The Benefits of Pumped Storage Hydro to the UK

Scottish Renewables

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Contents

1. Executive Summary

The Pumped Storage Hydro Working Group (PSH WG) is a newly formed group consisting of UK industry and government representatives with an interest in PSH. The group's purpose is to ensure that the interests of pumped storage hydro developers are accurately reflected within the Scottish Renewables Storage Network in response to a range of ongoing work streams and consultations expected over the year ahead.

This work has been commissioned by Scottish Renewables on behalf of the PSH WG. Funding partners are ScottishPower, SSE and Scottish Government.

In this report DNV GL conducts an exhaustive analysis of the multiple benefits of PSH for power systems, as well as the many issues that obstruct its development.

The benefits of PSH for the operation of power systems and the integration of variable renewable energy are widely acknowledged. However, the large majority of the benefits derived from the deployment of PSH schemes are subjective or not quantifiable, which proposes a challenging task for regulators in developing market arrangements and mechanisms to allow measuring and monetizing those benefits so as to fairly compensate PSH operators.

From an economic perspective, current market conditions and business models in liberalized electricity markets for energy storage, and specifically for PSH, do not provide the right incentives to attract investors. Revenues and policy uncertainty are the main sources of risk for PSH investment. Only electricity markets that still have a degree of monopolistic structure show large deployments of PSH.

2. Introduction

The storage of electric energy is essential for balancing demand and supply. For low penetration levels of renewables, net-demand[1] can be forecasted with low error, and existing conventional generation can provide the required load following capability to balance the system. However, large-scale deployment of renewables will make this task much more complex, because those generation resources will greatly increase the variability and uncertainty of net-demand [1]. Larger amounts of system flexibility will then be required to balance the system at all times and under the range of expected operating conditions [2]. In this scenario energy storage will play a key role, as it will be useful for storing excess renewable energy, generate electricity when net-demand peaks, or also when net-demand rate of change is high and cannot be compensated by available system flexibility [3] [4].

A traditional way of storing energy on a large scale is through the use of hydrologic storage facilities, such as hydroelectric dams and pumped-storage power plants. Almost 99% of worldwide large-scale electricity storage capacity is provided by hydrologic storage systems [5]. The ambitious renewables agendas and the CO_2 emissions reduction targets of many countries around the world, and specifically those of the UK, highlight the relevance that traditional hydro storage technologies will have for the development of a sustainable and affordable future low-carbon power system.

The need for additional system flexibility has attracted increasing attention into energy storage technologies, which has resulted in substantial research and development over the last two decades. A number of works have studied the key role and value of energy storage in power systems with a high penetration level of renewable generation, concluding that storage allows reduction of system operation costs, and helps to integrate large volumes of renewable generation [6] [7] [8] [9]. The flexibility potential that can be obtained from energy storage facilities highlights their importance for the operation and expansion of future power systems [10].

Among all available energy storage technologies [11] [12] [13], hydroelectric storage is still, and will be, the most important one in modern power systems, at least until the multiple barriers that limit the applicability of other potential large-scale energy storage technologies have been overtaken. Within the available hydroelectric technologies, pumped storage hydro is today the most popular one not only because its high operational flexibility, but also because is the most developed large-scale energy storage technology currently available [14].

Identifying and acknowledging all potential benefits that pumped storage hydro can have, and also the issues that act as impediments, is not only crucial for informing regulators, but also to raise awareness about the importance of creating the required market arrangements and supporting structures for promoting the development of this type of project.

In the UK, a variety of Energy Storage schemes have been deployed over the years – some of the most recent projects arising as a consequence of Ofgem's £500m Low Carbon Network Fund, and the new enhanced frequency response service that National Grid is procuring for managing system frequency. Whilst there remain no 'formal' market incentives, except the four years contract that National Grid will sign with the providers of enhanced frequency response, the level of interest in the technology is on a rapid upward trajectory [15] [16].

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[1] The net-demand is defined as the total system electricity demand minus the power contribution of 'intermittent' or 'variable' renewable resources. This residual power demand must be supplied by conventional generation and other controllable generation and demand resources in the power system.

Pumped storage hydro provides one of the few large-scale, affordable means for storing and generating carbon-free and low cost electricity. Pumped storage is one of the most cost-effective utility-scale options for grid energy storage [17], acting as a key provider of ancillary services. With an ability of responding almost instantaneously to changes in the amount of electricity flowing through the grid, pumped storage is an essential component of the electricity network for countries that have an aggressive renewables agenda, as is the case of the UK, and have the potential for developing this type of hydro projects.

This report looks to inform and create awareness about the relevance of pumped hydro for the integration of large-scale deployments of renewables and the development of sustainable, secure and cost-effective future low-carbon power systems. For this purpose, this report presents a comprehensive coverage of the benefits of pumped storage hydro for the development of future power systems, and also addresses the multiple issues that put at risk the development of this large-scale energy storage technology.

The rest of this document is structured as follows:

1. Section 3 describes the research methodology used in the development of this report.

2. Section 4 gives a general overview of the deployment of pumped storage hydro worldwide.

3. Section 5 starts by analysing the maturity and key features of pumped storage hydro technology, to then describe available configurations and latest technological developments. The last part of this section summarizes what have been the developments of this technology until today, and which new projects have been proposed, in the UK.

4. Section 6 analyses the benefits of pumped storage hydro throughout the electricity supply system, and at different timescales.

5. Section 7 starts by analysing the engineering and economic issues that affect and restrict the investment in pumped hydro storage, to then analyse the current markets and mechanisms in five international regions in relation to energy storage and pumped storage hydro.

6. Section 8 outlines a set of key facts and recommendations for acknowledging the benefits of pumped storage hydro for the UK, as well as the techno-economic barriers that today impede the development of this technology.

3. Methodology

The research methodology, shown in **Figure 1**, used to produce this report was based on three lines of actions:

1. *Market research:* DNV GL UK conducted an exhaustive market research of publically and internally available information on pumped hydro storage.
2. *International discussions:* International discussions were organized across the network of consultants of DNV GL around the world in order to identify regional initiatives and common barriers for the deployment of pumped storage hydro technology.
3. *Industry stakeholders interviews:* Local industry stakeholders were interviewed in order to get their views about the role and barriers for the development of pumped storage hydro in the UK.

The specific and common objectives that guided the three lines of actions were:

a) understand which are the multiple issues and barriers for the development of this type of power generation project;

b) identify the full range of benefits that can be achieved by promoting investment in this traditional and mature technology; and

c) identify which have been the local initiatives and market arrangements that have successfully induced the market to deliver this type of energy storage project.

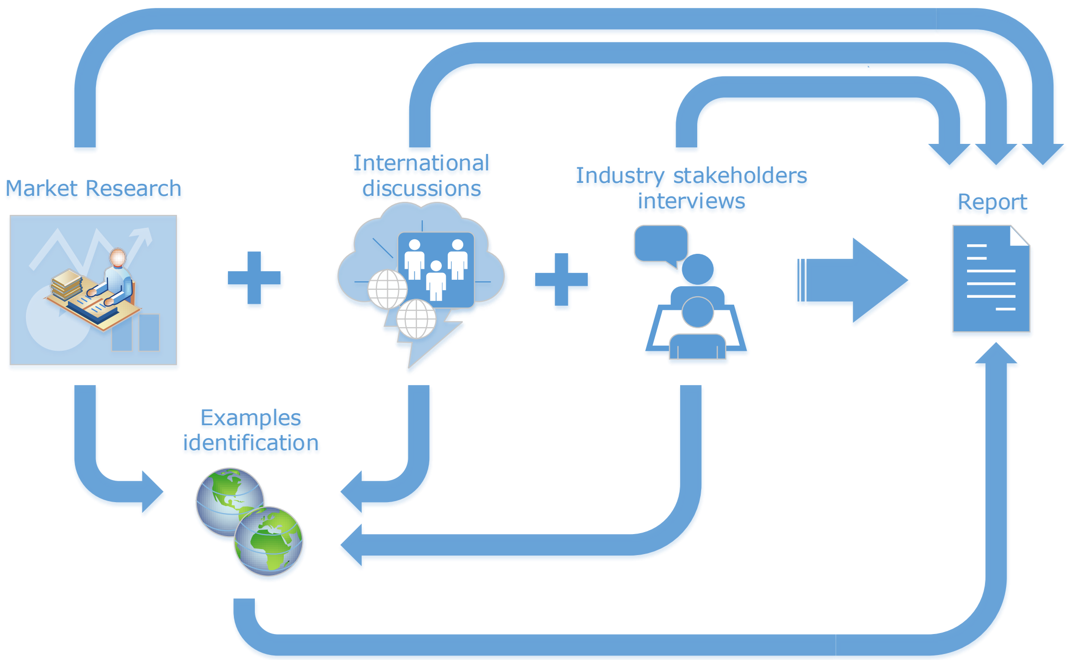

Figure 1: Conceptual representation of the research methodology.

The industry stakeholders interviews were motivated by the following set of questions:

- what are the benefits that pumped storage hydro can bring, specifically for the UK now and in the foreseeable future?;
- what needs to happen to make those benefits reality?;
- what barriers need to be removed?, and maybe also how?; and
- is there anything else you think is relevant regarding the promotion of pumped storage hydro in the UK.

Several industry stakeholders in the UK were interviewed, with the following results:

- Internal and external documents provided for reference by Scottish Government, SSE, and Forestry Commission.
- Meeting with British Hydropower Association.
- Meeting with Engie/First Hydro.
- Meeting with SSE.
- Meeting with Scottish Power.
- Meeting with National Grid.

4. Global Overview

Many governments around the globe have committed themselves to boost the share of renewables in their generation energy mix. Such a global movement has been driven not only by concern about greenhouse gas emissions and their impact on climate change, but also by the goal of ensuring security of supply through the development of sustainable and affordable low-carbon power systems.

The rapid and large-scale deployment of intermittent renewable technologies has led to a complex and challenging scenario not only for the operation of power systems, but also for their long-term planning and development [1]. The power injections of wind and solar generation have increased the variability and unpredictability of net-demand, which needs to be supplied by available controllable demand and generation side resources [18].

The larger variability of net-demand in amplitude, frequency and rate of change have translated into the need for operating conventional generation against its operational limits, and when those have been reached, into the need of curtailing renewable energy as an additional source of flexibility for balancing supply and demand [2]. Also, the lower predictability of net-demand requires larger volumes of flexible and fast response resources that can provide the ancillary services required to ensure the system can be safely operated in all operating conditions, and that demand can be satisfied with minimal disruptions at all times.

