide with regards to reliability or resilience as controllable energy system assets (15).

These services will be especially valuable as VRE penetration increases and replaces existing spinning machinery. Variable technologies cannot inherently provide inertia or primary frequency response and are not sufficiently controllable to address reliability or resiliency requirements. In addition, pumped storage can provide value across the electric system functions of generation, transmission, and distribution. However, it is often explicitly restricted from obtaining revenue in doing so or the avenues for participation and remuneration are not clear for PSH, particularly in organized markets where PSH does not have a clear pathway to participation as both a generation and transmission resource.

Figure 7 – Remuneration for multiple grid services

Source: IEA - Hydropower Special Market Report Analysis and forecast to 2030 (4)

Country	Sub-seconds to seconds Inertia, voltage control, reactive power, etc.	1-5 minutes Primary and secondary, frequency regulation
Austria	🔴	🟢
Czech	🔴	🟢
Germany	🔴	🟢
Belgium	🔴	🟢
Italy	🔴	🟢
France	🔴	🟢
India	🔴	🟡
Turkey	🔴	🟡
China	🔴	🟡
US – CAISO	🔴	🟢
US – PJM	🔴	🟢
US – ERCOT	🔴	🟢
US – MISO	🔴	🟢
Australia	🟡	🟢
Colombia	🟡	🟡
Switzerland	🟡	🟡
Canada – Quebec	🟡	🟡
Canada – Alberta	🟢	🟢
Japan	🟡	🟡
Ireland	🟢	🟢
Finland	🟢	🟢
Norway	🟢	🟢
Sweden	🟢	🟢
United Kingdom	🟢	🟢

🟢 services remunerated 🟡 services partially remunerated 🔴 services not remunerated

2.2.3 Changes in the operations of existing PSH

Before the emergence of significant variable renewable resources PSH plants were largely used to complement non-flexible generation, particularly nuclear power plants, by shifting the peak demand. As markets in Europe and the United States have become organized, and generation resources spun off from regulated entities, PSH operations have changed to follow market prices. In Europe arbitrage of market price variations has maintained PSH revenue streams until recently.

The growing deployment of renewables has seen more volatile price spreads. PSH plants should be able to take advantage of this increasing volatility and charge or dispatch as market prices move. However, with decreasing demand following the 2008 financial crisis and the emergence of low-cost natural gas these price spreads have dropped, and fast-moving carbon emitting natural gas units have been able to respond to price as well as PSH plants. Accordingly, arbitrage revenues have decreased for PSH plants to the point that invested capital expenses cannot be recovered. In the United States, more robust ancillary service markets have supported existing revenues with PSH plants being operated in a far more flexible fashion. PSH plants in Europe with less robust ancillary service markets have not been as fortunate.

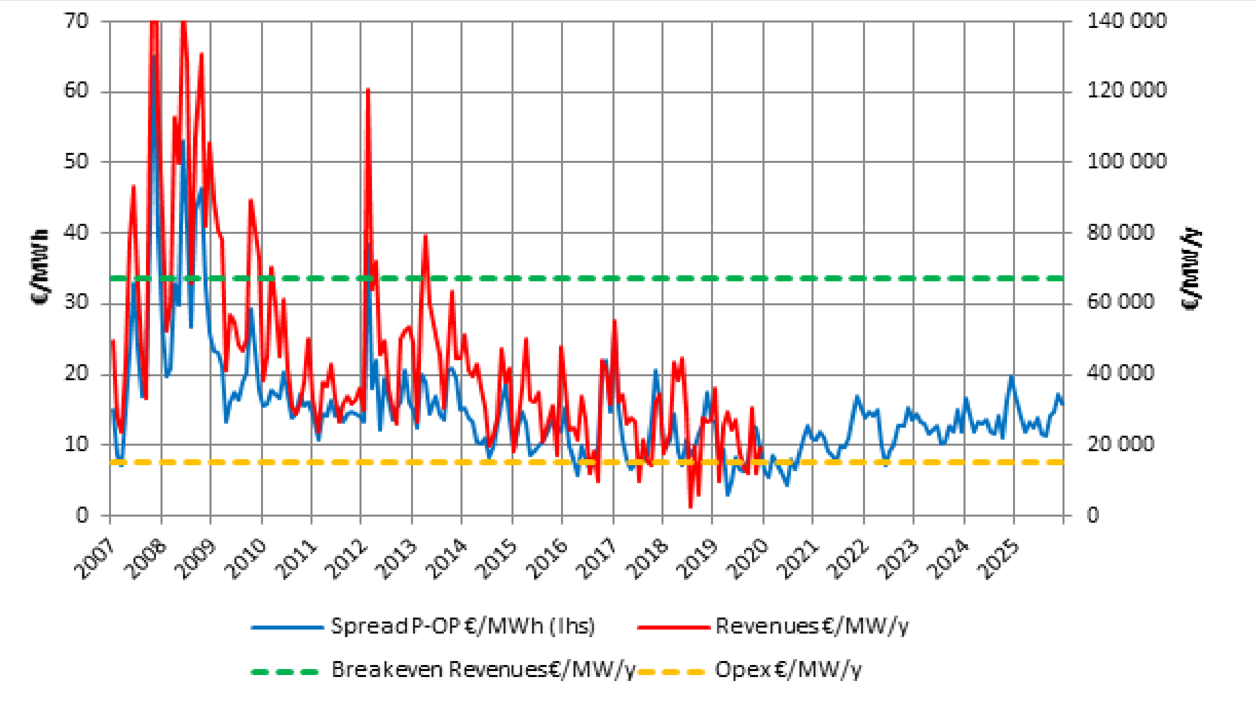
For example, Figure 8 below highlights PSH performance in the Swiss market. Revenues per capacity have dropped significantly since 2008 with dropping prices and price spreads[11] and have fallen below project breakeven revenue. They have maintained above operating expenditures allowing existing projects to continue operating but preventing any new development.

[11] P-OP in the chart refers to the difference between Peak and Off-Peak price.

On top of revenue uncertainties, further economic barriers penalize the viability of projects and prevent investment in new or other energy storage technologies. In many EU countries, double grid fees apply to operators of pumped storage power plants in some Mem3ber States[12]: they have to pay when consuming electricity (Load-charge) as well as when generating electricity (Generator-charge). Double charges penalise the complementary benefits of storage to the networks for balancing the wider electricity system.

Figure 8 – Swiss market PSH performance

Source: Alpiq



2.3 Ownership models and transmission / generation considerations

Ownerships models for energy storage have become a critical issue with the deregulation of electricity markets. Historically, in many markets, PSH plants were developed under regulated market conditions and were owned by vertically integrated utilities which managed the overall value chain of electricity from generation to transmission and distribution. Such models allowed energy storage to be integrated into long-term system-wide resource planning, achieving economies of scale, and benefiting the overall power system.

However, new market designs have emerged, and the unbundling of power entities requires clear ownership rules for energy storage assets to enable investments. The categorization of energy storage as either transmission or generation, or even potentially under its own category as a unique asset, helps to determine its potential revenues, i.e., whether it can provide flexibility and balancing services in competitive markets or contribute to transmission and distribution deferral. Most recent regulatory and legal frameworks classify storage as a generation asset preventing transmission or distribution system operators from owning storage devices. While this helps to develop a level playing field for all energy asset owners it is a significant barrier to transmission and distribution services, one of the highest-value applications for energy storage.

Legal frameworks can also impact the economic viability of projects. In several EU countries, India and other countries, PSH plants were classified both as a generation asset and as a final consumer, requiring them to pay

[12] The EU's recent 'Fit for 55' announcement included an amendment to the Energy Tax Directive to avoid the risk of double taxation for energy storage devices; however, taxation is an EU Member State competency.

the grid access fee twice[13]. There was a proposal as part of the European Clean Energy Package (CEP) in 2019 to define storage as a separate entity from generation, transmission, or load, preventing it from being double-taxed when charging and discharging. In the new electricity market designed by the CEP, storage services would be market-based and competitive, and therefore regulated functions of distribution or transmission should not cover energy storage activities, and they can own, develop, manage, or operate energy storage facilities only under exceptional and restricted circumstances.

In China, energy storage is categorized as transmission and distribution assets, and grid companies are responsible for the construction of PSH plants. State Grid and China Southern Grid companies own approximately 75% of the 60 GW PSH installed base under operation or construction. However, in 2019, regulations changed, and grid companies can no longer include storage costs in their transmission and distribution fees.

In the U.S., energy storage has historically been classified by the type of service it provides, nearly always generation, but transmission in a few instances. In 2019, the Federal Energy Regulatory Commission (FERC) published a note, suggesting that energy storage resources could be operated as "dual use" assets, providing both generation and transmission services, but left it up to its regulated markets to propose specific rules. Accordingly, both California's Independent System Operator (CAISO) and the Midcontinental Independent System Operator (MISO) undertook stakeholder proceedings to identify "dual use" rules. However, due to logistical complexity in operations and disagreement across stakeholders, both suspended these proceedings for future consideration. Instead, both reaffirmed and detailed rules for energy storage resource participation as solely transmission assets.

In Chile the national law was changed to allow for storage to serve as transmission network reinforcement in emergency cases (2).

