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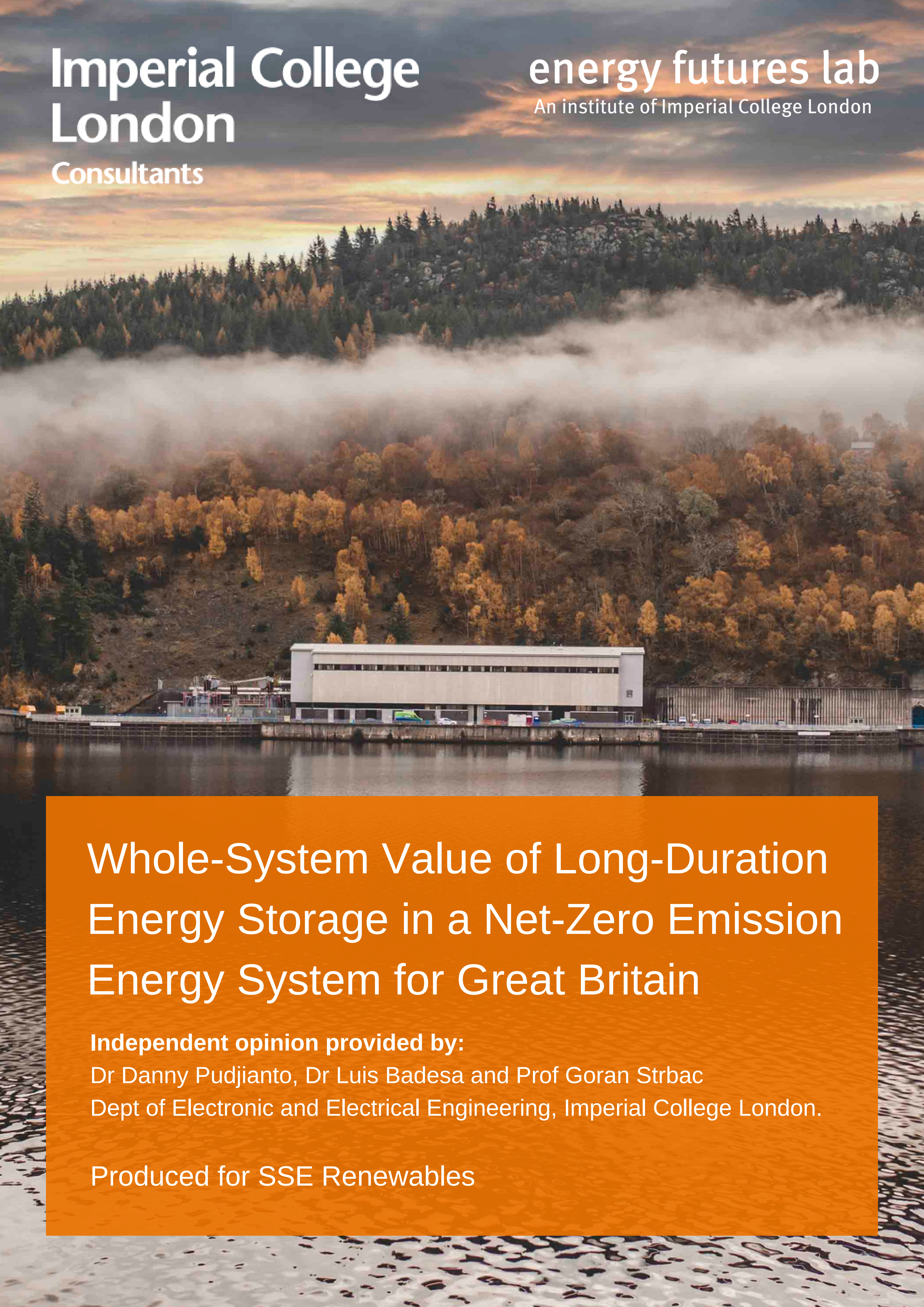

Whole-System Value of Long-Duration Energy Storage in a Net-Zero Emission Energy System for Great Britain

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Produced for SSE Renewables

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Contents

Abbreviations

CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
DER	Distributed Energy Resources
DR	Demand (Side) Response
GB	Great Britain
IWES	Integrated Whole Energy System model
LCOE	Levelized Cost of Electricity
LD-PHES	Long-Duration Pumped Hydro Energy Storage
OCGT	Open Cycle Gas Turbine
P2G	Power to gas (electrolysers)
PHES	Pumped Hydro Energy Storage
PV	Photovoltaics
RES	Renewable Energy Sources
LT-TES	Long-term Thermal Energy Storage

Executive Summary

Context and objective of the studies

This report describes the role and value of new long-duration energy storage in facilitating a cost-effective transition to a net-zero carbon Great Britain (GB) energy system. The report is specifically focused on quantifying the value of new long-duration pumped hydro energy storage (LD-PHES) in Scotland, as the current most established long-duration energy storage technology. The assessment approach used in the studies can be applied to other energy storage technologies (e.g. thermal and hydrogen storage), taking into consideration specific technology characteristics.

A range of studies has been carried out via Whole-Energy-System Model to quantify the system integration benefits and value of LD-PHES across the entire system. This modelling provides core evidence related to both system implications of the technology, focusing on the impact on the optimal portfolio of other technologies and infrastructure requirements, particularly the amount and value of the avoided investment in low carbon and conventional generation, investment in transmission network between Scotland and England, including the savings in system operation cost through providing balancing services.

Moreover, the key parameters that drive the system integration benefits of LD-PHES are identified and have been subject to furthermore specific modelling focusing on the impact on the value of LD-PHES of:

- The presence of other flexibility technologies including on the demand-side, e.g. EV batteries
- Energy storage capacity on the provision of frequency response
- Network constraint at the Scotland-England boundary
- Higher GB interconnection capacity with Europe
- Lower-cost offshore wind
- Different carbon targets
- Prolonged periods of extremely low-wind conditions
- Seasonal thermal storage

Finally, the report assesses the current market and policy framework's suitability for delivering appropriate investment signals for long-duration storage.

Key findings

Benefits of long duration pumped hydro energy storage

- New LD-PHES reduces the system costs by providing the following services to the GB energy transition to a net-zero emission energy system:

Total system cost savings

Using the Integrated Whole-Energy System (IWES) model developed by Imperial, the following system savings are:

- The range of new LD-PHES capacity analysed in the study is between 300 MW and 4500 MW power rating with 30 GWh and 90 GWh of energy storage volume.[1] The total gross electricity system cost savings from new LD-PHES are between £44m and £690m per year in 2050, with more savings made when the energy storage volume is higher, and system flexibility is lower.
- 75% of these system savings are from the avoided capital cost in low carbon electricity generation technologies that would otherwise be needed to meet decarbonisation and security of supply objectives. For example, assuming 100h of storage, new 1GW of LD-PHES capacity can help to "firm up" variable renewables to replace 750MW of firm low carbon generation (such as nuclear, hydrogen-based generation, CCS). This ability depends on the duration of energy storage and system conditions that drive the demand for long-duration storage (e.g. a prolonged low-wind period).

Wider benefits of LD-PHES

- New LD-PHES reduces the system costs by providing the following services to the GB energy transition to a net-zero emission energy system:
  - New LD-PHES reduces wind curtailment in the GB electricity system (between 3TWh and 11TWh a year), by storing excess renewable output and discharging it when needed.
  - LD-PHES, in particular, can provide critical ancillary services needed for integrating a high penetration of renewable generation, e.g. frequency response, significant contribution to system inertia and operating reserves.
  - LD-PHES can reduce system emissions by displacing some conventional (fossil-fuel based) mid-merit and peaking plant.
  - LD-PHES supports network congestion management. New LD-PHES in Scotland could reduce the need for up to 2GW of transmission between Scotland and England in 2050, saving up to £2bn in avoided capex.

LD-PHES complements other storage and flexibility technologies

- Comparing the cases of LD-PHES of 900MW power rating with 30 GWh and 90 GWh

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[1] The values are based on 77 GW of wind in GB under the 2050 system background used in the study.

of energy volume, the savings are still considerable, between £100m and £231m p.a. in 2050, even with high flexibility levels from DR, EVs and interconnection. As the modelling optimises the use of all flexibility technologies to minimise the total system costs, it will first allocate DR and EVs and then LD-PHES to provide short-term services as needed (which is system condition dependant). Hence LD-PHES provides both short and long-term system services.

- New LD-PHES could reduce the need for hydrogen storage by up to 10% (110GWh) in 2050 given the close interactions between the hydrogen and electricity systems (H2 for power generation).

Value drivers of LD-PHES

- If, as expected, the electricity sector needs to achieve zero carbon emissions by 2050 then system savings from new LD_PHES (2GW, 200GWh) would reach £411m per year in a highly flexible GB system (a high level of distributed demand-side response is available). In the case of lower availability of flexibility, the savings rise to £511m per year.
- As expected, the benefits of flexibility provided by LD-PHES are strongly affected by the carbon intensity target. The results demonstrate that the value in 2030 with 50g is much smaller than the value in 2050 with 0g carbon target. For example, with LD_PHES (2GW, 200GWh), no DR and 50g carbon target, the savings are £99m/year, while the savings increase to £511m/year when the carbon target reaches 0g.
- The savings from new LD_PHES increase with growth in wind generation penetration. For example, LD-PHES of 4.5 GW power rating with 90 GWh of energy volume, the system savings increase to £550m per year in a system with 120GW of wind, compared to the £316m savings with 77GW of wind.
- Insufficient network capacity between Scotland and England or limited boundary capacity – a lower transmission capacity increases the value of LD-PHES (4.5GW, 90GWh storage) from £316m to £350m per year
- Increase in the ratio between energy storage volume (MWh) and capacity (MW) increases storage value as it can provide the system services more often and over longer duration.
- Modelling results present both total system benefits and per-unit benefits of LD-PHES installed. As expected, increasing the amount of LD-PHES installed, increases the total system benefits, while the per-unit benefits reduce.
- The system's ability to cope with a prolonged period of low renewable output during peak demand whilst not substantially increasing emissions;

The Policy and Market Framework for LD-PHES

- The value of LD-PHES can be remunerated via current market frameworks as these are evolved to ensure carbon intensity aligns with net-zero objectives, e.g. arbitrage in wholesale markets, ancillary services, and new addition flexibility services. However, there is a large amount of uncertainty related to those revenue streams' size and volume, making the investment case challenging for high capex long-duration storage technologies like LD-PHES.

- Furthermore, the current market framework does not recognise the benefit of LD_PHES in reducing future capex costs of new high-cost firm low carbon generation, which are otherwise needed to meet decarbonisation and security of supply objectives.
- The development of such a market framework, or the alternatives, warrants further analysis. One of the options is to develop a real-time carbon price market that captures the investment and operating cost of the system to meet the carbon target. In this case, it can provide an appropriate economic signal and incentive for the LD_PHES to support the integration of renewables and reduce the required capacity of high-cost firm low-carbon technologies.
- Moreover, there is also a need to investigate further how the cross-sector technology benefits of LD_PHES, e.g. integration between hydrogen infrastructure and the electricity system, can be recognised to maximise potential cost savings to energy consumers.

Chapter 1. Introduction

1.1 Context

Previous analysis[2,3] carried out at Imperial College London demonstrated that meeting the zero-emission target cost-effectively would require a significant capacity of firm low carbon generation (such as nuclear, hydrogen-based generation, CCS). The need for nuclear is primarily driven by the variability of renewable production and the need to eliminate emissions associated with management of demand-supply balance. The analysis also demonstrated that the need for firm low-carbon generation is significantly less critical for the 2030 carbon targets. Hence, in the zero-carbon case, a significant amount of variable renewables are replaced by firm low-carbon generation capacity, although the cost of renewable generation is significantly lower. The analysis revealed the need for long-duration energy storage to achieve zero-carbon emissions with a lower capacity of higher-cost firm low-carbon generation.

However, there are still many open questions regarding the value of long-duration energy storage, and the synergy or competition with other flexibility technologies such as demand response, short-duration storage, and other forms of energy storage such as hydrogen and seasonal thermal storage. For example, the previous analysis results that focused on hydrogen storage showed that during periods of high RES output, the excess energy would be converted into hydrogen by electrolysers ("Power-to-Gas") and stored in hydrogen storage. While during periods of low output of RES, the stored energy would produce electricity via hydrogen-based power generation. The previous analysis also demonstrated the stronger coupling between different energy vectors that indicates more complex challenges in evaluating the role and value of specific flexibility technologies, such as long-duration pumped hydro energy storage (LD-PHES).

Optimising the interaction across energy storage technologies also needs to consider the technologies' specific technical characteristics, e.g. efficiency losses, ramping capability, ability to provide response and reserve services. For example, the efficiency of LD-PHES is

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[2] G.Strbac, D. Pudjianto, et al,"Analysis of Alternative UK Heat Decarbonisation Pathways", a report to the Committee on Climate Change, June 2018. Available at: https://www.theccc.org.uk/wp-content/uploads/2018/06/Imperial-College-2018-Analysis-of-Alternative-UK-Heat-Decarbonisation-Pathways.pdf

[3] G.Strbac, D.Pudjianto, F.Teng, D. Papadaskalopoulos, G.Davies, and A.Shakoor,"Roadmap for Flexibility Services to 2030," a report to the Committee on Climate Change, London, May 2017. Link: https://www.theccc.org.uk/wp-content/uploads/2017/06/Roadmap-for-flexibility-services-to-2030-Poyry-and-Imperial-College-London.pdf

c.75% while using hydrogen storage to store energy to be used for electricity later is currently much lower, i.e. around 40%-50%. Therefore, the efficiency losses are lower if LD-PHES is used instead of hydrogen storage. In the long term, hydrogen storage could provide significant energy storage capacity, and the cost is relatively lower; therefore, the optimal portfolio of energy storage should be assessed considering all the aspects above.

1.2 Key objectives

In this context, this report describes in detail the role and value of new long-duration energy storage in facilitating a cost-effective transition to a low carbon energy system. LD-PHES is currently the most mature, proven long-duration electricity storage technology. However, it can be used as a proxy for other long-duration energy storage technologies such as compressed air, liquid air, flow batteries, seasonal thermal storage, and stacked blocks technologies. In this work, we focus our studies on the new LD-PHES in Scotland, although we also investigate the interaction between different energy storage technologies.

We have carried out a range of studies and applied the whole-energy-system modelling approach to quantify the system integration benefits and value of LD-PHES across the entire system in 2050, as the first objective of the work. This work identifies both the system implications of the technology (how it will change the optimal portfolio of other technologies and infrastructure requirements, particularly the amount and value of the avoided investment in conventional and low carbon generation and transmission network between Scotland and England) and the value of benefits along the value chain, i.e. savings in operation cost through providing balancing services.

The second objective is to identify the key parameters that drive the system integration benefits of long-duration energy storage. We have carried out a spectrum of sensitivity studies looking at the impact of:

- The presence of other flexibility technologies such as demand response
- Energy storage capacity on the provision of frequency response
- Network constraint at the Scotland-England interconnector
- Higher GB interconnection to Europe
- Low-cost offshore wind
- Different carbon targets
- Prolong period of extremely low-wind conditions
- Seasonal thermal storage

on the value of LD-PHES.

Finally, the third objective is to assess the appropriateness of the present market and policy framework. The studies provide the revenue streams associated with the provision of different system services by long-duration energy storage. This work provides fundamental evidence regarding the weaknesses of the current market design and decarbonisation policy framework in delivering appropriate incomes that justify investment in long-duration energy storage technologies. A key consideration is to assess the efficiency of the current energy system planning processes while considering cost-effective energy system decarbonisation, contribution to the security of supply and ESO's Network Options Assessment process, and how this could quantify the optionality / least-regret benefits of an LD-PHES asset compared with network assets.

1.3 Energy demand scenario

The study is based on an optimised system constructed by the IWES model, which assumes that full coordination across all energy system components can be achieved. The study uses the future (2050) annual system energy demands of domestic and non-domestic sectors provided by the CCC[4]:

- Total annual non-heat and non-transport electricity demand: 367 TWh
- Total heat energy demand: 633 TWh; it is assumed that heat will be decarbonised through electrification.
- Total transport-related-electricity demand: 111 TWh

The composition of the energy demand used in the study is summarised in Figure 1-1.