Traditionally, system flexibility was provided by fast response thermal generation. Emission restrictions, fuel availability and price uncertainties, technological developments and ever increasing cheap and carbon free renewable capacity are making energy storage technologies the next step in the development of future low-carbon power systems [3] [7] [8]. Development of storage technologies has been supported by many governments through policies that include funding for demonstration projects, subsidies and mandatory storage requirements for utilities [19]. However, the high capital cost remains as one of the most important barriers to their wide deployment.

According to the DOE Global Energy Storage Database [5] and IEA [20], the global deployment of battery energy storage systems rose from about 0.1GW to 0.8GW, and thermal, mechanical and hydrogen energy storage capacity from about 0.9GW to 3.1GW, between 2005 and 2015. Non-hydro energy storage contributed less than 3% of the total large-scale energy storage capacity in 2016, which topped 148.2GW as shown in **Figure 2**.

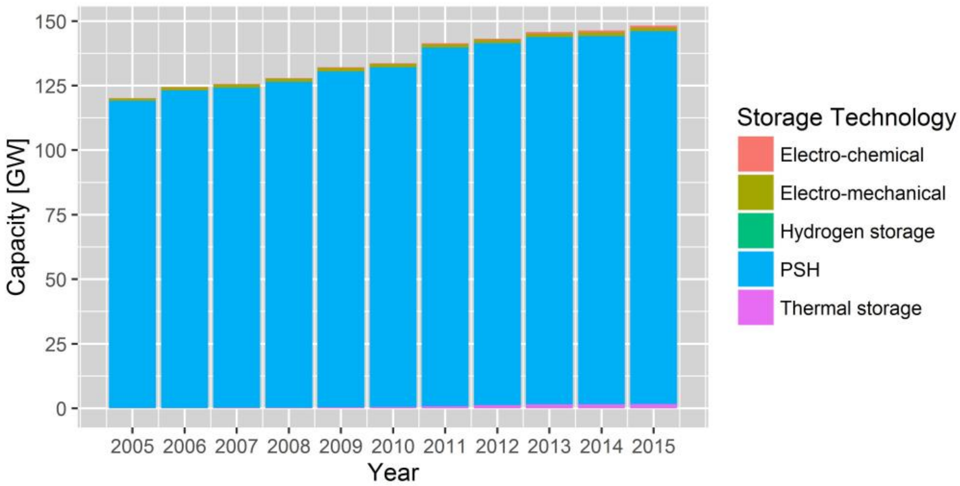

Figure 2: Installed global capacity for energy storage (data source [5]).

Pumped storage hydro is by far the most predominant large-scale energy storage technology worldwide. More than 97% of worldwide storage capacity was PSH by 2015, more than 23GW of additional capacity are currently under construction, and another 8.3GW have been announced to be constructed in the near future [5].

In the UK there are four PSH facilities which amount to 2,828MW of total capacity and which have an energy storage capacity of approximately 26.7GWh [21]. Existing PSH plants were commissioned between 1963 and 1984, and since 1984 there have not been any new developments, and the only signs of new or potential developments in the near future are given by:

1. the announcement made by ScottishPower in early 2016 of their intention to upgrade the Cruachan pumped hydro power station in order to double its power output;
2. the proposed new pump storage schemes Coire Glas, Balmacaan, and Glyn Rhonwy;
3. the planned Sloy power station conversion into a pumped storage facility; and
4. two new PSH schemes recently announced that are under planning: Muaitheabhal[2] and Glenmuckloch[3] [22][23].

All those projects together might contribute more than 1.75GW of additional PSH capacity, and can potentially increase energy storage capacity by at least 88GWh.[4]

System flexibility will be crucial in achieving the UK green agenda [10]. According to the National Grid Future Energy Scenarios 2015 [24], installed wind and solar capacity will increase by a factor between two and four over the course of the next 15 years, and conventional thermal generation will shrink by between 11% and 23%. This means that larger volumes of system flexibility will be required to accommodate new renewable generation in a cost-effective manner [9]. Non-hydro distributed energy storage systems will contribute to balancing net-demand and keeping the system stable. However, their relatively small energy capacity together with the dynamic operating regime under which those energy resources are expected to be operated will limit their capability of absorbing the excess of renewable energy to a few hundred MWh.[5] Bulk fast response and reliable large-scale energy storage capacity will then be needed in the UK for absorbing excess renewable energy and providing the range of ancillary services that allows security of supply.

Pumped hydro is the most developed and reliable large-scale energy storage technology, with facilities dating from the 1890s in Italy and Switzerland. It is an extremely fast ramping technology that can go from zero to full output in less than a few minutes. For example the Dinorwig PSH scheme, with all motor/generator units synchronised and spinning-in-air, can achieve full output in approximately 16 seconds [25]. PSH technical characteristics, in addition to being a carbon-free energy resource, provide a very good complement for the development and integration of large-scale volumes of renewable resources and a key for reducing greenhouse emissions [26]. However the high cost of capital and long construction time of this technology, lack of market arrangements to support development, added to the geographical and environmental aspects related to it, have limited its development.

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[2] According to Renewable Energy News issue No. 337, 9 June 2016, the estate owner and developer Eishken Ltd is understood to be planning a pumped storage facility of up to 150MW close to its planned Muaitheabhal mega wind farm on the Isle of Lewis off north-west Scotland.

[3] Buccleuch is working alongside 2020 Renewables to develop plans for a pumped storage hydro scheme at the Glenmuckloch Surface Coal Mine, Kirkconnel, Dumfries and Galloway, which would be capable of generating up to 400MW of electricity.

[4] Refer to **Table 5-1** for further details about these numeric figures.

[5] Assuming that non-hydro energy storage will be mostly used for providing dynamic and non-dynamic frequency response services.

5. The Technology

5.1 Technology Maturity & Key Features

Pumped storage hydro, or pumped hydroelectric energy storage (PHES), uses two water reservoirs for storing energy in the form of gravitational potential energy of water. Water is pumped from the lower to the upper reservoir at off-peak times when electricity cost is low. When required, the water is released from the upper to the lower reservoir through turbines that generate electricity which is then injected into the grid. The roundtrip energy efficiency of PSH varies between 70% and 85% typically, making it a net consumer of energy [27]. The energy losses however are compensated by the charging-discharging price differential, and also by providing ancillary services.

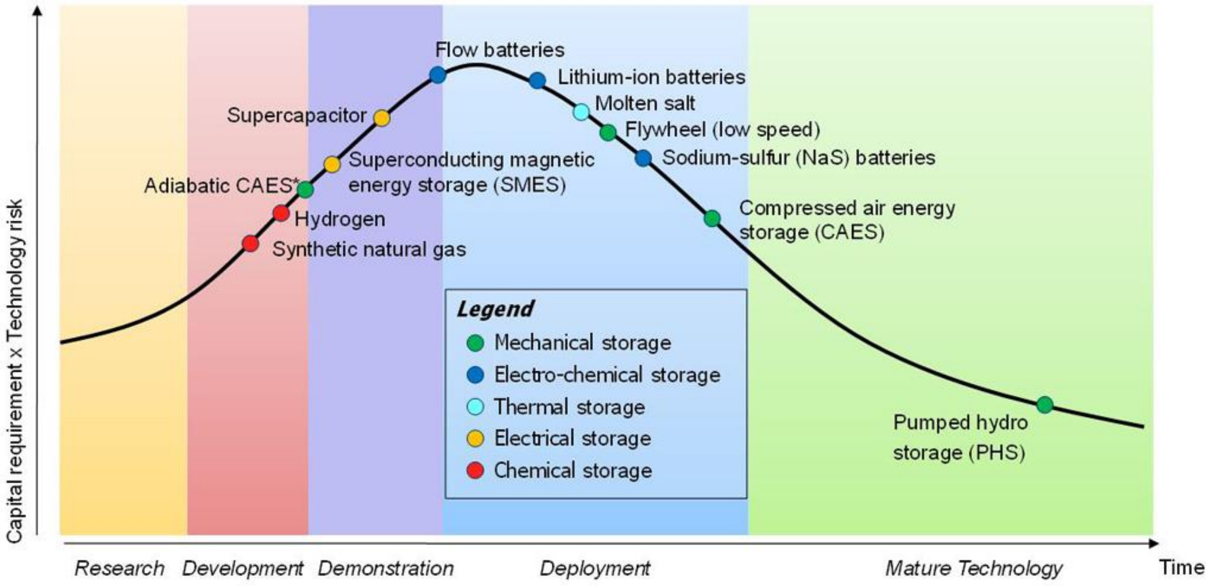

Figure 3: Energy Storage Technologies Maturity Curve [27].

Pumped storage is the most developed and largest capacity form of grid energy storage available as shown in **Figure 3**, with the first plants built at the end of the 19th century. All other grid-connected energy storage technologies are less mature, and therefore have higher levels of risk, real and perceived.

PSH can provide a wide spectrum of services for supporting the operation of the grid. The longevity of PSH installations also aids the long-term planning and development of power systems.

Traditional pumped storage plants however have techno-economic drawbacks that limit their development. From a physical perspective the main disadvantage of PSH is the specialist nature of the site required, needing both suitable topography and water availability, and there are also a series of social and ecological issues. From an economic perspective, PSH projects require long construction times and high capital expenditures, which creates risks for investors when there are no guaranteed income streams, or other arrangements to support their investment in PSH projects.

5.2 PSH Configurations & Recent Developments

A typical conventional PSH power plant consists of four components:

1. *Water reservoirs:* normally two[6] interconnected water reservoirs.
2. *Water piping:* tunnels that allow moving water from one reservoir to another.
3. *Powerhouse:* facility with one or more pump/turbine and motor/generator assemblies that allow pumping water into the upper reservoir at off-peak hours, and discharging water into the lower reservoir.[7]
4. *Grid connection:* power transmission lines to move the generated power from the plant into the grid.

Traditionally PSH projects use as reservoirs natural lakes, large rivers, or existing conventional hydro-power facility reservoirs. Depending on the source of the water and how it is moved PSH can be classified into two types: open-loop and closed-loop. Open-loop PSH plants are continuously connected to naturally flowing water sources. Closed-loop PSH plants, on the other hand, are constructed independently from a naturally occurring river or lake, and therefore have fewer impacts on the natural environment.