2.4 Licensing / permitting

Large infrastructure projects such as new PSH development are subject to long processes that include many steps from site selection, pre-feasibility / feasibility studies as well as environmental and social assessments, to permitting/licensing from one or various entities. Unlike other technologies that can go from proposal to realization in under six years, a pumped storage plant might take more than ten years from conception to operation (14 pp. 8-14). As noted previously, pumped storage plants have the characteristic of major infrastructure investments, namely that they are capital intensive, have relatively low operational costs in use, and once construction begins there is little opportunity to change course and modify investment in response to a change in market conditions. Other electric system technologies such as natural gas plants, renewables or even other smaller energy storage assets, namely batteries, have smaller total upfront capital costs (i.e., generally they are smaller plants) and smaller development timeframes (14) (16).[14]

In the U.S., a new license from the Federal Energy Regulatory Commission (as well as other state and federal permits) can take from 3-5 years and include significant investments in planning and studies. Most PSH projects can take up to 3-5 years for construction in addition to the 3–5-year license application process. To facilitate the development of projects, FERC has established an expedited process within its existing licensing framework for issuing original licenses for qualifying low-impact PSH such as off-channel or closed-loop projects (17). Projects qualify based on criteria that include minimal water flow impacts and other environmental concerns. Under the expedited licensing process, the Commission works to issue a final decision no later than two years after it receives a completed license application.

The regulator should make this process more explicit in its licensing material, extend this accelerated process in non-powered dam and existing reservoir pumped storage. In the event of multi-purpose projects, licensing

[13] The fees are noted in Central Electricity Regulatory Commission (Terms and Conditions of Tariff) Regulations, 2019. However, the Indian Ministry of Power issued a waiver in June 2021 of inter-state transmission charges for PSH projects if at least 70% of annual electricity used for pumping water is from solar / wind power.
[14] The recent Tennessee Valley Authority Integrated Resource Plan uses a 60-year plant life for pumped storage plants. *See* https://www.tva.gov/Environment/Environmental-Stewardship/Integrated-Resource-Plan.

can be even more challenging since additional externalities and related costs (such as establishing new parks, recreational facilities, new environmental studies, etc.) must be integrated.

In India, PSH is considered as a river valley project even if there is no construction of a new dam, resulting in a very long time (3–5 years) for obtaining the environment and forest clearances from the Ministry of Environmental and Forest and Climate Change (MoEF&CC). Utility scale off-river PSH integrated with renewable power are not being treated as renewable projects and thus all incentives and easy clearances available to solar and wind renewable projects are not available to PSH. Separate guidelines for off-river PSP for early concurrence from MOEF&CC are not available, resulting in a longer time for obtaining financial closure.

In the Philippines, the Department of Energy's (DoE) Framework for Energy Storage System in the Electric Power Systems explicitly includes PSH as a technology to maintain power reliability and integrate VRE. This DoE circular also highlighted licensing and permitting, frameworks for market participation, connection, and operational requirements. To meet ambitious targets of tripling RE capacity by 2030, demand for conventional hydropower and PSH is projected to increase to provide grid stability and reliability. As of 2018, projects deemed of "national significance" can be streamlined through the regulatory procedures and fast-tracked under Executive Order 30.

The shorter and simpler the development phase is, the more attractive the investment will be. Clearly this cannot be at the expense of robust and appropriate environmental and other assessments. Governments and regulatory authorities can learn from best practice deployment around the world and ensure the most appropriate assessment tools are deployed.[15] In recognition of the longer lead times required for PSH to meet the appropriate assessment timelines, participation in the relevant market and incentive mechanisms should allow for these timelines. Finally, it is important that technologies are considered as equitably as possible, including full consideration of lifecycle impacts for example[16].

15 For example, the hydropower sustainability tools governed by a multi-stakeholder council (https://www.hydropower.org/sustainability-tools)

16 For further information on lifecycle impacts, please see International Forum on Pumped Storage Hydropower's (IFPSH) WG.2 paper on Sustainability.

Chapter 3

Recent government-led developments and best practices

Summary

- There are many examples of successful incentive schemes and other mechanisms to support the deployment of low carbon technologies, but these are rarely available to PSH.
- Where PSH does have specific mandates, such as in China, deployment is happening at pace.
- Structural issues with capacity market mechanisms have limited PSH participation, short term contracts, limited carbon obligations and requirements to build within short time frames have implicitly supported other technologies.
- Direct targeted support for PSH can result in significant local economic benefit.
- Direct support for specific projects or sites can secure low cost reliable PSH capacity.
- Mechanisms used to support certain types of transmission infrastructure while minimizing consumer costs has the potential to be used, with some adjustment, for PSH.

3.1 Government policies (mandates, targets and support mechanisms)

Following sustained government intervention in the form of mandates, targets, investment and other technology incentive support mechanisms, wind and solar resources have seen widespread deployment worldwide and achieved grid cost parity with traditional fossil fuel energy technologies. A similar pattern is being repeated with short duration energy storage. Successful examples have included the UK's Low Carbon Contract Company (LCCC) that runs the Contract for Difference scheme, Investment Tax Credit and Production Tax Credit in the US, or feed-in-tariffs in Germany.

In these examples, market signals on their own were insufficient to enable investment in these technologies. Government intervention, for example, in the form of subsidies made the difference in making these VRE competitive with fossil fuel options.

PSH faces a similar challenge: its value as a system resource to enable a reliable clean energy future is clear. However, as discussed in the prior section, the market incentives and regulatory and market environments are not sufficient to attract investment. Whilst it is in society's interest to support the deployment of new technologies, support mechanisms that are only available to emerging technologies risks distorting markets and may restrict investment in the most efficient options.

PSH has the advantage of being a mature technology where costs have been optimized, and importantly, it is widely used and recognized across industry as a reliable resource. Yet, the market frameworks within which it was previously built are no longer applicable, with the exception of some markets e.g., China.

The need for energy storage to integrate variable renewable technologies has been accepted in energy planning communities, and in some governments for the last decade; however, long duration energy storage, and in particular PSH, has been left out of these considerations. More recently, planners and governments have begun to recognize the need for long duration storage, especially as evidence mounts that ensuring energy delivery and reliability in a system of high VRE penetration will require long duration storage. Energy markets as currently designed will not on their own incentivise the development of long duration storage, such as PSH.

In the draft 14th Five Year Plan, China identified solar and wind power generation as the main contributor to China's incremental power capacity for the next decades to come. Unlike the 13th Five Year Plan, solar and wind have overtaken hydropower to become China's second-largest power generation source.

The 14th Five Year Plan mentions building a series of pump-hydro storage plants, as well as demonstrations of battery storage, compressed air and flywheel storage (18) and the NEA's recent announcement means China could see more than 300 GW of PSH capacity in the coming decades.

European countries are also planning a significant increase of the installed capacity in energy storage, pumped hydro storage particularly: the Spanish National Energy and Climate Plan (NECP) considers 6 GW of additional storage capacity by 2030, 3.5 GW of which from PSH; Italian NECP plans +6 GW of new storage capacity, with at least 50% from PSH plants; the Portuguese Roadmap for Carbon Neutrality 2050 with energy storage to account for 7.5 GW by 2050, and the Swiss last updated version of Energy Perspectives 2050+ considers +1.8 GW PSH in Zero-carbon scenario by 2050.

Boxed 3 PSH development support in India

With increasing deployment of wind and solar expected over the coming years to meet ambitious targets, the Indian government has identified a need for a significant expansion in power system flexibility to ensure grid stability and avoid power shortages (40). Reflecting this, in March 2019, India declared that large hydropower (greater than 25 MW) was officially a renewable energy resource. This move will enable new, large projects to benefit from the non-solar Renewable Purchase Obligation which mandates that regional utilities must purchase a portion of their electricity from hydropower. More recently, India also moved to a real-time market in electricity which will encourage and reward more flexible generation sources.

To further support this aim, the Indian government has requested the World Bank to carry out a study to determine the flexibility of hydropower and investigate appropriate market and regulatory framework for hydropower flexibility, particularly for pumped storage (41).

In addition, the country recently amended its National Wind-Solar Hybrid Policy to clarify that pumped storage could be used in hybrid wind-solar projects, to promote large grid-connected hybrid wind-solar PV development and efficient grid utilization. Putting this policy into effect, the Solar Energy Corporation of India awarded the world's largest renewables-plus-storage tender for the 1,200 MW Pinnapuram Integrated Renewable Energy PSH Project in the state of Andhra Pradesh in southern India. This project will see a 1,200 MW PSH system, coupled with a 2,000 MW solar PV plant and a 400 MW wind farm tied together at a single substation to be available by 2022. Furthermore, the project was also recognized as a Mega Industrial Project by the State Government which enabled it to benefit from streamlined and accelerated grant clearances.

Experts speculate that this project may revive new interest in PSH development in India, particularly in hybrid projects, beyond the existing 1,000 MW Tehri PSH project currently under construction.[1] For instance, Greenko has received US$ 500 million in equity financing from the Abu Dhabi government and from Singapore's GIC last year for development of PSH hybrid projects in India (42).

A mechanism used to promote development of new generating capacity, or for existing capacity to remain in operation, has been capacity markets in the United States and Europe. The capacity market mechanism was specifically designed to help ensure that electricity supply continues to meet demand as more volatile and unpredictable renewable generation plants come online. Capacity markets are auctions or trading sessions for exchanging capacity guarantees, where system operators seek a certain amount of capacity for future system needs thereby ensuring security of supply. Under the mechanism, if successful, participants are generally paid a per MW rate for the capacity they offer to the market. This capacity needs to be available when providers are called upon by the system operator at any time during the contracted period.

However, these capacity markets have not, to date, enabled the development of greenfield long-term energy storage, and have instead largely supported natural gas generation which in current market frameworks provides a much faster return on investment. Most capacity markets do not consider the clean energy potential of technologies being deployed and are not incentivized to price carbon externalities properly.

Figure 9 – Short and long-term remuneration of capacity in selected countries

Source: (4)

Country	Short-term Remuneration	Long-term Remuneration
United Kingdom	🟢 1 Year	🟢 15 Years
Belgium	🟢 1 Year	🟢 15 Years
Italy	🟢 1 Year	🟢 15 Years*
Ireland	🟢 1 Year	🟢 10 Years
France	🟢 1 Year	🟢 7 Years
Israel	🔴	🟢 18-20 Years
US – CAISO	🟢 1 Year	🔴
US – PJM	🟢 1 Year	🔴
US – ERCOT	🟢 1 Year	🔴
US – MISO	🟢 1 Year	🔴
Australia	🟢 1 Year	🔴
Colombia	🟢 1 Year	🟡

🟢 available 🟡 partially available through other types of contracts 🔴 unavailable

*Contracts of up to 15 years are available upon bidder request.

