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To whom it may concern,

Dorothea Pumped Hydro Ltd response to draft NDF consultation

This letter provides Dorothea Pumped Hydro Limited's "DPH" response to the Welsh Government's consultation on the draft National Development Framework (NDF).

In summary, these representations set out that:

- the NDF is a once-in-a-generation opportunity for Wales to secure the investment in low carbon and renewable energy generation and storage that is required to tackle the climate emergency. DPH welcomes the ambition shown by the NDF in its role as the development plan for the determination of Developments of National Significance (DNS), but considers that the current draft falls short of its potential and requires amendment to ensure it is fit for purpose;
- the NDF should recognise the inter-relationships between renewable and non-renewable energy technologies and that a mix of technologies is required to create a resilient energy system and to deliver the Welsh Government's low carbon and renewable energy objectives – the energy system in Wales simply cannot function on renewables alone;
- the status of the NDF as the development plan for DNSs needs to be clearly stated within the NDF and the policy framework should include all types of DNS (i.e. pumped hydroelectric energy storage and generating schemes, underground gas storage facilities, facilities for liquid natural gas (LNG), gas reception facilities, airports, railways, rail freight interchanges, dams and reservoirs, transfer of water resources, waste water treatment plants and hazardous waste facilities[1]) not just energy generation projects.

The representations are made on the basis that the NDF has two principal functions:

1. To provide a policy context for energy development in Wales (be that generation, distribution or storage) that is unambiguous and provides clear 'in principle' policy support; and
2. To provide a clear message to investors that Wales is open for business from a low carbon energy perspective.

[1] The Developments of National Significance (Specified Criteria and Prescribed Secondary Consents) (Wales) Regulations 2016 (as amended)

Overview of Dorothea Pumped Hydro Limited

DPH has been established as an entirely new corporate entity as owners and the controlling party of the former Dorothea & Twll Slate Quarries in the Nantlle Valley in Gwynedd. The site, known as Dorothea Lakes, has been identified as a suitable location for the development of a grid scale pumped hydro-electric energy storage and generation scheme.

The long term vision for the site is the creation of an energy storage and generating facility which is entirely in-keeping with its surrounding landscape (as the majority of infrastructure will be underground), and allows for the preservation of the site's historic assets and respects the Outstanding Universal Value of the candidate World Heritage Site, makes a meaningful contribution to the local economy, and creates a heritage-based leisure tourism destination which links to the North Wales Slate Trail.

Initial engineering assessments have confirmed the suitability of the geology at the site and a potential generating and storage capacity of circa 450MW has been identified – this will utilise the existing quarry pits at the site for headponds and tailponds. It is anticipated that the penstock connecting the tailponds to the headpond will be underground as will the grid connection.

Work to date has focussed on the engineering design and feasibility, alongside health and safety matters to divert public footpaths which pose a danger to public health, to introduce way-marking and signage and also to clear vegetation to improve safety and the experience generally. Dialogue has been undertaken to date with the following:

- National Grid
- Gwynedd Council (Economic Development, Planning and the World Heritage Bid Team)
- Snowdonia National Park (Planning);
- CADW
- Royal Commission for Ancient & Historical Monuments of Wales
- NRW
- Llanllyfni Community Council
- Local Members in Llanllyfni, Talysarn.

The scheme has the potential to make a vital contribution to the UK's energy mix at a time of increasing climate change pressure, generating capacity (from fossil fuels) coming off-line, and the growth in renewables (which have an intermittent supply profile and therefore lead to a need for 'grid balancing'). Not only will the project provide an essential function that will facilitate the deployment of large scale renewable energy development by providing balance to the grid against the intermittency of renewable energy, but it will also make an important contribution to the local community in terms of direct employment, and a boost to the heritage, leisure and tourism economy of the area.

Pumped Hydro Storage – the technology and the benefits

It is widely acknowledged that greater flexibility is required in our electricity system to decarbonise at acceptable cost to consumers. The National Infrastructure Commission (NIC), in its "Smart Power" report in 2016, estimated that greater flexibility within the electricity system could save consumers up to £8bn annually by 2030. Similarly, a report for the Energy and Climate Change Committee showed that energy storage in particular could provide £2.4bn per year in benefit to the UK by 2030, if market barriers are removed.

In 2016, Scottish Renewables commissioned a report on the benefits of pumped storage hydro (PSH) to the UK – a copy of the report is enclosed with this submission. The report was prepared to inform policymakers about the relevance of PSH for providing flexibility, integrating large-scale deployment of renewables, and developing sustainable, secure and cost-effective low-carbon power systems. As one of the best proven technologies available at scale to provide the flexibility required to decarbonise the electricity system, it offers a number of operational and cost benefits along with wider social and environmental benefits. The report found that these benefits included:

- ***System operation**: PSH can provide a wide range of ancillary services needed for system operability in the future low-carbon world, with capabilities similar to or better than thermal generation and other energy storage technologies (e.g. frequency response, reserve, voltage management, black start).*
- ***Congestion costs**: PSH can alleviate network congestion costs by storing excess generation in constrained zones for later use, thereby avoiding or deferring investment in network reinforcement.*
- ***Environmental benefits**: PSH avoids waste of electricity production during periods of low electricity demand, and avoids the environmental impact of new transmission infrastructure.*
- ***Security of supply**: PSH is the most economical storage technology for the long discharge periods required to contribute to security of supply.*

The flexibility that PSH offers can provide substantial benefits in reducing costs, ultimately to the benefit of consumers, while meeting the demands of changing approaches to both planning and operation of electricity systems. These changing approaches are the result of several factors, including:

- the need to decarbonise electricity production;
- increased levels of renewables, especially 'variable' or 'intermittent' renewables such as wind and solar;
- changes in electricity consumption including demand management, the growth of electric vehicles, and in future possible substantial electrification of heat demand;
- a shift to distributed generation, one result of which is less generation capacity which is able to or is willing to participate in providing services to the system operator;
- greater international trade in electricity through interconnectors; and
- greater difficulty obtaining public consent for new transmission lines.

Hydroelectric storage is extremely significant in modern power systems even in the context of the range of available energy storage technologies. PSH is particularly significant due to its high operational flexibility and the fact that it is the most developed large-scale energy storage technology currently available (in 2015, more than 97% of global storage capacity was PSH).

PSH can provide energy-balancing, stability, storage capacity, and ancillary grid services such as network frequency control and reserves. This is due to the ability of pumped storage plants, like other hydroelectric plants, to respond to potentially large electrical load changes within seconds. Pumped storage historically has been used to balance load on a system, enabling large nuclear or thermal generating sources to operate at peak efficiencies. A pumped storage project would typically be designed to have 6 to 20 hours of hydraulic reservoir storage for operation at. By increasing plant capacity in terms of size and number of units, hydroelectric pumped storage generation can be concentrated and shaped to match periods of highest demand, when it has the greatest value. Pumped storage projects also provide ancillary benefits such as firming capacity and reserves (both incremental and decremental), reactive power, black start capability, and spinning reserve.

Pumped storage is one of the most cost-effective utility-scale options for grid-scale energy storage, acting as a key provider of ancillary services. With the ability to respond almost instantaneously, pumped storage is an essential component of the electricity network for countries which have a need for electricity system flexibility and have the potential sites.

Significantly, not all areas of the UK are suited to the deployment of PSH. The quarrying history and geology of Wales, however, means that certain parts of the country are ideally suited to this technology. This provides Wales with a significant opportunity for economic diversification and growth in the PSH sector - growth that will provide the backbone to a decarbonised electiricty system.

The significance of the opportunity is compounded when PSH is considered against the well-being goals of the Well – Being of Future Generations (Wales) Act 2015.

Well – Being Goals	**How does PSH comply with the Well – Being Goals?**
A Prosperous Wales	PSH provides is an innovative technology in a low carbon economy providing skilled jobs and an essential resilience to the energy system. It makes efficient use of existing natural resources as supports the decarbonisation of the Welsh economy. It will provide a high number of jobs during construction, including the supply chain, and offer specialist opportunities during operation.
A Resilient Wales	The proposed development provides electricity to the grid, improving the resilience of the network. It will also maintain and enhance the natural environment, subsequently, providing support to the social, economic and environmental resilience of the site and Wales overall.
A More Equal Wales	Presents an opportunity for people to be involved in the development of an innovative energy storage and generation scheme through direct and supply chain employment.
A Healthier Wales	Proposes a low carbon energy development addressing the current climate emergency, improving people's well-being and health. Also has potential to open the area to increased heritage and outdoor tourism.
A Wales of Cohesive Communities	Providing employment opportunities for local communities creating social cohesion and a sense of place.
A Wales of Vibrant Culture and Thriving Welsh Language	The proposed development has an opportunity to promote the site's industrial heritage and history, whilst protecting its cultural and heritage assets and respecting the Welsh Language.
A Globally Responsible Wales	The proposed development will contribute positively to global well–being by facilitating the deployment of renewable technologies and therefore helping to tackle the climate emergency.

The Scottish Renewables report highlighted that one of the major risks associated with projects for commercial operators is future policy decisions by Government. The report therefore recommended that policy certainty could assist in risk reduction for a developer.

Pumped Hydro Storage – consenting

As the proposed pumped hydro scheme is anticipated to have a generating capacity of circa 450MW, it will be classified as a Nationally Significant Infrastructure Project (NSIP) under s14 and s15 of the Planning Act 2008 (as amended) and will require development consent in line with s31 of the Planning Act 2008. Despite its status as a non-devolved energy development, the decision-making framework for NSIP applications is provided by s104 and s15 of the Planning Act 2008, depending on whether or not a relevant designated National Policy Statement (NPS) is in place for the development being proposed. As there is no technology specific NPS for pumped hydro storage schemes, the application is likely to be determined in accordance with any local impact report provided by the affected local authorities, any matters prescribed that are specific to the development proposed, and any other matters which the Secretary of State (SoS) thinks are both important and relevant to the decision. Matters which the SoS may consider to be important and relevant include policy provisions at the national and local levels in Wales. For this reason, it is critical that the NDF provides a supportive context for technologies which will have a critical role in the deployment of large scale renewable energy and the attainment of the Welsh Government's carbon reduction targets.

As currently drafted, the NDF does not include any reference to the range of technologies required to deliver a resilient and flexible energy system. Given the Welsh Government's target to generate 70% of electricity consumption from renewable energy by 2030, the absence of policies or narrative relating to conventional generation (i.e. the remaining 30%), storage and grid balancing is a significant omission. It also fails to recognise the potential for hybrid projects to come forward which incorporate wind, solar and energy storage.

DPH welcomes the Welsh Government's desire to introduce a National Development Framework, with the purpose of providing a co – ordinated approach to develop very much needed strategic infrastructure. We are pleased to offer our views on how the NDF can assist in the development of renewable energy and move towards Wales' energy targets. However, it is DPH's view that, as drafted, the NDF will fail to deliver the level of energy generation required to transition to a decarbonised economy. This is considered to represent a major shortcoming of the NDF, but one that can be rectified.

DPH's comments on, and suggested changes to, the NDF are set out below.

Overall Comments on the National Development Framework

DPH recognises the significant opportunity the NDF presents and believes it can capitalise on the current interest in Wales as an investment location for renewable and low carbon energy development. DPH strongly believes that the NDF presents a once–in–a–generation opportunity, and it is imperative that the Welsh Government gets the NDF 'right first time'. The recent Ofgem *'State of the Energy Market 2019'* report has highlighted that the decarbonisation of energy has retracted to its slowest rate of decline since 2012, and if carbon budget commitments from 2023 onwards are to be met then more investment in low – carbon generation is required. To achieve the level of deployment of renewables required, a range of technologies will be required to account for the intermittency of renewables – pumped hydro storage presents the only grid–scale opportunity to achieve this.