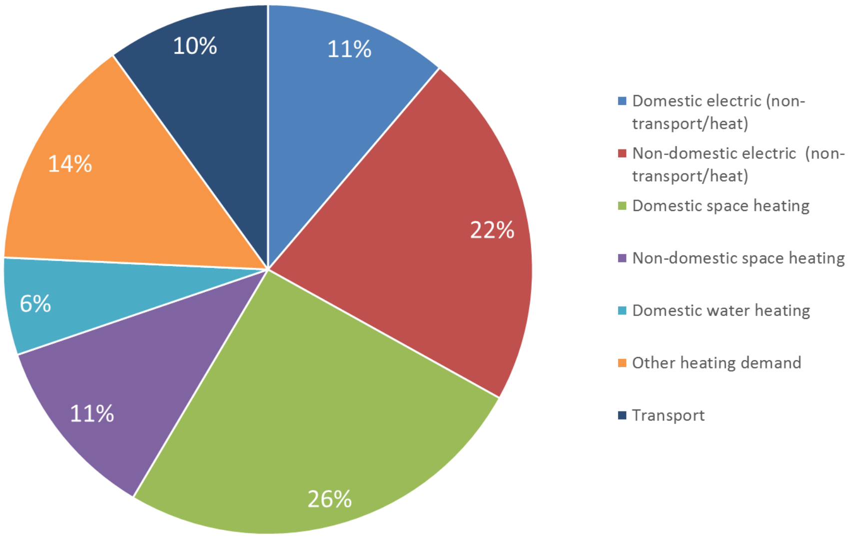

Figure 1-1 Composition of energy demand

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[4] G.Strbac, D. Pudjianto, et al,"Analysis of Alternative UK Heat Decarbonisation Pathways", a report to the Committee on Climate Change, June 2018. Available at: https://www.theccc.org.uk/wp-content/uploads/2018/06/Imperial-College-2018-Analysis-of-Alternative-UK-Heat-Decarbonisation-Pathways.pdf

1.4 Whole-energy system modelling framework

To study the role and value of longer duration PHES considering the interaction between different energy vectors, we will simulate and optimise a set of pathways using the Integrated Whole-Energy System (IWES) model developed by Imperial.

The IWES model incorporates detailed modelling of the energy system, heating technologies, including district heating, heat network, heat pumps (air/ground source, hybrid) and a module that optimises the hydrogen infrastructure. Overall, the IWES model includes electricity, gas, hydrogen and heat systems and captures the complex interactions across those energy vectors, as shown in Figure 1-2.

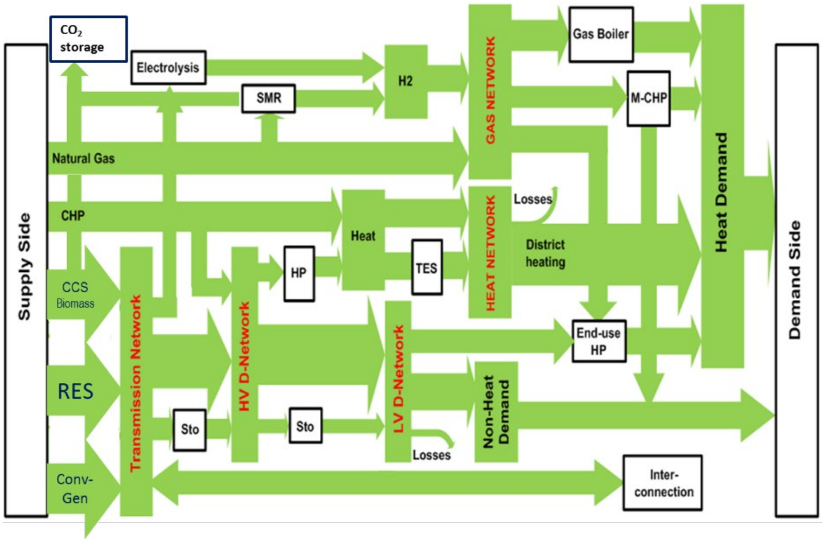

Figure 1-2 Interaction between gas, heat, and electricity systems

In summary, the IWES model minimises the total cost of long-term infrastructure investment and short-term operating cost while considering the flexibility provided by different technologies and advanced demand control while meeting carbon targets. The IWES model includes electricity, gas, hydrogen and heat systems, simultaneously considering both short-term operation and long-term investment decisions covering both local district and national/international level energy infrastructure, including carbon emissions and security constraints.

For the purposes of this study, the IWES model has been set up to:

- Take into consideration system variability and optimise the operation of the energy system on an hourly basis;
- Reflect the technical needs of balancing the supply and demand of energy across different time horizons (seconds to years), including maintaining grid frequency and providing system inertia; while reflecting the dynamic parameters and technical limitations of the selected portfolio of energy sources;

- Have a robust representation of demand and outputs of intermittent technologies on an hourly/half-hourly basis, considering spatial differences, correlation of renewable output and demand; whilst allowing opportunities for demand-side response to be analysed;
- Model electricity systems in GB and Europe to reflect the correlation of both electricity demand and supply with interconnected markets (e.g. benefit from diversity in renewable generation patterns through optimising interconnectors flows);
- Identify operating reserve requirements at different timescales;
- Include all components of system cost, i.e. capital, generation, carbon, operation and maintenance, transmission and distribution, energy storage (thermal, electricity, hydrogen), and transport of gas/hydrogen/carbon to storage;
- Reflect the impact on bulk transmission and distribution infrastructure requirements and costs for different network characteristics (e.g. urban and rural) and
- Incorporate distributed generation (e.g. solar PV, battery storage) connected directly to the distribution network.

The main outputs of the model include:

- Optimised energy infrastructure including the capacity and technology choices for power generation, hydrogen and heat sources
- The capacity of transmission and distribution infrastructure for electricity and gas/hydrogen, including the consideration of grid constraints and required reinforcements
- Energy storage, including electricity, thermal and hydrogen storage
- Emissions and generation/production by technology, including electricity and hydrogen production
- Capital and maintenance expenditure of gas and electricity infrastructures
- Operating costs including fuel costs, and balancing costs for the energy system and the cost of transporting hydrogen/carbon

The model results are used to analyse the technical and cost implications of LD-PHES when considering an optimised development and operation of the future UK's low carbon energy system.

Chapter 2. Whole-system benefits of long-duration energy storage in supporting the cost-effective transition to a zero-carbon energy system

This chapter quantifies and analyses the energy system implications, and the cost savings attributed to new long-duration pumped hydro energy storage (LD-PHES) in Scotland with different configurations. The study was carried out using the test system background described in section 1.3, and the IWES modelling tool explained in section 1.4.

Key highlights

- The total system cost savings from new LD-PHES (range: 30 GWh – 90 GWh, 300 MW - 4500 MW) are between £44m and £316m per year with more savings the higher the storage volume is (assuming high flexibility levels from DR, EVs and interconnection).
- Avoided capital cost in electricity generation technologies makes up 75% of the value of new LD-PHES. Most of the savings come from the reduction of low-carbon generation. There other substantial savings are in terms of avoided generation operating costs and network reinforcement costs.
- New LD-PHES integrates more wind on to the system (between 3TWh and 11TWh a year), whilst substantially reducing the need for nuclear and other firm low carbon generation technologies.
- New LD-PHES in Scotland could reduce the need for up to 2GW of transmission between Scotland and England in 2050.
- New LD-PHES could reduce the need for hydrogen storage by up to 10% (110GWh) in 2050 given the close interactions between the hydrogen and electricity systems. However, they would continue to play complementary roles.

2.1 Value of long-term duration storage

Scenarios

The study uses two aggregated effective energy storage capacities, i.e. 30 GWh and 90 GWh with different power ratings such that it creates three energy storage configurations with 20h, 33.3h, and 100h duration. It would be attributable to the total fleet of new LD-PHES, rather than a single new station. These durations indicate how long the new LD-PHES fleet can produce electricity at the maximum output. Therefore, six LD PHES configurations are being studied:

- 30 GWh storage with 300 MW, 900 MW, and 1500 MW power rating
- 90 GWh storage with 900 MW, 2700 MW, and 4500 MW power rating

The system's annual costs with the new LD -PHES following the above configurations are compared with the annual costs of the counterfactual system, i.e. the system without the new LD-PHES. The changes in the annual system costs are analysed, and the results are presented in Figure 1-2.

Total cost savings

The total annual cost of the system with 30 GWh of new PHES is lower by 44 million to 121 million pounds per year in 2050 (depending on its power rating) than the counterfactual system's total cost. The saving with 90 GWh of new PHES is larger (between 200 million to 316 million pounds per year). It is important to note that the cost of new PHES is not included and therefore, the savings should be treated as gross savings that can be used to inform the investment case for new LD-PHES. Nevertheless, even with the cost of new PHES included, there are significant savings.

The results below demonstrate that the new LD-PHES can reduce the capex investment costs required in power generation (both low-carbon and non-low-carbon generation), the capital cost of the electricity network, and decrease electricity operating costs. The presence of new PHES also affects the capacity requirement of hydrogen infrastructure. The interaction between the PHES and hydrogen storage has also been analysed and discussed later in section 3.6.

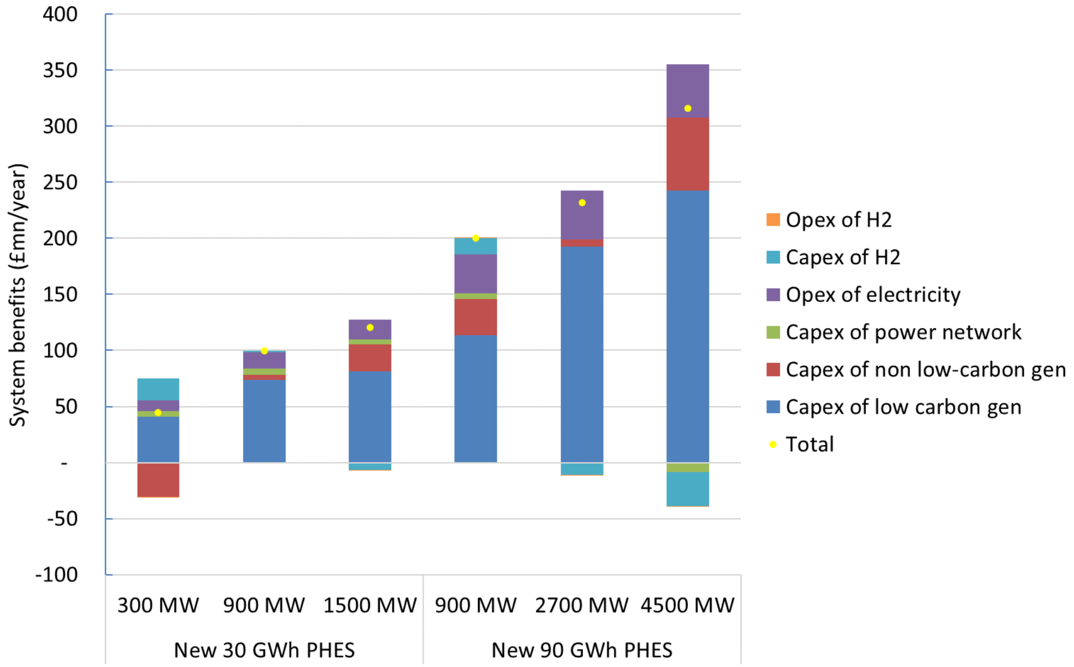

Figure 2-1 Changes in the annual energy system costs attributed to the new long-term duration PHES

Except for the case with 300 MW and 30 GWh storage, **the savings in power generation's capital cost are the highest compared to other benefits. It represents more than 75% of the value of the new PHES**. **Most of the savings come from the reduction of low-carbon generation.** While for the 300 MW case, the savings in the generation, transmission, and electricity operating cost are relatively similar. The implications of the new PHES on the power generation are discussed in more detailed in section 2.2.

The second-largest benefit is obtained from the reduction in operating cost, followed by the reduction on the electricity network, i.e. transmission. However, the impact on transmission is quite complex since it is affected by the presence of LD-PHES and the changes in the generation portfolio. While the required capacity of the Scotland-England interconnection (as discussed later in section 2.4) decreases, other parts of the transmission system, e.g. the transfer capability between North and South Scotland may need to be reinforced. The impact on the hydrogen system also varies; in some cases, the new PHES may increase the cost of hydrogen infrastructure due to the increased level of renewables in the system.

Savings per MW

While increasing the power rating of the PHES increases the cost savings non-linearly, the average cost savings per MW will decrease, as shown in Figure 2-2 and Figure 2-3 below. For the 30 GWh cases, the average values of PHES are between £80 and £150 per kW per year. While for the 90 GWh cases, the values vary between £70 and £222 per kW per year.

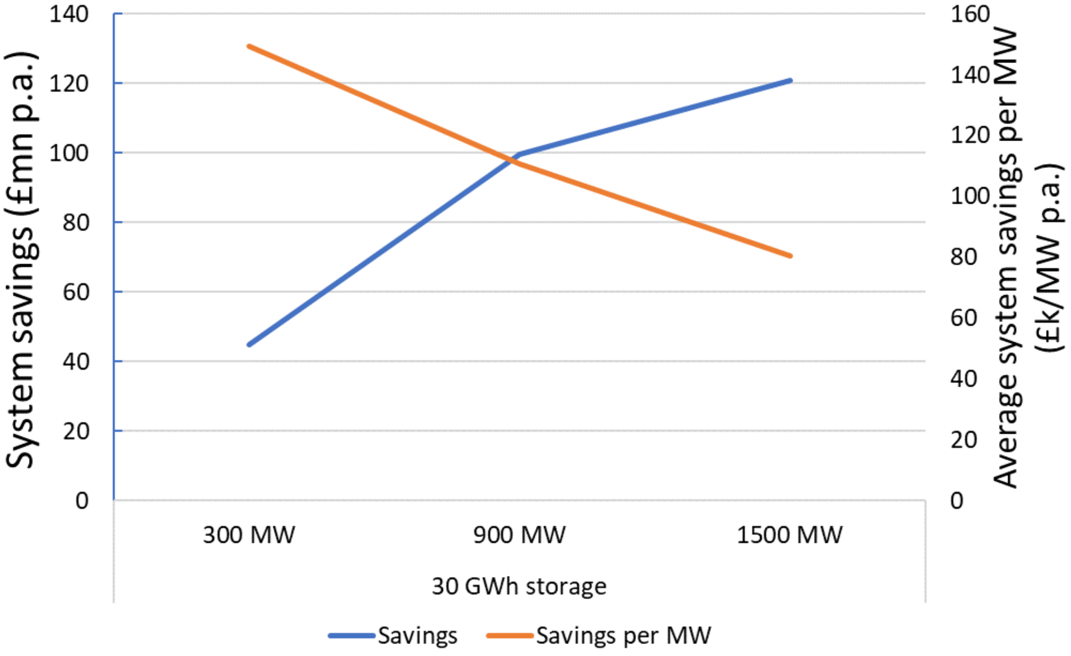

Figure 2-2 The whole-system value and the average system savings of 30 GWh storage with different ratings

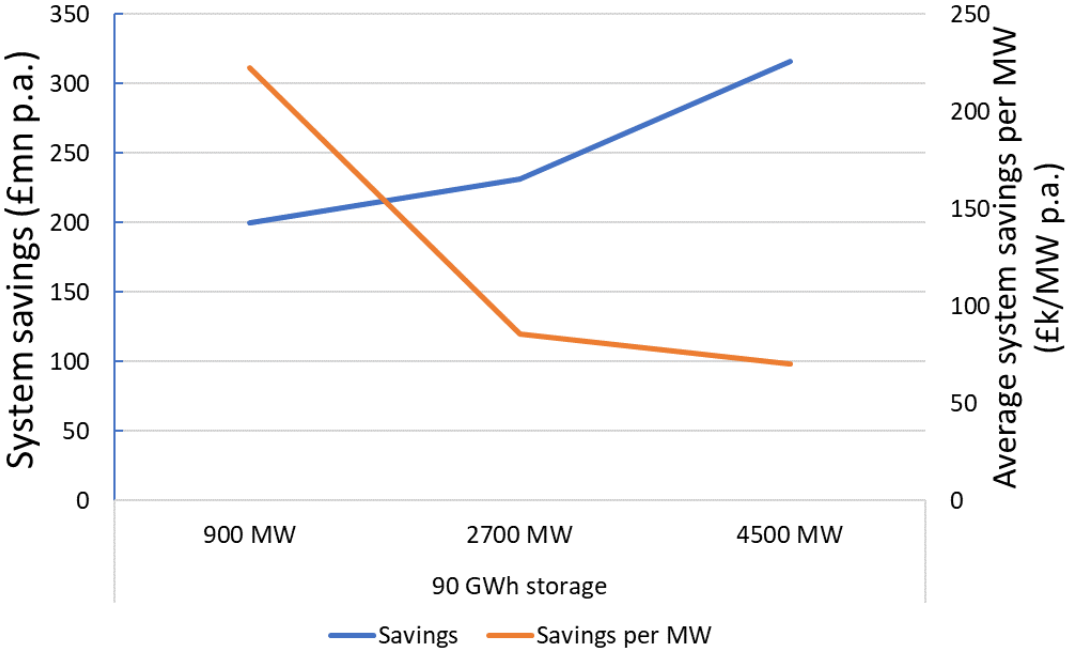

Figure 2-3 The whole-system value and the average system savings of 90 GWh storage with different ratings

Based on these results, we can conclude the following:

- Higher storage volume increases the value of LD-PHES. The savings from a 90GWh

LD-PHES fleet are double those from 30GWh.