PSH installations vary in size, with the largest one in the UK, Dinorwig Power Station in north Wales, having a capacity of 1,728MW and an energy storage capacity of 9.1GWh. The smallest PSH installation in the UK is Foyers Hydro-Electric Power Scheme in Scotland, which has a capacity of 300MW and an energy storage capacity of 6.3GWh. Independently of the size, all PSH in normal operation mode follow an operational cycle (usually daily) where during periods of low demand or when electricity prices are low, water is pumped from the lower reservoir to the upper reservoir. The water stored in the upper reservoir is then discharged into the lower reservoir during peak demand periods, which allows injecting more valuable electricity into the grid (so-called 'energy arbitrage') and reduces the need for running expensive peaking generation plants.[8]

Conventional fixed-speed is the most common PSH technology, where both the pump/turbine and motor/generator assemblies operate at a fixed synchronous speed. The last big technological developments in PSH technology include variable-speed and ternary PSH plants[9] [28]. Some of the advantages of these technological developments are [29] [30]:

1. Variable-speed:
   - There is no need for a pony motor[10] to start pumping/generating.
   - Full power output can be delivered from water-head variations of a factor of two.
   - Rotational speed can be adjusted to avoid resonances within the equipment and cavitation modes in the water flow. This leads to longer life and less maintenance.
   - Higher overall efficiency and improved flexibility.
   - Frequency regulation can be provided independently of the operating mode and speed.
2. Ternary PSH:
   - Higher overall efficiency.
   - Impacts from hydraulic transients are significantly reduced.
   - Improved flexibility: the machine can move rapidly from the full pumping mode to the full generating mode, unlike a reversible machine, which must stop before restarting in the opposite direction.

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[6] More than two reservoirs can be connected in cascade.

[7] It should be noted that the pump/turbine and motor/generator assemblies can be either reversible pump/turbine-motor/generator sets, or separate turbine-generator and pump-motor sets.

[8] PSH plants can also generate and consume at other periods, depending on the ancillary services they provide.

[9] A ternary pumped storage system consists of a separate turbine and pump on a single shaft with a single electrical machine that can operate as either a generator or a motor. The major difference between a ternary plant and other types of pumped storage plants is that the ternary plant can simultaneously operate both the pump and turbine. All other pumped storage plant designs operate either in a generating mode or a pumping mode, and the shaft rotates in opposite directions in these two modes.

[10] Auxiliary motor used to bring synchronous machinery up to speed before synchronizing.

- Ability to employ different turbine technologies for the pump and turbine.
- Better natural response to system disturbances for which transient stability is a concern. A ternary unit inherently has a higher total inertia, since this inertia includes both a pump and a turbine in addition to the generator.

Whilst PSH is mature, reliable and well understood by planners, the technology continues to evolve to accommodate changing market conditions, as well as to mitigate environmental impacts of new and existing stations. Technological innovation over the past few years has focused on increasing the scale of turbines, improving their durability and flexibility, and reducing environmental impacts [31] [32]. Such advancements continue to increase generating capacity, and mitigate the impact of new and existing stations.

5.3 PSH in the UK: Past, Present & Future

Pumped storage hydro development in the UK was motivated by two reasons: a) the need to store nuclear power overnight when electricity demand was low; and, b) the need for fast response resources for grid stability.

The UK currently has only four operational fixed-speed PSH schemes that in conjunction contribute 2,878MW of generation capacity and can store approximately 26.7GWh of energy as shown in **Table 5-1**. Additionally there are five new schemes, four in planning stage (Coire Glas, Sloy, Glenmuckloch, and Muaitheabhal) and three that have been proposed (Glyn Rhonwy, Balmacaan and Cruachan upgrade) [5] [22] [23] [33] [34].

Table 5-1: Operational, Planned and Proposed PSH Schemes in the UK.

Scheme status	*Name*	*Power (MW)*	*Energy Capacity (GWh)*
Operational	Dinorwig	1,728	9.1
	Cruachan	440	10.0
	Festiniog	360	1.3
	Foyers	300	6.3
Planning	Coire Glas	300-600	30-40
	Sloy *(conversion)*	60	20-40
	Glenmuckloch	400	TBD
	Muaitheabhal	150	TBD
Proposed	Glyn Rhonwy	100	1.2
	Balmacaan	300-600	30-40
	Cruachan *(upgrade)*	+440-600	+7.2

6. Benefits

The operation of the electric grid is a very complex process that requires balancing demand and supply at all times so as to maintain system frequency within normal operating limits and ensure the stability of the grid with the purpose of supplying reliable and affordable electricity to consumers. For such a purpose the system operator needs to control hundreds of generation and demand side energy resources in timescales ranging from microseconds to days as shown in **Figure 4**.

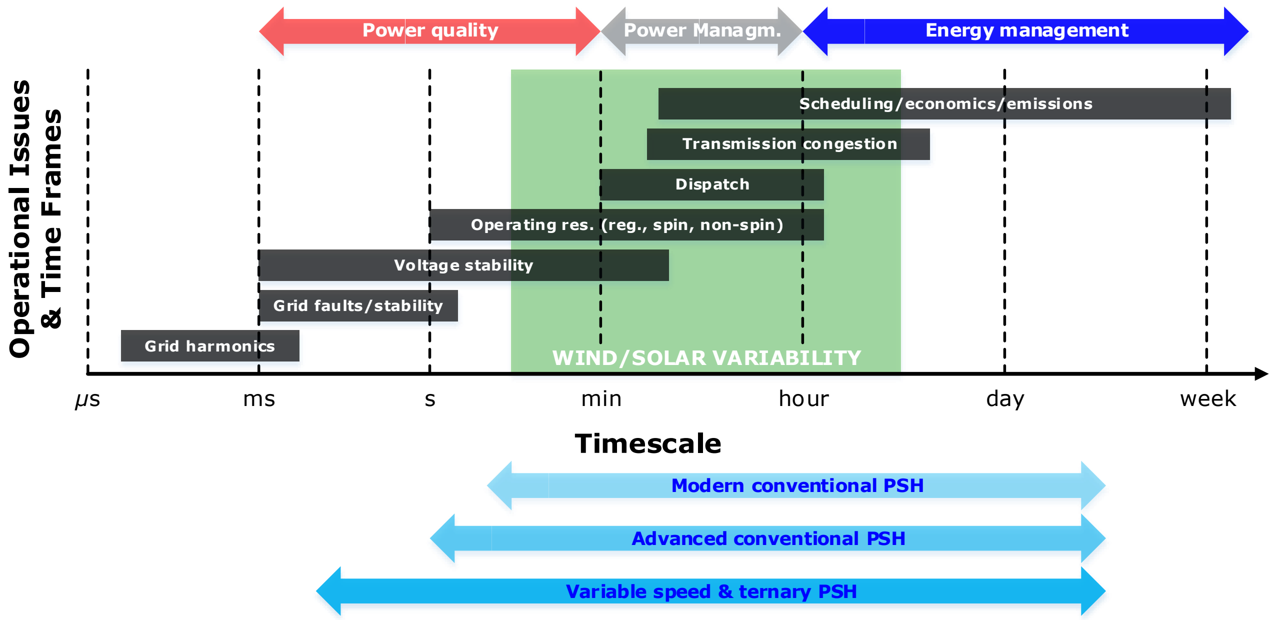

Figure 4: Timescales of Power System Operational Issues and PSH Operational Ranges (adapted from [26] and [35]).

Grid harmonics and stability are managed in the very short term through system control and automated response actions of online controllable and fast response resources. In the mid-term, frequency regulation, spinning and non-spinning reserve deployment and dispatch actions are employed to balance supply and demand and maintain system frequency. Finally, at longer timescales, the system operator needs to schedule, in a cost-effective manner, sufficient resources so as to handle the variability and uncertainty in net-demand created by intermittent generation, with the additional objective of minimizing emissions [36].

The large-scale deployment of intermittent renewables and their increasing power injections will impact the grid operation and economics at all timescales. This will require using all available system flexibility in order to avoid renewables curtailment as a final measure to ensure grid stability. New flexibility resources will also be required, especially in the timescale range where intermittent generation has the biggest impact on grid stability, i.e. between a few seconds and a couple of hours. PSH is the perfect match for such requirement due to its fast response and large-scale energy capacity as shown in **Figure 4** [37] [38].

6.1 System Level

Variability and uncertainty are inherent characteristics of modern power systems. Penetration of electricity in modern society is making electricity demand a very dynamic and complex process, characterized by constant changes and increased variability. The large-scale penetration of intermittent renewables is one of the key factors in the increased variability and unpredictability of net-demand, product of their inherent intermittency and stochastic nature.

It is in this context where flexibility begins to play a key and important role [39] [40]. Generally speaking, flexibility refers to the extent to which a power system, or a component of it, can modify the electricity production or consumption in response to expected or unexpected variations in electricity demand or supply. To understand why flexibility is important for the ongoing development of future low-carbon power systems and the role that PSH can play, it is necessary to appreciate the features introduced by renewable generation in the time dynamics of net-demand when the share of such renewables in the power system is not negligible [41].

Large shares of renewables are expected to boost existing net-demand variability in amplitude, frequency and rate of change, as shown in the top-left graph of **Figure 5**, where the variability of demand and net-demand is depicted in a simulation of a challenging winter week in 2030. The blue line corresponds to the total electricity demand, while the red one corresponds to the demand net of wind and solar PV power output, assuming all the energy provided by renewables is fully utilized, and perfect forecasts of demand and renewables power generation.