The Committee on Climate Change (CCC) has recognised that '*substantial renewables deployment between now and 2030',* along with new policies, is required in order to hit the 2050 carbon targets. It is clear that action needs to be taken now and the Welsh Government's *'Prosperity for all: A Low Carbon Wales'* document identifies that the NDF as a mechanism will ensure the planning system in Wales plays a vital role in facilitating clean growth and decarbonisation. Overall, this should build resilience against the predicted impacts of climate change over the next few decades.

The above clearly presents how important the NDF will be to the decarbonisation agenda. It also highlights the importance for it to maximise the ability to facilitate the development of a low carbon energy system. DPH considers that the NDF as currently drafted does not demonstrate the urgency of the current situation, and does not provide the policy landscape that will establish Wales as a leader in low carbon and renewable energy development. However, DPH emphasises that with some minor changes, the NDF can be fit for purpose.

Comments on the 11 Outcomes of the National Development Framework

Outcome 11 presents that the climate change issue demands urgent action on carbon emissions and sets out that the planning system must help Wales lead the way in promoting and delivering a competitive, sustainable decarbonised society. However, as emphasised above, the NDF as currently drafted does not provide the urgency required. It fails to recognise that a range of energy generating technologies will be required to deliver a resilient and equitable low carbon economy, with clean and efficient transport infrastructure. The climate emergency should run through all 11 NDF outcomes and should be a clear priority.

Considering the above, it demonstrates the importance of ensuring the NDF facilitates the delivery of large scale renewable and low carbon energy developments. Without this, DPH considers that some of the outcomes set out in the NDF may not be achieved.

Support for a decarbonised economy and energy system

There is widespread governmental support for the transition to a low carbon and prosperous society through the delivery of renewable sources.

In July 2018, the National Infrastructure Commission (NIC) published the first ever National Infrastructure Assessment (NIA) for the United Kingdom. It makes recommendations for how the UK's identified infrastructure needs and priorities should be addressed. Chapter 2 of the NIA refers to low cost and low carbon infrastructure and sets out that "*reducing carbon dioxide emissions from the power sector no longer needs to be considered expensive*". The NIA sets out that matching energy supply and demand means the electricity system needs flexibility, both within days and across the seasons. Under the sub section 'a more flexible power system', the NIA states that flexibility can "*be provided by a combination of flexible supply (energy that can be generated on demand), energy storage and flexible demand*".

Therefore, the NIC believes there is significant scope to build resilience through deployment of a mix of renewables working collectively providing a flexible system. As currently drafted, the NDF places a large emphasis on solar and wind and does not include any reference to the range of technologies required to deliver a resilient and flexible energy system.

The Welsh Government published *'Prosperity for All: A Low Carbon Future'* in March 2019. This plan demonstrates the foundations for Wales to transition to a low carbon nation and sets out how it aims to meet the first carbon budget (2016 – 2020) and consequently the 2020 interim target through 100 policies and proposals. The vision of this plan states that:

> "*in 2050, there will be different energy systems that will be ready to fully exploit the inter – relationships and synergies between the power, heat and transport sectors and we will also see greater energy efficiency in buildings and appliances, and the use of new building fabrics turning buildings into power stations*".

On the 12th of June 2019, the Welsh Government announced its commitment to reducing carbon emission levels by 95% by 2050 and strive to be carbon zero by 2050. The Welsh Government's '*Prosperity for All: Economic Action Plan'* (December 2017) states:

> "*the shift towards a low – carbon future offers huge opportunities for our economy to diversify and grow – but it also challenges us to support business, people and places in transitioning toward that low carbon future*".

This ability of the NDF to facilitate the realisation of the opportunities identified will be critical to its success. DPH believes that, as drafted, the NDF has failed to consider the need for a range of technologies and must provide a supportive policy framework for any renewable technology except for wind and solar.

Suggested Policy Amendments

In light of the comments made above, DPH contends that amendments need to be made to Policies 13 and 22 of the NDF, and the supporting text to these policies, if the short-comings of the NDF as drafted are to be addressed.

Policy 13: *Other Renewable Energy Developments* provides that large-scale renewable energy generation developments (other than wind or solar) will be determined in accordance with the criteria of Policy 11.

It is DPH's view that the NDF must include provisions for all energy generating projects particularly those which are low carbon and / or will facilitate the large scale deployment of renewables. The transition to a low carbon economy cannot be achieved through wind and solar in isolation. DPH strongly disagrees with this approach as the criteria included within Policy 11 are very much directed towards wind and solar. If a standardised approach to the criteria is to be taken, then they need to be more reflective of the technical considerations of all types of large scale energy generating projects.

Policy 13 states that energy schemes can generate direct social, environmental and economic benefits and that they are supported in principle. However, it is considered that the transition to a resilient, low carbon energy system will require a mix of renewable technologies, which complement wind and solar, including hydro pumped storage schemes. Recent work by the Institute of Welsh Affairs (IWA) as part of its "*Re – energising Wales*" project reinforces this view and provides a practical plan by which, Wales could achieve its ambition to maximise its renewable energy sources by 2035. As part of this project, *Regen* conducted an analysis of Swansea Bay City Region's future, including energy demands and potential sources of energy generation. The vision included the deployment of a mix of energy storage and generating technologies. Taking this into consideration, DPH suggests that this should be reflected in Policy 13 and altered to reflect this.

DPH's proposed revision to Policy 13 is set out below:

Policy 13: Low Carbon Energy Developments

The Welsh Government supports large scale low carbon energy development. There is a presumption in favour of development for these schemes across Wales outside of the areas identified by Policy 12.

When determining planning applications for large scale low carbon energy development, significant weight will be given to the proposal's contribution to:

- *reducing Wales' greenhouse gas emissions and meeting decarbonisation and renewable energy targets*
- *delivering wider environmental, social and economic benefits*
- *facilitating the deployment of large scale renewable energy development.*

All applications will be considered on the basis that the Welsh Government has demonstrated that there is a need for renewable and low carbon energy infrastructure and significant weight shall be afforded to the contribution which projects would make towards satisfying this need.

Planning applications must demonstrate the proposal is acceptable in social, economic and environmental terms and that there are no unacceptable adverse effects on, or due to, the following (where relevant to the technology proposed):

- *Biodiversity and geological conservation;*
- *Civil and military aviation and defence interests;*
- *Coastal change;*
- *Dust, odour, artificial light, smoke, steam and insect infestation;*
- *Flood risk;*
- *Historic environment;*
- *Landscape and visual;*
- *Noise and vibration;*
- *Socio-economic;*
- *Traffic and transport;*
- *Waste management;*
- *Air quality and emissions;*
- *Water quality and resources; and*
- *Cumulative impact.*

Suitable access to the site for construction and maintenance purposes must be provided. Plans must also be in place for the end of the development's lifetime, including the decommissioning of the site at the end of its operational life.

It is also suggested that the following text is added to the supporting text to Policy 13 to provide clarity to the issues to be considered in the planning balance:

> *In considering any proposed development, and in particular when weighing its adverse impacts against its benefits, the Welsh Ministers should take into account:*
>
> - *its potential benefits including its contribution to meeting the need for energy infrastructure, job creation and any long-term or wider benefits; and*

- *its potential adverse impacts, including any long-term and cumulative adverse impacts, as well as any measures to avoid, reduce or compensate for any adverse impacts.*

In this context, the decision-maker should take into account environmental, social and economic benefits and adverse impacts, at national, regional and local levels.

To summarise, DPH agrees with the overall objectives of the NDF for energy development but considers that as drafted they do not go far enough in the context of a climate emergency. DPH believes that the support provided for these developments needs to be strengthened and policies need to recognise the benefits a mix of technologies can bring, most notably the delivery of a flexible, resilient, low carbon energy system. DPH suggests that the NDF must include a presumption in favour of renewable and low carbon energy development in all areas except those identified under Policy 12.

Recent events evidently demonstrate the need for a resilient energy system, particularly the Low Frequency Demand Disconnection (LFDD) as a result of generator trips and frequency excursion on the 9th of August 2019. National Grid's interim report (dated 16th August 2019) confirmed that the loss of two transmission connected generators resulted in a loss of 1,378MW. This event meant that secondary backup systems were required to disconnect some demand by automatically disconnecting customers on the distribution network in a controlled way. The interim report states that "*c.5% of Great Britain's electricity demand was turned off to protect the other 95%*", resulting in approximately 1.1 million customers being without power for between 15 minutes and 50 minutes. This event has not happened in over a decade and National Grid described it as a 'extremely rare event'. Western Power Distribution confirmed that roughly 29,060 customers in Wales were affected by the LFDD.

The above clearly highlights that storage and fast response generation is essential to protect energy security and to minimise disruption and the duration of any power outage by such an event. It also indicates that, even if an event does not occur in Wales, it can still directly affect Wales, reiterating DPH's position that the NDF needs to offer explicit support for other renewable and low carbon energy development and strengthen or amend existing policies in line with the comments made above. In addition, the NDF should provide explicit support for all energy development, particularly energy development that will facilitate renewable energy, e.g. pumped hydro. Consequently, DPH believes this will ensure Wales is prepared for the future and will overall generally improve Wales's energy security.

Policy 22: *North West Wales and Energy* is supported by DPH. However, taking into consideration the comments made in this representation, it is proposed that this policy is amended to provide explicit support for renewable and low carbon energy development within the region.

DPH takes into account that Policy 22 refers to determining nuclear energy generating stations in this region, however, applications for nuclear energy generating stations (which are likely to exceed 350MW) are not devolved and consequently, DPH suggests that the wording within Policy 22 needs to be reviewed carefully.

Policy 22 also states that "*the planning system has a key role in supporting renewable energy and ensuring the North plays its part in decarbonising society, and that the region has a strong potential for generating wind, solar and tidal energy*". It also refers to the positive impacts the nuclear sector can present in terms of investment, skills and training.

Immediately following this statement, Policy 22 highlights that the 'Anglesey Energy Island Programme' seeks to co-ordinate action around new energy developments. DPH is of the view that the policy appears to be overly focussed on nuclear, without making reference to other energy developments and the benefits they can deliver. This policy needs to be reworded to emphasise the economic benefits of other energy developments, including pumped hydro. In this context, DPH proposes the following changes to Policy 22 (suggested new text is underlined; suggested deletions are struck through).

Policy 22: North West Wales and Energy

The Welsh Government supports North West Wales as a location for all types of new energy development and investment.

New energy-related development should support local and regional communities; provide jobs and investment in training and skills; and work with universities and businesses across the region and North West England to co-ordinate and maximise new investment to support the wider region.

In determining any applications for ~~nuclear~~ energy generating stations in this region, including nuclear, consideration should be given to ~~the need for further non-renewable energy generation,~~ their contribution towards Wales' energy mix, their ability to facilitate the deployment of renewables, their impacts on the natural and historic environment and the economic benefits they would bring to the region.

DPH also proposes a change to the supporting text to Policy 22:

> "*The Welsh Government supports the North West Nuclear Arc initiative which is a shared vision (with the UK Government, Universities and the National Nuclear Laboratory) of realising the potential impacts the nuclear can bring into an area in terms of investment, skills and training. The Anglesey 'Energy Island' Programme researches into low carbon energy development, production and servicing and the potential economic rewards that would come forward with such developments*". *Outside of the nuclear sector, the Welsh Government supports all types of energy storage and generation and the economic benefits they bring, including large scale pumped hydro.*

Conclusions

DPH would be pleased to continue engaging with the Welsh Government over the coming months to discuss any of the matters raised in this letter. We look forward to being part of the NDF conversation as it continues to progress.

Yours faithfully

BEN LEWIS

Infrastructure & Energy Director

Enc. *The Benefits of Pumped Storage Hydro to the UK* - Scottish Renewables

The Benefits of Pumped Storage Hydro to the UK

Scottish Renewables

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Contents

1. Executive Summary

This work has been commissioned by Scottish Renewables on behalf of the Pumped Storage Hydro Working Group. Funding partners are ScottishPower, SSE and Scottish Government.