- Increasing the power rating of storage increases non-linearly the system savings as it reduces the power system capacity requirement, but the benefit diminishes with the increased power rating.

2.2 Impact on the optimal electricity generation portfolio

The highest benefit of LD-PHES is in the capital cost savings of electricity generation. Figure 2-4 shows the system's optimal generation portfolio changes with the new LD-PHES compared to the counterfactual. The positive change indicates that the new LD-PHES enables more capacity to be integrated into the system, while the negative change indicates that those capacities have been displaced.

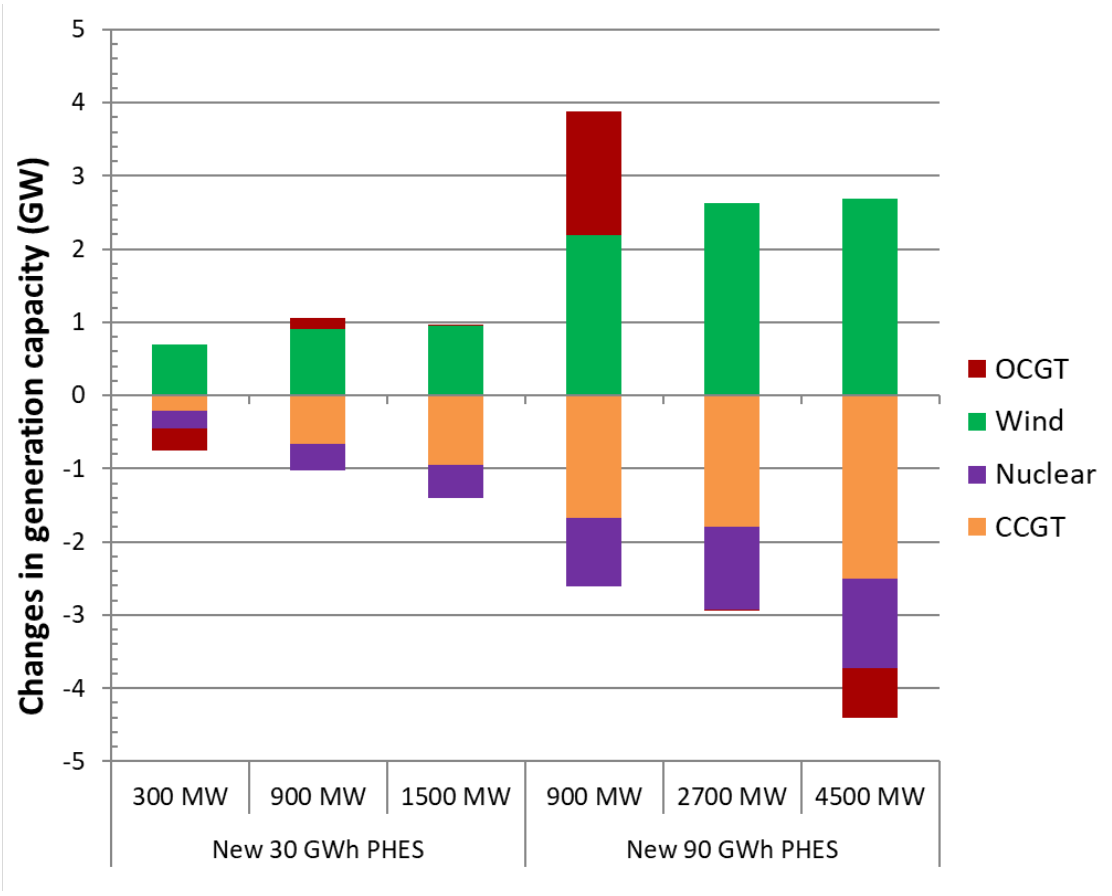

Figure 2-4 Impact of new LD-PHES on power generation capacity

The results show the following:

- **More wind power can be integrated with new LD-PHES.** New LD-PHES brings more flexibility, improving the system balancing capability and reducing wind energy curtailment. Flexibility reduces the system integration cost of wind[5], making it more competitive. Therefore, it can increase the wind capacity that can be integrated into the system.

- Increased storage volume is more important than increased power capacity. It demonstrates that LD-PHES facilitates the integration of wind power more effectively than shorter-duration storage. The increased volume of wind is not linear to the increase in the rating of LD-PHES. For example, 900MW 30GWh storage enables around 900MW more wind power to be connected. Having a higher power rating of the LD-PHES fleet to 1500MW increases the new wind capacity slightly to around 1000MW. However, increasing energy storage volume from 30GWh to 90GWh enables 900MW to 2200MW wind capacity to be integrated.
- **LD-PHES acts to 'firm up' variable renewables, and therefore, the need for firm low carbon power generation (such as nuclear, hydrogen-based generation, CCS) is reduced**. The volume of nuclear that can be displaced per MW of installed LD-PHES depends on the energy storage volume. For example, for the 100h storage, between 0.75 to 1 MW the nuclear capacity can be displaced by increased wind capacity supported by 1 MW LD-PHES. The ratio decreases to around 0.3 MW nuclear per MW LD-PHES for the 20h storage.
- **LD-PHES has capacity value, and therefore, it can displace firm generation capacity.** Studies demonstrate that the capacity value of storage depends not only on the power rating of the storage but also the energy storage capacity as it has to cover the duration of the peak demand. In this study, the 20 h to 100 h of energy storage capacity is sufficient to maximise its capacity value.
- Some CCGT capacity can also be displaced by OCGT running with green gas as the CCGT capacity factor decreases along with the increased wind penetration. It is important to highlight that the capex of CCGT is higher than the OCGT capex, and therefore, it may be more cost-efficient to displace low load factor CCGT with OCGT using green gas.

2.3 Impact on electricity production from wind and nuclear

The benefits of LD-PHES in integrating a higher capacity of wind power whilst reducing the need for firm low-carbon generation technologies such as nuclear are also depicted in Figure 2-5. It shows the annual electricity production changes from wind power and nuclear power compared to the production in the counterfactual scenario. The results demonstrate increased electricity production from wind power while the nuclear power output decreases because it is not needed. In Figure 2-5, the electricity generation changes by wind power are

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[5] G. Strbac, M. Aunedi, D. Pudjianto, F. Teng, P. Djapic, R. Druce, A. Carmel, and K. Borkowski, “Value of Flexibility in a Decarbonised Grid and System Externalities of Low-Carbon Generation Technologies,” Imp. Coll. London, NERA Econ. Consult., 2015.

greater than the displaced electricity production from nuclear primarily due to the loss efficiency of the storage.

The results also demonstrate the same findings as discussed previously, that long-duration storage will be able to integrate more wind than shorter duration storage. For example, comparing the results from the 900 MW power rating with 30 GWh and 90 GWh energy storage, the case with LD-PHES increases the electricity production from wind three times compared with high flexibility levels from DR, EVs and interconnection shorter-duration storage.

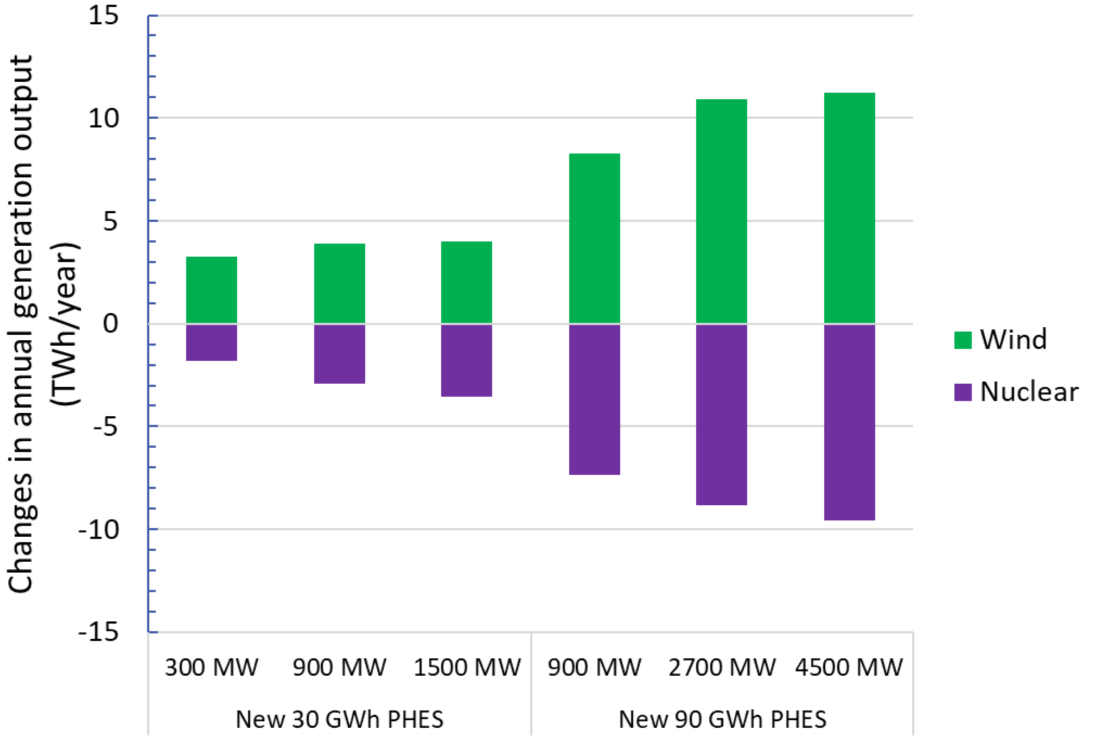

Figure 2-5 Impact of LD-PHES on electricity production from nuclear and wind

While increasing the power rating of the new LD-PHES increases the volume of electricity production from wind power, the benefit diminishes, as shown in Figure 2-5. For example, the volume of additional wind energy in the case with 900 MW and 90 GWh storage is around 8 TWh year^{-1}, the volume increases to around 11 TWh year^{-1} for the 2700 MW. From this point, the volume does not increase substantially even if the capacity is increased to 4500 MW.

2.4 Impact on the transmission transfer capability between Scotland and England

LD-PHES in Scotland can also provide a service to manage transmission network congestion, for example, at the Scotland-England border. During high wind periods, when the network is congested, the LD-PHES can store the wind energy to relieve the congestion and discharge the energy back to the grid during low-wind conditions. Using IWES, the volume of transmission capacity needed and the implications of the new LD-PHES to the capacity needed can be quantified and analysed.

In this context, the required capacity of the Scotland-England interconnectors (East and West, i.e. SS-NEE and SS-NEW) for different cases is calculated by IWES, and the results are shown in Figure 2-6.

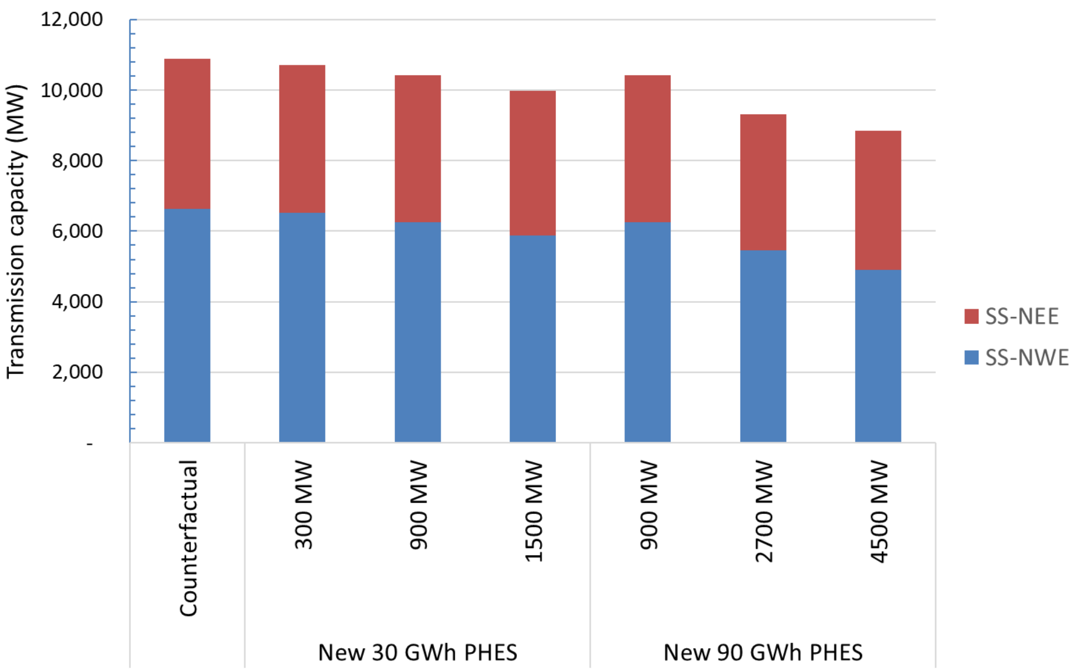

Figure 2-6 Impact of LD-PHES on transmission capability between Scotland and England

Without the new LD-PHES plants, the counterfactual system will require a total interconnection capacity of around 10.8 GW between Scotland and England in 2050 compared to circa 6 GW today. With new LD-PHES plants, the transmission capacity required reduces, as shown in Figure 2-6. For example, with 900 MW 30 GWh storage, the total capacity required decreases to 10.4GW. The capacity required does not change when the storage capacity increases to 90 GWh. However, if the rating of LD-PHES is 4500 MW (although with the same 90 GWh energy storage), the total transmission capacity requirement decreases by 2 GW to 8.8 GW. It is important to note that storage may have capacity benefits across multiple system boundaries.

The results demonstrate that the benefit of the LD-PHES in providing network congestion management correlates more strongly to the rating of the LD-PHES, although the benefit also diminishes along with the increased capacity of new LD-PHES. Although it is not demonstrated in the study, we can conclude that sufficient storage capacity is also required since there may be a need to reduce the flows for several hours. Given the assumptions taken in the study and the assumed storage capacity (20h – 100h), the results show that such capacity is sufficient for transmission congestion services.

2.5 Impact on the hydrogen storage requirements

Power-to-gas (electrolysers) and hydrogen-based power generation create links between the electricity and hydrogen systems. The flexibility in the hydrogen system provided by hydrogen storage can benefit the electricity system. On the other hand, since part of the hydrogen demand potentially comes from power generation, the electricity system's flexibility that changes the temporal variation of hydrogen demand may also affect the need for hydrogen storage. In this context, we investigate the impact of LD-PHES on the need for hydrogen storage in the system. The results are presented in Figure 2-7.

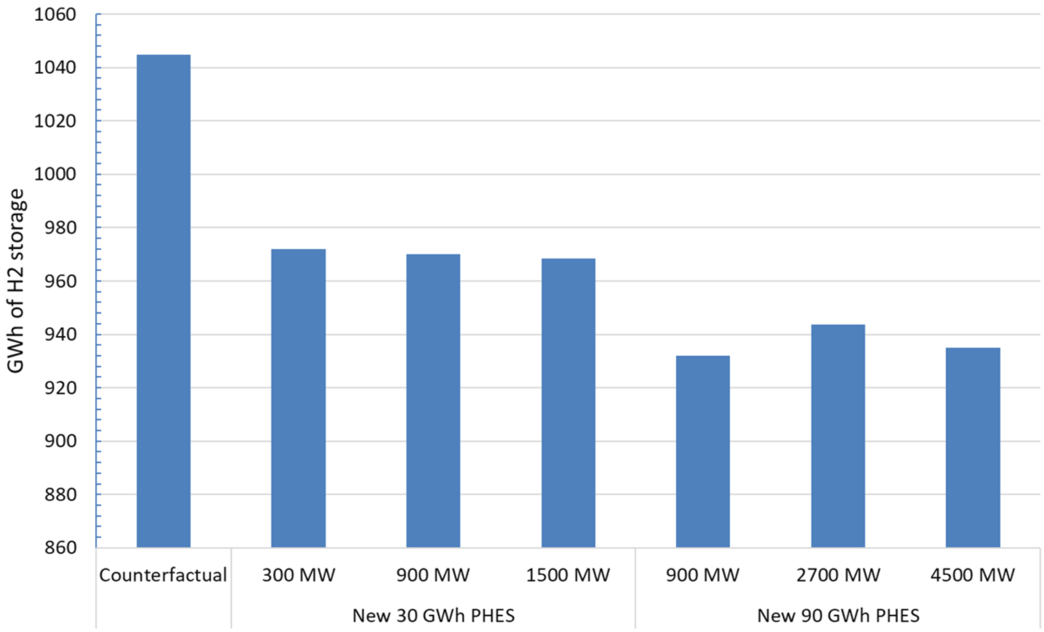

Figure 2-7 Impact of LD-PHES on the requirement of hydrogen storage

In this study, hydrogen is used to fuel power generation. The main source of hydrogen is bioenergy through gasification with carbon capture and storage. The biomass plants run at a high load factor to reduce its capex but the hydrogen demand for power generation (around 93 TWh/year) varies in time depending on, among others, wind power output. Therefore, hydrogen storage is needed to enable supply and demand balance in the hydrogen system.