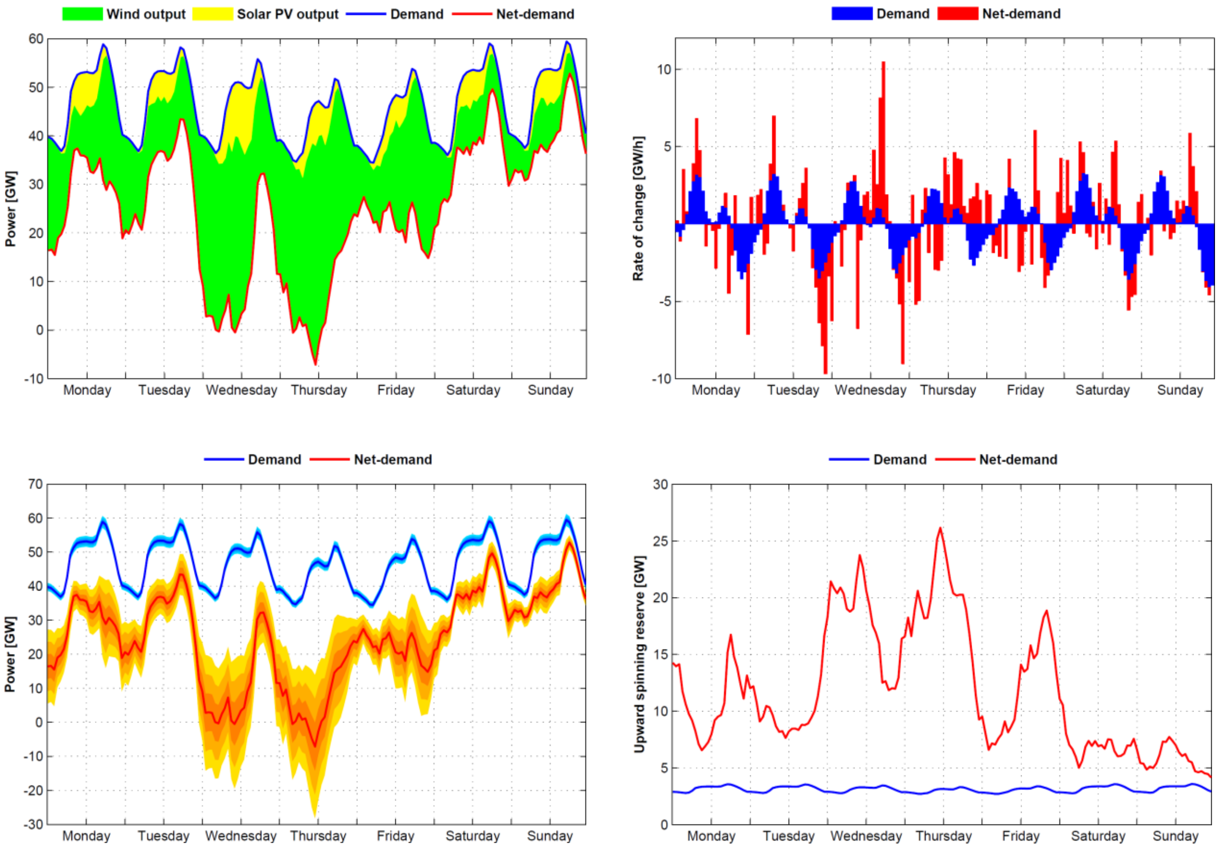

Figure 5: Simulation of demand and net-demand (top-left), rate of change (top-right), forecast uncertainty (bottom-left), and required level of upward spinning reserve (bottom-right), during a challenging week in 2030 assuming 50% intermittent generation share [40].

Demand shape follows a regular and smooth pattern characterized by an increasing demand during working hours, with a peak in the early evening when people arrive home from work, after which it gradually decreases into the night time. Net-demand on the contrary exhibits an irregular and non-smooth pattern, which highlights the boosted variability caused by renewables power injections. Larger shares of renewables will translate into a larger variability and uncertainty in net-demand, which will need to be supplied by existing and new controllable and flexible generation capacity, demand side resources, interconnectors, energy storage, etc. Current power systems have the flexibility resources to accommodate moderate amounts of renewables. However, increasing renewable penetration levels will put power systems under stress, revealing the need for additional system flexibility. Interesting features in net-demand, which will be more frequent for larger shares of renewables can be highlighted from **Figure 5** as follows:

1. Net-demand falls below zero during four periods, which means that there is an excess of energy in the system which will need to be stored or exported, or otherwise curtailed.

2. The rate of change of net-demand is much larger than that of demand, as shown in the top-right graph of **Figure 5**, which shows the rate of change of demand and net-demand. This will translate into available generation needing to increase and decrease its production at higher rates ('ramp rates').

3. The uncertainty of net-demand is much bigger than that of demand, as shown in the bottom-left graph of **Figure 5**, which shows the 4-hour ahead forecast error of demand and net-demand. This will increase the level of the reserve services required to handle unexpected deviations from the original forecasts, as shown in the bottom-right graph of **Figure 5**, which compares the required levels of upward spinning reserve.

In the operational timescale, the described features will put conventional generation under stress. Excess of renewable energy will require lowering power output of online generation, which is not economical as it means running thermal power plants partially loaded where efficiency is low. In extreme cases, it might be required to run inflexible generators at their minimum stable generation[11] points and curtailing renewables in order to avoid needing to turn them off. Below the minimum stable generation level, generating units need to be turned off, and they cannot be brought online for at least their minimum down time[12]. Once generators are brought online, on the other hand, they need to stay connected to the grid for at least their minimum up time, which is the same order of magnitude as the minimum down time.[13] Frequent and successive excesses of renewable energy will then be missed due to these timing restrictions. Additionally, start-up and shut-down manoeuvres of inflexible baseload generators are not only complex and time consuming, but also costly, which might instead justify renewable energy curtailment [39].

The increased rate of change of net-demand will require changing the power output of conventional power plants more frequently and at higher rates. Such situations are costly not only because of the thermal efficiency, but also because it will increase the stresses and wear to which generators are exposed. Increased rate of change of net-demand will also raise the level of ancillary services required to ensure the system can be operated safely in all operating conditions. This will translate into the need to increase the number of online fast ramping units, and also the number of quick-start fast ramping, that are capable of providing those services. Ultimately, the increased cycling of conventional generation will reduce the lifetime of those assets.

In the absence of alternative sources of system flexibility, larger shares of gas fired flexible thermal generation will be required to accommodate renewables and to ensure security of supply. Flexible gas power plants are expensive to run and are not carbon-free, which means that the emissions savings from renewables will be less than anticipated.

In the long-term, larger shares of intermittent generation will exacerbate the net-demand features described before as shown in **Figure 6**. This will not only change the investment and operation economics of

[11] Minimum power output level at which a thermal power plant can stably produce power, and at which can be synchronized and connected to the grid.

[12] For baseload generation technologies, i.e. nuclear and coal power plants, the minimum down time can vary from several tens of hours for coal generation, up to weeks for nuclear power plants.

[13] Minimum up and down times are the minimum amounts of time during which a conventional generation plant needs to be on/off due to thermal constraints, before they can be turned off/on respectively.

conventional generation, but also will increase the energy bill of electricity consumers if no new, cheap, carbon-free and reliable sources of flexibility are developed, and no changes in the current electricity market regulation and arrangements are implemented [42].

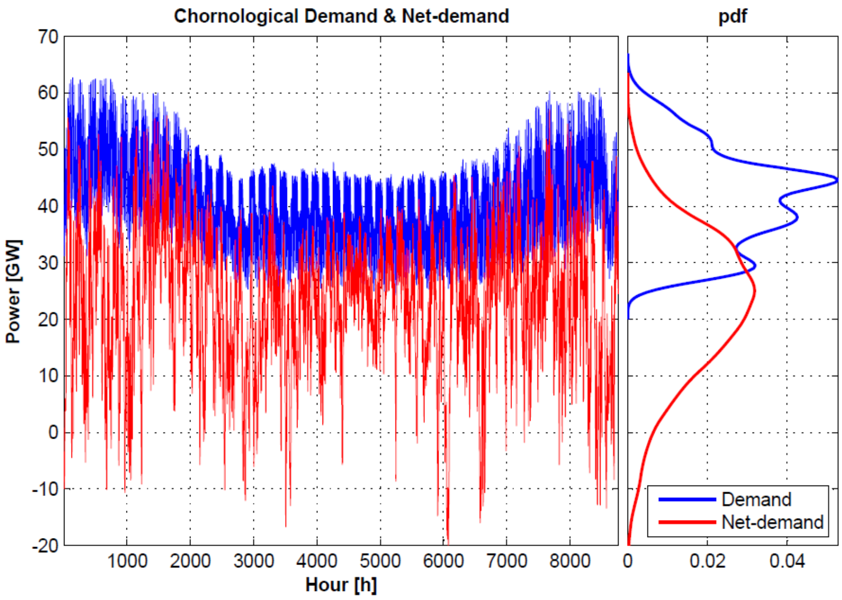

Figure 6: Simulation of the variability of demand and net-demand (left), and probability density functions of demand and net-demand (right), in 2030 assuming 50% intermittent generation share [40].

6.1.1 System Operation

The system operator must balance demand and supply on a second-by-second basis so as to ensure system stability at all times. For this purpose the system operator uses a series of automatic and non-automatic services that range from a few micro-seconds up to a couple of hours in the short-term [18]. This is shown in **Figure 7** that shows how the frequency of the system evolves after a contingency that can be successfully managed by the system operator.

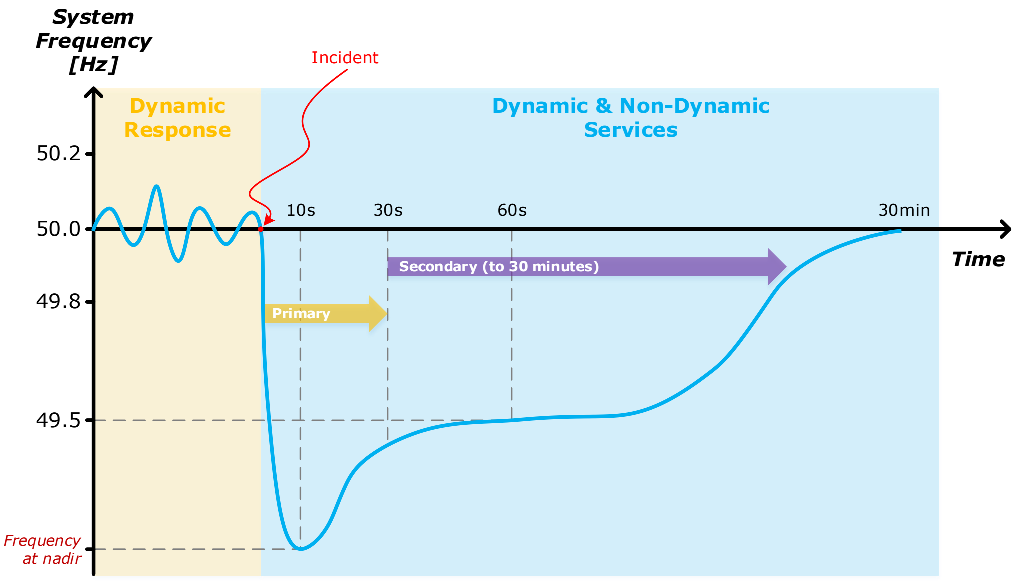

Figure 7: Evolution of system frequency after a contingency (National Grid).

The versatility and flexibility of PSH enable this technology to provide a wide range of dynamic and non-dynamic services as shown in **Figure 4**. Furthermore, the much larger energy storage capacity of PSH compared to other storage technologies enables it to provide those services for extensive periods of time.