In this report DNV GL conducts an in-depth analysis of the multiple benefits of PSH for the UK power system, as well as the many issues that obstruct its development.

It is widely acknowledged that greater flexibility is required in the electricity system of Great Britain (GB) to decarbonise at acceptable cost to consumers. In its Smart Power report, the National Infrastructure Commission estimated that greater flexibility could save consumers up to £8bn annually by 2030.

Pumped Storage Hydro (PSH) is one of the best proven technologies available at scale to provide the required flexibility. It delivers many operational and cost benefits to the GB electricity system as well as wider societal and environmental benefits, including:

- **System operation**: PSH can provide a wide range of ancillary services needed for system operability in the future low-carbon world, with capabilities similar to or better than thermal generation and other energy storage technologies (e.g. frequency response, reserve, voltage management, black start).
- **Congestion costs**: PSH can alleviate network congestion costs by storing excess generation in constrained zones for later use, thereby avoiding or deferring investment in network reinforcement.
- **Environmental benefits**: PSH avoids waste of low carbon electricity production during periods of low electricity demand, and avoids the environmental impact of new transmission infrastructure.
- **Security of supply**: PSH is the most economical storage technology for the long discharge periods required to contribute to security of supply.

There are four PSH schemes in GB, with aggregate power output and storage capacity of 2.8GW and 24GWh respectively. No new schemes have been commissioned since the 1980s, but a number of sites have been identified by investors at which additional PSH capacity could be developed. This includes significant storage capacity which now has planning consent, one of which alone could more than double the total existing UK storage volume.

Investment in PSH infrastructure is characterised by relatively high up-front costs, long project lead times, lengthy lifespans (>50 years), and long project payback periods. As recognised in the NIC's Smart Power report, the range of different roles played by PSH in the electricity system means that storage providers will need to 'stack' multiple revenue streams. However these revenues are subject to considerable uncertainty, particularly arising from long term uncertainty in energy policy. This makes it extremely difficult to develop a robust long-term business case based on projected market revenues alone, Moreover, some of the benefits and positive externalities that PSH can deliver, for example environmental benefits and savings on network reinforcement costs, cannot be easily or directly monetised.

Internationally, less than 5% of existing PSH capacity has been built under liberalised market conditions. Most PSH has been developed in electricity systems controlled by a State electricity board or other quasi-Government institution. This is because such organisations tend to value longer term benefits more (through lower discount rates) and they can include in their decision-making ('internalise') long-term benefits which are likely but uncertain, and risks which are highly unlikely but severe.

The investment challenge is illustrated by the mismatch between the long project payback period and the short durations of typical contracts in the markets in which PSH operates:

- Capacity market: agreements are available for a maximum 15-year duration up to four years ahead of delivery (meaning that a PSH project would be approximately half way through its construction phase before it could be awarded a Capacity Agreement);
- Energy market: liquidity exists to support trading activity only up to two years ahead of delivery;
- Ancillary services market: long-term agreements are not generally available beyond the two-year horizon of the System Operator's agreed incentive scheme.

Whilst these markets are difficult to forecast and revenues are not easily bankable, the outlook of up to £8bn annual consumer benefits from flexibility by 2030 suggests there could be many scenarios in which PSH project investments prove to be in the interest of consumers. However, given the long lead times and high upfront capital requirements of PSH, existing market arrangements do not provide a clear route to market with sufficient certainty for investment in additional PSH.

To mitigate these investment challenges and realise the potential consumer and electricity system benefits of PSH, it is recommended that Government considers options to provide the long-term confidence required by investors. This report does not set out to identify specific options. It does however recommend consideration of market mechanisms which recognise the long-term nature of the benefits of storage and place a value on all of the services which storage can provide. This report also notes that distortions within charging arrangements require a holistic review, and that commercial risk from policy decisions requires mitigation.

It is notable that Government has already introduced a Cap and Floor (C&F) support mechanism for interconnector projects. Such projects face very similar challenges in financing as PSH, namely high initial capital expenditure, long project life, and uncertain revenue streams which are strongly influenced by policy decisions. They also compete against PSH in providing some element of flexibility. A C&F agreement is a risk mitigation mechanism rather than a subsidy, allowing consumers to share in the gains should revenues turn out to be above the cap, whilst limiting the risk to investors (and hence reducing the cost of capital) should revenues turn out to be significantly less than forecast. In common with interconnector projects, a rigorous Cost Benefit Analysis (CBA) would need to be conducted by the independent regulator to ensure that PSH projects demonstrate significant consumer benefits in order to be awarded C&F agreements. The regulator would also need to ensure that C&F agreements do not unfairly disadvantage other forms of energy storage.

Commercial operators are well placed to manage commercial risks; however they are unable to manage, predict, or hedge risks associated with future policy decisions. Therefore a positive move would be for Government and Regulators to provide a degree of risk reduction behind future policy direction. This would substantially reduce a developer's project risk and therefore reduce cost of capital, reduce the cost of new projects, increase the likelihood of projects coming forward, and ultimately reduce the cost to customers of the electricity system.

2. Introduction

It is widely recognised that the UK electricity system[1] will benefit from becoming more 'flexible'. A recent report published by the National Infrastructure Commission [82] indicates that 'smart power' (including flexibility) could save consumers up to £8 billion a year by 2030; similarly a report for the Energy and Climate Change Committee [129] showed that energy storage in particular could provide £2.4bn per year in benefit to the UK by 2030, if market barriers are removed.

'Flexibility' in electricity systems is provided by four main sources:

- Flexible generation, such as gas turbines capable of rapid change of output, and rapid startup;
- Flexible demand, for example industrial customers prepared to reduce demand at critical periods, or automatic control of domestic customers' water heaters and storage radiators;
- Interconnectors to other electricity systems;
- Energy storage.

Energy storage is identified as one of the most important sources of flexibility. Additional flexibility offers substantial benefits in reducing costs, ultimately to the benefit of consumers, while meeting the demands of changing approaches to both planning and operation of electricity systems. These changes are the result of several factors, including:

- the need to decarbonise electricity production;
- increased levels of renewables, especially 'variable' or 'intermittent' renewables such as wind and solar;
- changes in electricity consumption including demand management, the growth of electric vehicles, and in future possible substantial electrification of heat demand;
- a shift to distributed generation[2], one result of which is less generation capacity which is able to or is willing to participate in providing services to the system operator;
- greater international trade in electricity through interconnectors;
- and greater difficulty obtaining public consent for new transmission lines.

This report is intended principally for policymakers, and looks to inform and create awareness about the relevance of pumped storage hydro for providing flexibility, 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 an in-depth coverage of the benefits of pumped storage hydro in the UK, and also addresses the multiple issues which could impede the full realisation of the benefits of this large-scale energy storage technology.

To take one specific example; for low penetration levels of renewables, net-demand can be forecasted with low error, and existing conventional generation can provide the required load-following capability to balance the

[1] Strictly speaking, the electricity system of Great Britain (GB). The electricity system of Northern Ireland forms part of the system of the island of Ireland, which is operated and developed as a single system, including a single electricity market for both Northern Ireland and the Republic. Opportunities for PSH in Northern Ireland are lim ted compared to the GB system; however the conclusions in this report for all forms of energy storage are also relevant for Northern Ireland, particularly given the relatively high levels of renewable generat on.

[2] Distributed generation: smaller generators, connected at lower voltage levels than trad tional generation, including in individual homes, offices and businesses.

system. However, large-scale deployment of wind and PV, as with other system changes, will make this task much more complex, because those generation resources will increase the variability and uncertainty of net-demand[3] [1]. Larger amounts of system flexibility will then be required to balance the system [2]. In this scenario energy storage will play a key role, as it will be useful for storing excess renewable energy, generating electricity when net-demand peaks, or when the rate of change of net-demand is high and cannot be compensated by available system flexibility [3] [4].

As another example, with the anticipated electrification of heating via heat pumps, peak electricity demand on winter days could increase markedly. Under current conditions, this increased peak demand is likely to be met by new open-cycle gas turbines: this would significantly reduce the carbon emissions savings from using heat pumps. Energy storage capable of storing large amounts of energy and meeting the peak demand on a daily cycle would instead allow the energy to be provided by a smaller fleet of combined-cycle gas turbines, at higher efficiency and therefore lower emissions.

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 [5]. The decentralisation of energy systems 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 flexible, sustainable and affordable future low-carbon power system.

The need for additional system flexibility has attracted increasing attention towards 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 flexible and decentralised 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 secure operation and cost-effective expansion of future low-carbon power systems [10].

Among all available energy storage technologies [11] [12] [13], hydroelectric storage is still extremely significant in modern power systems, and in particular pumped storage hydro, not only because of its high operational flexibility, but also because it is the most developed large-scale energy storage technology currently available [14].

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 more now expected under the Enhanced Frequency Response service that National Grid is procuring for managing system frequency[4]. Whilst there remain no 'formal' market incentives, except the four year 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].

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

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[3] 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 convent onal generation and other controllable generation and demand resources in the power system.

[4] A high level of interest was demonstrated in bidding into the Enhanced Frequency Response service: the prequalification process resulted in 1.3 GW, over six times the target of 200 MW of EFR capacity. The winning projects were all battery storage.

grid-scale energy storage [17], acting as a key provider of ancillary services. With the ability to respond almost instantaneously, pumped storage is an essential component of the electricity network for countries such as the UK which have a need for electricity system flexibility, and have the potential sites.

The rest of this document is structured as follows:

- Section 3 describes the research methodology used in the development of this report.
- Section 4 gives a general overview of the deployment of pumped storage hydro worldwide.
- Section 5 starts by analysing the maturity and key features of pumped storage hydro technology (a more detailed explanation is given in Appendix A). The latter part of this section summarises the status of PSH in the UK.
- Section 6 analyses the benefits of pumped storage hydro throughout the electricity supply system, and at different timescales. Further detail is given in Appendix B.
- Section 7 starts by analysing the engineering and economic issues that affect and restrict the investment in pumped hydro storage, then analyses the current markets and mechanisms in five international regions in relation to energy storage and pumped storage hydro.
- Section 8 outlines a set of key facts and recommendations for acknowledging the benefits of pumped storage hydro for the UK.

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 in depth market research of publically and internally available information on pumped hydro storage.
2. *International discussions:* International discussions were organised 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 stakeholder 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 the multiple issues and barriers for the development of this type of power generation project;

b) identify the key 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.

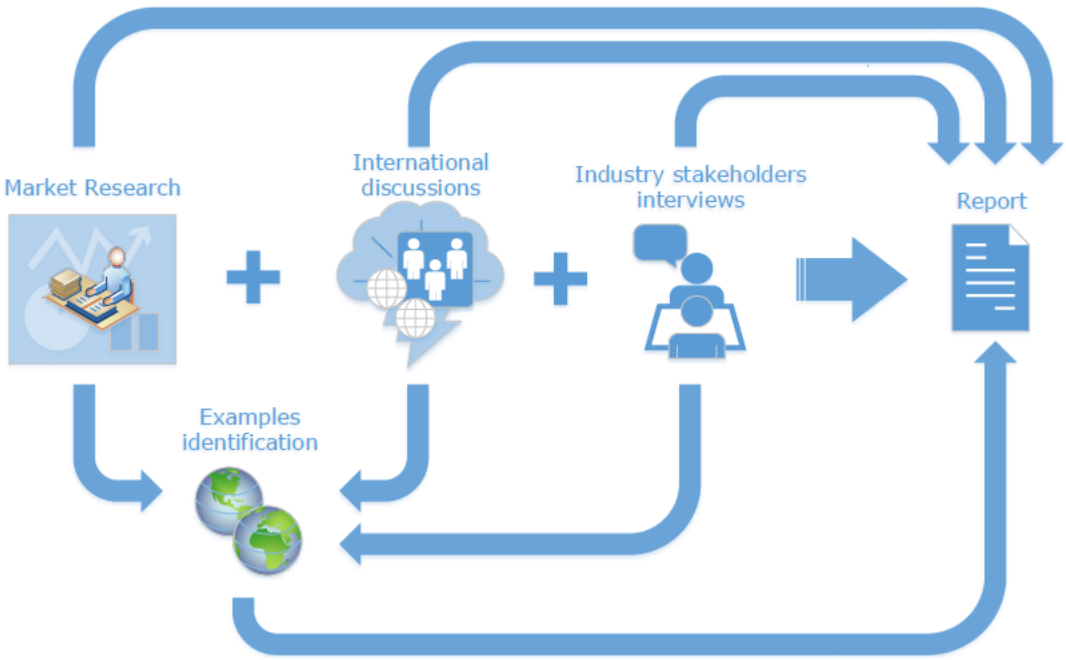

Figure 1: Conceptual representation of the research methodology.