As shown in Figure 2-7, the integration of new 30 GWh or 90 GWh LD-PHES reduces the need for hydrogen storage by around 70 GWh in the case with 30 GWh LD-PHES. Increasing the power rating of LD-PHES has a small impact. A similar pattern is found with the 90 GWh LD-PHES; it reduces the hydrogen storage requirement by around 110 GWh. The reduction is not linear to the increased LD-PHES capacity since the whole-system evolves and optimised by the model.

While hydrogen storage can provide low-cost bulk energy storage, converting electricity to hydrogen and back to electricity incurs substantial losses. The overall energy conversion efficiency is only 40%-50%. In comparison, the efficiency of LD-PHES is above 75%. Therefore, it is expected that both technologies will work complementarily, although at a certain extent, also compete with each other.

Chapter 3. Key parameters that drive the system integration benefits of long-duration energy storage

This chapter discusses the main findings from the sensitivity studies that have been analysed to identify the implications of different system conditions on the system value of the LD-PHES. The sensitivity studies analyse the impact of the following:

- The presence of other flexibility technologies including on the demand-side, e.g. EV batteries
- Energy storage capacity on the provision of frequency response
- Network constraint at the Scotland-England border
- Higher GB interconnection
- Lower-cost offshore wind
- Different carbon targets
- Prolonged periods of extremely low-wind conditions
- Seasonal thermal storage

Key highlights

- The value of new PHES is between £100m and £231m per year in 2050 even in a highly flexible system with competing technologies (for 900MW plant capacity and volume of energy storage between 30GWh and 90GWh). In an inflexible system the benefit of new PHES increases to £190m - £481m per year.
- Value of flexibility diminishes; technologies deployed upfront will have a higher value. The value of PHES after the deployment of demand response is around £100m year while if the PHES is deployed upfront, the value is £190m/year.
- LD-PHES complements the presence of short-duration flexibility such as DSR, short duration energy storage.
- The value of frequency support provided by PHES in pumping mode is significant for a system with 20GW - 60GW wind capacity (potential value of £200m - £1bn/year in inflexible system).
- The value of variable speed is small.
- LD-PHES provides more valuable frequency support than short-duration storage as it can operate longer to provide the services continuously.

Key highlights

- The benefits of LD-PHES in Scotland amplifies if there is no transmission reinforcement between Scotland and England.
- The impact of a higher GB interconnection capacity (30GW total) on the value of new LD-PHES is relatively small, a reduction of up to £40m/year across all cases. It indicates that there is not only competition but also synergy between the flexibility from interconnection and the long-duration energy storage.
- Low-cost offshore wind increases the penetration of wind which amplifies the benefits of LD-PHES (4500 MW, 90 GWh) to £550m/year.
- The benefits of LD-PHES are strongly affected by carbon targets. Considering a case of 2GW of LD-PHES with 20 GWh storage (10h) and 200 GWh (100h), for the 50gCO_2/kWh the benefits are between £6m (10h) in a flexible system and £99m (100h) per year in an inflexible system; while the benefits with net-zero emissions are between £93m (10h) in flexible and £511m (100) per year in inflexible system.
- The utilisation factor of LD-PHES increases by 3% in a system with a lower carbon target. A higher volume of energy storage also increases the utilisation factor of LD-PHES.
- Since the main benefits of LD-PHES are in enabling low-cost variable low-carbon technologies, the prolonged extreme low-wind conditions beyond the energy storage capacity will reduce significantly the benefits of LD-PHES.
- LD-PHES competes but also works in synergy with Long-duration Thermal Energy

3.1 Value of PHS in a flexible and inflexible system

A set of studies is used to investigate the impact of other flexibility technologies, such as EVs, on the value of new PHES. We assume no increased demand response in an inflexible system compared to today, no new energy storage except the new PHES. The study assumes a high demand response in the flexible system, and IWES is allowed to install new battery storage if needed. The demand response comes from different sources, including industrial and commercial customers (3.5%), electric vehicles (40%), and smart appliances (20.5%). In this study, the demand response provides short-term flexibility as some percentage of the energy demand can be shifted within one day. Demand response can also provide frequency response and balancing services. Thus, the demand response-based services compete directly with the flexibility services from the new PHES. The cost of demand response is negligible, and the efficiency losses due to load-shifting are assumed to be small.

Using the same approach as described previously, we quantify the value of new PHES under two system conditions: an inflexible and flexible system. The 30 GWh and 90 GWh energy storage capacity results are compared and presented in Figure 3-1 and Figure 3-2, respectively.

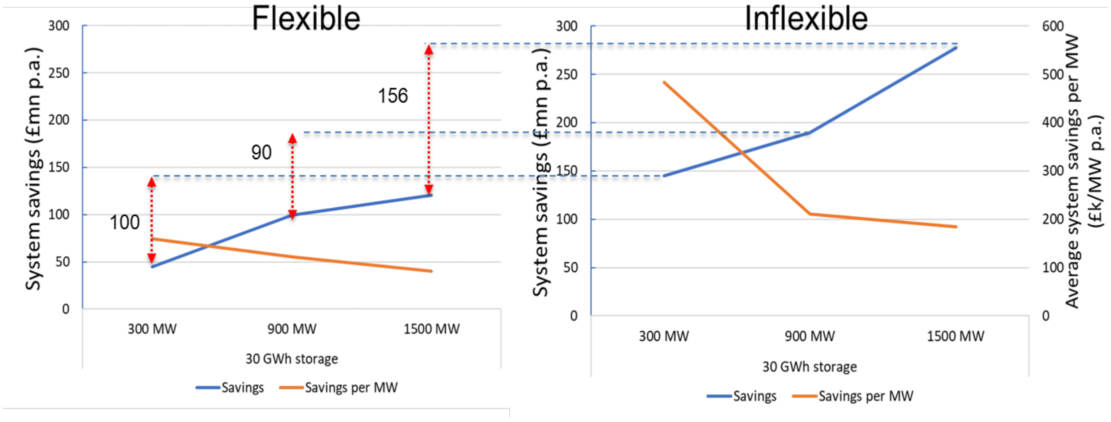

Figure 3-1 Value of new 30 GWh PHES in a flexible and inflexible energy system

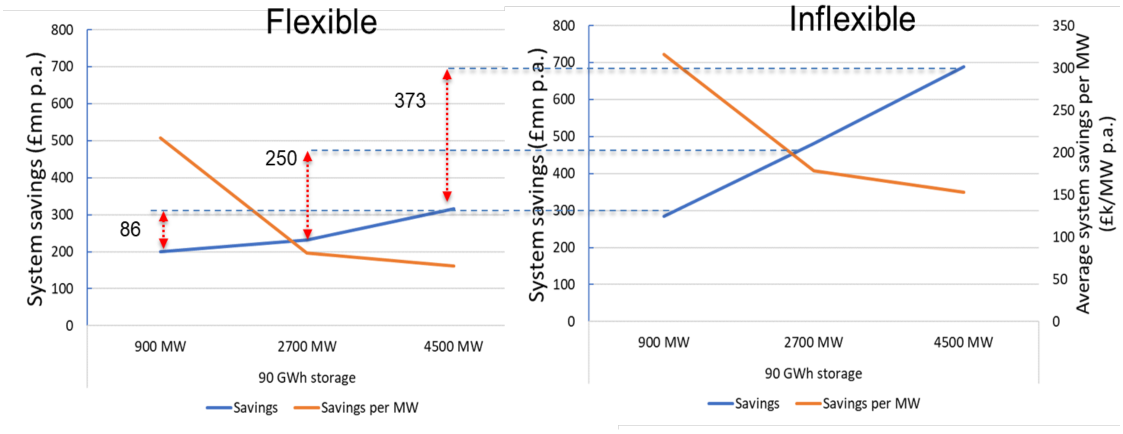

Figure 3-2 Value of new 90 GWh PHES in a flexible and inflexible energy system

As demonstrated by Figure 3-1, the system benefits of the new PHES in a flexible system are much lower than in the inflexible system. Consequently, the impact on the system savings will also be reflected in the savings per MW PHES. For example, for the 900 MW 30 GWh storage, the benefit is around £100m/year in the flexible system. Without other flexibility technologies, the benefit increases to around £190m/year; the difference is £90m/year. For the 90 GWh storage, the finding is the same, but the difference tends to be higher. For example, for the 2700 MW 90GWh storage, the benefit is around £231m/year; this value increases to £481m/year in the inflexible system; the difference is £250m/year. The impact of other flexibility technologies is also more profound with the short- duration storage (i.e. with large rating). The results are expected since the shorter duration storage will compete more strongly to demand response and battery storage.

In conclusion, these findings highlight that LD-PHES is still valuable and complementing the presence of other short-duration flexibility technologies.

3.1.1 Incremental savings: DR or PHES first

Since the value of flexibility technologies is system-specific, depending on the presence of other flexibility technologies, it indicates that the technology that can be deployed first will have a higher value than the subsequent technology, assuming both provide the same flexibility services. In order to demonstrate this effect, two case studies were carried out. The first case assumes that demand response flexibility, e.g. EVs and short duration batteries are deployed upfront then PHES, and the second case assumes the other way round. The savings are the difference between the system's cost with and without DR and PHES. The results are shown in Figure 3-3.

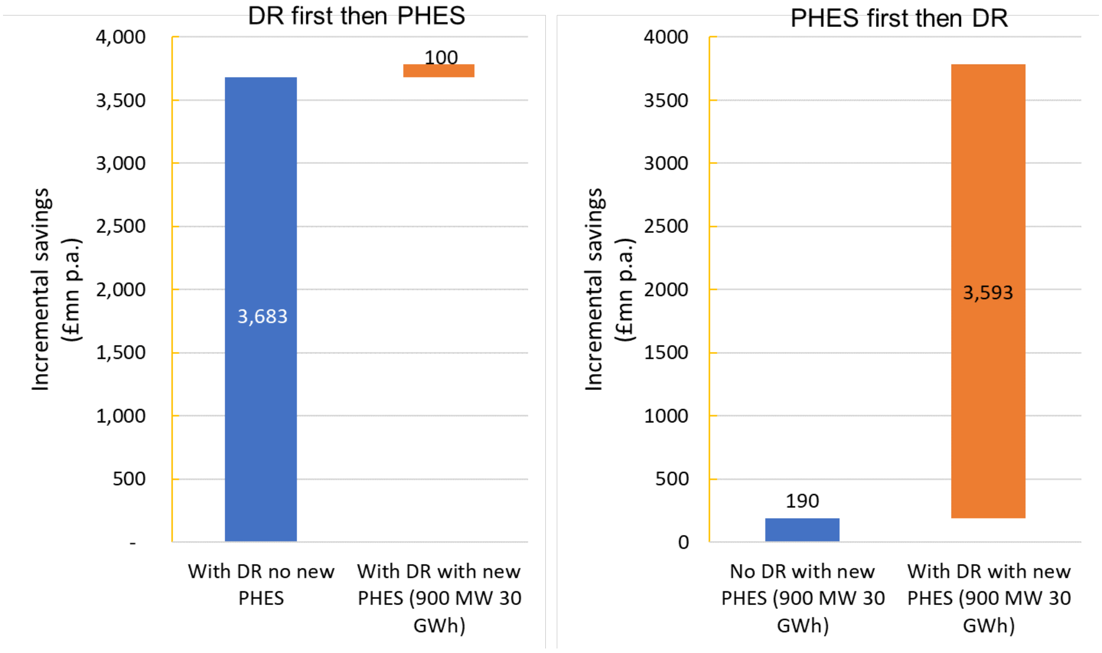

Figure 3-3 Incremental savings of demand-response technologies and PHES

The left diagram of Figure 3-3 shows that the value of PHES after the deployment of demand response is around £100m/year while if the PHES is deployed upfront, the value is £190m/year. In any case, it demonstrates that the value of LD-PHES will not be nullified entirely with the presence of demand response and short duration battery storage.

It is important to highlight that there is significant uncertainty, at least at present, related to whether, when, where, and how much distributed flexibility technologies such as demand response will be deployed in the system in future. On the other hand, the deployment of large-scale PHES can be planned and executed with more certainty. It is also possible that in the least-worst regret approach, the new PHES can be part of the solution to deal with the uncertainty of demand response technologies. It may warrant further investigation looking at the transition towards a zero-carbon system considering uncertainty in flexibility technologies' deployment.

3.2 Role and value of variable speed PHES in the context of frequency regulation

The need for ancillary services to maintain frequency stability will increase as renewable penetration increases in electricity grids to meet the emissions target. The cost associated with ancillary services is predicted to increase by 15 times in 2030, compared to 2015 levels, and this cost could reach 25% of the total operating cost of the Great Britain power grid[6]. In this context, a sufficient amount of inertia and frequency response must be available to maintain stability: the frequency limits must be contained, so that the Rate-of-Change-of-Frequency (RoCoF) and frequency nadir do not exceed the acceptable values set by the standards.

In this context, the key topic investigated in this study is the difference in benefits between short and long-duration PHES, in providing frequency support. This includes consideration of automatic disconnection, when in pumping mode, in the event of a generation loss in the system, as this operational strategy would effectively reduce the generation loss by the power being pumped by the PHES. Simultaneously, the inertia provided by the PHES would be removed from the system when the PHES is disconnected. The analysis is conducted using advanced frequency-secured Stochastic Unit Commitment (SUC) model, considering two key characteristics: (a) uncertainty from renewable generation is explicitly considered while (b) ensuring that security of supply related to frequency stability is met after the largest generation loss. Full details on how to characterise uncertainty in the SUC through the scenario tree are available in (Sturt and Strbac, 2012)[7]. The frequency-secured framework used in this SUC is unique as it co-optimises the different ancillary services for frequency support: Inertia, Enhanced Frequency Response (EFR), Firm Frequency Response (FFR) and implication of reserve requirements[8].

The SUC simulations results for two different wind power penetration levels are presented in Figure 3-4 (the system characteristics can be found in (Badesa et al., 2019) [9]. The results presented in Figure 3-4 show the following key findings:

- In case of penetration of wind of 20GW, there is no significant difference in the value between short and long term PHES (blue bars)

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[6] Imperial College London & Pöyry Management Consulting, “Roadmap for flexibility services to 2030,” A report to the Committee on Climate Change (CCC), 2017.

[7] A. Sturt and G. Strbac, “Efficient Stochastic Scheduling for Simulation of Wind-Integrated Power Systems,” IEEE Transactions on Power Systems, 2012

[8] L. Badesa, F. Teng and G. Strbac, “Simultaneous Scheduling of Multiple Frequency Services in Stochastic Unit Commitment,” IEEE Transactions on Power Systems, 2019

[9] Imperial College London & Pöyry Management Consulting, “Roadmap for flexibility services to 2030,” A report to the Committee on Climate Change (CCC), 2017

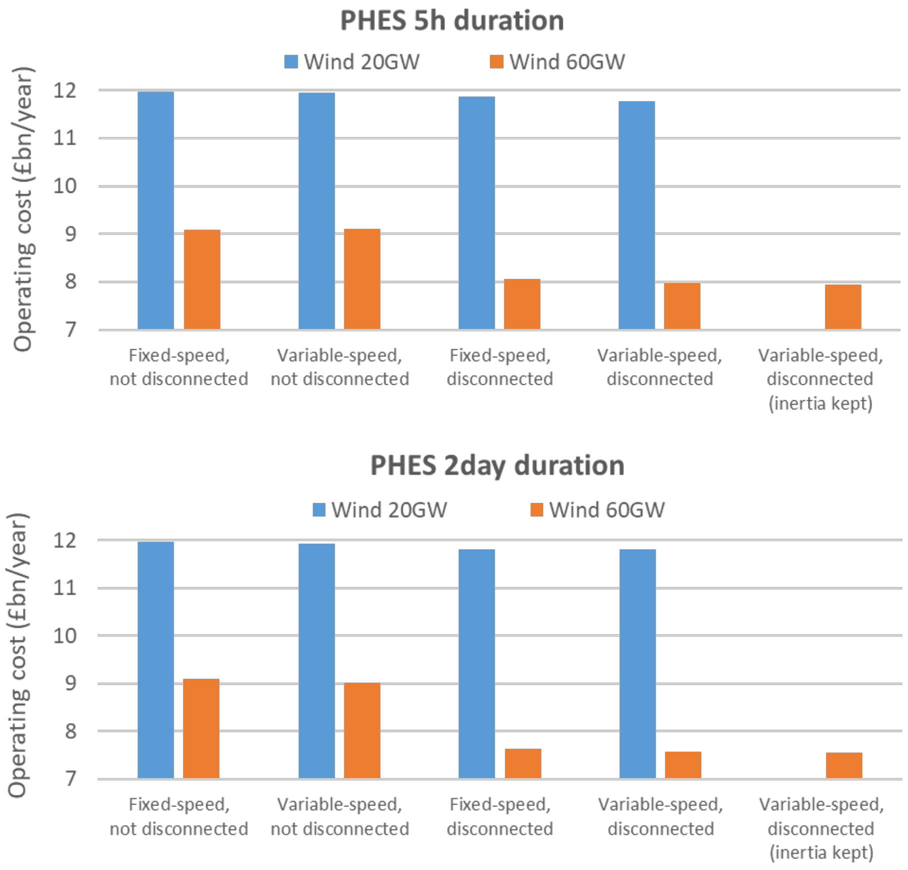


Figure 3-4 Analysis of the system operating cost under 20 GW and 60 GW of wind capacity. Several sensitivities of pump hydro storage are presented: 1) 5h and 2-day duration; 2) fixed- and variable-speed; 3) no frequency support provided by PHES vs frequency support provided through disconnection after a generation loss.