6.1.1.1 Inertial Response

System frequency needs to be maintained within a narrow band around its nominal value, which is 50Hz in the UK. The inertial response is given by the large mass of rotating generators connected to the grid, which automatically accelerate or decelerate in response to imbalances. Larger shares of intermittent generation reduce system inertia, making the power system less robust to contingencies. Conventional and modern PSH plants can provide inertial response through their rotating generators in the case of fixed speed and ternary PSH, and through the power electronic converters in the case of variable-speed PSH.

6.1.1.2 Governor Response, Frequency Response, or Primary Frequency Control

The governor control, governor response, or primary frequency control, is the automatic control system that automatically regulates the generator's speed in response to deviations from a reference speed value. Advanced PSH have the capability of providing primary frequency control when they are either pumping or generating, and conventional PSH can only provide it when generating.

6.1.1.3 Operating Reserves

PSH can provide all types of operating reserves to the grid. Variable-speed PSH has the advantage with respect to fixed-speed PSH of being able to provide reserve services during pumping and generation.

A. Frequency Regulation, Regulation Reserve, or Secondary Frequency Control

Frequency regulation, or regulation reserve, is a form of secondary automatic frequency control that sends signals to generating units every 4 to 6 seconds to either increase (upward frequency regulation) or decrease (downward frequency regulation) their power output in response to small frequency deviations.

B. Flexibility Reserve

New type of ancillary services introduced to compensate the additional uncertainty and variability introduced by intermittent generation [36] [43].

C. Contingency Reserve: Spinning & Non-Spinning

Rapid response services (typically within 10 minutes) that are deployed to compensate system contingencies, such as generating units and transmission lines outages. Synchronized units that operate at lower than full capacity can provide spinning reserve, while off-line quick-start units can provide non-spinning reserve.

D. Replacement/Supplemental Reserve

Ancillary service provided by standby generating units (or reductions in load) to replace generating capacity on outage after the contingency event, and to restore contingency reserves to normal operating values.

E. Load Following

Long-term (hourly) changes in electricity demand are compensated by the load following reserve. This type of reserves either increases or decreases power output of generation units over a wider time span to balance demand and supply.

6.1.1.4 Load Levelling/Energy Arbitrage

The ability to consume and generate electricity enables PSH to provide load-levelling or load shifting services, that refers to the capability of this technology to increase net-demand during off-peak periods (electricity consumption for water pumping) and decrease net-demand during peak periods (generation of electricity when discharging water). The capability of absorbing and injecting energy from the grid at different times, combined with the large energy storage capacity, allows PSH to do energy arbitrage that has the benefits of reducing overall system production costs by offloading expensive peaking generation during peak-demand periods, and by increasing usage of cheap baseload generation during low demand periods.

6.1.1.5 Generating Capacity

PSH plants typically have a generation capacity of the order of several hundred megawatts, which provides a considerable volume of flexible capacity to a power system. PSH plants can improve system reliability and resilience since they can be quickly dispatched and ramped up to meet demand, compensate large swing in intermittent generation power injection, and provide contingency reserves to compensate generation units outages. The high flexibility of PSH plants allows reducing, or even avoiding, the need for running expensive peaking generation. The operational flexibility of modern PSH technology matches or exceeds that of peaking conventional thermal generation and has the extra benefits of avoiding the greenhouse emissions produced when those power plants are dispatched. One more unique advantage of PSH plants is that they can operate in pumping mode. This enables PSH technology to double the dispatchable capacity it can provide to the system when it is switched from pumping to generating mode.

6.1.1.6 Reduced Environmental Emissions

PSH plants allow reductions in greenhouse emissions when they are dispatched during peak-hours instead of conventional thermal peaking plants. The extent of this reduction depends on the capacity mix, due to the marginal generation capacity during off-peak hours will define the emissions generated. The larger the amount of the pumping requirements of PSH plants supplied by renewable generation capacity, the larger the reduction of emissions that can be achieved.

6.1.1.7 Integration of Intermittent Energy Resources

PSH technology can support the integration of renewables by storing the excess of renewable energy. This allows reducing the curtailment of cheap carbon-free energy and increasing the economic efficiency of renewables assets. Stored renewable energy can then be used at peak hours that have the benefits of reducing emissions and consumption of fossil fuels, and decreasing system operating costs. Additionally, PSH plants can enable the large-scale penetration of renewables by providing the required amount of flexible capacity needed to compensate the variability and uncertainty that intermittent generation introduces in net-demand.

6.1.1.8 Reduced Cycling and Ramping of Thermal Units

The flexibility characteristics of PSH plants allow reducing the thermal generation stress created by intermittency of wind and solar generation resources. The fast ramping characteristics of PSH technology, and its capability for absorbing and generating electricity allows smoothing the net-demand profile that needs to be supplied by conventional generation. This allows running conventional power plants in a steadier mode, which improves operation efficiency, and reduces ramping stress and cycling. A more stable net-demand allows reducing to the number of start-ups and shut-downs of thermal generation what contributes to diminish the wear and tear of these assets, and also achieving significant savings in the system operating costs.

6.1.1.9 Other Portfolio Effects

PSH plants in addition to allow reducing ramping and cycling of thermal generation units, and reducing the costs associated with start-up/shut-down manoeuvres, and wear and tear, have other positive effects on the operation and scheduling of thermal generation. By levelling net-demand, thermal generator can operate steadily and for longer times at higher power outputs, which translates into more efficient operation and better fuel-to-electricity conversion efficiencies. Additionally, a smoother net-demand makes the scheduling and dispatch of the power system easier.

6.1.1.10 Reduced Transmission Congestion & Improved Assets Utilization

The flexibility of PSH plants can be used in the scheduling and dispatch of the system so as to modify the power flows in the transmission network, helping to alleviate transmission congestion, reduce transmission congestion prices, and improve the transmission assets' utilization.

6.1.1.11 Transmission & Distribution Deferral

The PSH plants, by improving the usage of transmission and distribution assets, and reducing transmission congestion prices, can help to defer investment in new network assets.

6.1.1.12 Voltage Support

Voltage control is a relatively local issue that is controlled by controlling the supply of reactive power. Reactive power cannot be transferred over long distances due to voltage drops, and reactive and active power losses, so it needs to be supplied relatively close to where it is needed. Advances PSH technologies have the capability of supplying voltage control, through either the conventional generators used in fixed-speed and ternary PSH units, or by using the power electronics of variable-speed PSH plants that can allow mimicking the voltage control capability of conventional generators.

6.1.1.13 Improved Dynamic Stability

Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact [44]. Variable-speed PSH units have a fast response and because they use power electronics, their controls and capabilities can be designed to improve their performance under particular disturbances, which can contribute to the dynamic stability of the power system.

6.1.1.14 Black-Start Capability ('System Restoration')

Black-start units are generating units that have the capability of starting by themselves without needing an external source of electricity. These generating units are the kernel to start the restoration process after a widespread blackout. Advanced PSH and ternary PSH are candidates for providing black-start capability. Variable-speed PSH however, because they required an external source of electricity to power their power electronics, cannot provide this capability today.

6.1.1.15 Energy Security

PSH flexibility acts as enabler for other renewable energy resources, contributing to their integration into the power system. Higher reliance on renewable generation translated into less dependency on local and imported fossil fuels, which not only has positive effects in terms of the de-carbonization of the generation mix, but also in reducing the usage of fossil fuels in other energy sectors. Therefore, PSH can contribute toward improving energy security goals.

6.1.2 System Planning

The increased variability and uncertainty of net-demand created by intermitted generation are making the planning of the power system a complex decision-making process due to the increased importance of flexibility in the long-term timescale. Traditional power systems' planning is focused on estimating the overall level of generation capacity needed to supply demand at minimum cost, generally assuming a highly simplified representation of electricity demand, and ignoring the flexibility characteristics of generation and demand side resources [40].

The large-scale integration of variable renewable resources in modern power systems has radically changed the time dynamics of net-demand, making it much more variable and unpredictable. This has critically changed the operation of conventional generation, largely increasing the ramping and cycling regimes to which they were traditionally exposed. In the short-term, the utilization of intermittent renewable energy is limited by the available flexibility in the power system. In the long-run, on the other hand, the amount of available and new flexibility limits the amount of renewable capacity that can effectively and efficiently be incorporated into the system.

PSH plants and their multiple benefits for the operation of power systems can make easier the planning of future low-carbon power systems. By providing large volumes of highly flexible capacity, PSH contributes to reduce the need for other sources of flexibility. Their capability of levelling net-demand additionally helps smoothing net-demand, diminishing the importance of taking into account the flexibility characteristics of conventional generation for planning purposes.

6.1.3 Generation Investment

6.1.3.1 Renewables Deployment

The uncertainty and variability linked to this source of energy prevents it from being the unique source of electricity for supplying demand if not supported by additional flexibility that can shift excess of energy in time and generate electricity when renewable generation is lower than demand. The higher is the penetration of renewable generation in a power system the higher the volume of flexible resources that are required to support its operation and to maximize the utilization of available renewable energy in an effective and efficient manner.

The development of future low-carbon power systems that rely on a large contribution of renewables will require large amounts of flexibility. Independently of how flexible conventional thermal generation is or can be in the future, its operation will be always limited to some extent by thermal and mechanical limitations. This means that additional and reliable sources of flexibility will be needed. In the demand side, flexibility can be provided by demand side response, demand side management, residential and industrial energy storage, smart-grid electric devices, electric vehicles, among others. Although the potential and the role of the demand side is large, the extent of the demand side flexibility contribution is limited by many factors that include the rate of technology adoption by customers, the development of the tools and supporting technological infrastructure to utilize that flexibility, among others. Interconnectors to neighbour countries are another source of flexibility. However, their flexibility is limited by their capacity, operation and also by how demand/supply behaves in the neighbour country.

Utility-scale energy storage systems are also a source of high flexibility because of their fast response and their capability to consume and inject power into the grid. Developments of battery technology combined with economies of scale in their production have motivated the widespread penetration of this type of technology. However, their energy capacity is still limited for storing large amounts of energy.

PSH is the only technology that can provide at the same time large-scale energy storage and highly flexible capacity for supporting the electricity generation of intermittent generation and the operation of conventional generators.

6.1.3.2 Conventional Generation

The incorporation of intermittent renewable generation in power systems has increased the volatility and uncertainty of net-demand, and therefore the volatility and uncertainty of energy prices. This has increased the risk exposure of conventional generator investors, which in turn is putting in risk security of supply due to the lower investment levels observed in the generation sector.

The capability of PSH plants to level net-demand can contribute to stabilize energy prices, which can help providing stable and clear price signals for generation investors and at the same time reduce their risk exposure.