The industry stakeholder 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?;
- Which 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.
- Discussions with:
  - British Hydropower Association.
  - Engie/First Hydro.
  - SSE.
  - Scottish Power.
  - National Grid.

4. Global Overview

Many governments around the globe have committed themselves to energy efficiency and an increasing share of low-carbon generation in their electricity mix while ensuring a secure electricity supply, and there is a growing realisation that improving system flexibility helps these objectives in many ways.

These commitments have three main effects which are relevant for this report, for both the operation of power systems, and their long-term planning and development:

- Many low-carbon sources of electricity tend to be 'inflexible', either because of technical constraints[5] or because their economics require high load factors[6].
- Decarbonisation objectives are also likely to result in new electrical loads such as electric vehicles and heat pumps, which could change electricity demand patterns relatively rapidly in future.
- The rapid and large-scale deployment of renewable generation with varying output affects net-demand [1]. Wind and solar generation increase the variability[7] of net-demand, which needs to be met by controllable demand and generation resources [18]. Conventional generation is operated closer to its operational limits, and when those have been reached, renewable energy production is often curtailed, as a simple (though expensive) means of reducing the impact [2].

Traditionally, system flexibility was provided by fast response thermal generation. Emission restrictions, price volatility, and technology developments are making energy storage technologies strong alternatives [3] [7] [8]. Development of storage technologies to provide flexibility has been supported by many governments through policies that include funding for demonstration projects, subsidies and mandatory storage requirements for utilities [19].

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 between 2005 and 2015, and thermal, mechanical and hydrogen energy storage capacity from about 0.9GW to 3.1GW. However, this is dwarfed by existing and new PSH, which topped 148GW as shown in **Figure 2**.

Pumped storage hydro is therefore by far the dominant large-scale energy storage technology worldwide. More than 97% of worldwide storage capacity is PSH (2015 data), more than 23GW of additional capacity is currently under construction, and another 8.3GW has been announced for construction in the near future [5]. PSH is an established, well-understood technology, with very low technology risks, and continuing performance improvements through technology development. It is an extremely fast ramping[8] 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

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5 Combined Heat and Power (CHP) plants may be 'heat-led', i.e. need to generate electr c ty in some circumstances in order to prov de a certain heat output. Also, some designs of thermal generation, including some nuclear plant designs, are inflexible in that their output can only be changed very gradually, over periods of hours.

6 Many low-carbon technologies including nuclear and carbon capture and storage (CCS) have high capital costs and low operational costs, and therefore have a strong econom c incentive to run as close to full output as possible. This is in contrast to conventional thermal generation, where fuel costs are a large part of total costs.

7 There are three principal effects: net-demand varies over a greater range (i.e. increase in amplitude), the rate-of-change becomes greater (i.e. more MW per minute), and the predictability decreases. This latter point is less significant than is often presented, because on the most important operat on timescales (minutes to hours), wind and solar production can be forecasted relatively accurately.

8 Ramping – change of output power, upwards or downwards. 'Ramp rate' is often defined in MW/minute.

units synchronised and spinning-in-air, can achieve full output (over 1,700 MW) from zero in approximately 16 seconds [25].

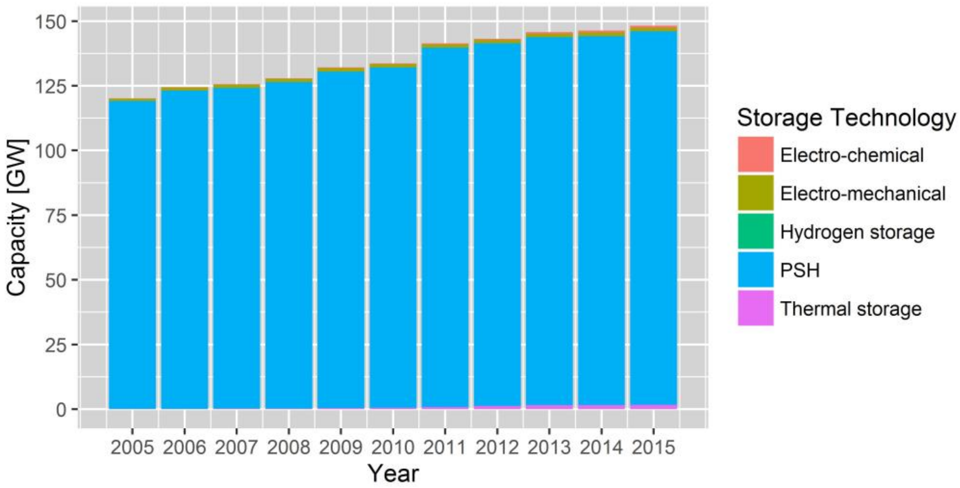

Figure 2: Installed global capacity for energy storage (data source [5]).

The position of pumped storage hydro in the UK is covered in Section 5.2. For the UK, system flexibility will be crucial [10]. According to National Grid's Future Energy Scenarios 2015 [24], installed wind and solar capacity could increase by a factor between two and four over the course of the next 15 years, and conventional thermal generation capacity could shrink by between 11% and 23%. This and other factors mean that larger volumes of system flexibility, especially energy storage, will be required [9]. Non-hydro distributed energy storage systems can contribute to balancing net-demand and keeping the system stable. However, their relatively small energy storage capacity together with the dynamic operating regime under which they are expected to operate will limit their capability.[9] Bulk fast-response and reliable large-scale energy storage capacity will therefore be needed in the UK. Pumped storage hydro fits this requirement.

[9] Assuming that non-hydro energy storage will be mostly used for prov ding dynamic and non-dynamic frequency response serv ces.

5. The Technology

5.1 Technology Maturity & Key Features

Pumped storage hydro 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, typically 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. The energy losses however are compensated by the charging-discharging price differential, and also by providing ancillary services.

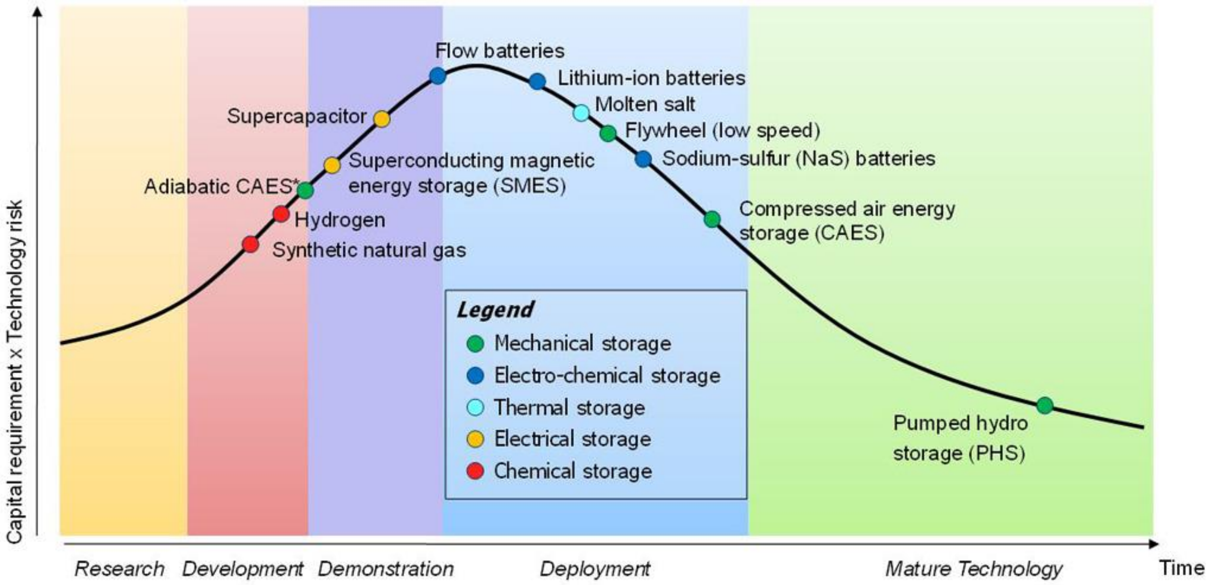

Figure 3: Energy Storage Technologies Maturity Curve [27].

Pumped storage is the most developed 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. The main challenge is the physical requirements of the site, needing both suitable topography and water availability. There can also be social and ecological issues, though for the UK these are well understood.

From an economic perspective, PSH requires long construction times and high capital expenditures, which like most infrastructure-type investments do not match well with market-driven mechanisms for cost recovery.

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].

Further details of the technology and recent technical developments are given in Appendix A.

5.2 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 2,828MW of generation capacity and can store approximately 24GWh of energy, as shown in **Table 5-1**. These existing PSH plants were commissioned between 1963 and 1984, and since 1984 there have been no new developments. There are three new potential projects in the planning stage[10] and four that have been proposed or discussed [5] [22] [23] [33] [34].

Two important points should be noted about the potential new capacity, particularly in Scotland:

- The increase in generation capacity (MW) could be substantial, but perhaps as importantly there is also an increase in stored energy (GWh), increasing the current UK figure by a factor of roughly three.
- Political and public opinion of PSH is generally favourable, and experience suggests that if stakeholder engagement is strong the planning and consenting processes can be relatively straightforward.

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	7.2
	Ffestiniog	360	1.3
	Foyers	300	6.3
Planning consent achieved	Coire Glas	300-600	30-40
	Sloy *(conversion from conventional hydro)*	60	5-10
Planning consent applied for	Glenmuckloch	400	To be determined
Proposed	Glyn Rhonwy	100	1.2
	Balmacaan	300-600	30-40
	Cruachan *(upgrade)*	+400-600	To be determined
	Muaitheabhal	Up to 150	To be determined

[10] Coire Glas and Sloy have achieved development consent but are not currently being progressed.

6. Benefits

6.1 Introduction

This section reviews the benefits that PSH can provide to the energy system, in the UK context. The benefits are considered in detail in Appendix B, but in general they result in:

- Lower system costs, which in turn result in lower costs to electricity consumers;
- Reduced carbon emissions;
- Better fuel security, especially in terms of energy independence;
- A more resilient electricity system.

The lower costs may come from reduced operational costs, reduced need to build other generation capacity, avoided reinforcement of the transmission system, and more efficient operation.

It is important to note that many of these benefits are 'external', i.e. which the storage provider is not rewarded for providing unless specific mechanisms are created to do so. Sections 6.2.3 and 6.2.4 address this.

6.2 Description of Benefits

6.2.1 System Operation and Planning Benefits

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]. **Figure 4** shows how the frequency of the system evolves after an incident successfully managed by the system operator.