These markets are largely focused on short duration capacity development over three to five years in the future with auction periods that have capacity obligations of only one year. Even with longer contract periods (e.g., some auctions have 15-year contracts, see Figure 9) requirements to build within a short timeframe (e.g., 2-5 years) precludes more cost-effective but longer-to-develop technologies such as PSH from competing as they will not be operational on-time. This requirement for short construction-time is especially unfair for longer-to-develop technologies' when considering PSH plants have an economic lifetime of 40-60 years. Capacity markets should not exclude longer-to-develop technologies and need to provide long-term remuneration schemes to help stimulate new PSH projects in electricity markets.

Other structural factors also play a role: energy markets are based on marginal operating costs which means they are inherently biased to natural gas plants, particularly in light of retirements of other price-setting resources. With the price of electricity tied to natural gas in most markets, when gas prices go up, electricity prices go up, and vice versa, effectively protecting gas generators and those financing them. Conversely, for resources with low operating costs and high capital costs, such as PSH, capital costs do not change and need to be recovered regardless of market conditions. Therefore, even though capacity markets might be a mechanism to ensure reliable capacity, in their current form they do not help greenfield PSH development.

In the United States, capacity market clearing prices are usually of the order of USD $5 to $10 per kilowatt per year of capacity cleared, which is an insufficient incentive for developing PSH resources. Even when coupled with potential energy and in ancillary market revenues the revenues are still insufficient.

However, in the UK capacity market payments have benefited *existing* PSH stations, to the extent that such payments have helped finance modernization and refurbishment work.

As discussed earlier, in Section 1.3, *Long duration storage and PSH as a key enabler*, various studies show that on a system level PSH is often the most cost-effective solution, but if developers are only able to participate in mechanisms on a limited basis their investors will not have the confidence that they will be sufficiently remunerated to risk the investment. As the world moves away from fossil fuels, even gas, it is vital that whole system analysis takes account of the provision of low carbon grid services across multiple timeframes in order to ensure the lowest cost outcomes.

Box 4. Capacity markets supporting the modernization of pumped storage plants in the UK

First Hydro operates over 2 GW of pumped storage in the UK at their Dinorwig and Ffestiniog PSH plants, and in recent years have successfully taken part in the UK's Capacity Market. For example, the company bid generating units at its 360 MW Ffestiniog plant into a capacity auction that was held in 2016. After securing a 15-year contract that year, which covered part of the plant's installed capacity, First Hydro and its parent owners (ENGIE and Brookfield Renewables) proceeded with a decision for the plant's modernisation. In 2017, a GBP £50m investment was announced to fully refurbish two of the plants' four turbine-generator units (43). Originally commissioned in 1963, the modernisation project is expected to extend the life of the plant while also improving its performance and fast response capabilities (43). With capacity options also available for other units, the project additionally supports the owner's wider strategy to participate in future ancillary service and balancing markets (44).

3.2 Financing supports (from state, regional – EU's projects of common interest, R&D funding programmes, grants and green bonds)

Financing for PSH can be provided by governments (federal, state, or regional), EU funded projects of common interest, R&D funding programmes, grants, and green bonds (as shown in Table 3) and will be required to meet sustainability criteria based on the country or regional context.

Table 3 – Possible financing mechanisms for hydropower projects

Source: *(19)*.

Type of Finance	Source	Interest	Tenor
Concessionary finance grants of soft loans	Bilateral sources or multilateral development agencies; carbon credits	Very low	Long-term
Public equity	Public investment (government-supported) Some public equity is indirectly funded through bilateral/multilateral development banks	Dividends cans start low and increase over time	Indefinite
Public debt	Government loans, public bonds, or multilateral development banks	Low rates set by government or development banks	Medium to long-term with optional grace period
Export credit	Finance through Export Credit Agencies	Medium to high	Variable but commonly short- to medium -term
Private commercial debt	Private banks, commercial arm of development banks	High (may be lower with a guarantee)	Short- to medium- term (possibly extended with guarantees)
Private equity	Private sponsors, private investors, commercial arm of development banks	High dividends are expected as risk compensation	Depends on concession length

Table 3 shows a summary of the types of financial mechanisms that might be used when public or private entities are looking to finance hydropower projects. It is worth noting that because of the similar characteristics (including high upfront capital cost and large civil works component) similar types of finance might be used for PSH projects.

Direct financial support to promote wider economic benefits of PSH

Another factor that has supported the development of renewable energy has been its potential to promote economic development; this includes the promotion of technology development and manufacturing companies as well as project developers. It also includes jobs created from construction, maintenance and operations, industry and supply chains, and indirect increases in local commerce (e.g., hotels, restaurants, and stores) associated with infrastructure development. A recent example hydropower project in Peru saw the creation of 12,500 direct jobs and 10,000 indirect jobs and improved roads access for rural communities (20). Accordingly, governments have long supported the development of emerging renewable and smart grid technologies to achieve economic objectives via direct support. Direct support has come in the form of grants, loans, tax incentives, and special economic zones where access to government requirements such as licenses and permitting is streamlined (21; 22).

Similarly, to renewable energy projects, PSH projects require significant infrastructure development in the building of reservoirs, dams, powerhouses, and related infrastructure, including transmission and roads. Such projects include a major civil works component, often representing upwards of 70% of the total project capital expenditure that provide opportunities for local employment and businesses. The development of a PSH project requires long construction timeframes and significant investment. Projects are generally in remote areas which may not have the same economic development opportunities as more populated regions. These factors make PSH plants excellent candidates to leverage economic development and promote synergies with wider socio-economic goals.

A recent example is the proposed 250 MW/2,000 MWh Kidston pumped storage project in Far North Queensland, Australia. This project benefitted from grant funding and is set to receive a 30-year concessional loan, worth AU$ 610 million, from the federal government's Northern Australia Infrastructure Facility (NAIF) to support its development. Led by Genex Power, the project will be the first pumped storage scheme in the world to be located in an abandoned gold mine and will create over 500 jobs locally during the construction phase along with considerable upstream and downstream opportunities and generate an estimated AU$ 800 million of economic activity across the region (23).

Outside of market policy mechanisms

Outside of market policy mechanisms are targeted, technology, or even project-specific interventions carried out by governments to meet an agreed upon energy need. One notable example is in the UK where in 2016 the government agreed an inflation-linked set rate for the first 35 years of operation of the 3,200 MW Hinkley Point C nuclear power station (currently under construction).

Targeted intervention has also taken place in the hydropower sector. In Portugal, the government established the National Plan on Dams with High Hydro Power Potential in 2007-08. This programme focused solely on increasing hydropower capacity, including PSH, to support VRE in order to reach their climate targets and has led to several important projects being built (24).

The Australian Federal Government's Underwriting New Generation Investment scheme is another example of an outside of market policy mechanism designed to support the development of dispatchable generation and storage assets. Six of the 12 projects short-listed for support under this programme are pumped storage hydro, including projects identified in the Tasmanian *Battery of the Nation* initiative. This investment programme will support investment confidence for a 750MW 20-hour PSH plant at Lake Cethana in Tasmania.

Snowy Hydro 2.0 in Australia is a further example. In 2017, the federal government identified the value and need for large scale long duration energy storage as a necessary system resource in light of the increasing penetration of VRE across Australia's National Electricity Market and imminent closure of significant coal-fired capacity. In response, the government supported the development of the 2,000 MW/350 GWh project by becoming the sole shareholder of the project's developer, Snowy Hydro Limited, as well making an AU$ 1.4 billion equity investment in the project. It is expected to be fully operational in 2025.

In Europe, the EU taxonomy is a classification system establishing a list of environmentally sustainable economic activities to implement the European Green Deal. It is expected to create security for investors, protect private investors from greenwashing, help companies to plan the transition, mitigate market fragmentation and eventually help shift investments where they are most needed. The Act is now aligned with hydropower sector good practice requirements described in the Hydropower Sustainability ESG Gap Analysis Tool, compliance with which is necessary to secure green bond financing through the Climate Bonds Initiative. Importantly, the Act also now recognises all types of pumped storage hydropower as making a substantial contribution to climate change mitigation.

Any finance mechanism or funding, and particularly those that will help mitigate the economic impacts of COVID-19 by implementing large-scale infrastructure projects, should be made available also for flexible hydropower, and in particular PSH.

Box 5. Pumped storage and the green bond market

The Climate Bonds Initiative (CBI), a not-for-profit organisation which develops certification standards for green bond issuances, has recently published its hydropower criteria (including PSH) (49). The hydropower sector has received the green light for climate bond finance, meaning that owners and developers can now benefit from this mechanism to finance or refinance hydropower projects. Certified climate bonds are a very good lever to direct investment to infrastructure that supports the Paris Agreement while reducing negative impacts on local environments and communities.

To-date, worldwide green bond issuances have reached over US$1 trillion (50). Green bonds fund projects that have positive environmental and climate benefits and the market has experienced significant growth since the first bond was issued in 2007.

The published criteria recognise PSH projects as key supporting infrastructure for the deployment of VRE sources and vital for grid stability. The green bond market could prove to be an important source of financing and re-financing providing developers with a diversified investor base.

3.3 Other sectors' initiatives

3.3.1 Transmission

The case can be made that PSH resources are very much like transmission infrastructure: not only can PSH provide several transmission services, (e.g., network congestion relief, system reliability, or voltage and reactive power support) but is a capital-intensive resource with a long asset life that has system-wide benefits. Accordingly, it is worth considering transmission investments, specifically merchant, or non-rate regulated investments, as potential models for PSH development that may help to address high capital costs and revenue uncertainty. Transmission that is rate regulated may also serve as a model for PSH development.