6.2 End Customers

The benefits of PSH plants for the operation of power systems create multiple measurable and unmeasurable benefits for end customers. The number of unmeasurable benefits is however much larger than the ones that the end customer can perceive, what creates the challenge for regulators of first creating the metrics required for measuring those benefits, and second, designing and implementing the market arrangements needed to valuate and compensate the providers of those benefits.

The benefits that can be perceived by end customers are basically two:

- Improved quality of supply.
- Lower electricity bills and tariff changes over time.

The benefits that cannot be directly perceived by the end customers include:

- Improved security of supply and resiliency of the power system.
- Reduction of greenhouse emissions.
- Stabilization of energy prices.
- New job creation due to manufacturing, construction, installation, commissioning, and operation of new PSH facilities, which also can boost the economy and provide a new source of tax revenue.
- Improvements in the utilization of transmission and distribution assets, and deferral of upgrade investments, which ultimately reduces electricity bills.

7. Issue Areas

Penetration of renewable generation is driving the need for more and new sources of flexibility. Fast conventional thermal generation has been traditionally one of the main sources of system flexibility. However whilst this type of technology can provide the required flexibility to integrate large-scale deployments of intermittent generation, the associated costs will be extremely high, encouraging renewables curtailment as a more attractive overall financial position than building peaking plants that have very high operating costs. An additional driver for new sources of flexibility are the damaging carbon emissions of thermal generation, which can be expected to increase if only gas and oil fired power plants, in addition to renewables curtailment, are used to support the integration and operation of intermittent generation.

The large-scale integration of renewables has been mainly driven by the effort to decarbonize power systems. This in turn has reignited the research and development on energy storage, which in the past was mainly driven by the interest in shifting the energy generated by baseload generation at periods of low demand. The massive amount of renewables that need to be incorporated in the UK power system for achieving the 2050 decarbonisation targets will require large volumes of system flexibility not only for compensating the variability and uncertainty of the intermittent generation, but also to maximize their utilization in a cost-effective manner.

Large-scale energy storage will be needed for achieving a cost-effective and efficient integration of renewables. However, despite the increased interest and research funding on bulk energy storage, actual deployment of this type of technology still remains low in most electricity markets with increasingly large shares of intermittent generation. Despite the evident need for new technological developments and the capability of mature bulk energy storage projects, the economics and timing required to build these facilities are not being adequately addressed within modern electricity markets.

Pumped storage hydro is the most mature and popular large-scale energy storage technology since the 1960s. However, in general most developments occurred before 1990, except in fast growing economies in which electricity markets have not been fully liberalized, or where the regulator is playing an active role supporting the development of PSH.

7.1 Engineering Issues

7.1.1 Technology

PSH is a mature technology. The latest technological developments include variable-speed and ternary PSH plants that have improved flexibility and efficiency, and the reliability of PSH plants. However, PSH plants do not have a standardized size and capacity, but instead they need to be designed and build on a site-by-site basis.

The site-dependent characteristics of PSH plants translate into the need for a customized design and site-specific civil works. This can translate into the need for customized turbines and/or other PSH machinery, which may be time-consuming and technically challenging. Additionally, given that these types of power plants are normally installed in remote locations, the access to the grid also demands a customized design and construction considerations.

7.1.2 Siting

To generate electricity, PSH plants need to move water from an upper reservoir that is at a higher elevation to a lower reservoir. The larger the altitude difference between the reservoirs, the larger is the gravitational potential energy of water that can be used to generate electricity. However, due to the relative low energy density of PSH systems, a large variation in height between reservoirs is not the only critical factor for deciding the location of a PSH plant. PSH plants need a very large body of water for generating electricity, and the larger are the reservoirs used to store the water in PSH plants, the longer is the time they can generate electricity.

Locating the site for justifying the economics and building of a PSH plant is not a straightforward task. It requires finding a site that allows maximizing the volume of water that can be stored and at the same time the height variation that can be achieved. Additionally, this needs to be balanced against the feasibility/costs of the required civil works and access to the grid, and a number of environmental considerations.

7.1.3 Permissions

PSH plants normally require building at least one reservoir. This implies an intervention in the ecosystem of the site where the PSH plant is to be built as it means inundating large extensions of land and potentially intervening aquatic life of natural reservoirs. This translates into the need for environmental impact studies and also construction permissions applications that risk non-approval or might take long times to be approved [45].

7.1.4 Construction Time

The magnitude of PSH plants normally demand considerable civil works, which in turn take long construction times. This not only involves the risks associated with the construction companies involved, but also potential for unforeseen risks given by the geology of the site, that can ultimately delay the commissioning of the power plants.

7.2 Economic Issues

The research and development of large-scale energy storage seeks to address the issue that today there is a restricted number of conventional technologies that can provide load-following capability and flexibility at the levels required for the large-scale deployment of renewables. Over the course of the last ten years or so, the research on energy storage has experienced an exponential growth, as evidenced by the fruitful literature available on this topic [46] [47] [48] [49].

Available academic and non-academic literature arrive at the same conclusions, one of them being that energy storage will play a crucial role for integrating large shares of intermittent generation into power systems, as it can provide the flexibility volume required for such purpose [50] [51] [52] [53] [54]. However, they also conclude that current market structures and arrangements are poor and deficient for supporting the development of energy storage [55] [56] [57].

Lack of revenue mechanisms, market access and participation rules, supporting arrangements, long-term and steady regulation, unpriced services, subjectivity and measurability of benefits, etc., are some of the multiple economic issues that affect PSH plants. These multiple economic issues can be categorized in two: benefit-related and market-related issues.

7.2.1 Benefit-related Issues

Only the energy and ancillary services that PSH plants currently provide are well understood, can be measured and are being financially realised. However, most of the benefits that PSH plants can offer in the new paradigm shift towards low-carbon power systems with large-scale deployments of intermittent generation are subjective, hard or impossible to measure, and complex to internalize. Even where a benefit can be defined and measured, an additional degree of complexity is given by the challenge of apportioning the benefit, as it can span across multiple levels of the power system and many stakeholders.

Many of the benefits of PSH plants are in the form of 'avoided costs.' This means that in order to financially benefit, the PSH operator needs to be the bearer of a large portion or these costs, or a mechanism should exist that allows sizing the savings and transferring a share of them from the benefited stakeholders to the PSH operator.

Another portion of the benefits of PSH plants are in the form of positive externalities, which requires the additional and much more complex challenge of measuring their extent and monetize them. Such a task is not only controversial and highly subjective, but will require a mind-set change of electricity stakeholders as they will need to internalize the intrinsic value of those benefits in order to understand and accept their monetary value.

7.2.2 Market-related Issues

7.2.2.1 Market Structure

The market structure under which PSH plants are developed plays a crucial role, as shown in **Figure 8**, which shows total PSH capacity installed in the four regions with the largest deployments of PSH versus the market structure under which those capacities were commissioned. As shown in **Figure 8**, the vast majority of PSH capacity came into operation under monopolistic market conditions, while less than 5% have been under liberalized market conditions.

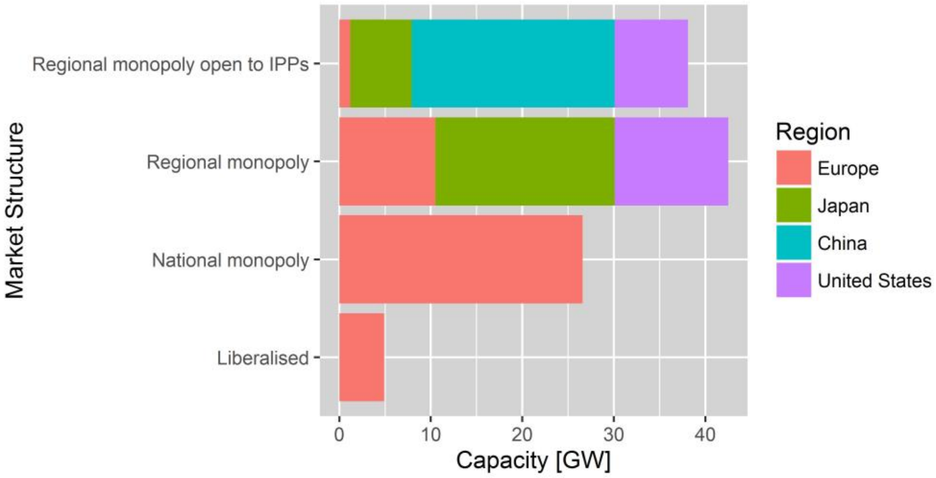

Figure 8: Total installed PSH capacity under different market structures (data source [5]; adapted from [46]).

This suggests that the role of the regulator for supporting the development of PSH is crucial and also that the open participation of PSH plants in liberalized markets seems unable to create enough incentives for the wide deployment of this technology. The investment in PSH plants requires long-term periods for recovering the CAPEX due to their capital intensiveness and the long construction times they require. The capital recovery process for PSH plants is then exposed to the risks created by unstable and short-term regulation, in addition to the risk due to electricity prices that are also heavily influenced by the ruling market regulation.

As it is in the case of investment in nuclear power plants, the investment in capital intensive generation requires supporting arrangements to ensure recover of fixed costs if electricity price spread does not create the required level of scarcity rents to allow this to happen. The large-scale penetration of renewables will make net-demand much more variable compared to current levels, which in turn has the potential to make electricity prices highly volatile. This will increase the price risk exposure of investors due to the increased uncertainty in the scarcity rents and also because it is likely that regulators will need to intervene in the market with pricecapping measures. On the other hand, large-scale deployment of energy storage or other sources of non-generating flexibility can be expected to stabilise net-demand, which will reduce the volatility and therefore the spread of electricity prices. Although this will help reduce the uncertainty of scarcity rents, it will also reduce their levels, which will increase the required capital recovery time of investment in PSH plants.

Independent of how the large-scale deployment of intermittent generation will be handled by regulators, long-term support arrangements are needed for PSH investment in order to minimize the regulation and price risk exposure of investors. However, this can be highly controversial, as it can give a significant market advantage to the investment in PSH plants, and can affect the investment in other types of low-carbon technologies.

7.2.2.2 Revenue Mechanisms

Investment in large-scale energy storage under liberalized market structures has been limited, and most of recent investment has happened in markets where there is some degree of public ownership, as shown in **Figure 8** and analysed in the previous section. This appears to indicate that public ownership helps to mitigate the regulation and financial risks that exists in liberalized markets.

Long-term and secure revenue streams are a necessary condition for the investment in high capital long lifetime assets. However, despite the international agreement on the multiple benefits of PSH plants for stakeholders across the power system [51] [56], little or no agreement exists regarding the optimal policies to incentivize PSH investment, strategies to operate PSH, and the ownership structure for those assets.