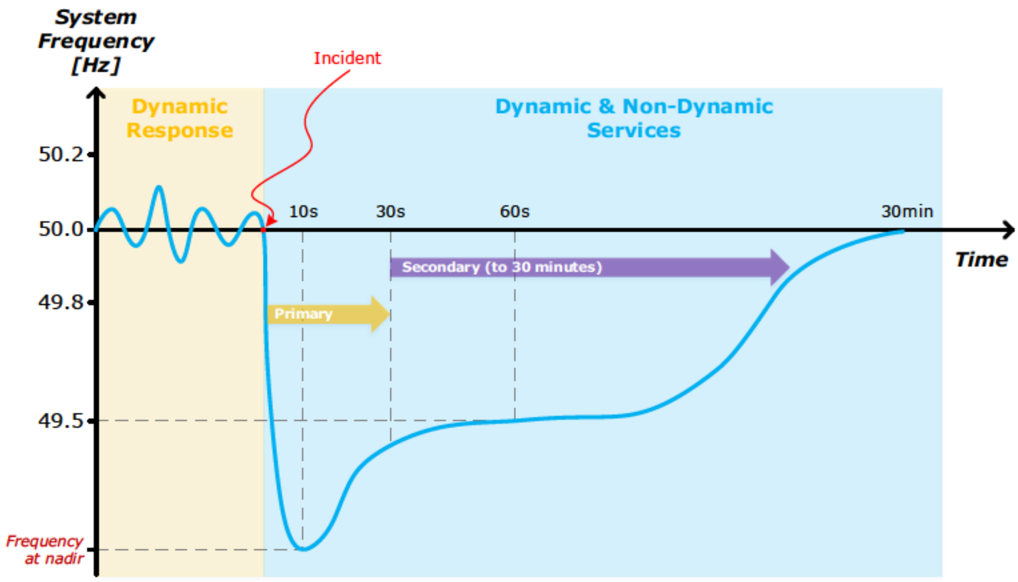

Figure 4: Evolution of system frequency after a contingency (adapted from National Grid).

The versatility and flexibility of PSH enable this technology to provide a wide range of dynamic and non-dynamic services (see Appendix B). 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.

6.2.1.1 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[11] is given by the large mass of synchronous rotating generators connected to the grid[12], which automatically accelerate or decelerate in response to imbalances. Larger shares of intermittent generation, combined with the retirement of large synchronous generators, will reduce system inertia, making the power system less robust to contingencies. Traditional 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.

By providing this function, PSH avoids the need for conventional thermal generation to provide it, often by operating at very low load, with low efficiency and relatively high emissions.

6.2.1.2 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 provide it when generating.

6.2.1.3 Operating Reserves

PSH can provide all types of operating reserves[13]. Variable-speed PSH has the additional advantage of being able to provide reserve services during both 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

A 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 less than 10 minutes) deployed to compensate for system contingencies, such as generating units and transmission lines outages. Synchronised units that operate at lower than full capacity provide spinning reserve, while off-line quick-start units can provide non-spinning reserve.

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[11] The power system inertia is the mechanical kinetic energy stored by rotating equipment, almost entirely conventional generation. The inertial response is a function of these large synchronous rotating masses, which speed up (if supply exceeds demand) or slow down (if demand exceeds supply). The change in speed is used to adjust the energy input to the generators (in most cases, steam) in order to quickly rebalance electric ty supply and demand, and return the system frequency to around 50 Hz.

[12] Other interconnected electr city systems also contribute inertia, if the interconnection is AC. However interconnect ons between the Great Br tain electric ty system to Ireland, France and Belgium use high-voltage DC, and HVDC will also be used in further proposed interconnectors. HVDC interconnector technology does not inherently allow the inertia of one system to contribute to the inertial response of another system; however in principle this is technically feasible, and may be implementable in future.

[13] Terminology varies between jurisdictions, but the terms used in this subsect on are appropriate for the UK.

D. Replacement/Supplemental Reserve

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

E. Load Following

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

6.2.1.4 Load Levelling/Energy Arbitrage

PSH can provide load-levelling or load shifting services, i.e. consume energy during low-price periods and generate at high-price periods. This reduces overall system production costs by avoiding use of expensive peaking generation during peak-demand periods, and by increasing use of cheap baseload generation during low demand periods.

6.2.1.5 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. This contributes to estimates of system security, avoiding the need to secure additional capacity from other sources.

An advantage of PSH plants is that they operate in pumping mode for some of the time. When pumping, PSH technology can double the dispatchable capacity it can provide to the system by being switched from pumping to generating mode.

6.2.1.6 Reduced Cycling and Ramping of Thermal Units

The flexibility characteristics of PSH plants reduce the demands on thermal generation created by the variability of wind and solar generation resources[14]. 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, which contributes to diminishing the wear and tear of these assets, and also achieving significant savings in the system operating costs.

6.2.1.7 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 generators 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.

6.2.1.8 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.

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[14] Both wind and solar generat on are technically capable of being controlled to limit the rate-of-change of output power ('ramp rate'), both upwards and (with forecasting) downwards. However this results in reduced renewables production, with significant economic penalty.

The proposed location of PSH plants in Scotland will help with transmission congestion resulting from high volumes of onshore and offshore renewables in Scotland. This will allow the renewable assets to reach their full potential by reducing curtailment, bring benefits to the overall low-carbon economy, reduce costs to the consumer and require less transmission capacity.

6.2.1.9 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.

6.2.1.10 Voltage Support

Voltage control is a relatively local issue that is controlled by controlling the supply of reactive power. Reactive power 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.

6.2.1.11 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, 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.

6.2.1.12 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 units can also help provide PSH station black-start capability if coupled with advanced, ternary or conventional units to provide their start up external source of electricity to power their converters.

6.2.1.13 Generation Investment

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 reducing investment and putting at risk security of supply.

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

6.2.2 Societal Benefits

6.2.2.1 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 translates into:

- less dependence on local and imported fossil fuels, not only for electricity production, but also of heating and transport fuels, by electrification;
- reduced need to import electricity through interconnectors from other electricity markets.

Therefore, PSH contributes to improving energy security goals.

6.2.2.2 Reduced Environmental Emissions

In the UK context, PSH plants will allow reductions in greenhouse emissions in the following ways:

- PSH can generate during peak hours in place of conventional thermal peaking plants, which have relatively low efficiency and high emissions;
- PSH reduces the variability of net-demand, thereby allowing thermal generation to operate in a steadier regime, at higher efficiency;
- PSH will allow increased output of variable renewable or other low-carbon generation without curtailment, thereby displacing more fossil-fired generation;
- PSH will ease the effects of large-scale electrification of heat and transport, thereby providing a route to decarbonise those sectors.

6.2.2.3 Integration of Intermittent Energy Resources

PSH supports the integration of renewables in many ways. This will reduce the total system costs of integrating renewable generation, and should facilitate the cost-effective achievement of low carbon goals.

6.2.3 Benefits to End Customers

The benefits of PSH plants for the operation of power systems create multiple measurable and unmeasurable benefits for electricity consumers, the end customers. The number of unmeasurable benefits is larger than those the end customer can perceive, which 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 compensate the providers of those benefits.

The benefits that can be perceived by end customers are:

- Security of supply and resilience of the power system
- Lower electricity bills.

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

- Improved quality of supply[15].
- The many technical benefits to the electricity system listed above (which should result in lower electricity bills).
- Reduction of greenhouse gas emissions.
- Stabilisation of energy prices.
- New job creation due to manufacturing, construction, installation, commissioning, and operation of new PSH facilities.
- Benefits to the national economy by replacing imported fuels and electricity with indigenous sources.

[15] For example: improved voltage quality, fewer interruptions, more stable frequency.

6.2.4 Benefits to PSH owners and investors

The principle benefits to owners and investors under current market arrangements in GB are:

- Payment for some of the benefits to system operation, by ancillary services contracts for frequency response and reserve;
- Energy arbitrage;
- Capacity, through the capacity market, though it should be noted that no new-build PSH asset has yet achieved a contract in the capacity market.

However, only a small portion of the realisable revenues associated with PSH listed in this section are bankable over the timescales associated with development, construction and economic lifetime of PSH, and will therefore be heavily discounted in investment decisions.

7. Issue Areas

Large-scale energy storage will be needed for achieving a flexible electricity system for the UK, in particular 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, and the capability of mature bulk energy storage, the economics and timing required to build these facilities are not being adequately addressed within modern electricity markets, including the UK.

This section reviews issues that can impede energy storage, in particular PSH, from achieving the benefits discussed in Section 6, and reviews international experience with implementation of PSH.

7.1 Engineering Issues

Engineering issues are generally not seen as major risks for PSH projects in the UK.

7.1.1 Technology

PSH is a mature technology. The latest technological developments include variable-speed and ternary PSH plants that have improved the flexibility and efficiency, and reliability of PSH plants.

However, the site-dependent characteristics of PSH plants result in a customised design, site-specific civil works, and perhaps project-specific major items of plant.

The influence of the site characteristics makes the final configuration of the number of units, size and type for the project a complex process of optimisation, which is made more complex if, as in the UK, the markets for the potential income streams available over the lifetime of the project are themselves subject to substantial uncertainty.

7.1.2 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. In the UK, this requires environmental impact studies, and applications for consents [45].

7.1.3 Construction Time

PSH plants normally require considerable civil works, which in turn have long construction times. However, as this is a mature technology, and the UK has a substantial and experienced civil construction industry, the risks of extended construction times are not great.

7.2 Economic Issues

Published academic and non-academic literature arrive at the same conclusions, one of them being that energy storage will play a crucial role in providing flexibility, particularly for integrating large shares of renewable generation [50] [51] [52] [53] [54]. However, they also conclude that current market structures and arrangements are 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 categorised in two: benefit-related and market-related issues.

7.2.1 Benefit-related Issues

The range of different roles played by PSH in the electricity system, and the associated benefits, means that storage providers will need to 'stack' multiple revenue streams, all of which are subject to considerable uncertainty, making it extremely difficult to develop a robust business case, particularly affected by long term energy policy uncertainty.

In addition, some of the benefits that PSH plants can offer in a future low-carbon UK system, as described in Section 6.2, are difficult to measure, and complex to internalise. 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.

Another portion of the benefits of PSH plants are in the form of positive externalities (for example environmental benefits and savings on network reinforcement costs) which are more complex to measure and monetise. Any assessment of these benefits has substantial uncertainties, and in the context of the UK electricity system will change over time.

A secondary effect of the uncertainty of future revenue streams is that the design of the PSH project becomes more complex. An example is the balance between prioritising power (MW) and storage capacity (GWh), but there are others. This is likely to lead to investors choosing to minimise risk rather than optimise overall economic performance, i.e. to get a design that is robust to a range of uncertainties, even if some of these uncertainties are extremely unlikely.

To summarise:

- Those benefits which can be quantified and are currently (or could in the near future be) recognised in revenue streams for PSH projects are highly uncertain, over the lifetime of any PSH project, particularly as there is a period of perhaps 5-7 years for financing and construction before any revenues start to flow.
- Some of the benefits that PSH can provide are not quantifiable easily, or at all: methods to quantify these or devise a proxy for them, to provide further revenue streams for PSH, may be seen by investors as vulnerable to future regulatory and political change.
- PSH projects have high capital expenditure, low operational expenditure, and little opportunity to influence expenditure in response to changes, once the project is committed: the typical characteristics of 'infrastructure'-type projects.
- Thus, revenue risk is the major risk for PSH project developers. This was borne out in the interviews with industry stakeholders.

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 5**, 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. The figure shows that the vast majority of PSH capacity came into operation under the responsibility of strong Government or quasi-Government institutions, while less than 5% have been under liberalised market conditions.