3.3.2 European transmission development

Europe has developed a multitude of transmission links and high voltage interconnectors between countries. For example, the NordBalt interconnector, which was partially funded by the EU, was commissioned in 2015, provides undersea transmission from Sweden to Lithuania, and facilitating trade between the Baltic and Nordic electricity markets. Following the development of the interconnector, Lithuania's 900 MW Kruonis PSH plant has seen additional use supporting operational efficiency and back-up to Lithuania's system, when the NordBalt interconnector is unavailable (25). There are plans to further expand capacity by another 225 MW to address wind intermittency expected from an expansion of wind generation in the region and to take advantage of price differentials between regional markets.

Expansion studies for Kruonis PSH have been financed by the European Commission (26), and the project is included in the EU Projects of Common Interest (PCIs). The PCI programme comprises a list of proposed cross-border infrastructure and storage projects, mainly high voltage interconnectors between two or more countries, but which also currently includes 12 PSH projects spanning Europe (in the UK, Ireland, Spain, Baltics, Balkans, Central Europe, an innovative offshore concept Belgium, etc.). Projects are listed through a stakeholder selection process conducted every two years by the European Commission. The process supports development studies, fast tracking of approvals, and makes it easier to obtain financing. The interconnectors on this list can also access Connecting Europe Fund (CEF) facility for capital support, and the recent review may allow the possibility for listed PSH plants to also access this support (27). It is important that cost benefit analysis and other tools used by parties assessing PCI projects take full account of the benefits of storage technologies.

3.3.3 Cap and floor: Insights from UK's interconnector process

In the UK, to unlock greater investment in electricity interconnectors which enable the large-scale imports and exports of energy to the European mainland, the market regulator, Ofgem, developed the "Cap and Floor" mechanism. In simple terms, the mechanism supports the development of transmission where otherwise private developers were not able to secure financing due to uncertainty of long-term revenues. The Cap and Floor mechanism establishes a rate recovery floor, that is a minimum return, that transmission projects are guaranteed to receive from customers through regulated transmission rates. The scheme also establishes a cap, or a maximum return that projects can receive, permitting market participation while protecting ratepayers and preventing windfall profits for the developer. Any revenues generated above this cap are transferred to the system operator which are used to reduce transmissions charges across the system.

Since the scheme was implemented in 2012, there are six installed and operating transmission projects. Review of these projects carried out by Ofgem have indicated that the scheme is operating as intended (15) (28). PSH projects might benefit from a similar Cap and Floor mechanism if it has long-term contracts, is open to all long-duration storage technologies, and where the annual income floor value could be competitively set with conditions placed on the availability of flexibility services.

3.3.4 Chinese PSH Development

China's 13th Five Year Plan targeted a total pumped storage capacity of 90 GW by 2025 and the 14th Five Year Draft Plan includes mention of a series of PSH plants. The National Energy Administration has drafted a long-term industry plan that will double the scale from the 13th Five Year Plan to 62 GW by 2025, and aim to have 120 GW installed capacity by 2030 (5). Currently China has 32 GW pumped storage installed capacity and another 52 GW under construction. These projects have been developed by state owned transmission operators or in joint venture with local governments with state supported financing. Local governments often welcome the PSH projects as stimulus for the local economy and actively support benefit sharing and resettlement programmes. Pumped storage was regarded as a grid asset rather than a generation asset, deploying it in such a manner that it can capture benefits beyond generation services. The costs in the construction and operation of PSH are absorbed by the total costs of the power grid. PSH revenue in China is currently decided by the Chinese government using a two-part tariff system, which is combination of a fixed annual capacity-based payment and generation-based tariff intended for cost recovery.

However, under the currently on-going electricity market reform, China is aiming to exclude the cost of energy storage from transmission and distribution costs in an attempt to reduce consumer electricity prices, with the goal of transitioning to spot markets, with an ancillary services market. Since 2019, pilot spot markets haves been trialled in eight provinces across the country, however PSH was not included in these spot markets. Regional ancillary service markets are also being trialled, but PSH is still excluded in some markets such as Shanxi and Shandong. PSH can participate in some ancillary service markets in regions of eastern China regions, and some services such as black start have been compensated, yet revenue has been too low to be self-sufficient. China's National Development and Reform Commission (NDRC) in May 2021 released a policy paper, which sought to consolidate PSH pricing mechanism and suggested to optimize the two-part tariff mechanism based on capacity and energy.

Box 6. PSH supporting a cleaner, more secure energy mix in the Middle East and North Africa

Egypt's electric system is currently operated by state-owned companies, with some private entities delivering renewable energy under contracts with the state utilities. Energy is largely produced by fossil fuels with 75% of the generation from natural gas resources. Egypt is working to diversify its energy mix and develop 10 GW of new solar and wind capacity by 2022, and is undertaking efforts to develop regional interconnections to increase cross-border trading. (51).

As part of this diversification approach, the Attaqa Mountain PSH plant is a 2.4 GW project planned for development in Suez, developed by the Hydro Power Projects Executive Authority, and will be the first PSH plant in the country. The Export-Import Bank of China agreed to provide US$ 2.6bn in February 2019 following a memorandum of understanding signed between Egypt and the Chinese state-owned Sinohydro Corporation which is the engineering, procurement and construction (EPC) contractor for the project (52). The project will be used to provide energy during peak hours where available system capacity is limited, help integrate VRE resources and diversify Egypt's energy system (53).

In the United Arab Emirates, the Dubai Electricity & Water Authority (DEWA) is the government owned utility responsible for generating and delivering electricity across the Emirate of Dubai. Historically its generation has been entirely natural gas fired but under the Dubai Clean Energy strategy has recently greatly expanded solar generation. Dubai aims to produce 75% of its generation from clean resources by 2050 and is developing a 5 GW solar farm by 2030 (25). DEWA awarded an EPC contract for the 250 MW Hatta PSH Plant in August 2019 in the Dubai exclave of Hatta in the Hajar Mountains (26). The project, expected to be operational by 2024, is intended to pump water using collocated solar energy during off-peak hours and generate electricity during peak hours. The project benefits from the existing Hatta dam infrastructure (54). DEWA has targeted the Hatta area renewable energy development to meet Dubai's 2050 Clean Energy Strategy (25).

Pumped Storage Hydropower International Forum

Policy and Market Frameworks Working Group

Chapter 4

Remuneration schemes

Summary

1. Real time power settlement supports more efficient allocation of generation resources.
2. Ancillary services in many markets are not compensated.
3. Where ancillary services are procured and remunerated PSH can be competitive.
4. Bespoke capacity mechanisms matched with longer-term power system modelling can share risk appropriately and deliver secure long term PSH services.
5. PSH – variable renewable hybrids can provide firm, low cost, low carbon electricity.

As part of the energy transition, most policymakers are changing market structures in lock step with their transitioning generation mixes. For this to be successful, remuneration schemes must become more sophisticated and take into account the need for long-term power system planning to identify power system needs ahead of time and recognise the role hydropower can play in delivering grid stability. Table 4 summarizes the remuneration schemes or mechanisms available to PSH across different electricity markets.

Table 4 – Electricity market services that PSH can provide

Payment Mechanism/Service	Description	Example
Energy	Delivery of energy [MWh]	Most power purchase agreements/contracts around the world
Capacity	Presence of capacity on the system [MW]	Capacity markets in the UK/US or power purchase agreements that include a capacity term (Nevada PV and Energy Storage Projects)
Availability	Potential to deliver a certain amount of energy over a period of time. The resource must be available to deliver that energy if called upon.	Israel PSH Contracts; Hydro Tasmania "Virtual Storage" contract
Ancillary services (reserves)	Delivery of different ancillary service reserve products (spinning reserve, firming, ramping, etc.)	Snowy Hydro Super Peak Firming Payment California's Market Ramping Product
Ancillary services (frequency regulation)	Delivery of short-term (seconds) reserves (energy) in response to a system operator signal (automatic generation control)	Batteries delivering frequency regulation in Germany: EnspireME project
Ancillary Services (inertia/fast frequency response)	Delivery of inertia or primary (fast) frequency response to a system. This is an immediate delivery of energy in response to a frequency shortfall through spinning machinery or inverters.	Ireland's inertia and fast response market product
Ancillary services (reactive power, voltage regulation)	Delivery of reactive power [VARs]	National Grid UK's inertia/reactive power contract with Drax PSH
Black Start	Payment for delivery of energy to the grid that can enable other generators to start following a grid outage.	Competitive tender to procure this capability in New Zealand, Texas, Alberta and Ontario.
Performance incentives	Performance of plant relative to present levels (can be speed of response, time to start up, etc.)	Israeli PSH Contracts
Start up and shut down	The start up or shut down of a power plant	Israeli PSH Contracts

4.1 Wholesale market signals

Real-time power settlement

In recent years, markets in regions like the US, Europe and Australia have announced or implemented moves towards closer to real-time dispatch and settlement of generation. Real-time dispatchability will be critical especially as it becomes more and more apparent the volatility of renewable resources that will require more frequent balancing intervals.

Studies indicate that shorter settlement periods promote efficiencies in market operations with an overall more efficient allocation of generation resources to meet load, provide price signals closer to actual operational requirements, and in the end save money for consumers. Improved price signals also better direct investments in generation that brings the highest value to the system, and in particular incentivizes flexible generation and load response (29) (30).

India's move towards a 5-minute market from the two-decade old existing 15-minute market is an important development on the road to meeting the country's target of 175 GW of renewable energy capacity developed by 2022 (31). At present, existing private PSH and hydropower plants are compensated at very low contract rates with state-owned utilities. The introduction of a real-time market may allow for an increase in revenues for existing plants and an additional driver for more PSH development.