In terms of market participation there are three broad classes of revenue models for compensating PSH plants: cost-of-service, direct-participation and behind-the-meter. These remuneration schemes are not mutually exclusive, and a PSH plant might be remunerated through a combination of these [58]. Under the cost-of-service business model the cost of the project is remunerated through a regulated arrangement with the regulator that typically covers operating costs and an agreed rate of return on the capital costs. However, whilst this model has been successfully used for transmission and distribution assets in unbundled liberalized electricity markets, it creates the concern of potential market abuse exercised by bulk energy storage facilities that can also participate in the competitive part of the market, in the case of partially-liberalized electricity markets.

Market participants need to compete to provide competitive market services in the case of direct-participation in a partially or fully liberalized competitive electricity market. In this case and if there is no special arrangement for PSH plants, they get part of their revenues through energy arbitrage, i.e. from consuming cheap electricity at off-peak times and generating at peak hours, which has the effect of reducing the electricity price spread between those periods. Although this should have the positive effect of increasing social welfare, the reduction of peak/off-peak price differential will reduce the income of PSH plants.

Behind-the-meter is a third business model that applies to energy storage facilities that are located in the generator’s/consumer’s/end-user’s side of the electricity meter. Financial benefits in this case can be achieved through the utilization of energy storage to avoid high electricity prices, improve own-renewable energy usage, access renewables incentives, and improve supply reliability, among others, which might justify investing in an energy storage facility. Even in this case, an energy storage facility can in theory participate in the competitive electricity market, as there are no regulatory barriers for market participation from this point. However, due to the size and site requirements of PSH, behind-the-meter applications do not yet exist in the UK. Potentially, some very large electricity consumers could implement this, similar to the private hydro-electricity plants for aluminium smelters.

Independent of the revenue model used for compensating a PSH plant, and the market structure under which it is being operated, the benefits of PSH extend to other levels of the power system and stakeholders. Creating the policies and mechanisms to correctly reward PSH for those additional benefits is very complex because, as was discussed earlier, the subjectivity of those benefits makes them hard to measure and price, and complex to apportion.

The licensing conditions and restrictions are another critical factor that needs to be carefully designed as it can restrict the development of PSH plants and the extent of their benefits for both owners and the system. In unbundled markets licensing conditions normally preclude or restrict the ownership of large-scale energy storage in non-competitive market areas, because the concern that might be used as both a regulated asset and simultaneously participate in the competitive market.

Finally, despite large-scale energy storage, and specifically PSH, appearing to be a safe, secure, environmentally friendly, and cost-effective way for integrating large-scale volumes of intermittent generation, revenue streams for supporting the investment in this technology are uncertain. Energy arbitrage and traditional ancillary services can not be assumed to generate the required level of revenues for ensuring capital recovery. New steady and long-term revenue streams, and business models, are required to provide the level of certainty required to attract investment in PSH. This will not only require the need to recognize and monetize as far as possible the multiple benefits that PSH can offer for the operation and expansion of the power system, but also the firm and long-term commitment of regulators for creating the mechanisms, market arrangements and policies required for such a purpose.

7.2.2.3 Other Economic Barriers

Additional economic barriers for the development of PSH schemes include:

- High grid access charges, particularly given the possible locations of PSH projects, remote from load centres.
- Economic support of other technologies. This is the case of the Cap & Floor mechanism introduced by Ofgem in 2014 for interconnectors. The cap and floor mechanism provides a balance between incentives to stimulate competition and investment, and ensuring that the risks and rewards are bounded. The provision of the floor overcomes some of the uncertainty associated with wholesale price fluctuations between markets, and other income streams. In doing so, this seeks to ensure that the benefits of interconnection can be realised. Further, the presence of a cap ensures that consumers are protected from unbounded developer revenues.

7.3 International Markets and Mechanisms

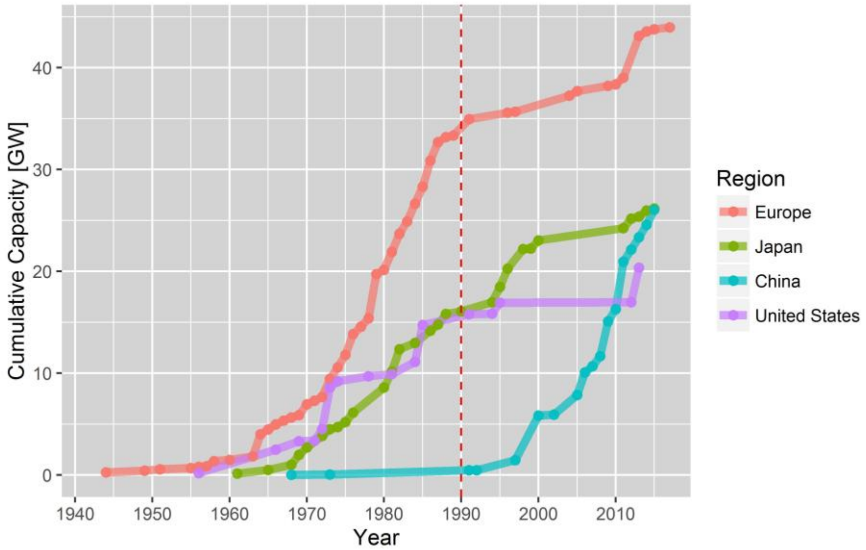

Figure 9: Cumulative PSH installed capacity (data source [5]).

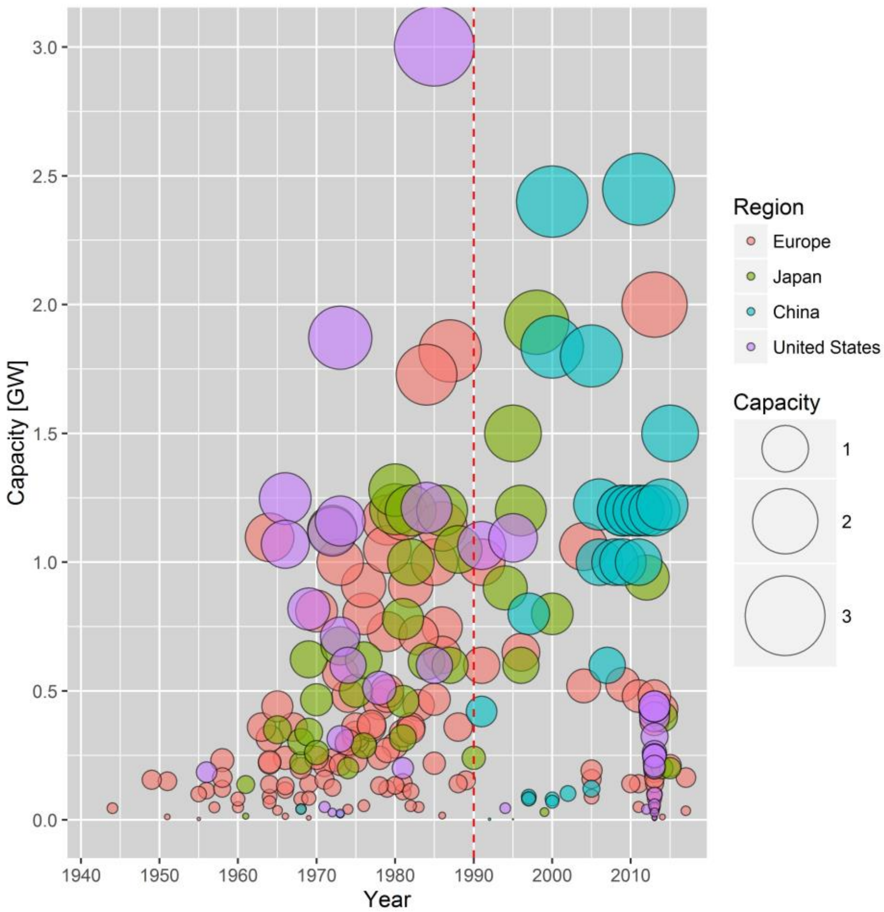

Figure 10: Historical PSH deployment (data source [5]).

7.3.1 Japan

Nuclear power is the major source of electricity in Japan, and has been one of the main drivers for the deployment of PSH plants [59]. Additional drivers for such development include energy security reasons, no electrical interconnections with other countries, geographical suitability, and high electricity prices [60].

The electricity market in Japan is partially liberalized and has not been fully unbundled. Although the market has been open to Independent Power Producers (IPP) since 1995, there is a low portion of IPP due to: a) presence of regional monopolies and privately owned vertically-integrated utilities that have a mix of generation and transmission/distribution infrastructure; and, b) high transmission access fees [61] [62]. Because of these reasons, most PSH schemes in Japan are operated through regulated arrangements (cost-of-service business model) that ensure costs recovery.

In reaction to the Fukushima incident, the Japanese government has decided to reduce their reliance on nuclear power by supporting renewables development through new subsidies [63], and has also approved further liberalization and unbundling of the electricity sector [61] [64].

7.3.2 China

Whilst the electricity sector in China was unbundled in 2002, the vast majority of the electricity infrastructure is owned by the state and electricity prices are centrally defined [65] [66] [67]. Because of these reasons, and also since PSH plants can be used as transmission and distribution assets, PSH schemes in China are operated under different price mechanisms that have cost-of-service aspects [68].

The most common price mechanisms for PSH are single capacity-based payment and Transmission/Distribution tariffs. In the former mechanism, PSH owners rent the schemes to the grid company, who can freely dispatch them in order to maximize system-wide benefits. In the latter mechanism, the capital investment is provided by the grid companies, who own the PSH plants, and is recovered through the transmission/distribution tariff charged to end users.

7.3.3 US

Unbundled liberalized and partially-unbundled/partially-liberalized markets exist in the US [37]. In the unbundled liberalized markets PSH schemes operate under the direct-participation business model, and they need to compete with other market participants for the provision of electricity and ancillary services [69].

With the exception of PJM, PSH schemes are at a disadvantage in US power systems, as they are required to specify their discharge and charge windows, in addition to declaring their production costs, in the day-ahead market using price forecasts. The ISO then optimizes the PSH scheduling within those windows, which in other words mean that PSH consumption and generation bids are evaluated independently, which potentially might translate into a loss. In the PJM market, on the other hand, PSH charging and discharging scheduling is co-optimized in the day-ahead market.