- In the case of 60GW of wind, the additional benefit of 2-day duration PHES in providing frequency regulation services is about £400m/year larger than a 5h duration PHES. This is because long-duration PHES can charge for a significantly longer period, so it can be ready to disconnect while pumping for a much longer period (i.e. LD-PHES will provide ancillary services more frequently). When compared with battery storage, that can provide frequency response services from the standby mode, the additional benefit of LD-PHES is in the order of £90m/year (this will reduce further when flexibility technology/systems provide frequency response services, e.g. V2G, flexible demand, electrolysers, interconnectors, renewable generation with grid-forming converters).

- The loss of inertia due to disconnecting the pump is negligible compared to the savings brought by disconnecting the PHES when in pumping mode.

In this context, it is informative to highlight that the COVID-19 pandemic led to a reduction in electricity demand and the coincidence with large renewable outputs, created conditions that were not expected until renewable capacity increases to meet emissions targets in coming years. The system experienced periods of very high instantaneous production of non-synchronous renewables, challenging system frequency stability due to reduced inertia. Ancillary-services costs increased by £200m in May to July 2020 compared to the same period in 2019 (a threefold increase), highlighting the importance of ancillary services in low-carbon systems. In this context, it may be appropriate to consider early deployment of technologies that can provide flexibility services, including frequency response services, such as PHES.

The ability of LD-PHES to reduce the need for firm low-carbon generation

Further detail modelling has been carried out to assess the value of LD-PHES, using the stochastic optimisation, in supporting displacement of firm low carbon generation by renewables. In this case study, it was assumed that 2 GW of nuclear generation would be replaced by 6 GW of wind generation (as both have a similar annual energy production) while considering the impact of PHES, with different levels of storage duration, on short term operating costs and carbon emissions. The base case considers a renewable scenario with 80 GW of wind capacity in the system.

The operating cost for each case considered is presented in Figure 3-5. The results demonstrate that replacing 2 GW of nuclear with 6 GW of wind would increase the system operating cost. However, the extra wind capacity combined with additional PHES of 2 GW would reduce system operating costs. It is shown that the system operation costs reduce more when the duration PHES increases while providing balancing services, including frequency regulation.

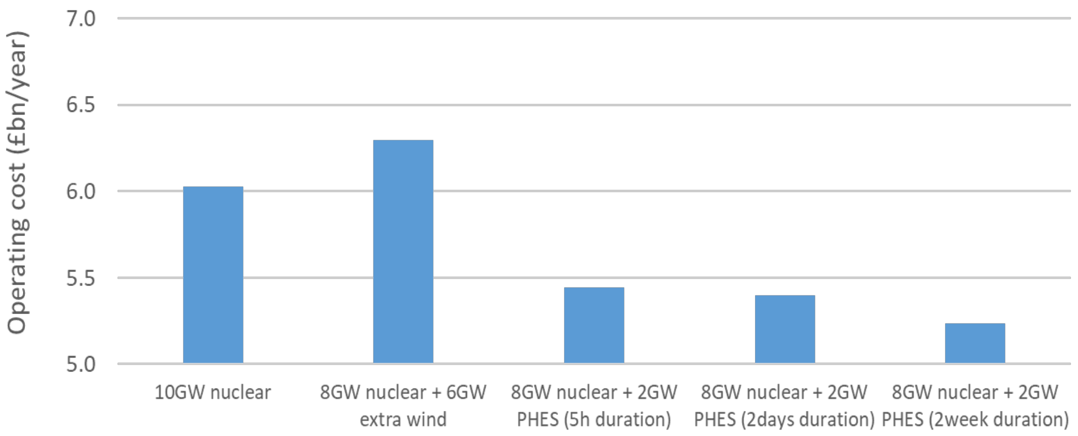


Figure 3-5 Analysis of the economic benefits in replacing 2 GW of nuclear capacity with 6GW of wind in combination with 2 GW of pump-storage hydro

The analysis also demonstrated that LD-PHES would maintain/increase the security of supply during prolonged no-wind periods. The case study was carried out, considering zero wind generation for two consecutive weeks, showing that LD-PHES can replace firm low carbon generation capacity, assuming the duration of storage of 2 weeks. More discussions on this topic can also be found later in section 3.7. In the rest of the report, the studies are carried out by IWES.

3.3 Impact of constraint at the Scotland and England boundary

In this study, we investigate the impact of network congestion at boundary B6 (i.e. Scotland-England boundary). We study two cases. The first one assumes that there will be no further capacity reinforcement at B6 and the second one assumes optimal development of that corridor. The system savings of the new PHES with different configurations are analysed, and the results are shown in Figure 3-6.

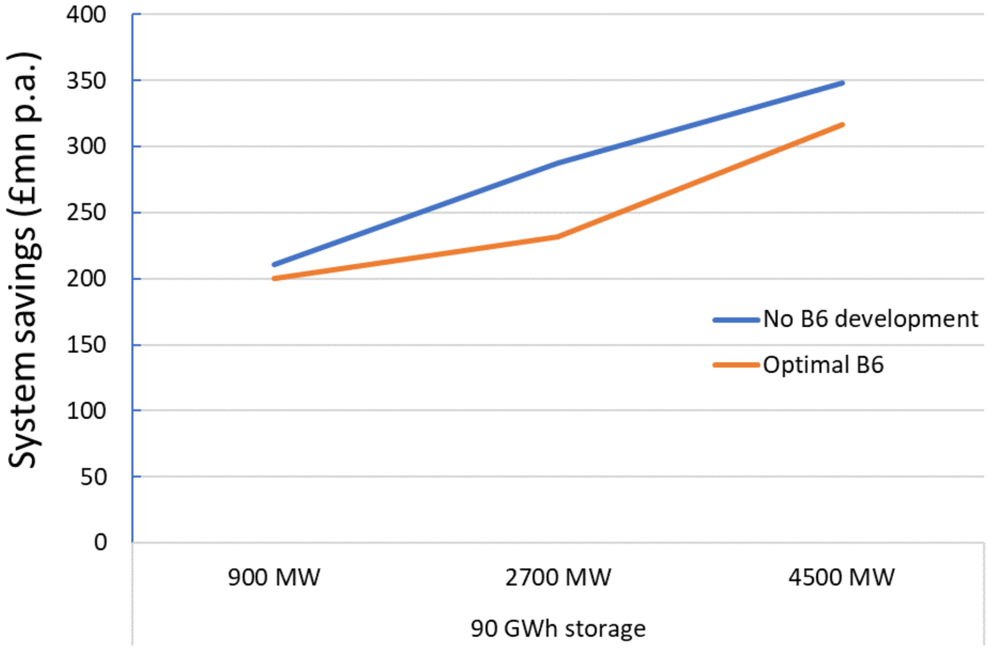


Figure 3-6 The benefit of new PHES with and without the optimal development of B6

If the capacity of B6 is optimised, the value of the PHES storage for managing the congestion at B6 decreases. For example, for 2700 MW 90 GWh storage, the savings made by PHES are £286m/year if there no reinforcement of B6; but the savings reduce to £231m/year if B6 capacity is optimal. It can be concluded that the optimal network development tends to reduce the value of flexibility used for network congestion management services, including the services provided by PHES.

3.4 Impact of higher GB interconnection

Another technology that can provide balancing services is the interconnection between GB and other countries. The power exchange across the interconnectors helps both regions balance their supply and demand while optimally using the most economical available resources. Interconnection also allows sharing of balancing resources and generation capacity across regions. By maximising the benefit of diversity in demand and supply across regions, the interconnection facilitates reducing the total capacity required to maintain the security and allows the development of low-carbon technologies cost-efficiently across Europe.

In this context, we analyse the impact of higher GB interconnection capacity to the rest of Europe on the value of LD-PHES. Two scenarios, i.e. 25 GW and 30 GW GB interconnection capacity, are used in this study. The results of the cases with 30 GWh and 90 GWh storage capacity are presented in Figure 3-7 and Figure 3-8, respectively.

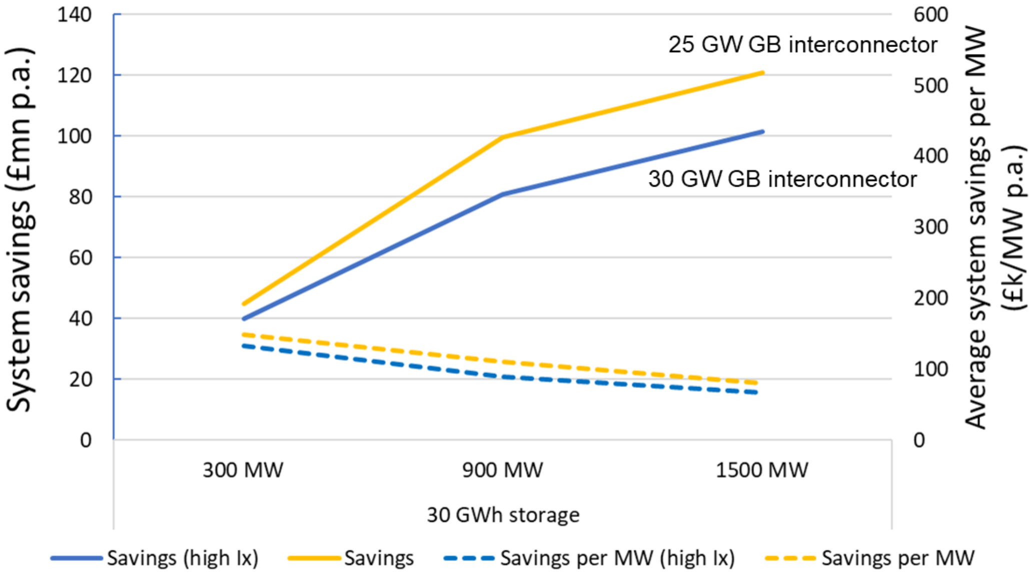


Figure 3-7 Impact of higher GB interconnection capacity on the value of 30 GWh new PHES

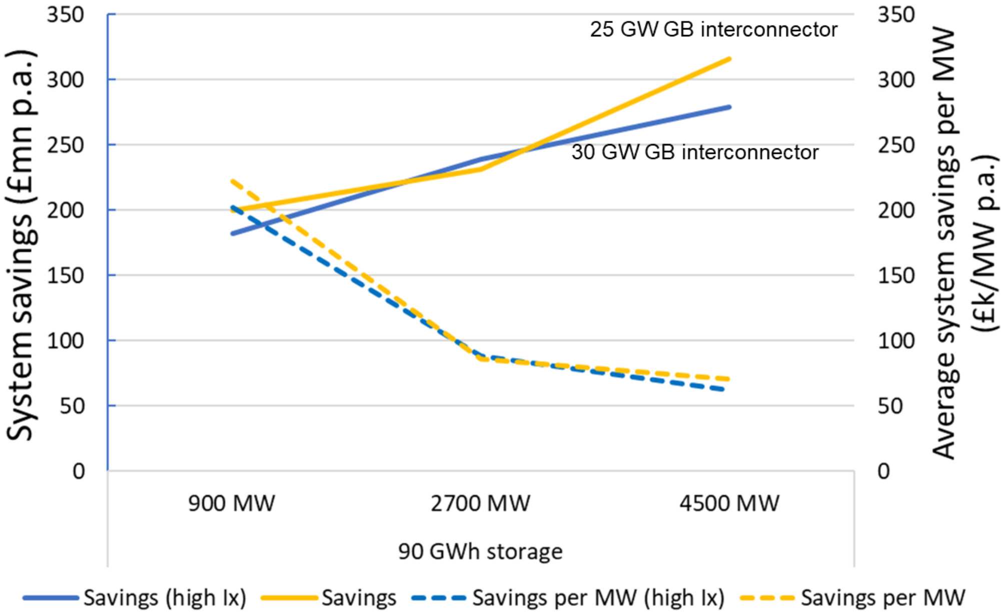


Figure 3-8 Impact of higher GB interconnection capacity on the value of 90 GWh new PHES

The results demonstrate that the impact of a higher interconnection capacity on the value of new LD-PHES is relatively small; it reduces the value up to £40m/year across all cases. It indicates that there is not only competition but also synergy between the flexibility from interconnection and the long-duration energy storage. It suggests that the value of LD-PHES is not reduced significantly by an increase in interconnection capacity. Another reason is that the GB flexibility, including flexibility from long-duration energy storage, may also help the neighbourhood system.

3.5 Impact of low-cost offshore wind

Demand for system flexibility is triggered by the increased penetration of variable and intermittent generation from renewables and the need to meet the emission target. In this context, we investigate the impact of increasing total wind capacity (including both onshore and offshore wind) connected to Scotland network by reducing the LCOE of wind on the value of new LD-PHES. Two cases are investigated: (i) 30 GW of wind generation connected in Scotland (offshore and onshore) out of 77 GW of wind (offshore and onshore) connected across GB, and (ii) 52 GW of wind (offshore and onshore) connected to Scotland infrastructure out of 120 GW wind (offshore and onshore) connected across GB. The cases with 30 GWh and 90 GWh of energy storage are presented in Figure 3-9 and Figure 3-10.