4.2 Ancillary or flexibility support services (frequency control, voltage regulation, black-start and inertia)

Payments for uncompensated ancillary services

PSH plants are not compensated for all the services and benefits that they can, and often do, provide to electricity systems. This includes their delivery of system inertia and primary frequency response, which are not currently market products in many jurisdictions[17]. It also includes the value they provide with regards to reliability or resiliency as controllable energy system assets (16). These ancillary services will be especially valuable as VRE penetration increases and replaces conventional power plants (typically coal and natural gas) that have provided these key system and balancing services in the past for free.

As noted previously, the valuation of PSH benefits is essential but complex, requiring detailed modelling and simulation tools. The failure to provide the required certainty and clarity in policies and regulations can increase borrowing costs and deter investment in new PSH projects.

Both Ireland and the UK have started to pay for inertia services that are not otherwise compensated in most other countries, primarily as a result of reliance on existing fossil synchronous generation to deliver these services. System operators in Ireland have introduced synchronous inertial response and fast frequency response as grid services to be compensated. A market participant capable of delivering both inertia and fast frequency response is allowed to bid to provide and be remunerated for both services (32).

[17] Inertia in the context of the electric system is defined as the kinetic energy contained in rotating synchronous machines, like generators and turbines, that can immediately inject energy into the system in case of disturbances. As fossil generation is retired to meet clean energy goals, system inertia is decreasing, leading to possible grid instability. Development of PSH is one way to return inertia to the system.

Box 7. A new approach to procuring inertia and reactive power

In 2020, the UK saw the award of a six-year contract that will permit one of the four turbines at Drax's 440 MW Cruachan pumped storage station to be used to provide flexibility support services to the grid, specifically, inertia and reactive power. This contract was a part of National Grid Electricity System Operator's System Stability Pathfinder Tender (45). National Grid estimates that its contract with Drax and five other developers will save consumers up to £128 million over the six-year contract period. This is an effort by National Grid to ensure that by 2025 it will be able to operate the grid safely and securely at zero carbon (46).

These are particularly important outcomes for PSH because synthetic inertia, that is inertia derived from inverter response, is not proven at scale. Comparatively, system operators value inertia delivered from a rotating mass, such as a PSH turbine, as a proven inertia service. In addition to paying for inertia, National Grid is also establishing a fast frequency product, called dynamic containment. The product, while technology-neutral, has only had battery storage projects meet the requirements as it will require autonomous response within one second to respond to a sudden demand or generation loss, and could be an exciting opportunity for Variable Speed PSH technology to deliver high-value service for the system operator. In addition to dynamic containment, National Grid will also enable the delivery of modified dynamic regulation and moderation products (47) (48).

The Australian Energy Market Operator and the Electric Reliability Council of Texas (ERCOT), the Texas electric market operator, are also considering inertia and faster response products. In the Tasmanian region of Australia, the market operator declared a shortfall of inertia as well as system strength (fault level) at 4 distinct locations in the Tasmanian network. These shortfalls are commonly observed during periods of high import via HVDC interconnection, high wind output, and low energy demand in Tasmania, which can result in over 85% non-synchronous penetration in Tasmania. To remedy these shortfalls, the Tasmanian network company has contracted directly with Hydro Tasmania to operate some hydropower assets in synchronous condenser mode. This capability required some modest investments to the existing hydropower fleet, but was easily the most cost-effective solution to deliver this integral grid service when compared to the costly investment in new standalone synchronous condensers.

Continental Europe is looking at evolving technical definitions and requirements on ancillary services as part of broader plans to harmonise services between participating countries; this is being led by the European Network of Transmission System Operators (ENTSO-E). While currently the inertia and faster frequency services are not defined or remunerated on the continental grid system, their introduction in future may prove likely as the energy mix changes. European platforms are already being set-up to support cross-regional markets and exchange of proposed service products (known by acronyms PICASSO, MARI, and TERRE). An ongoing research and innovation project called XFLEX HYDRO, funded by the EU, is also investigating the role of hydropower technologies in meeting ancillary services and emerging requirements, with a particular focus on PSH plants[18].

4.3 Capacity and availability payments

As part of the Israel Electric Corporation determination that the system required a significant deployment of long duration storage, Israel developed a payment mechanism with a remuneration structure intended to ensure private financing and development. Based on this structure, two major pumped storage projects have been evaluated for the Israeli market: the 344 MW Kokhav Hayarden project owned by Star Pumped Storage which is under development, and the 300 MW Gilboa pumped storage project which is already operational.

The payment structure pays on plant availability over an 18 to 20-year timeframe, the long-term nature of which, as discussed above, is traditionally not available to resources in liberalized electric markets. This approach mimics, in some form, an asset in a vertically integrated market with a guaranteed level of payment

[18] For an ancillary Services Matrix recently published: https://xflexhydro.net/ancillary-services-matrix

to ensure development, but at the same time includes delivery and performance requirements to promote efficiency and a high level of resource performance.

The three-part payment scheme consists of the following revenue streams:

1. Primary source of revenue: An availability payment which forms the bulk of revenue and requires the plant to be available for a minimum time during a year. In addition, an availability requirement is passed on to the equipment manufacturer, supplying plant availability guarantees through a long-term operations and maintenance contract. This payment also includes bonus payments for dynamic benefits including ramp rates, pumping to generation switching timeframes, start-up and shutdown speeds, etc.
2. Payment for energy.
3. Start up and shut down payments based on how often the plant is operated.

These plants are being provided a fixed revenue stream over a long time based on certain performance requirements, and additional incentives for flexibility and reactivity. Developers support this mechanism as it mitigates market and regulatory risks for the project's business case. The grid operator bears long-term development risk while the developer bears the plant's performance risk, which is also being shared by equipment suppliers. This allows for risk allocation and sharing amongst all the involved parties and has led to these two successful deployments (for further information on risk sharing, see section 2.2.1 *Large capital outlay – project finance risk*).

4.4 Others (hybrids auctions, firming products, PPA etc.)

Hybrid and firming products

Hybrid projects have recently gained a lot of interest around the world. These projects combine renewable energy with an energy storage device often in the form of batteries or a PSH development. In some cases, these projects involve co-development of the PSH resource with a wind or solar farm, and the output from the entire project is sold to a utility as a single entity. In other cases, a standalone PSH project can sign firming contracts with renewable energy developers for wind and solar projects. These firming contracts are often long-term and turn renewable output into a dispatchable unit that can meet capacity or resource adequacy needs. These contracts may also be multi-part payment contracts with capacity or availability, and energy and performance payments similar to the Israeli framework. Long-term contracts open new markets for PSH developers, help mitigate financing risk, and promote development.

One example is Hawaiian Electric Industries Inc. (Hawaiian Electric) developing PPAs for renewable dispatchable generation. These contracts are intended to solicit firm renewable energy capacity in the form of solar and energy storage, or wind and energy storage. Hawaiian Electric worked extensively with industry to develop these contracts and ensure competitive participation in their request for proposals. The contracts permit guaranteed payment for net energy potential and facility availability rather than energy delivery. This permits the developer a guaranteed revenue stream that is less subject to curtailment and permits the utility, and its ratepayers, a lower cost dispatchable renewable energy resource.

Nevada Energy took a similar approach with a recent procurement of hybrid solar and storage capacity. The PPA structure pays a price during system peak hours (i.e., 4:00pm to 9:00pm) that is 6.5 times higher than the price paid for output during other hours. This PPA ensures that the projects provide capacity value in addition to energy. Nevada Energy additionally has the flexibility to dispatch the plant during non-peak hours to minimize system costs (33).

In Australia in 2018, Snowy Hydro signed eight wind and solar contracts totalling 888 MW which are to be firmed with Snowy Hydro's existing assets enabling the company to deliver extremely competitive prices to customers (34). More recently, Snowy Hydro started exploring a new 'super-peak' contract designed to cover demand during the high-priced morning and evening periods, when solar output is low (35). This new hedging product enables participants to manage the risk of very high prices and is a perfect fit for hydropower, including

PSH. Such firming products are also an important revenue stream for the Snowy 2.0 pumped storage project currently under construction.

Also in Australia, Hydro Tasmania recently announced the signing of a “Virtual Storage” contract with Macquarie and ERM Power. Under the contract Hydro Tasmania sell the rights to power stored in their hydro catchments during the highest priced parts of the day and buy energy to charge their plants when prices are low. This allows Hydro Tasmania to take advantage of the swings in daytime prices due to weather-dependent renewable energy and lock in their price spread. This virtual storage contract trial is a ‘world first’ product and is among a range of financial derivatives that could provide part of the much-needed revenue certainty to support future PSH investments.

Chapter 5

Recommendations to governments and stakeholders

Summary of Policy Recommendations

1) Policymakers should assess the long-term storage needs of their future power system now, so that the most efficient options, which may take longer to build, are not lost.

2) Comparisons between energy storage and flexibility options must follow a consistent, technology neutral approach that considers all impacts and benefits.

3) Providers of essential electricity grid, storage, and flexibility services should be remunerated for all services that they provide.

4) Licensing and permitting arrangements must be timely, proportionate and take advantage of the range of internationally recognised sustainability tools.

5) Investors in long lasting assets, such as PSH, must have long-term visibility of revenues, with risk that is shared fairly to deliver the lowest overall cost to society in the long term.

6) Existing hydropower assets and prospective sites should be assessed and mapped for their potential to provide the most efficient long duration storage.

7) Green recovery programmes should include and support PSH, and green finance mechanisms should incentivise PSH.

Over the past decades, policies and support mechanisms have been devised and implemented covering nearly all renewable and low carbon sources, but long duration storage, and especially PSH, were the forgotten enabler. Given the undeniable need for long duration storage solutions, to support net zero and security of supply, it is now necessary to bridge that gap.