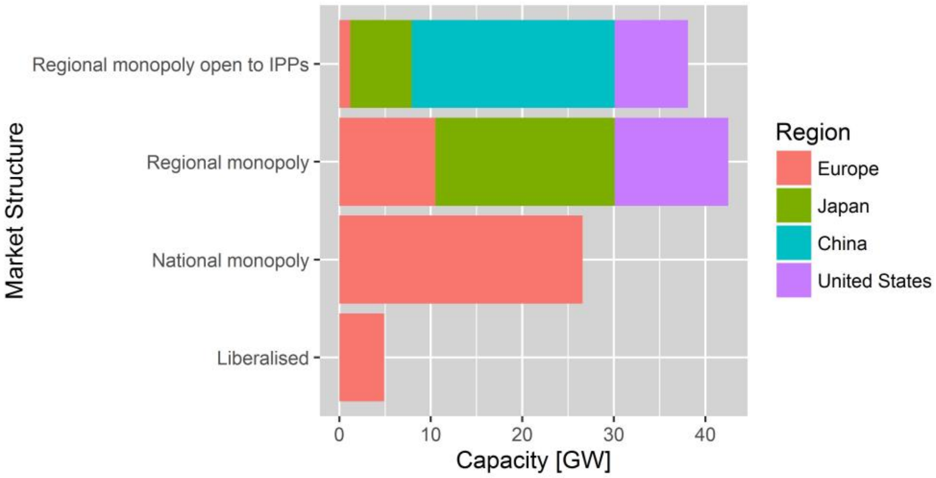

Figure 5: Total installed PSH capacity under different market structures (data source [5]; adapted from [46]).

This implies that liberalised markets do not currently create the right incentives for the wide deployment of PSH. One reason for this could be that PSH plants operating in a liberalised market are exposed to uncertainty around future electricity prices (which in turn may be heavily influenced by market regulation, and possibly political intervention[16]).

As it is in the case of investment in nuclear power plants, investment in capital intensive generation requires supporting arrangements to ensure recovery of fixed costs. The current Capacity Mechanism in the UK is a recognition of the problem of investing in large capital projects with long payback times, with considerable uncertainty of future revenue streams. However, the development & construction period, and operational lifetime of PSH, goes well beyond the timescales inherent in the current Capacity Market[17].

The objective of the Capacity Market is only to incentivise a set level of generation capacity and it does not, therefore, reward storage capacity for the other valuable services that it provides. Whilst the Capacity Mechanism can provide a valuable revenue stream, alone it is unlikely to provide enough certainty for large energy storage projects.

Licensing conditions and restrictions for PSH are another possible area for consideration. In unbundled markets, licensing conditions normally preclude or restrict the ownership of large-scale energy storage in non-competitive market areas, because of the concern that they might be used as both a regulated asset and simultaneously participate in the competitive market.

[16] For example, econom c theory could show by modelling of the UK electricity system that investment in a PSH would be justified, as (say) it would earn sufficient income from very high wholesale electric ty prices on a few occasions per year: but very high electr city pr ces, even if they occur rarely, may be seen as politically unacceptable. Therefore once these high pr ces occurred, there could be strong pol tical pressure to change wholesale, capacity and ancillary services markets to ensure this did not reoccur.

[17] The Capacity Market mechanism was designed around timescales generally experienced by CCGT projects.

7.2.2.2 Revenue Mechanisms

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 incentivise 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 liberalised electricity markets, it creates the concern of potential over-reward for bulk energy storage facilities that can also participate in the competitive part of the market, in the case of partially-liberalised electricity markets.

Market participants need to compete to provide competitive market services in the case of ***direct-participation*** in a partially or fully liberalised 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 on 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, reduce demand-based charges, and improve supply reliability, among others, which might justify investing in an energy storage facility. It is recognised[18] that investment cases in Behind the Meter assets could be driven by inadequate charging methodologies, which could lead to inefficient outcomes. A Behind the Meter 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.

7.2.2.3 Marginal costs

In economic terms, markets act to drive price towards the short-run marginal cost. Particularly for assets with high capital cost and low operating costs, the short-run marginal cost can be substantially lower than the revenue needed to pay for the capital costs, i.e. the long-run marginal cost. Some form of intervention, such as the UK capacity market, may be required to ensure that the optimum long-run solution (i.e. to build the asset) is achieved.

7.2.2.4 Other Economic Barriers

Additional economic barriers for the development of PSH schemes include:

[18] https://www.ofgem.gov.uk/system/files/docs/2016/07/open_letter_-_charging_arrangments_for_embedded_generation.pdf

- High grid access charges, particularly given the possible locations of PSH projects, remote from load centres.
- The de-risking of other technologies which compete directly with PSH in provision of flexibility. This is the case of the Cap and Floor (C&F) mechanism introduced by Ofgem in 2014 for interconnectors[19]. The C&F 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

This section reviews international experience with support mechanisms for PSH. The figures below indicate the growth of PSH in each area considered. **Figure 6** shows the growth of PSH capacity. Most developments occurred before 1990, except in fast growing economies in which electricity markets have not been fully liberalised, or where the regulator is playing an active role supporting the development of PSH. The dramatic reduction in growth in Europe and the US in the 1990s coincides with large-scale deregulation or unbundling of electricity markets in these regions.

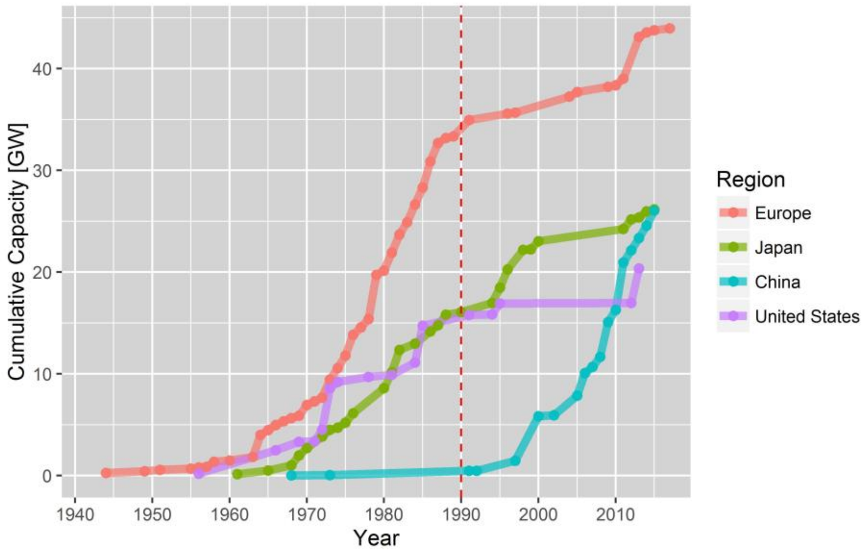

Figure 6: Cumulative PSH installed capacity (data source [5]).

Figure 7 shows similar information, but for individual PSH projects.

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[19] Ofgem, 2 Dec 2014: https://www.ofgem.gov.uk/sites/default/files/docs/2014/12/final_cap_and_floor_regime_design_for_nemo_master_-_for_publ cation_1.pdf

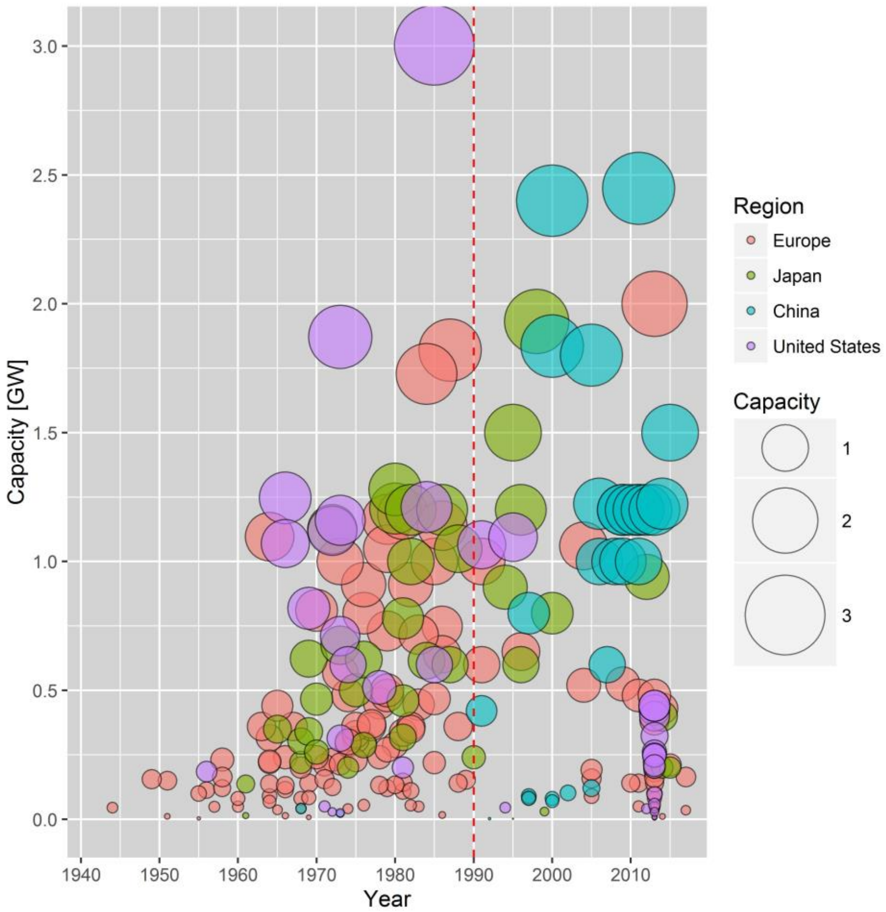

Figure 7: Historical PSH deployment (data source [5]).

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 liberalised 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 cost 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 payments 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 maximise 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 liberalised and partially-unbundled/partially-liberalised markets exist in the US [37]. In the unbundled liberalised 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[20], 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 Independent System Operator (ISO) then optimises the PSH scheduling within those windows, i.e. 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-optimised 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: *'.. 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 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

[20] The PJM system operator covers Pennsylvania, New Jersey and Maryland.

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 (particularly) solar generation [74], have resulted in the suspension or abandonment of several PSH schemes in Switzerland and Germany [75] [76]. While this is a result of very specific circumstances (very rapid growth in solar production which correlates well with periods of high demand, resulting in a surplus of peaking generation), which may be short lived as renewable penetration increases [75], it illustrates the severe long-term uncertainty in potential revenue for PSH projects discussed earlier in this section.

The harmonization of European electricity markets, in combination with improved levels of interconnection, can be expected to act to reduce wholesale price spreads in many European markets, which will reduce energy-only market revenues.

The first signs that seem to reveal that a generalised 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 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 liberalised 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 most attractive market arrangement for energy storage in the UK so far is given by the new Enhanced Frequency Response product created by National Grid to provide sources of flexibility. Although not aimed at any specific technology, energy storage may be particularly suitable, especially battery installations. An auction is taking place during Summer 2016 which targets 200MW capacity. Successful bidders will be awarded a four-year contract. Additionally, energy storage is allowed to participate in the Capacity Market, but new energy storage missed out in the 2015 auction [81]. Other opportunities exist to provide ancillary services, such as Short Term Operating Reserve and other forms of reserve and frequency response, but so far energy storage has not been successful in these markets.

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. Government and the regulator (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 expresses its concern about network ownership of storage, and calls on Government 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 Government to clarify the scope of this issue and identify approaches to addressing it, in discussion with the industry.
2. Undertake work with Government 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.

Considering other options for providing flexibility, as already noted a Cap and Floor mechanism for supporting interconnector projects was instigated in 2015. Interconnectors to other European electricity systems compete against energy storage, in particular PSH, in providing some aspects of flexibility. This C&F mechanism effectively socialises some of the risks and rewards of interconnector projects. The argument for this is that interconnector projects have the characteristics of 'infrastructure', i.e. long construction timescales, few or no alternative income streams, and financed over long periods. These characteristics also apply to some energy storage technologies, including PSH.