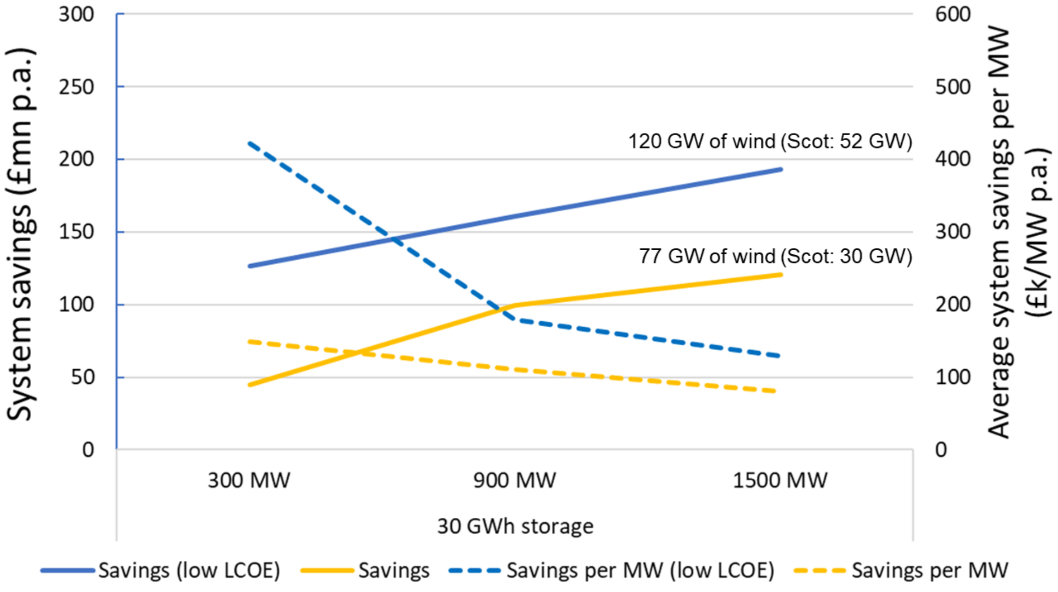


Figure 3-9 The impact of higher wind penetration on the value of 30 GWh LD-PHES

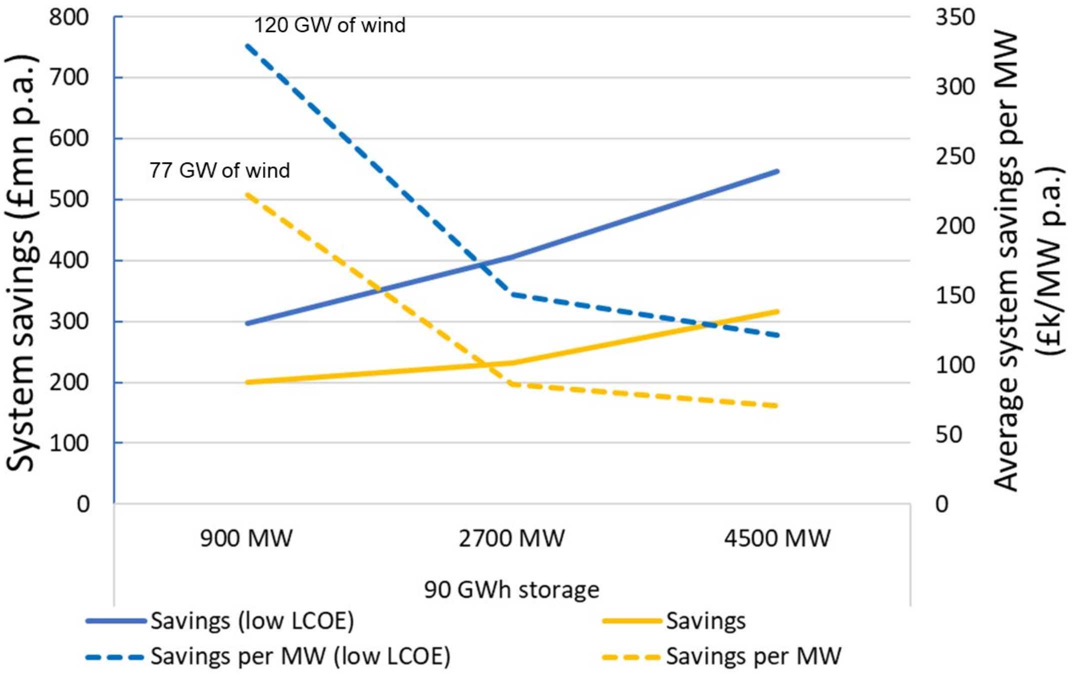


Figure 3-10 The impact of higher wind penetration on the value of 90 GWh LD-PHES

As expected, the cost savings attributed to the new LD-PHES increases considerably with a higher penetration of wind power. For example, for the 900 MW 30 GWh storage, the savings increase from around £100m to £160m per year. The impact is more profound in the 90 GWh storage case as the system relies more on the flexibility provided by storage; the system benefits of LD-PHES are up to £550m/year.

Considering the rapid development of offshore wind in the UK driven by the cost reduction and improvement of technologies, it can be expected that further penetration of wind farms in Scotland may boost further the value of LD-PHES. The emergence of floating offshore wind farms that can release the full potential of wind resources in the UK's waters can drive additional value for LD-PHES in the future.

3.6 Value of PHES with different storage capacity in the system with 50g and zero-emission electricity sector target

The value of LD-PHES is driven by the volume of renewables connected to the system and the need to meet the carbon target. In this context, we investigate the impact of having 50g and 0g carbon intensity target for the power sector on the value of 2GW of PHES with 20 GWh storage (10h) and 200 GWh (100h) long-duration energy storage. The 50g carbon intensity target for the power sector can be associated with the 2030 timeline, as recommended by the CCC. A 0g carbon intensity target for the power sector is assumed for 2050 to achieve overall economy-wide net-zero emissions. We also investigate its impact on the system with and without demand response. The system cost savings attributed to the 2 GW storage are presented in Figure 3-11.

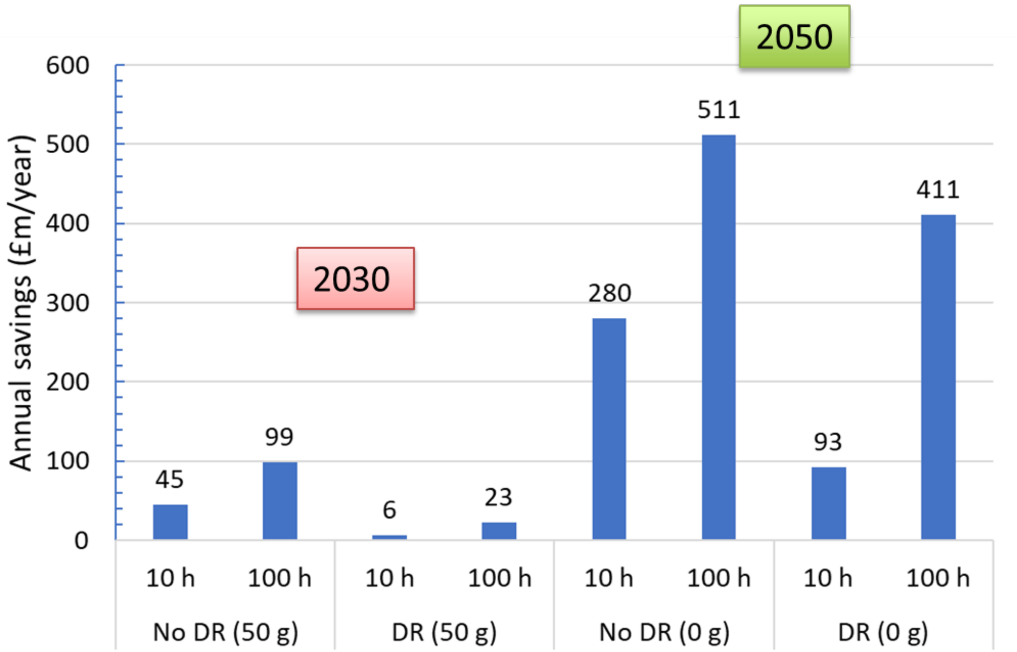


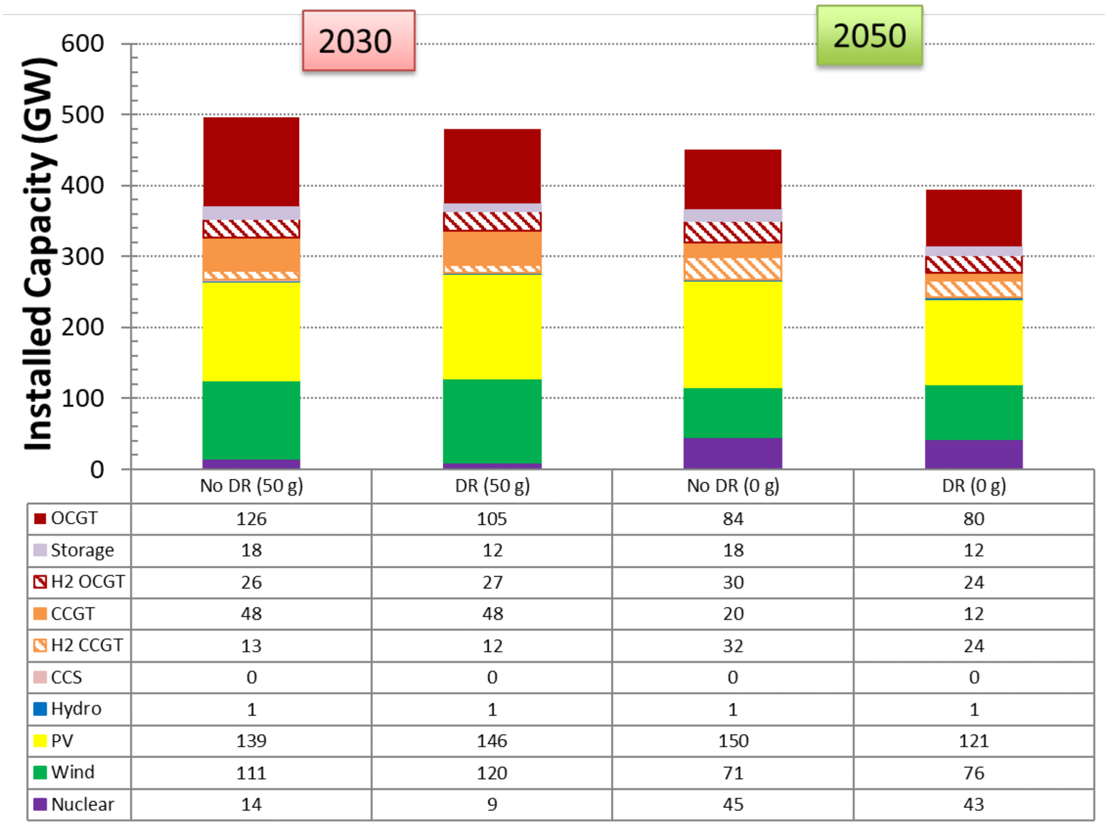
Figure 3-11 Value of PHES in the system with 50g and zero-emission target with and without demand response

As expected, the benefits of flexibility provided by 2 GW LD-PHES depend on the carbon intensity target and other flexibility sources such as demand response. The results demonstrate that the value in 2030 with 50g is much smaller than the value in 2050 with 0g carbon target. For example, with 100h storage, no DR and 50g carbon target, the savings are £99m/year. The savings become £511m/year when the carbon target is changed to 0g. The utilisation of traditional gas plants will be very limited in a system with a low-carbon target; therefore, without LD-PHES, the system will need to have high-cost but firm low-carbon sources (such as nuclear, hydrogen-based generation, CCS). The results are consistent with the analysis discussed earlier. It can be concluded that the value of LD-PHES' flexibility is strongly affected by the carbon target.

3.6.1 Impact on the optimal generation portfolio

We also analyse the implication of having 50 g and 0g carbon target on the optimal generation portfolio. The results are presented in Figure 3-12. The results show the following:

- The capacity of renewables in 50g case is higher than in 0g case. For example, installed wind capacity in 50g cases is 111-120 GW, but in 0g, it is only 71 – 76 GW. The opposite is true for nuclear. In 50g, the nuclear capacity is 9 – 14 GW, but it increases significantly to 43 – 45 GW in 0g. The results suggest that in a system with very low carbon target (e.g. 0g), the value of a firm low-carbon generation capacity such as nuclear increases, bringing nuclear power generation to be competitive against wind power generation. In 0g, there is a need to produce clean energy all times, and this is challenging for renewables, and the availability of energy resources varies across time.



	No DR (50 g)	DR (50 g)	No DR (0 g)	DR (0 g)
OCGT	126	105	84	80
Storage	18	12	18	12
H2 OCGT	26	27	30	24
CCGT	48	48	20	12
H2 CCGT	13	12	32	24
CCS	0	0	0	0
Hydro	1	1	1	1
PV	139	146	150	121
Wind	111	120	71	76
Nuclear	14	9	45	43

Figure 3-12 Optimal generation capacity portfolio in the scenarios with 50g and 0g carbon target

- The value of PHES is not always aligned to the installed capacity of wind (or renewables) and the carbon target. The lower the carbon target, the higher the value of energy storage since it can work in tandem with renewable power generation and firm up variable RES to energy supply.

- In 50g, we observe a considerable capacity of traditional CCGT (48 GW) and OCGT (105 – 126 GW). Their capacity becomes much less in 0g, although they can still be run with zero-emission gas, e.g. biogas. On the other hand, more H2 CCGT or H2 OCGT are installed in 0g case due to zero-emission requirement although some CCGT and OCGT are retained and run with biogas if needed. In this study, it is assumed that biogas is carbon neutral.

- Demand response can reduce the need for nuclear capacity and the firm capacity requirement. For example, the nuclear capacity needed in 50g without demand response is 14 GW; but only 9 GW is needed if it has DR.

The changes in the optimal generation portfolio due to the new 2 GW LD-PHES are presented in Figure 3-13. The results demonstrate:

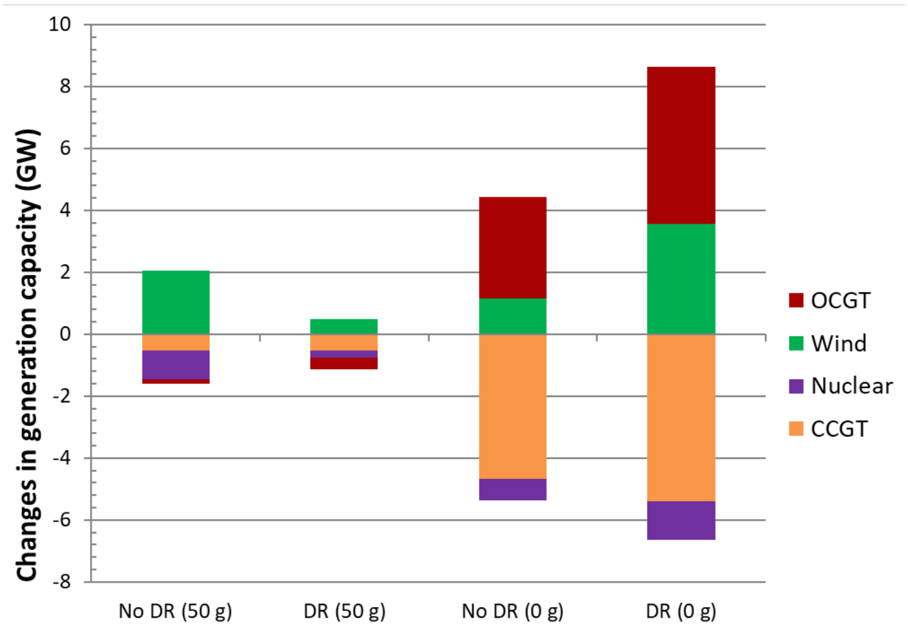


Figure 3-13 Changes in the generation due to 2 GW LD-PHES

- More wind power can be integrated with new PHES.
- PHES firms the supply of low-carbon electricity, especially from variable sources such as renewables, and therefore, the need for nuclear power generation becomes less.
- Some CCGT capacity can also be displaced by OCGT running with green gas as the CCGT capacity factor decreases along with the increased wind penetration.
- PHES has capacity value, and therefore, it can displace firm generation capacity.

3.6.2 The utilisation of LD-PHES

Figure 3-14 shows the comparison between the average load factor of electricity storage with and without DR and for the 50g and 0g carbon target. In this context, the load factor is defined as the percentage of the storage's electricity output compared to its maximum annual electricity output. While it indicates how the storage is used, it does not include utilising the storage for the frequency response services; for example, if it spins on air. So it is likely that the storage will operate longer than what is indicated below.

The results demonstrate that the utilisation of LD-PHES (200GWh) is substantially higher than the utilisation of shorter-duration PHES (20GWh). In 50g no DR case, the utilisation of 100h storage (rating 2GW) is 23% compared to 13% for the 10h storage capacity.

The results also show that the utilisation of the storage decreases when the system has DR. for example, in 50g no DR case, the utilisation is 13%, and down to 9% with DR. The reduction is lower if the storage capacity is higher. It indicates that the DR competes more directly with shorter-duration storage. This trend is observed in both 50g and 0g emission case.

The utilisation factor of storage tends to increase by 2% - 3% in the system with a lower carbon target.

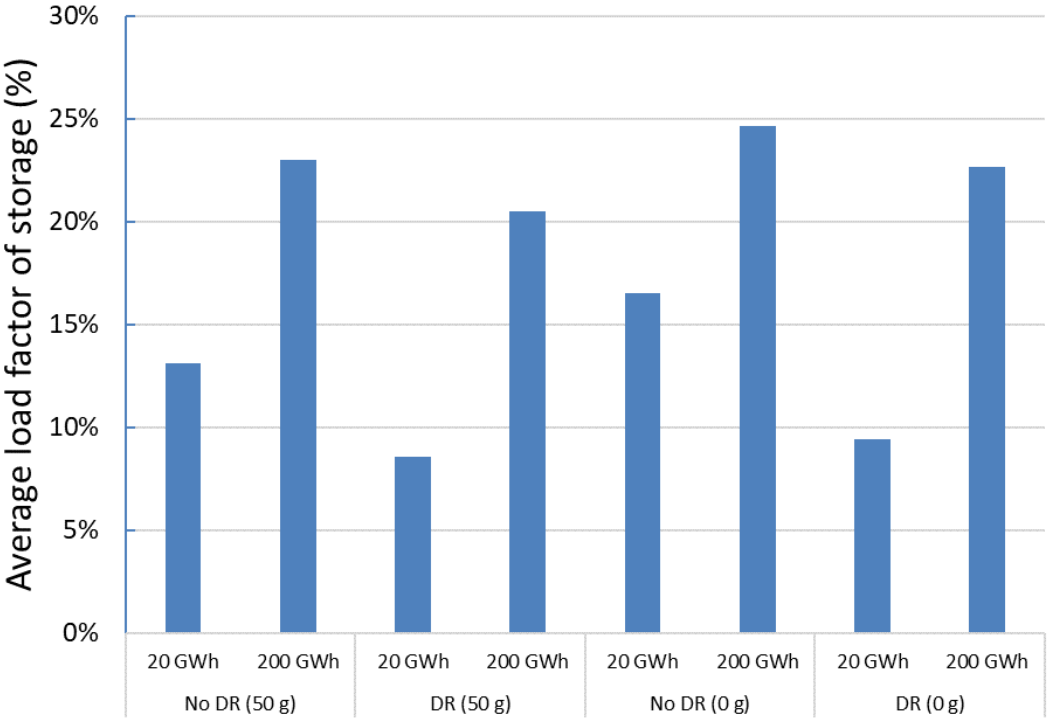


Figure 3-14 Average load factor

LD-PHES can generate electricity for a few days without the need to be charged during that period. This characteristic is essential, especially if there is a prolonged period of low-availability of renewable energy resources or generation capacity. In this context, the charging and discharging cycle of LD-PHES, electricity demand, and electricity production from different generation technologies are plotted for a winter week where the peak demand occurs coinciding with a 3-days low-wind period. The plots are shown in Figure 3-15.