Each country or state has its own unique regulatory framework, market design and dispatch operations. Based on the contributions of the various stakeholders, as well as the best practices identified in some markets, hereafter are several specific recommendations which could be applied or used as a guide in other jurisdictions.

5.1 Non-economic levers: Policy, regulation, licensing, permitting, and others (modelling, ownership, IRP)

Policy/regulation

- To enable the energy transition, **the vital role of long duration energy storage must be recognised.**

- Renewable energy policies need to take into account grid stability issues, and the need to maintain an appropriate frequency and sufficient reserve capacity, and integrate flexible sources like PSH for efficient utilization of projected VRE. Absent such integration, the true cost of reserves to ensure grid stability will not be properly accounted for, which may result in an inefficient deployment of resources to ensure stability.

- Energy storage targets (in GWh) for short and long duration storage should be assessed and implemented, as they can ensure energy transition objectives are achieved in line with these targets. Such targets should be set on a technology neutral basis and incorporate medium (e.g., 2030) and long-term goals (2050) to ensure the most cost effective long-duration storage technology can compete with other technologies.

- Market and regulatory frameworks should be flexible enough to support innovative approaches to facilitate "firming" low carbon products. Those markets that procure firm low carbon electricity should not artificially restrict PSH hybrid projects with wind or solar as such plants bring comprehensive benefits such as reduction in VRE curtailment, energy savings, reduction of fossil fuel consumption and emission reductions.

- **Wider societal benefits from the investment in PSH** should be recognized as part of green post COVID economic recovery by governments. If the climate targets of the Paris Agreement are to be met with minimum financial commitments, annual investments in hydropower and PSH have to grow. It is therefore critical that hydropower is included in green recovery funding and planning to enable a smooth energy transition. Unusually among energy technologies PSH projects include a major civil part (often representing upwards of 70% of the total project CAPEX). The civil part of PSH projects enables bringing wider economic benefits through local jobs creation and opportunities for local businesses, workers, and communities. It can also contribute to technical skills development through the creation of a pool of Skilled engineers.

- Cost benefit and other studies must be undertaken to **leverage the significant hydropower installed base globally**, to evaluate the possibility of converting these assets to PSH where technically possible (and following a cost benefit analysis). Moreover, modernization projects to upgrade older PSH projects to more flexible solutions (e.g., variable speed technology) should be assessed and supported through dedicated programmes.

Modelling and System Planning

- A **standard 'modelling methodology' should be developed for evaluation of storage technologies** for system planning purposes (regarding both generation and transmission expansion) and covering technical, economic feasibility as well as sustainability. This common methodology should cover the operational performance characteristics and capabilities of storage technologies, the value of energy storage and capacity products that can be utilised across the spectrum of technologies available to provide these services. The methodology should also include the evolving needs of the electricity system, such as the increased need for ancillary services. Additional flexibility criteria such as the number of cycles for energy storage projects, as well as standard name plating with both energy and capacity at the facility level (MWh and MW), should be included to appropriately assess all storage technologies.

  The standard modelling methodology should further **enhance knowledge of long duration storage technologies such as PSH**, across different stakeholders, including utilities, regulator, and system planners so that it can be properly integrated within the planning process.

- The analysis of system adequacy, interconnection capacities, grid capacity requirements, and need for storage should be performed **at the country level and also across national boundaries**. Then appropriate policy frameworks that share the costs and benefits will increase the overall consumer and citizen benefits.

- **PSH inventory studies that map favourable sites**, define principle technical characteristics, and rank the best projects should be pursued; they should also feed into the planning process by applying multicriteria analysis decision methods (MCA). Prioritisation factors to be considered can include: location of project, capacity (MW and MWh), related system benefits and financial performance, off-river or on-river scheme, land and environmental impacts, development maturity (pre-feasibility and feasibility studies or project reports), existing infrastructure and grid connectivity at interstate and/or regional grid level, and efficiency gains by planning alongside future VRE deployment plans.

  Studies should also include innovative solutions such as **seawater pumped hydro storage (SWPHS) potential**, and hybrid pumped storage configurations with batteries and/or flywheel.

Licensing/permitting

- **Streamlining licensing and permitting procedures is critical to accelerate lead times and reduce transaction costs**. Streamlining can be done as a first step for low-impact PSH, such as off-channel, modular or closed-loop projects, while ensuring the projects are sustainable through the application of the sector best practices in development phase (e.g., Hydropower Sustainability Assessment tools, and IHA – ESG tool).

- **It is essential that governments create a favourable framework in which PSH projects can be implemented**. Countries and regulators should learn from best practice in other jurisdictions to ensure fast, efficient processes that take account of stakeholders' concerns. For some countries, it may be necessary to adapt the regulatory framework to facilitate development studies and procedures for site concession (environmental permit, water use authorization, pre-feasibility studies).

Ownership

- In many regimes, restrictions apply to the type of asset that network operators can procure or operate. These imposed constraints can lead to sub-optimal outcomes, if they do not take into account the potential network benefits of long duration storage technologies such as PSH, and may lead to higher costs for consumers. *Where appropriate*, **PSH assets should be considered part of a system and/or network solution for transmission** so that a transmission system operator can be a potential owner and/or operator to benefit from economies of scale and maximize intermittent VRE integration. A PSH project could then be included in future transmission planning, and would then be operated in accordance with the requirements of the grid operator. Tariffs for input power for pumping and output power would be set by the regulator. It may be necessary to review energy networks regulations, especially how storage solutions can compete in a fair and technologically neutral manner (e.g., utility-scale storage vs. transmission upgrades), as well as ensuring appropriate protections are in place.

- Constraints placed on transmission system operators should not restrict the procurement of the most efficient assets, such as PSH, directly or indirectly. Innovative transmission/generation hybrid products, appropriately regulated, may be cost-effective and lower overall costs for consumers. Governments, regulators, and other relevant stakeholders should assess the potential for such solutions. For example, grid deferral savings could be recognized and shared between the PSH operator and transmission system operator. Transmission operators could then sign long-term agreements with PSH operators on a non-discriminatory basis.

- Another option would be for an ISO or RTO to procure a PSH project (with or without VRE) under an availability contract. The ISO/RTO would then dispatch the system to provide critical transmission services that it is responsible for. The contracts would be paid for by ISO/RTO charges on all market participants through rates or other established mechanisms. Any additional revenues could be refunded to all participants.

- While these approaches to ownership by TSO/DNOs should be examined, it would be important to avoid distorting existing energy markets from which the majority of energy storage revenue would derive.

Vertically integrated markets

- Governments and regulators should fully integrate energy storage resources into long-term planning with VRE and modelling that considers all relevant factors when comparing different storage technologies.

- Consideration should be given to support the large capital costs and long-term implementation timeframe technologies, such as PSH, especially in the context of limited other clean capacity alternatives. This support could take the form of both mandates to evaluate PSH by the regulated utility in planning and financial support (i.e., rate-basing or inclusion in rates).

5.2 Economic levers: Financing, market designs, revenue schemes, others

Policies / incentives

- Policies to **secure timely investment in long duration storage technologies,** such as PSH**, must provide adequate revenue visibility to stimulate private sector participation by providing a suitable revenue de-risking mechanism**.

- Policy mechanisms must allocate all risks fairly to those parties best able to assume them**.**

- Policies should be technology-agnostic and provide **clear and enduring investment signals with secured guarantees, to improve predictability of revenue streams and long-term returns**. Solutions should compensate both system services (i.e., immediate operational priority) as well as incentivising new investments for system balancing (i.e., short/medium and long-term strategic priorities). These signals could take the form of an operating reserve market, a resource adequacy mechanism, compensation for inertia and/or system strength, or a combination of these features.

For example, an Income Floor model (based on existing Cap and Floor regime currently used to stabilise interconnector revenues in the UK) would de-risk revenue streams and provide sufficient long-term certainty (through 15 to 20-year contracts) by securing minimum revenues to meet annual costs and therefore attract debt finance. The annual income floor value could be competitively set, and open to all long duration storage technologies, with conditions placed on the availability of flexibility services such as frequency response, reactive power, or inertia. Owing to the long development and construction cycles for PSH, **it is vital that these signals arrive before the technical need has emerged to ensure the required capacity can be constructed in time.**

Another example is the New South Wales's Investment Safeguard that will provide an investment signal to deliver new electricity infrastructure. **Long Term Energy Services Agreements will be available for long duration storage** (which the Government recognises will be pumped hydro for at least the immediate future) and firming capacity. These will be awarded through a competitive process and will be option contracts that give the project optional access to a competitively set minimum price for their energy service. Additional support will be provided to pumped hydro projects through a new Pumped Hydro Recoverable Grants Programme that will help meet the significant upfront costs of establishing the feasibility of potential pumped hydro projects.

- **Specific long duration storage support schemes should be put in place to ensure long-term financial stability and revenues** (e.g., a storage tax credit that takes into account the long development timeline). Any government mandates, incentives, taxation and regulatory frameworks should be consistent across all technologies and not encourage perverse incentives: for example, not favouring less efficient options for decarbonisation through specific tax regimes, reduction of transmission network charges, exemption of grid tariffs for pumping, or introduction of differential tariff structure for peak and off-peak times.

- Policymakers and regulators should **review the existing incentive mechanisms and standards** to stress test their applicability to long duration storage, especially in respect of encouraging and enabling investment.

Green Recovery

- PSH should be included in green recovery programmes and be part of a sustainable approach to better build back and strengthen resilience strategies to meet national determined contributions for 2050 net zero targets.

- Green finance products and funding (including COVID recovery) should be available also for flexible hydropower and in particular PSH.

Financing

- The design and implementation of **suitable financing arrangements,** that take into consideration long development timeframes and high upfront capital cost of projects, is critical to attract private sector investors.

- **PSH should be permitted and encouraged to actively participate in finance mechanisms like green bonds or impact bonds**.