It is notable that there is no specific recognition in statements from Government and related bodies that revenue *risk* is a major issue for capital-intensive storage technologies, as important as the absolute level of potential revenues.

7.4 Summary

The important points from this section can be summarised as follows:

7.4.1 Risks

PSH technology is mature, though continuing to develop, and there are no major technical risks for any particular PSH project. The major risks for PSH project investors are the revenue risks.

The revenue risks arise from:

- The 'infrastructure' characteristics of PSH projects: long construction periods, long life over which to recoup costs, high capital costs, low operational costs, and (critically) the low opportunity to influence all costs once investment has been committed.
- The uncertainty in future revenue streams.

The uncertainty in future revenue streams is in turn driven by:

- The long timescales: 5-7 years before the start of operation, costs to be recouped over 25-50 years;
- Very few of the true benefits of PSH to the electricity system are currently realised as revenue streams at all;
- Those that do currently form revenue streams are subject to considerable uncertainty in future, due to competitors (for example, future growth in demand response competing on price arbitrage at peak demand periods);
- Some of the other true benefits of PSH may be realisable as revenue streams, but until this is done must be treated as highly uncertain by investors;
- All possible revenue streams (except perhaps arbitrage on wholesale markets) are vulnerable to future regulatory or even political intervention.

Therefore it is not clear that, even if mechanisms can be developed to allow all the true benefits of PSH to the UK electricity system to be realised as revenue streams, the resulting total would be considered by investors in PSH as sufficient, and sufficiently certain, to justify investment.

7.4.2 Short-run vs long-run marginal costs

As discussed in Section 7.2.2, markets act to drive price towards the short-run marginal cost. As PSH is characterised by high capital cost and low operating costs, the short-run marginal cost can be substantially lower than the revenue needed to pay for the capital costs, i.e. the long-run marginal cost. Revenues from the energy market alone may therefore be insufficient to develop this type of asset.

7.4.3 International experience with PSH

Little or no agreement exists internationally regarding the optimal policies to incentivise PSH investment, strategies to operate PSH, and the ownership structure for those assets. However it is clear that very little PSH investment has occurred recently in liberalised electricity markets.

This supports the conclusions above on revenue risk and marginal costs.

7.4.4 UK experience with similar issues

The Capacity Mechanism was introduced to resolve a similar problem with ensuring enough generation capacity (and demand-side response) was available to ensure system security. The Capacity Mechanism is, in effect, an insurance policy to protect consumers from very high and volatile prices, and ultimately 'the lights going out'.

However the Capacity Mechanism on its own is insufficient to support PSH as it does not provide certainty over the required timeframe. Further, energy storage should ideally be incentivised to provide the full range of storage services, not just to exist as storage capacity.

The OFTO (Offshore Transmission Owner) and CATO (Competitively Appointed Transmission Owner) regimes have been introduced to fund infrastructure-type assets, i.e. offshore and onshore transmission assets that can be clearly identified as separate parts of the transmission system. In these cases, the investors receive a regulated return on their investment; in the case of CATO, some of the risks (a few) are socialised across all electricity consumers. Again, this may not be appropriate for energy storage, as the CATO regime incentivises only reliable provision of transmission capacity.

Interconnectors to other electricity systems are also infrastructure-type investments, and are more closely related to PSH as they are providers of flexibility. The Cap and Floor regime instigated by Ofgem for new interconnector projects insulates the investors from the most extreme risks, effectively socialising both risks and potential rewards.

8. Key Facts & Recommendations

8.1 Key Facts

1. Pumped storage hydro (PSH) is a proven large-scale energy storage technology, able to provide large amounts of highly flexible capacity that can improve reliability and resilience of electricity systems, and also facilitate low-carbon future electricity systems. In comparison with the battery technologies which are gaining much attention, PSH provides very much larger unit sizes. PSH is more suited for storing energy for periods of tens of hours.

2. The UK, and in particular Scotland, has suitable locations for large PSH assets. From technical and economic perspectives, PSH is likely to be among the best and most cost-effective ways of providing large amounts of reliable flexibility in the UK. The GB electricity system will require new sources of flexibility in order to cope with factors such as large-scale deployments of variable renewable generation, inflexible low-carbon generation (CCS and nuclear), and changes in electricity consumption (such as electric vehicles, and heat pumps).

3. In the absence of such sources of flexibility, the likely alternatives are:
   a. flexible gas-fired and diesel generation, which will increase greenhouse gas emissions, and may increase electricity bills for end consumers;
   b. curtailment of variable renewables (wind and solar), which will limit their contribution to reducing greenhouse gas emissions, and affect the investment economics of renewables.

4. 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, some of the benefits that PSH can offer to the UK electricity system are difficult or impossible to measure, and complex to internalise.

5. PSH is an 'infrastructure'-type investment: the long lead times combined with the high capital investment required by this type of asset require extended periods of time for recovering costs. In particular, intervention is needed to mitigate the risks associated with the recovery of the long-run marginal costs. Further, the long project life exposes PSH investment to very large regulatory, market and policy uncertainty, which increases the risk of investment in this type of technology.

6. The vast majority of PSH schemes in the world have been constructed under some sort of Government-supported regime which has ensured long-term revenues and capital recovery. Liberalised markets do not appear to provide the required level of certainty of revenues for incentivizing investment in PSH.

7. Revenues from energy arbitrage, ancillary services provision and the capacity market are likely to be insufficiently predictable, especially in the long term, to support investment in new PSH schemes in the UK. Other benefits that could conceivably be monetised in some way are similarly unlikely to be sufficiently predictable. Therefore, even if mechanisms can be developed to allow all the true benefits of PSH to be realised as revenue streams, it is not clear that the resulting total would be considered by investors in PSH as sufficiently certain to justify investment.

8. Targeted support schemes for other types of flexibility resources, such as for example the Cap and Floor mechanism for interconnectors in the UK, currently discriminate against those technologies which do not have such support, such as PSH. However, such mechanisms may be appropriate in the UK for delivering the certainty required by PSH investors, whilst protecting consumers.

8.2 Recommendations

New storage assets will be valuable to enable the development of a more efficient and more secure low carbon energy system at a lower cost to customers. However, there are fundamental economic barriers in the existing market structures. If these barriers are not addressed, then there will be an under-delivery of storage. This is particularly the case for PSH. This under-delivery would cause a failure to achieve these societal benefits and result in a less efficient, less secure and higher cost electricity system. If a solution is to be found, then it is essential for Government and Regulators to take action to correct the market failures.

Internalisation of economic externalities and missing markets

It will be essential to develop market mechanisms which can internalise the value to society of economic externalities that are not fully reflected at the moment. Competitive markets can only deliver economically efficient results if the value to customers is appropriately reflected in the market prices which customers pay for the service.

However, even if fair monetisation of all feasible revenue streams for energy storage projects is realised, it is not clear that this will provide sufficient revenue certainty for PSH projects, as the future values of these may be highly influenced by long term energy policy decisions, such as levels of renewable electricity and national carbon targets.

Correct distortions within network charging arrangements

Within the current market, there are a number of issues that have called into question the appropriateness of existing charging arrangements. As it stands, National Grid[21] has set out its intention to conduct a wider review of commercial arrangements related to transmission charging, and Government[22] has set out that Ofgem intends to review the potential for 'embedded benefits' to have unintended consequences and offer certain technologies (particularly embedded diesel generation) a competitive advantage[23].

These issues have a significant impact on the viability of all storage projects and it is essential that they are considered together in order to ensure network charging arrangements create a level playing field and allow the most efficient technologies to compete. A careful, holistic and systematic review of the recovery of the costs of transmission and distribution systems and energy policies (capacity and low carbon support mechanisms) is required to allow PSH fair consideration.

Reduction of commercial risk associated with future policy decisions

Commercial operators are well placed to manage commercial risks; however they are unable to manage, predict, or hedge risks associated with future policy decisions. If storage developers are to be expected to place large amounts of capital at risk to deliver long-term investment in storage assets, then it will be essential for Government and Regulators to provide a degree of commercial guarantee behind future policy direction. This would substantially reduce a developer's project risk and therefore reduce cost of capital, reduce the cost of new projects and ultimately reduce the cost to customers of the energy system. This approach is already widely used in the UK energy market through examples such as the Cap and Floor

[21] Nat onal Grid: http://www2.nationalgrid.com/UK/Industry-information/System-charges/Electr city-transmission/Transmission-network-use-of-system-charges/

[22] DECC: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/504217/March_2016_Consultation_Document.pdf

[23] See correspondence from Ofgem on this topic: https://www.ofgem.gov.uk/system/files/docs/2016/07/open_letter_-_charging_arrangments_for_embedded_generation.pdf

mechanism for interconnectors, Contracts for Difference for low-carbon plant and the Capacity Mechanism for dispatchable plant. This conclusion is supported by the Energy and Climate Change Committee, who recommended that Government commissions a study on the future of large-scale storage in the UK, to include consideration of the support such projects would need to be viable. DNV GL strongly supports that recommendation.

Introduce market mechanisms to recognise the long-term nature of the benefits of storage

The wholesale and capacity markets for power, balancing and ancillary services are competitive and well suited for competition between assets with lower capital costs and shorter development and construction times. However, this market structure fails to deliver an efficient bankable result when the cost of providing those services involves relatively high capital cost assets, such as PSH. This issue is already successfully dealt with through existing competitive market mechanisms within the energy market discussed above, including the Cap and Floor mechanism for interconnectors. It will be essential for Government and Regulators to develop market structures which do appropriately reflect the long-run marginal cost of providing storage to provide the appropriate price signal to investors.

Careful analysis will be necessary to ensure that such a mechanism does not unfairly compete against other forms of flexibility or other energy storage technologies: it may be necessary to define the scope to cover only those technologies with 'infrastructure'-type characteristics. However, similar concerns have been satisfactorily addressed, for example in the Cap and Floor mechanism for interconnectors.

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APPENDIX A

Pumped storage hydro configurations and recent technical developments

A typical conventional PSH power plant consists of four components:

1. *Water reservoirs:* normally two[24] 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, and discharging water into the lower reservoir.[25]
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 conventional hydro-power reservoirs created by dams. 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[26] 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, injecting more valuable electricity into the grid (so-called 'energy arbitrage') and reducing the need for running expensive peaking generation plants.[27]

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 latest major technological developments in PSH technology include variable-speed and ternary PSH plants[28] [28]. Some of the advantages of these technological developments are [29] [30]:

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

[25] 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.

[26] Smallest in generating capacity (MW). Ffestiniog is smallest in energy storage capacity (MWh).

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

[28] 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 e ther in a generating mode or a pumping mode, and the shaft rotates in opposite directions in these two modes.

Variable-speed

- Higher overall efficiency.
- Improved flexibility.
- Frequency regulation can be provided independently of the operating mode and speed.
- There is no need for a pony motor[29] to start pumping or 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.

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.
- 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.

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

APPENDIX B

Benefits of Flexibility and Pumped Storage Hydro

This Appendix provides background on the fundamentals of electricity systems. Some details will not be necessary for most readers, but it provides a context in which specific benefits of PSH can be discussed in the main report sections.

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. The system operator needs to control hundreds of generation and demand-side energy resources in timescales ranging from milliseconds to days as shown in **Figure B1**. The figure also shows the timescales over which the variability of wind and solar is important (green), and the timescales over which PSH can contribute (in blue).