The upper graph in Figure 3-15 shows the output of different generation technologies and electricity production from LD-PHES (2 GW, 100h). On day 16 – 18, wind output is very low while the electricity demand is at the peak, as shown by the lower graph in Figure 3-15. To meet the peak demand on those days, the long-duration storage produces electricity supporting other generation technologies. Peaking generation such as OCGT running on biogas, H2 OCGT running on hydrogen, and electricity import are also used to meet the demand during those days. Without sufficient energy storage, the system will require the additional capacity of firm low-carbon generation technology (such as nuclear, hydrogen-based generation, CCS). The finding highlights the difference between the short-duration (1-4 h) storage with longer-duration storage.

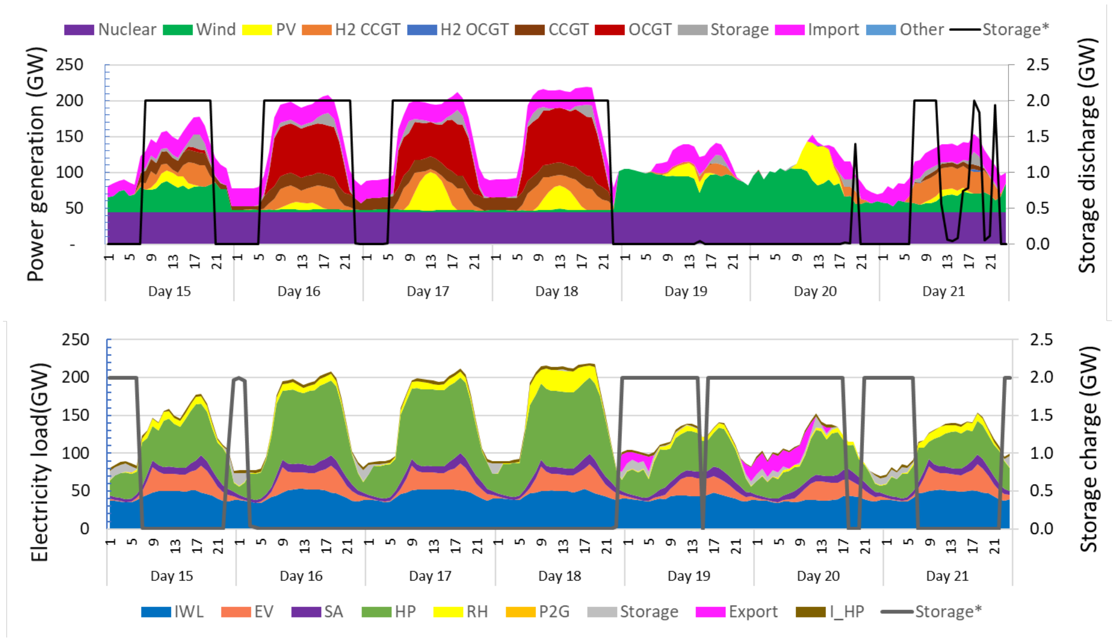


Figure 3-15 Charging and discharging of LD-PHES in a winter week with peak demand

On day 16 – 18, the storage is not being charged as baseload plants' capacity has been fully employed. For example, when the wind blows again on days 19-20, the storage is charged.

LD-PHES can also help balance the electricity system during low-demand conditions (e.g. in summer) with high renewable output. However, the wind in summer is relatively low, and the solar output has a constant diurnal pattern, so the flexibility from LD-PHES may not necessarily be visible as clearly as in the previous case. The balancing of the system can also be provided by demand response and exporting power to Europe, shown on day 67-68 of the lower graph in Figure 3-16.

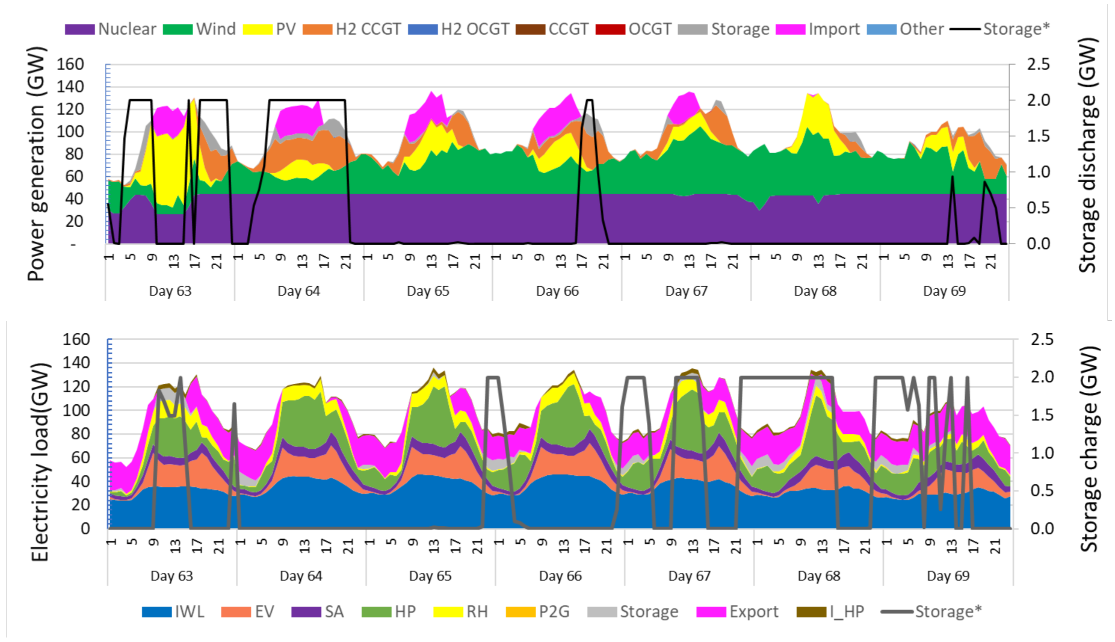


Figure 3-16 Charging and discharging of LD-PHES in a summer week with low demand

We also investigate the number of mode changes: charging (or pumping) and discharging (or generating) cycles of the LD-PHES across one year. We identify the number of transitions from storage charging to discharging and vice versa. The storage does not need to be charged or discharged at maximum, but it must be at a minimum level, e.g. 10%. If there is no mode change, e.g. if the storage continues to charge or discharge (although the level may vary and it may go to zero but not changing the mode), it is counted as 0[10]. The results are shown in Figure 3-17.

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[10] It does not mean that LD-PHES is doing nothing; it means that LD-PHES continues to charge or discharge during that day and there is no mode change (i.e. switching between charging and discharging).

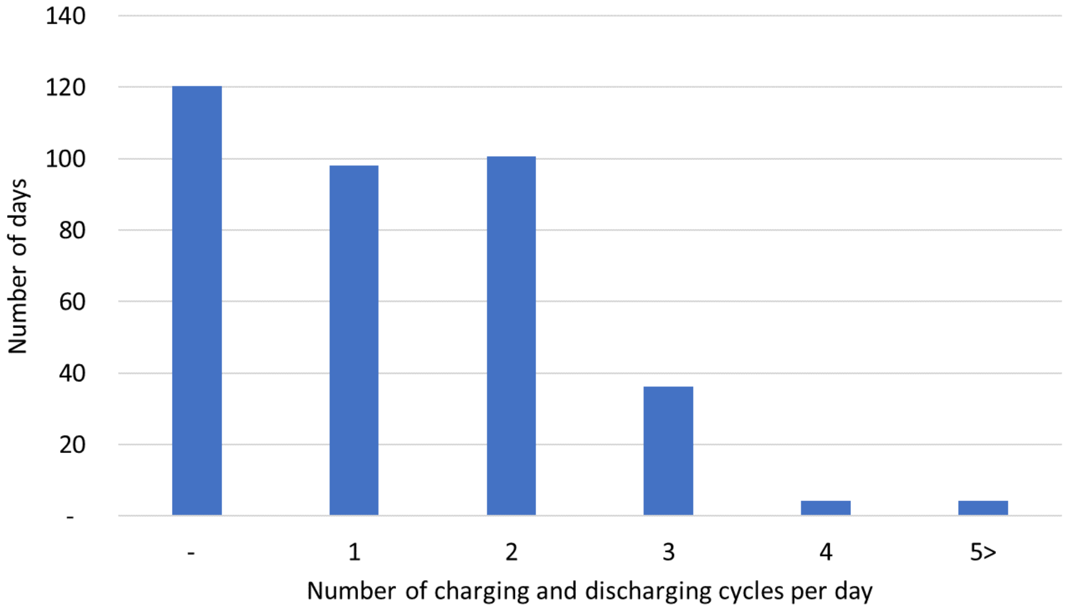

Figure 3-17 Number of charging and discharging cycles of long-duration storage per day

In around 88% of the time, the number of storage cycles per day is between 0 – 2. There are infrequent occasions where the number of storage cycles is more than 2.

The number of cycles is also affected by the presence of demand response. We compare the number of storage cycles per day in a system with and without demand response. The results are presented in Figure 3-18.

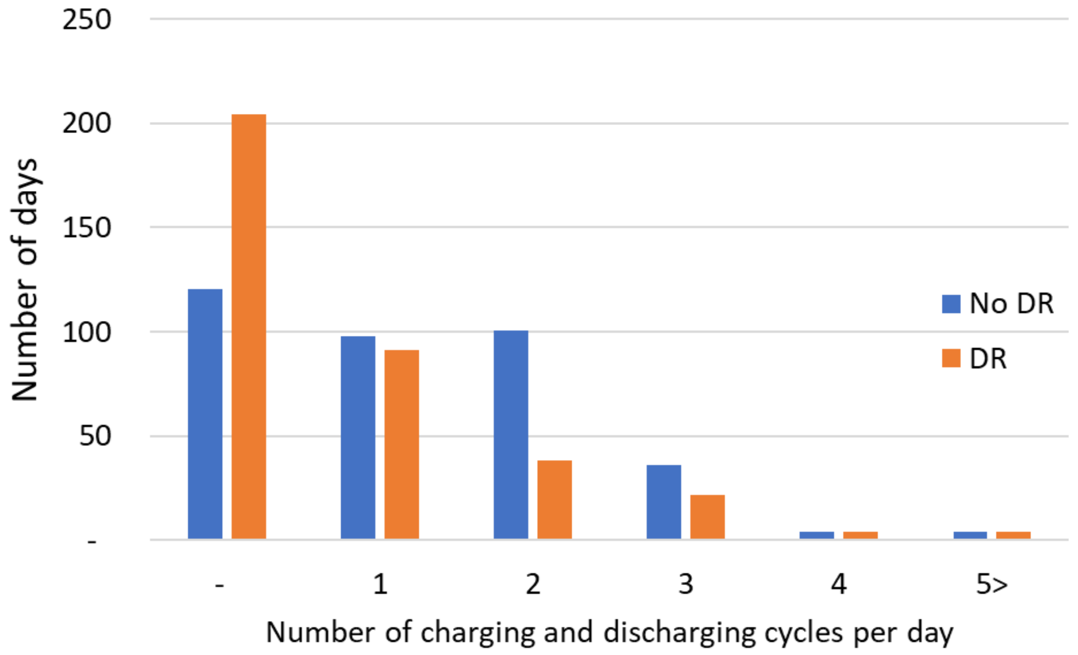

Figure 3-18 The impact of DR on the LD-PHES number of cycles per day

With demand response, the number of cycles decreases. For example, there are more than 200 days when there is no transition between charging and discharging in the case with demand response. It is compared with around 120 days in the system without demand response. The difference is also visible when the storage needs to change polarity twice in a day. In a system with DR, the number is 38 compared to 101 in a system without DR. It demonstrates that the demand for short-term balancing is less for LD-PHES since this flexibility service can also be provided by demand response.

We also investigate the number of storage cycles per day for the shorter-duration storage (i.e. 10 h) and compare it with the results of LD-PHES (100 h). The results are shown in Figure 3-19.

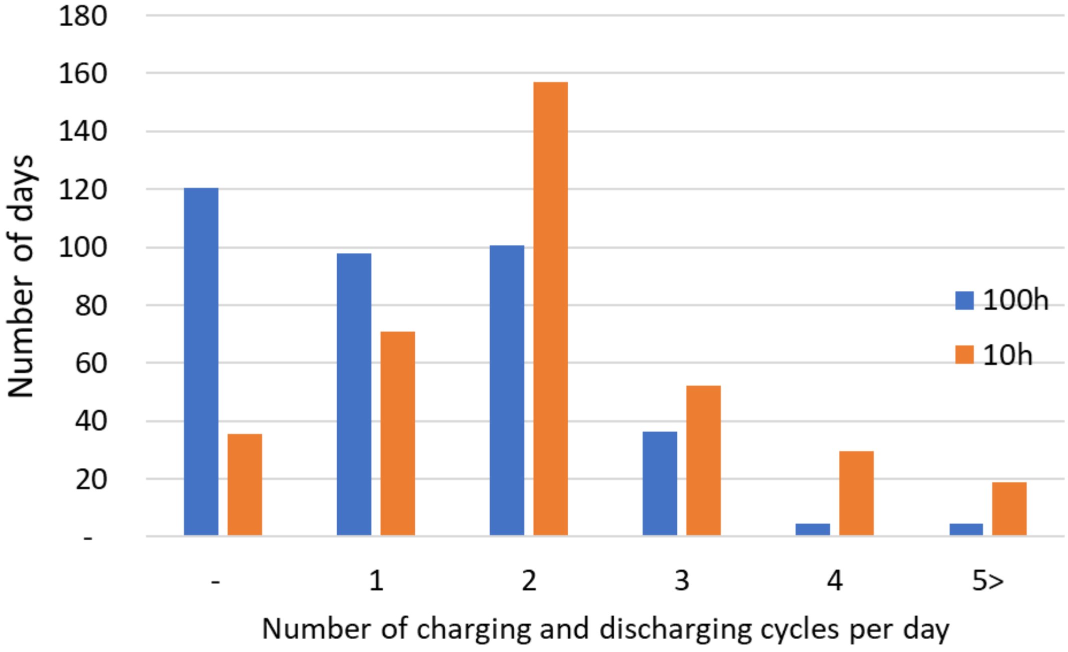

Figure 3-19 Number of charging and discharging cycles of storage per day for 10h and 100h energy storage capacity

The results demonstrate that shorter duration storage cycles more often than LD-PHES. The number of days without changing polarity decreases from 120 to 35 when the storage capacity duration becomes 10h. The number of days when storage has two cycles/day increases from 100 to 157 with the shorter duration storage. The increased number of cycling may affect the plants' wear and tear and increase its operating and maintenance cost. Although this topic is not investigated in this study, it may warrant further investigation.

3.7 Impact of a prolonged period of extremely low wind conditions

The previous analysis demonstrates how LD-PHES can be dispatched to generate electricity during 3-days low-wind conditions which coincide with the peak demand. There is uncertainty on how long low-wind period may occur in future. In this context, we carry out further analysis by extending the period of extremely low-wind output to one week and two weeks to investigate the impact on the value of LD-PHES. The system savings attributed to the 2GW 200 GWh storage for a system designed to withstands against prolonged low-wind periods during peak demand are shown in Figure 3-20.

The value of 2GW 200 GWh LD-PHES does not change significantly when the low-wind duration is extended from 3 days to 1 week. This is reasonable given that 100 h energy storage can provide continuous support for one week, considering the diurnal variation of electricity demand. Extending the low-wind period to 2 weeks has a substantial impact on the storage benefits; the savings plummet from around £371m to £121m per year.