- In addition to the **financing mechanisms listed in Table 3, the hydropower sector and financiers should issue green bonds in accordance with recognised criteria.**

- **Governments should consider issuing recoverable grants from governments** that effectively share project risks between governments and the private sector to support investment and development of PSH projects.

Market designs and revenue schemes

- **Suitable innovative business models for long-term sustainability of PSH need to be developed based on technology neutral products and services for future system needs**. Eligibility to provide key support services to the grid should consider energy storage technologies in terms of project lifecycle costs, performance, and energy storage system degradation.

- Clear policies should be developed to define how PSH can compete to provide grid services while:
    i. Ensuring consistency in contract length for different types of ancillary services and, where possible, auctions or other allocation mechanisms should operate at the same time to allow for the possibility of revenue stacking by the most efficient service providers.
    ii. Allowing for bundled service provision so that any technology that can provide multiple services at the lowest overall cost are able to compete.

- **New commercial products should be introduced.** In addition to ancillary services, such as primary frequency response or load following, new services such as inertia or ramping products to manage variability in net load should be compensated. New flexible capacity mechanisms should prioritize low carbon solutions and only reward un-abated fossil fuel if no low carbon alternative is viable. Examples of potential mechanisms include: more granular financial wholesale market products through real-time power settlement (15-minute intervals or less), fast ramping capacity mechanisms, storage capacity auctions, winter reserves, remuneration for grid deferral savings, VRE PPA integration, renewables firming, real time renewable supply, participation as demand response supplier, long-term agreements between transmission operators and energy storage developers.

  The special features of PSH and other long duration storage technologies (heavy capital investments and long payback periods) should be taken into consideration to **secure payments for more than 15 years and cross-border participation of flexible plants should be allowed and encouraged** (requiring the harmonization of grid tariffs and the costs for fair competition).

Vertically integrated markets

- Vertically integrated markets should put in place a model that captures the overall benefits of PSH for the power system including security of supply, VRE integration, transmission deferral etc. to properly run a comprehensive cost benefits analysis.
- In vertically integrated markets, the economic compensation mechanism for ancillary services should be assessed, including existing tariff and market structures as well as for a wider range of balancing services. They should also consider introducing a trading mechanism for flexibility services that could be traded in "competitive" wholesale markets such as energy, peak load regulating capacity and other ancillary services in the power system.

5.3 Planning for the long-term: Remuneration of PSH in a market dominated by zero-marginal cost VRE

The widespread deployment of variable renewable energy resources has changed worldwide energy markets and will continue to do so. As fossil fuel resources are replaced by zero marginal cost VRE, current market and regulatory constructs, based on the marginal costs of generation, will be less valid. It is clear that change will occur.

The barriers and recommendations that apply to PSH identified here also apply to other types of energy storage and large renewable capacity (e.g., hydroelectric and geothermal).

As policymakers, regulators, and market operators consider changes to their market and regulatory frameworks to enable the development of PSH and new clean capacity, they should ensure these changes are inclusive and technology-agnostic to the extent possible and permit other technologies, including those not yet developed, a fair chance to compete.

Energy storage resources of various capacities and durations will be an integral part of the future electricity system, providing reliable capacity and reserves to enable widespread VRE deployment.
Therefore, consideration must be given to incentivising PSH development now and to continue incentivising operation of these resources in future.

Absent an eye to the future, modifying current markets and regulatory constructs to deal with current problems is likely to lead to challenges for the operation of the future electricity system and the development of yet to emerge resources. Maintenance of the status quo and even changes that do not consider the future, will result in history repeating itself, where renewables were incentivized and rapidly deployed to build an industry and reduce emissions, but resulted in significant inequities to customers, an incremental rather than holistic response to intermittency and variability, and the exclusion of other resources that could provide value, such as PSH, historically.

Therefore, to achieve the decentralized, low carbon, efficient electricity grid of the future, policymakers and regulators must place value through financial incentives and market models, and include long duration storage options, like PSH, at the heart of their future energy planning.

Pumped Storage Hydropower International Forum

Policy and Market Frameworks Working Group

References

1. **International Renewable Energy Agency.** Global Renewables Outlook Summary Edition: 2020. *IRENA.* [Online] 2020. [Cited: 31 August 2021.] https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Apr/IRENA_GRO_Summary_2020.pdf.
2. **IRENA.** *Global energy transformation: A roadmap to 2050 (2019 edition).* : International Renewable Energy Agency, 2019.
3. **IEA.** *Renewables 2020 Key trends to watch.* : International Energy Agency , 2020.
4. **International Energy Agency (IEA).** Hydropower Special Market Report: Analysis and forecast to 2030. *IEA.org.* [Online] June 2021. [Cited: 1 July 2021.] https://iea.blob.core.windows.net/assets/4d2d4365-08c6-4171-9ea2-8549fabd1c8d/HydropowerSpecialMarketReport_corr.pdf.
5. **National Energy Administration (NEA).** "Pumped Storage Medium and Long-term Development Plan (2021-2035)" Issuance and Implementation. *NEA.gov.* [Online] 9 September 2021. [Cited: 14 September 2021.] http://www.nea.gov.cn/2021-09/09/c_1310177087.htm.
6. **Ministère de la transition écologique. Programmations pluriannuelles de l'énergie (PPE)**. [Online] https://www.ecologie.gouv.fr/programmations-pluriannuelles-lenergie-ppe., 8 July 2021. [Cited: 31 August 2021.] www.ecologie.gouv.fr.
7. **Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen**. Genehmigung des Szenariorahmens 2021-2030. [Online] https://www.netzentwicklungsplan.de/sites/default/files/paragraphs-files/Szenariorahmen_2035_Genehmigung_1.pdf., 26th June 2020. [Cited: 31 August 2021.] www.netzentwicklungsplan.de. .
8. **Department for Business Energy, & Industrial Strategy and Ofgem.** Transitioning to a net zero energy system: smart systems and flexibility plan 2021. [Online] 21 July 2021. [Cited: 30 July 2021.] https://www.gov.uk/government/publications/transitioning-to-a-net-zero-energy-system-smart-systems-and-flexibility-plan-2021..
9. **Uría-Martínez, Rocío, Johnson, Megan M. and Shan, .** *U.S. Hydropower Market Report.* Oak Ridge National Laboratory. Oak Ridge. s.l. : U.S. Department of Energy, 2021.
10. **Gates, Bill.** *How to Avoid a Climate Disaster: The Solutions We Have and the Breakthroughs We Need.* United States : Alfred A. Knopf, 2021.
11. **Pudjianto, Danny, Badesa, Luis and Strbac, Goran.** *Whole-System Value of Long-Duration Energy Storage in a Net-Zero Emission Energy System for Great Britain.* London : Dept of Electronic and Electrical Engineering, Imperial College London, 2021.
12. **SMC Global Power.** San Roque, Pangasinan. *smcglobalpower.com.ph.* [Online] [Cited: 20 August 2021.] https://smcglobalpower.com.ph/article-sanroque.html.
13. *A review of pumped hydro energy storage development in significant international electricity markets.* **Barbour, Edward, et al.** August 2016, Renewable & Sustainable Energy Reviews, Vol. 61, pp. 421-432. English Version.
14. **Torrealba, Pedro Javier Ramírez.** *The Benefits of Pumped Storage Hydro to the UK.* London : DNV GL, 2016.
15. **Ofgem.** *Guidance on the cap and floor conditions in National Grid North Sea Link Limited's electricity interconnector licence.* London : Office of Gas and Electricity Markets, U.K. Government, 2018.
16. **The National Hydropower Association.** *2018 Pumped Storage Report.* Washington, DC : The National Hydropower Association (NHA), 2018.
17. **Department of Energy, Federal Energy Regulatory Commission.** Report on the Pilot Two-Year Hydroelectric Licensing Process for Non-Powered Dams and Closed-Loop Pumped Storage Projects

and Recommendations Pursuant to Section 6 of the Hydropower Regulatory Efficiency Act of 2013. *FERC.gov.* [Online] 26 May 2017. [Cited: 31 August 2021.] https://www.ferc.gov/sites/default/files/2020-05/final-2-year-process.pdf.
18. **Yuki.** Renewable Energy in China's 14th Five-Year Plan: Five changes. *Energy Iceberg.* [Online] 24 March 2021. https://energyiceberg.com/14th-fyp-renewable-changes/.
19. **IFC.** *Hydroelectric Power: A guide for developers and investors Guide.* s.l. : International Finance Corporation, 2015.
20. Power to Peru - Chaglla hydropower dam, Peru. *Mott Macdonald.* [Online] [Cited: 31 August 2021.] https://www.mottmac.com/article/12276/power-to-peru.
21. **Michael, Taylor.** *Energy subsidies: Evolution in the global energy transformation to 2050.* Abu Dhabi : International Renewable Energy Agency, 2020.
22. **Grantham Research Institute.** *Do renewable energy technologies need government subsidies?* London School of Economics and Political Science. 14 May 2018.
23. **NAIF.** NAIF project update: Genex Power Limited Kidston Pumped Storage Hydro Project. *Northern Australia Infrastructure Facility, Australian Government.* [Online] 20th May 2021. https://naif.gov.au/media-releases/naif-project-update-genex-power-limited-kidston-pumped-storage-hydro-project/.
24. **Arcadis**. *Technical assessment of the Portuguese National Programme for Dams with High Hydropower Potential (PNBEPH) .* Brussels : ARCADIS, 2009.
25. **UAE.** Dubai Clean Energy Strategy. *The Official Portal of The United Arab Emirates Government.* [Online] November 2015. https://u.ae/en/about-the-uae/strategies-initiatives-and-awards/local-governments-strategies-and-plans/dubai-clean-energy-strategy.
26. **Proctor, Darrell.** Group Will Build 'First of its Kind' Pumped-Storage Project in Dubai. *POWER Magazine.* [Online] 19th August 2019. https://www.powermag.com/group-will-build-first-of-its-kind-pumped-storage-project-in-dubai/.
27. **European Commission.** Projects of Common Interest. *Official website of European Union.* [Online] 2021. https://ec.europa.eu/energy/topics/infrastructure/projects-common-interest_en.
28. **Ofgem.** *Cap and floor regime: unlocking investment in electricity interconnectors.* London : Office of Gas and Electricity Markets, U.K. Government, 2016.
29. **IRENA**. *Innovation Landscape Brief: Increasing Time Granularity in Electricity Markets.* Abu Dhabi : International Renewable Energy Agency, 2019.
30. FILATOFF, NATALIE. NEM 5-minute settlement delayed until 2022. *PV Magazine.* [Online] 13rd April 2020. https://www.pv-magazine-australia.com/2020/04/13/nem-5-minute-settlement-delayed-until-2022/.
31. **FOR Technical Committee Sub-Group**. *Sub-Group Report on Introduction of Five Minute Scheduling, Metering, Accounting and Settlement in Indian Electricity Market.* India : Forum of Regulation, 2018.
32. *Effects of decreasing synchronous inertia on power system dynamics—Overview of recent experiences and marketisation of services.* Hartmann, Bálint, Vokony, István and Táczi, István. 12, December 2019, International Transactions on Electrical Energy Systems , Vol. 29.
33. *Solar-Plus-Storage: The Future Market for Hybrid Resources.* Hledik, Ryan, et al. 2019, The Brattle Group, p. .
34. **SnowyHydro.** Snowy Hydro signs game-changing deals. *SnowHydro.* [Online] 11th January 2018. https://www.snowyhydro.com.au/news/shl_deals/.
35. **MAISCH, MARIJA. '**Super-peak' firming contracts open up new opportunities for battery storage. *PV Magazine.* [Online] 15th April 2020. https://www.pv-magazine-