The latest developments in relation to energy storage in the US are the FERC (Federal Energy Regulatory Commission) Order 755 [70], and the CAISO energy storage mandate AB 2514 [71] [72]. FERC stated that: '... *current compensation methods for regulation service in Regional Transmission Operator (RTO) and Independent System Operator (ISO) markets fail to acknowledge the inherently greater amount of frequency regulation service being provided by faster-ramping resources,'* which resulted in the issue of Order 755 in October 2011. The order stablishes that: *'.. requires RTOs and ISOs to compensate frequency regulation resources based on the actual service provided, including a capacity payment that includes the marginal unit's opportunity costs and a payment for performance that reflects the quantity of frequency regulation service accurately provided by a resource following the dispatch signal.'* The primary aim of FERC introducing the order was to ensure that technologies that could perform better than expected, and which benefited the energy system by doing so, should be remunerated correctly.

CAISO mandate AB 2514 instructed California's investor-owned utilities (IOU) (Pacific Gas & Electric (PG&E), Southern California Edison (SCE), and San Diego Gas & Electric (SDG&E)) to expand their electricity storage capacity and procure 1.3GW of electricity and thermal storage by 2020. Each IOU was awarded with an energy storage agreement that establishes that the seller will be compensated in the form of a fixed capacity payment and a variable energy/O&M payment, subject to adjustments for decreases in capacity, availability or efficiency of the storage project.

7.3.4 Europe

Energy storage will play a crucial role for achieving European Union goals (expansion of renewable energy, decarbonisation, energy security, energy market integration, increased competitiveness, etc.) [3]. However, deployment of energy storage is affected by existing regulations [57]. The European electricity system was not designed with energy storage in mind, as evidenced in the 2009 Electricity Directive in which energy storage is not included [73].

The observed depressed and less volatile energy spot market prices in Europe, and especially in Germany due to the large volume of subsidised wind and solar generation [74], have resulted in the suspension or abandonment of several PSH schemes in Switzerland and Germany due to the less favourable market conditions and profitability uncertainty [75] [76]. The harmonization of the European electricity markets, in combination with improved and larger levels of interconnection, can be expected to increase and expand those effects, which will undermine the deployment of energy storage in Europe even further.

The first signs that seem to reveal that a generalized European effort for promoting energy storage development in Europe is taking place are given by the fact that the European Commission announced in its Energy Union Summer Package of 15 July 2015 that it is working on a new energy market design [77]. This new energy market design will aim at providing an opportunity to reach a level playing field for energy storage, clarify the position of energy storage for both regulated and non-regulated entities and acknowledge the multiple services that energy storage can provide. At regional level, on other hand, some initial steps to promote the development of grid-scale energy storage are being made in Germany and The Netherlands. In May 2015, the German Federal Council proposed to extend the benefits of the German Federal Energy Industry Act Sec. 118(6), which exempts network access charges to hydrogen and hydrogen-based gas facilities, to new electricity storage facilities that are commissioned within a 15 year period starting (retrospectively) on 4 August 2011, for an exemption period of 40 years (currently is 20 years). In the specific case of already built PSH schemes, for which pump or turbine capacity increased by at least 7.5% or whose storage capacity increased by at least 5% after 4 August 2011, they are proposed to be exempt for 20 years instead of the current 10 years [78]. Additionally, the German Association of Energy and Water Industries have proposed definitions of energy storage to be used in legislation [79]. Finally, in February 2015 the Netherlands introduced a temporary regulation that allows 'Electricity Law experiments' combining local production, consumption and electricity storage to facilitate and promote smart grids. This regulation is meant for projects that combine local production of renewable energy and consumption for 'local' (up to 500 end users) or 'regional' scale (up to 10,000 end users) [57].

7.3.5 UK

The UK operates an unbundled liberalized electricity market, where PSH schemes compete with other market agents for providing electricity and ancillary services. The four PSH schemes in the UK are owned by private companies, as the current electricity legislation forbids transmission or distribution companies from owning energy storage, or other generation assets. The services provided by PSH plants include energy arbitrage, ancillary services (frequency response and fast reserve), and black-start capability [80].

Currently, there is no specific regulation for energy storage in the UK at any level. The only concrete market arrangement for energy storage in the UK so far is given by the new enhanced frequency response product created by National Grid in 2015, for which an auction will take place between July and August 2016 and which targets 200MW of storage capacity. Energy storage providers will be awarded with a four years contract. Additionally, energy storage is allowed to participate in the Capacity Market but energy storage missed out in 2015 auction [81].

The latest developments in the energy storage arena in the UK include the reports published by the National Infrastructure Commission and by the Energy and Climate Change Committee in 2016 [82] [83]. The central finding reported by the National Infrastructure Commission is that smart power could save consumers up to £8 billion a year by 2030, help the UK meet its 2050 carbon targets, and secure the UK's energy supply for generations. The commission also suggests that the UK could become a world leader in making use of storage technologies, not through subsidies, but by ensuring that better regulation creates a level playing field between generation and storage. For such purpose it concludes that the following two steps are required:

1. DECC and Ofgem should review the regulatory and legal status of storage and remove outdated barriers to enable storage to compete fairly with generation across the various interlinked electricity markets. The reforms should be proposed by Spring 2017 and implemented as soon as possible thereafter.
2. Network owners should be incentivised by Ofgem to use storage (and other sources of flexibility) as a means of improving the capacity and resilience of their networks as part of a more actively managed system.

The Energy and Climate Change Committee highlights the relevance for the UK of bulk energy storage developments and also emphasises the poor and unclear regulation on this matter. The report concludes and recommends that:

1. Further large-scale storage, such as Pumped Hydro and Compressed Air Energy Storage, could be of great value in managing variable generation, but there is uncertainty as to the potential for future deployment. The committee recommends that the Government commissions a study on the future of large-scale storage in the UK which includes consideration of potential sites and what support such projects would need to be viable.
2. The current regulatory conditions for storage are hindering its development. The committee welcomes the Government's consultative approach to this matter, but hope it will proceed with a sense of urgency. It urges the Government to publish its plans, as soon as possible, for exempting storage installations from balancing charges, and from all double-charging of network charges.
3. Storage technologies should be deployed at scale as soon as possible. The committee supports network utilisation of storage as this helps balance the system, and provides storage operators with a revenue stream that encourages its development. Allowing networks to operate and procure storage, especially in the short run, could also facilitate these benefits. However, it also manifest its concern about network ownership of storage, and calls DECC and Ofgem to analyse the long-term risks of network ownership, operation and procurement in their work on storage.

Finally, Ofgem also remarks upon the need for clarifying the legal and commercial status of storage in [84]. In this document Ofgem commits to:

1. Work with DECC to clarify the scope of this issue and identify approaches to addressing it, in discussion with the industry.
2. Undertake work with DECC to clarify the legal and commercial status of storage and explore whether changes to the regulatory and commercial framework are needed to enable its efficient use, seeking input on options from stakeholders.

3. Where changes are needed, they will be informed by considering the interactions and implications of a new regulatory framework for storage on all segments of the market, including interactions with energy efficiency policies.
4. Contribute to the European debate around the role of storage.

8. Key Facts & Recommendations

8.1 Key Facts

- Pumped storage hydro (PSH) is a proven large-scale clean and renewable energy storage technology able to provide large amounts of highly flexible capacity that can not only improve reliability and resilience of power systems, but also help to integrate renewables in a cost-effective manner, and contribute to the development of sustainable and affordable low-carbon future power systems.
- From technical and economic perspectives, PSH is likely to be among best and most cost-effective ways of providing large amounts of reliable flexibility and ancillary services for coping with large-scale deployments of intermittent renewable generation, and other factors that may affect the need for flexibility in the future.
- The benefits of PSH schemes extend throughout power systems, from generation down to end consumers and at multiple timescales. Some of these benefits can be measured and priced, i.e. energy and ancillary services. However, most of the benefits that PSH can offer are subjective, hard or impossible to measure, and complex to internalize.
- The long lead times combined with the high capital investment required by this type of asset require extended periods of time for recovering capital costs. This exposes PSH investment to revenue and policy uncertainty, which greatly increases the risk of the investment in this type of technology.
- The vast majority of PSH schemes in the world have been supported by some sort of monopolistic regime that has ensured long-term revenues and capital recovery. Liberalized markets do not provide the required level of certainty of revenues for incentivizing the investment in PSH technology.
- Revenues from energy arbitrage, ancillary services provision and capacity market are likely to be insufficient to support the construction of new PSH schemes.
- Targeted support schemes and subsidies for other types of flexibility resources, such as for example the Cap & Floor mechanism for Interconnectors, create unfair market conditions for the development of PSH in the UK.
- The large-scale deployment of variable renewable generation in the UK will significantly increase the variability and uncertainty of net-demand. Large volumes of flexibility will be required not only to ensure the stability of the power system and the security and reliability of electricity supply, but also to accommodate as effectively and efficiently as possible the power injections of intermittent renewable resources. In the absence of carbon-free sources of flexibility, this will require flexible gas and oil fired thermal generation that will increase system operation costs, greenhouse emissions, and electricity bills for end consumers. In order to avoid increasing greenhouse emissions, renewables curtailment will be required to provide the additional source of flexibility, which will affect the investment economics of renewables investment.
- As the integration of large volumes of intermittent generation progresses in the UK, periods of excess of renewable energy will become more and more frequent. Large-scale energy storage will then be required to time-shift this energy, or otherwise curtailment will be unavoidable, which will create substantial economic losses.

8.2 Recommendations

- The full range of benefits that PSH can offer to the UK needs to be recognised in order to create awareness in the regulator, and also in the end consumer, of the long-term implications that promoting the technology can have.
- New market arrangements and mechanisms need to be created in order to find the ways for compensating PSH for the whole range of benefits that cannot be directly measured and monetised. This will also require a mind-set change in the population and other industry stakeholders that will face new charges derived from those benefits.
- The regulation for energy storage operation needs to be developed and also new business models need to be proposed and understood in order to create the revenue streams for supporting the deployment of energy storage at multiple levels in the UK. In the specific case of PSH, long-term supporting schemes and market arrangements will be necessary in order to reduce the risk exposure of PSH investors.
- A collaborative and coordinated work between PSH developers and the regulator is required given the large-scale and long-term nature of PSH development.
- Providing further support for the development of new PSH units and upgrades to existing PSH units will contribute to grid reliability, facilitate a larger expansion of variable renewable energy, and thereby reduce UK power system emissions.
- The large-scale deployment of intermittent renewable generation is changing the investment and operation economics of conventional generation. The traditional operational regime of conventional generation is changing towards one where there a significant increase in the cycling frequency and more prominent power variability of power plants. New market mechanism to remunerate flexibility contributions need to be created to promote the investment in flexibility.

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