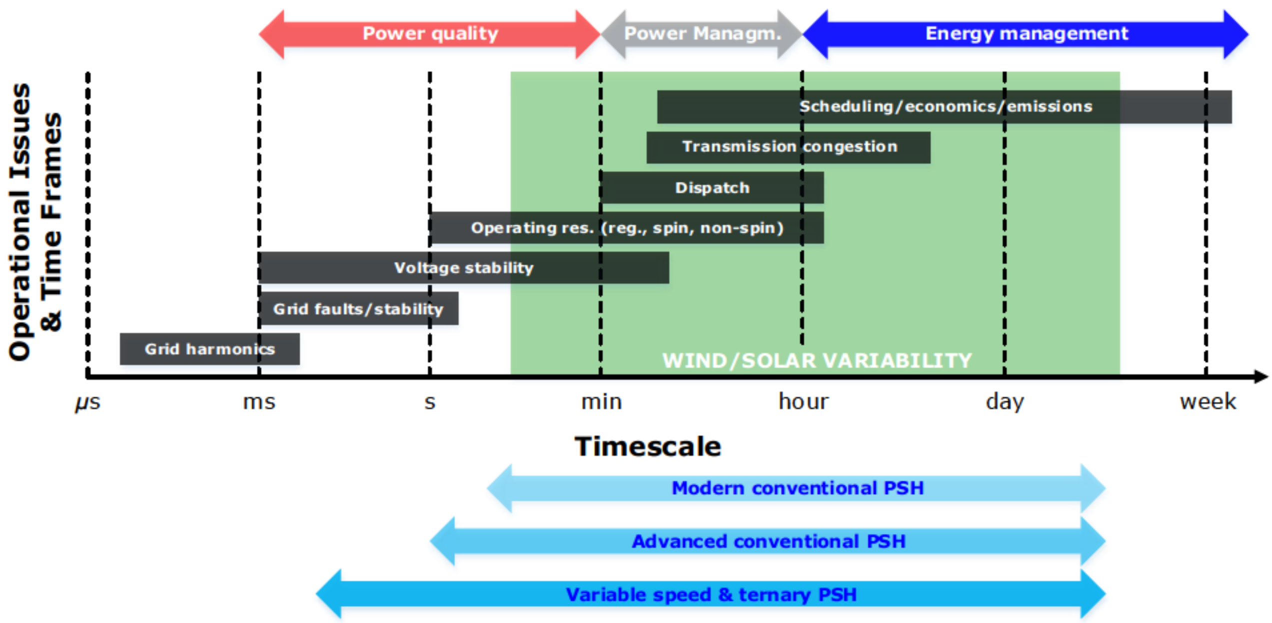

Figure B1: Timescales of Power System Operational Issues and PSH Operational Ranges (adapted from [26] and [35]).

In the very short term[30], stability issues are managed 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. At the longer timescales the system operator needs to schedule, in a cost-effective manner, sufficient resources to meet the variability and uncertainty of demand and generation, including unforeseen events, with the additional objective of minimizing emissions [36].

[30] Harmonics occur on very fast timescales and are primarily an issue on distribution networks. They are not relevant to this report.

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.

All sources of flexibility are useful to the system operator: flexible generation, controllable demand, interconnections to other systems, and most forms of energy storage. PSH is able to provide flexibility across all timescales noted above, and in particular is able to contribute on the longer timescales where wind and solar variability are important, and where fewer other energy storage technologies can contribute, due to its fast response and large-scale energy capacity [37] [38].

Increased renewable generation is not the only contributor to this need for additional flexibility in the UK context:

- Most other forms of low-carbon generation, including nuclear and CCS, are less flexible than the conventional forms of generation they displace.
- Electricity demand is changing, and in particular the possible widespread adoption of electric vehicles and heat pumps produces considerable uncertainty;
- Small-scale distributed generation is increasing, not all of it visible to system operators;
- Reinforcement of the electricity system, particularly at transmission level, can be subject to long delays and uncertainty in the consenting process.

Although renewables are only one of the reasons for increasing flexibility, it is useful to understand the impacts of increased renewable generation on the time dynamics of net-demand when their share in the power system is not negligible [41]. For clarity, 'net-demand' is the electricity production which must be met by the other generation capacity, i.e. not wind or solar.

Figure B2 shows a simulation of the GB system in a challenging winter week in 2030, assuming high generation capacity of wind and solar. In the top-left graph, 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 utilised, and perfect forecasts of demand and renewable power generation. Demand shape follows a regular and smooth pattern driven by 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 a more variable pattern.

The Figure also shows the increased rate-of-change of net demand, the forecast uncertainty (4-hour ahead forecast), and the effect of this on the amount of reserve which the system operator must plan for.

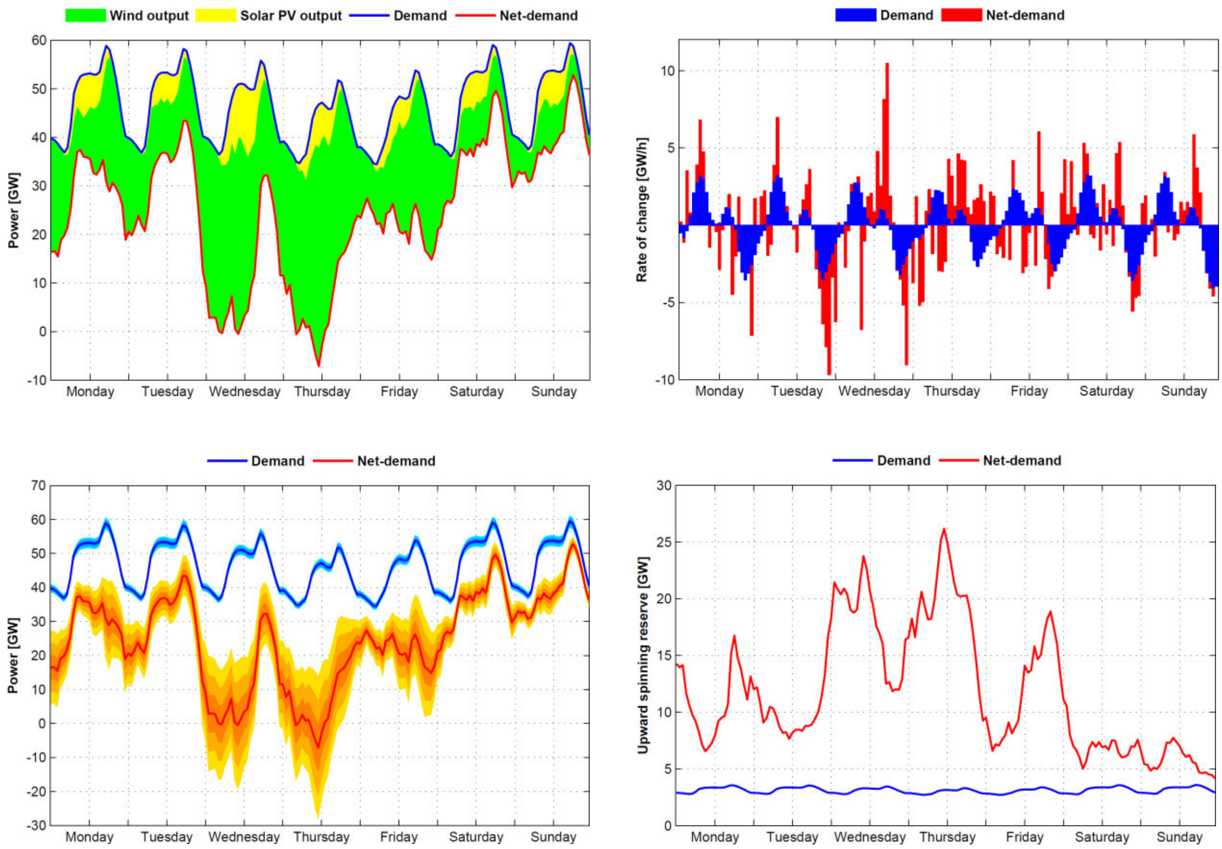

Figure B2: Simulation of demand and net-demand (top-left), rate of change (top-right), forecast uncertainty (bottom-left), and required level of upward spinning reserve (bottom-right), during a challenging week in 2030 assuming 50% intermittent generation share [40].

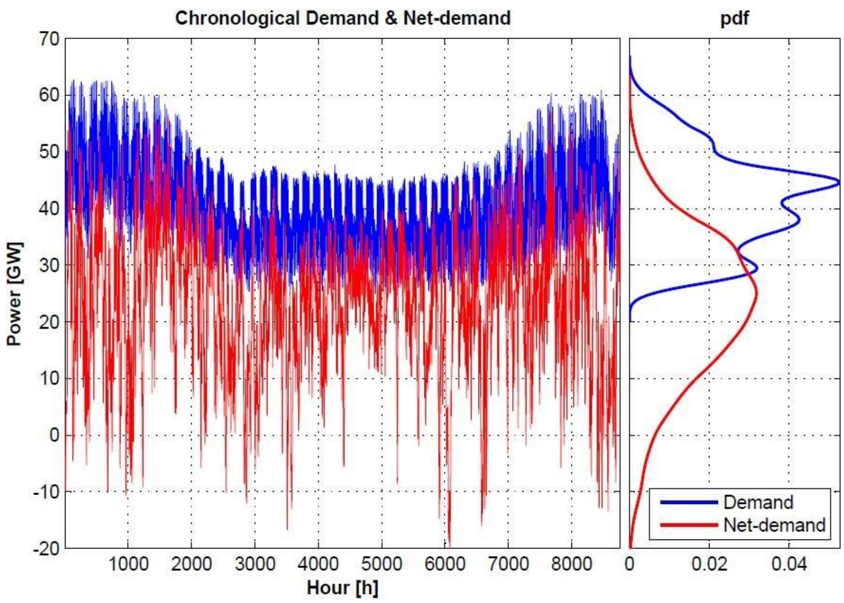

Figure B3: Simulation of the variability of demand and net-demand (left), and probability density functions of demand and net-demand (right), in 2030 assuming 50% intermittent generation share [40].

Figure B3 shows similar information but for a complete year (8760 hours). The right-hand side shows the frequency of occurrence of different levels of demand and net-demand.

Important points to note from both Figures relevant to the UK are:

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 curtailed (at a substantial economic cost). Even before that point is reached, the conventional generation may need to run at low output, where efficiency is low. Some thermal generation may be turned off, but then there is a minimum time before they can be restarted. Thermal generation may also have a minimum run time before it can be switched off again. These timescales can be tens of hours for coal plant, up to days and weeks for some nuclear plant. Start-up and shut-down manoeuvres of inflexible generators are not only complex and time consuming, but also costly, which might instead justify renewable energy curtailment [39].

2. The rate of change of net-demand is much larger than that of demand. In the absence of other sources of flexibility, this will require the other generation to increase and decrease production more frequently and at higher rates ('ramp rates'). This will increase the stresses and wear to which generators are exposed, reducing lifetime or increasing maintenance costs. Increased rate of change of net-demand will also raise the level of ancillary services required. This will require more generation capable of starting quickly and ramping fast.

3. The uncertainty of net-demand is much bigger than that of demand. This will increase the level of the reserve services required to handle unexpected deviations from the original forecasts.

In the absence of alternative sources of system flexibility, larger shares of gas fired flexible thermal generation will be required: combined-cycle gas turbines (CCGT) and some rapid-response open-cycle gas turbines (OCGT). 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 [42].

PSH is able to address all these issues:

1. The peaks and troughs of net-demand typically last a few hours or tens of hours - **Figure B2** supports this. PSH is able to smooth out these peaks and troughs, and therefore substantially reduce the stress on thermal generation, the numbers of starts and stops, and the amount of renewable electricity production lost. Thermal generation is also more likely to be able to run close to peak efficiency, saving cost and reducing emissions.
2. The very fast response of PSH allows it to reduce the high ramp rates which other generation would otherwise have to meet, thereby reducing costs.
3. The very fast response and large energy capacity of PSH allows it to provide reserve services, which may otherwise be provided by CCGT running close to minimum load. This minimum-load problem for CCGT means that more renewables need to be curtailed. In effect, PSH has no minimum load, and thereby significantly reduces renewables curtailment. CCGT at minimum load are also operating at low efficiency, thereby increasing emissions per unit of energy produced.