australia.com/2020/04/15/super-peak-firming-contracts-open-up-new-opportunities-for-battery-storage/.
36. **Eurelectric.** *Hydro in Europe: Powering renewables. Full report.* Brussels : Eurelectric Renewables Action Plan(RAP), 2011.
37. **POSOCO.** *Pan India Lights Off Event: Impact on Indian Power System.* s.l. : Power System Operation Corporation Ltd. (POSOCO), 2020.
38. **Ofgem.** *9 August 2019 Power Outage Report.* London : The Office of Gas and Electricity Markets, U.K. Government, 2020.
39. **Plummer, Judith**. *Options Assessment for Structuring and Financing new Hydropower in PNG.* s.l. : PPIAF, 2011.
40. **Saurabh.** India Proposes Mandatory Procurement Of Hydro Electricity. *CleanTechnica.* [Online] 4th May 2020. https://cleantechnica.com/2020/05/04/india-proposes-mandatory-procurement-of-hydro-electricity/.
41. **ETEnergyWorld.** India to have 70,000 MW of hydropower capacity by 2030: Official. *Energyworld.com From The Economic Times.* [Online] 21st May 2020. https://energy.economictimes.indiatimes.com/news/power/india-to-have-70000-mw-of-hydropower-capacity-by-2030-official/75859241.
42. **Hydro Review Content Directors.** Contract awarded for 1,200-MW Pinnapuram Integrated Renewable Energy Pumped Storage Project in India. *HYDRO REVIEW.* [Online] 30th April 2020. https://www.hydroreview.com/hydro-industry-news/contract-awarded-for-1200-mw-pinnapuram-integrated-renewable-energy-pumped-storage-project-in-india/#gref.
43. **ENGIE**. ENGIE Announces £50m Investment in Ffestiniog Power Station in North Wales. *engie.co.uk.* [Online] 16th August 2017. https://www.engie.co.uk/about-engie/news/engie-announces-50m-investment-in-ffestiniog-power-station-in-north-wales/.
44. **LLP, Deloitte.** *2019 three years ahead Capacity Auction (T-3) Delivery Year 2022/23 Auction Monitor Report.* London : Deloitte LLP, 2020.
45. Drax. Drax's Cruachan pumped storage hydro power station wins six year contract to keep electricity system stable. *drax.com.* [Online] 29th January 2020. https://www.drax.com/press_release/draxs-cruachan-pumped-storage-hydro-power-station-wins-six-year-contract-to-keep-electricity-system-stable/.
46. **National Grid ESO**. National Grid ESO outline new approach to stability services in significant step forwards towards a zero-carbon electricity system. *NationalGridESO.* [Online] 29th January 2020. https://www.nationalgrideso.com/news/national-grid-eso-outline-new-approach-stability-services-significant-step-forwards-towards.
47. —. New fast frequency product to boost National Grid ESO's response capability. *NationalGridESO.* [Online] 2nd December 2019. https://www.nationalgrideso.com/news/new-fast-frequency-product-boost-national-grid-esos-response-capability.
48. **National Grid ESO**. Power Responsive Annual Report 2020: A roundup of developments in demand side flexibility markets in GB. *PowerResponsive.com.* [Online] 01 April 2021. [Cited: 31 August 2021.] https://powerresponsive.com/wp-content/uploads/2021/03/Power-Responsive-Annual-Report-2020.pdf.
49. **Climate Bonds Initiative**. *The Hydropower Criteria for the Climate Bonds Standard & Certification Scheme.* : Technical Working Group (TWG), Climate Bonds Initiative, 2021.
50. **Filkova, Monica, et al.** *GREEN BONDS The State of the Market 2018.* : Climate Bonds Initiative, 2019.
51. **IRENA.** *Renewable Energy Outlook: Egypt.* Abu Dhabi, United Arab Emirates : International Renewable Energy Agency, 2018.

52. **Power Technology**. Attaqa Mountain Pumped Storage Power Plant. *POWER TECHNOLOGY.* [Online] 16th July 2019. https://www.power-technology.com/projects/attaqa-mountain-pumped-storage-power-plant/.
53. **Ingram, Elizabeth.** Project Spotlight: 2,400-MW Ataqa pumped storage in Egypt. *HYDRO REVIEW.* [Online] 7th Febreaury 2018. https://www.hydroreview.com/world-regions/project-spotlight-2-400-mw-ataqa-pumped-storage-in-egypt/#gref.
54. **Palanisamy, Senthil.** Dubai expected to award hydroelectric power plant construction contract in Q2. *Thomson Reuters Projects News.* [Online] 9th May 2019. https://www.zawya.com/mena/en/projects/story/Dubai_expected_to_award_hydroelectric_power_plant_construction_contract_in_Q2-ZAWYA20190509131906/.
55. **Head, Chris.** *The Financing of Water Infrastructure A Review of Case Studies.* s.l. : World Bank, 2006.
56. **Ofgem.** Appendices to the Technical Report on the events of 9 August 2019. *ofgem.gov.uk.* [Online] 6 September 2019. [Cited: 27 August 2021.] https://www.ofgem.gov.uk/sites/default/files/docs/2019/09/eso_technical_report_-_appendices_-_final.pdf.

Pumped Storage Hydropower International Forum

Policy and Market Frameworks Working Group

Acronyms

AU$	Australian Dollar
BOT	Build-operate-transfer
CAISO	California Independent System Operator
CAPEX	Capital expenditure
CBI	Climate Bonds Initiative
CCGT	combined cycle gas turbine
CCS	carbon capture and storage
CEF	Connecting Europe Fund
CEP	Clean Energy Package
CO2	carbon dioxide
CPUC	California Public Utilities Commission
DEWA	Dubai Electricity & Water Authority
DOE	U.S. Department of Energy
ENTSO-E	European Network of Transmission System Operators
EPC	engineering, procurement and construction contractor
ERCOT	Electric Reliability Council of Texas, Inc.
ESG	Environmental, Social, and Governance
EU	European Union
FERC	Federal Energy Regulatory Commission
GB	Kingdom of Great Britain comprising England, Scotland and Wales
GBP	British pound sterling – official UK currency
GHG	greenhouse gas
GIC	Government of Singapore Investment Corporation
GW	Gigawatt
GWh	gigawatt-hour
HVDC	High-voltage direct current
IEA	International Energy Agency
IFC	International Finance Corporation
IFPSH	International Forum on Pumped Storage Hydropower
IHA	International Hydropower Association
IRENA	International Renewable Energy Agency

IRP	Integrated Resource Plan
ISO	independent system operator
kWh	kilowatt-hour
LCOE	levelized cost of electricity
MARI	Manually Activated Reserves Initiative
MCA	Multi-Criteria Analysis
MISO	The Midcontinental Independent System Operator, Inc.
MoEF&CC	Ministry of Environmental and Forest and Climate Change
MT CO2	metric tonnes of carbon dioxide
MW	Megawatts
MWh	Megawatt-hour
NAIF	Northern Australia Infrastructure Facility
National Grid ESO	National Grid Electricity System Operator in the UK
NEA	National Energy Administration of China
NECP	National Energy and Climate Plan
NRDC	National Development and Reform Commission of China
PICASSO	Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation
POSOCO	India's Power System Operator Corporation
PJM	RTO for much of the Eastern United States[19]
PCI	Projects of Common Interest
PPA	power purchase agreement
PPP	public private partnerships
PSH	pumped storage hydropower
PV	Photovoltaic
RTO	regional transmission organisation
Snowy Hydro	Snowy Hydro Limited, an Australian developer
SWPHS	seawater pumped hydro storage
T	Tonne
TERRE	Trans European Replacement Reserves Exchange

[19] PJM is a regional transmission organization that coordinates the movement of electricity in all or parts of Delaware, Illinois Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and the District of Columbia.

TWh	terawatt-hour
USD	United States Dollar
UK	United Kingdom of Great Britain and Northern Ireland
U.S./United States	United States of America
VRE	variable renewable energy