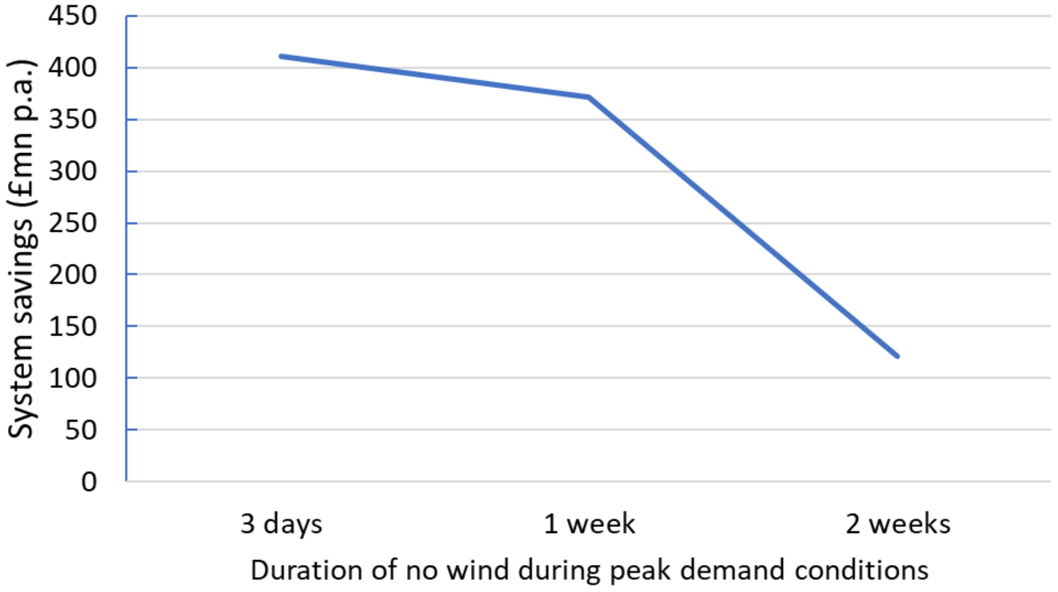

Figure 3-20 System savings of LD-PHES in a system with prolonged periods of extremely low-wind conditions

In order to deal with a two-week low-wind period, longer duration storage will be required. Without sufficient storage capacity, the storage can not substitute firm low-carbon generation (such as nuclear, hydrogen-based generation, CCS) and reduce the system costs.

3.8 Impact of seasonal thermal storage

Seasonal thermal storage is also seen as an alternative technology to store energy across different seasons, such as storing excess solar energy in summer and using it for heating in winter, to relieve system scarcity during peak demand. By reducing the heat-led electricity demand during peak demand conditions, especially when the generation capacity is limited, seasonal thermal storage can also reduce the need for firm low-carbon capacity. In this context, there may be competition between seasonal thermal storage and long-duration electricity storage. Therefore, we carry out studies to understand how seasonal thermal storage will affect the value of long-duration electrical storage. We compare the system savings of the long-duration electrical storage with and without seasonal thermal storage. The results are presented in Figure 3-21.

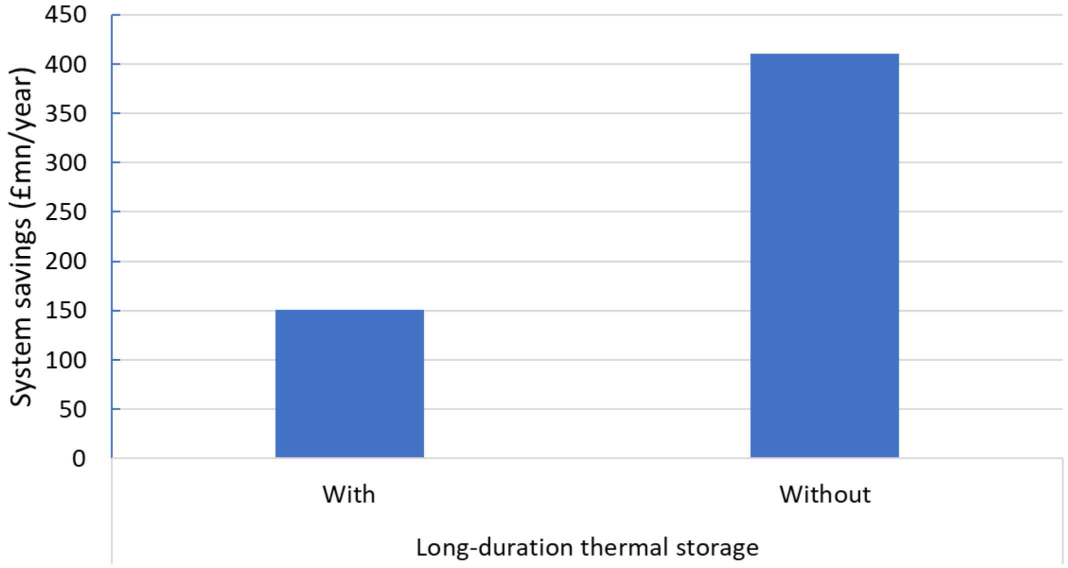

Figure 3-21 System savings of 2 GW 200GWh LD-PHES in a system with and without seasonal thermal storage

The results demonstrate that the value of LD-PHES reduces significantly in a system with seasonal thermal storage. The savings attributed to the long-duration storage reduce from £410m to £150m/year in the system with seasonal thermal storage.

From all the previous analyses discussed, we can conclude that the value of LD-PHES is system-specific and reduced by other flexibility sources such as demand response, seasonal thermal storage, and interconnectors. However, in the presence of other technologies, the value of LD-PHES is still considerable, indicating the synergy across different flexibility technologies.

Chapter 4. Review of the market and policy framework for long-duration PHES

In chapters 2 and 3, the system benefits of the LD-PHES under different future system development scenarios have been quantified. However, the current electricity market frameworks cannot capture the benefits of LD-PHES fully. Therefore, it may become a commercial barrier for the technologies to be developed and deployed in the system. This section uses the previous analysis to demonstrate the issues and outline a few approaches to stimulate more discussions in this area.

Key highlights

- The benefits of flexible technologies that allow more efficient investment in low-carbon generation technologies, are not yet recognised fully. More than 75% of the benefits of LD-PHES are in this segment.
- The CfD mechanism is designed to support investment in low carbon generation only, and it does not recognise the role and value flexibility technologies (such as energy storage) in facilitating cost-effective decarbonisation. Also, in its current form it would not be appropriate to support LD-PHES as the payments are based on the energy output, which is not appropriate for energy storage technologies. Possible existing approaches are “cap and floor” or Regulated Asset Base (RAB) model.

For example, based on the study described in section 2.1, the benefits of LD-PHES in the electricity system are shown in Figure 4-1.

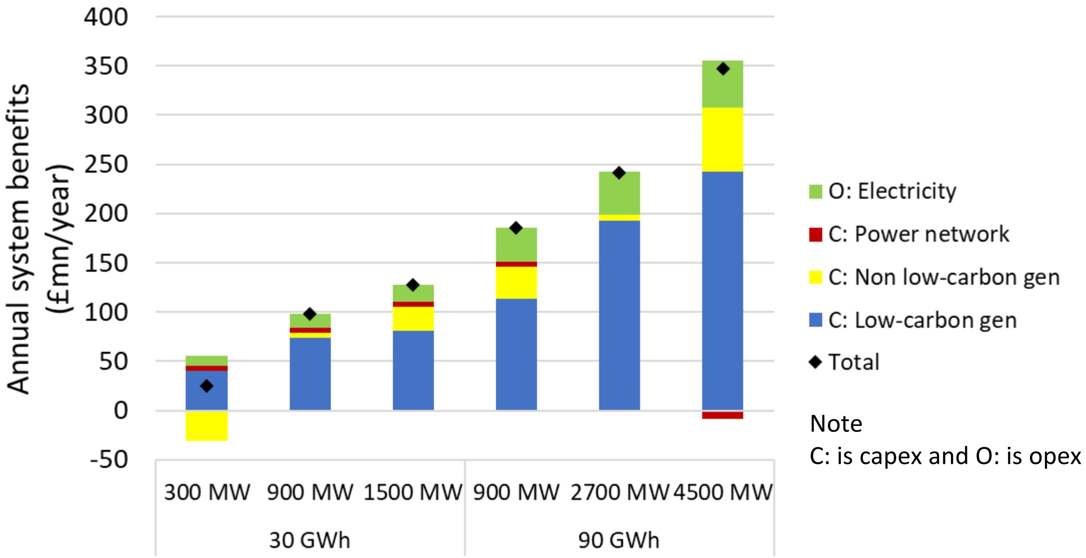

Figure 4-1 Annual system benefits of LD-PHES

The benefits of LD-PHES can be summarised as follows:

- It enables more cost-effective integration of variable renewables and reduces the need for higher-cost firm low-carbon generation technologies (such as nuclear, hydrogen-based generation, CCS). Considering the rapid reduction in wind and PV cost in the past few years, the ability to integrate more renewable generation would bring significant economic benefits. Thus, LD-PHES would reduce the investment cost in low-carbon technologies while meeting the carbon target.
- It contributes to security during peak demand, and therefore, it has a capacity value. Therefore, the presence of LD-PHES can also reduce the need for peaking or back-up plants.
- It enables more efficient generation investment since the increased renewables may shift some mid-merit plants such as CCGT to lower-cost peaking plants (OCGT).
- It helps to optimise network capacity by managing network congestion more efficiently.
- It improves the efficiency of system operation by reducing costs associated with the provision of frequency response and balancing services

The system benefits of the LD-PHES should be recognised and remunerated properly in electricity markets to incentivise technology development and deployment.

Figure 4-2 shows the links between the different value of LD-PHES to the current electricity market frameworks. For example, the capacity value of the LD-PHES can be remunerated in the capacity market. Similarly, network congestion services, energy arbitrage and frequency response services can be rewarded through network charges, wholesale electricity market, balancing mechanisms, and ancillary service market (although the design of ancillary services market would need to be enhanced to reflect more accurately the impact and changes of system inertia on the value of services). However, these revenue streams are highly uncertain, depending on several factors, many of which are discussed in this report.

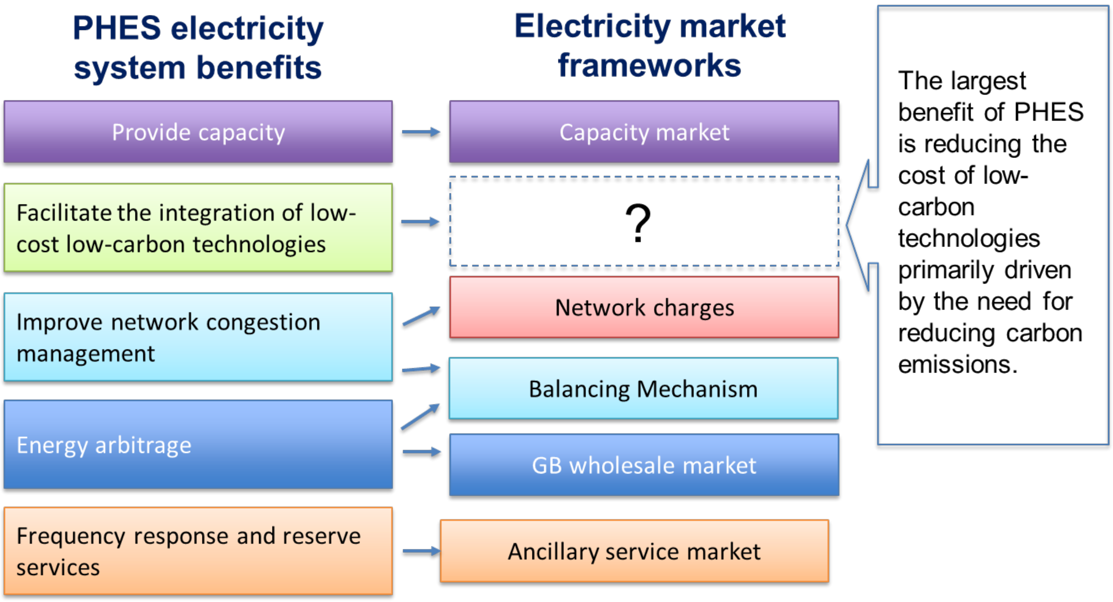

Figure 4-2 Commercial frameworks for long-duration energy storage

There is a significant gap in the present market framework that needs to be addressed since the current market framework does not recognise the benefit of flexible technologies that allow more efficient generation investment, especially in low-carbon technologies. As shown previously, the largest benefit of LD-PHES is minimising the capex of generation investment driven by security consideration and carbon reduction target. Therefore, it is important to have a commercial framework that recognises such value to provide appropriate economic signal and incentivise the development of suitable flexibility technologies such as LD-PHES.

The contracts-for-difference model (CfD) was designed to support the development of low-carbon technologies such as wind, solar, biomass, nuclear. The model uses an auction-based model to determine the strike-price, assuming a certain volume of expected energy generation across the contracting period. The energy generated will be qualified for payment at the strike price. However, the current CFD concept does not recognise the benefit of flexibility that long-duration storage would bring by firming up the low-carbon supply from intermittent renewables, and therefore, LD-PHES cannot access appropriate revenues**.** Furthermore, CfD in its current form would not be the appropriate instrument to support LD-PHES as the payments are based on the output, which is more suitable to generation technologies and not for storage.

The market framework should recognise that cost of long-duration storage technologies like PHES, have relatively high upfront capex and low opex, meaning there is a significant hurdle for investors given the uncertainty of currently available revenue streams in the electricity market. In this context, a concept similar to "cap and floor" model used to de-risk investment in interconnectors could be an appropriate model as the revenue streams, and operational profile is more similar to PHES. Revenues would be made in the various electricity markets segments, but the instrument would de-risk revenues to a floor level, reflecting the societal benefit of PHES and the return required for the investment.

As an alternative, the development of LD-PHES could also be incentivised using regulated asset base (RAB) model. It requires government intervention and may not provide a level playing field and facilitate competition between different technologies. In this model, part of the commercial risks in the investment of the technology would be socialised.

This would need to be linked with CfD, as LD-PHES would significantly reduce system integration costs of variable renewable generation and them more competitive from the whole-system perspective.

Another option may be to develop a real-time carbon price market that would capture the system's investment and operating cost to meet the carbon target. In this case, it can provide appropriate economic signal and incentive for the LD-PHES to support the integration of renewables and reduce the capacity required for high-cost firm low-carbon technologies. The development of such a market framework or the alternatives warrants further analysis. Moreover, there is also a need to investigate further how the cross-sector benefits of LD-PHES, can be recognised, e.g. the impact on hydrogen infrastructure.

Chapter 5. Conclusions

Based on the preceding analysis in Chapter 2 – 4, the key findings are summarised as follows:

- New LD-PHES will have the following roles in the GB future energy transition to a net-zero emission system:

    - It Improves integration of variable RES and firms the output of low-carbon energy, especially during low renewables output.
    - It reduces the need for high-cost firm low-carbon energy sources (such as nuclear, hydrogen-based generation, CCS).
    - It provides ancillary services and capacity (displacing capacity of mid-merit and peaking plant).
    - It supports network congestion management.
    - It allows arbitrage that can improve the utilisation of baseload or RES plant.

- The value of new LD-PHES varies widely depending on system conditions and carbon targets. The analysis demonstrates that the value in 2030 with 50g is much lower than the value in 2050 with 0g carbon target. High value is driven by net-zero emission target which drives the need for firm low-carbon energy sources and

    - High RES penetration, e.g. driven by low wind LCOE;
    - Low level of other system flexibility, e.g. limited availability of demand response technology;
    - The system is designed to cope with a prolonged period of low renewable output during peak demand; this will drive the need for long-duration energy storage.
    - Ability to provide ancillary services, e.g. frequency response will be very important in the future low-inertia system;
    - Insufficient network capacity between Scotland and England or limited boundary capacity;
    - High ratio between energy storage capacity and power rating, but higher power rating facilitates stronger network congestion management.

- There are competition and synergy between the LD-PHES with other flexibility sources.

    - The presence of other flexibility resources, such as demand response, reduces the value of LD-PHES, but its value is still considerable, suggesting that the long-duration storage technology is synergetic with other flexibility sources.

- COVID-19 pandemic led to a reduction in electricity demand and the coincidence with large renewable outputs, created conditions that were not expected until renewable capacity increases more significantly. The ancillary-services costs increased by £200m in

May to July 2020 compared to the same period in 2019 (a threefold increase), highlighting the importance of ancillary services in low-carbon systems. In this context, it may be appropriate to consider early deployment of established technologies that can provide flexibility services, including frequency response, such as PHES.

- In the future, long-duration storage will provide more valuable frequency response (benefit of about £500m/year in the extreme case with no frequency regulation provided by other flexibility technologies/systems). Long-duration PHES can charge for a significantly longer period, so it can be ready to disconnect while pumping for a much longer period and therefore provides ancillary services more frequently. The studies with different scenarios and PHES designs, including the variable-speed PHES, demonstrate that:
    - For 20 GW of wind, the value frequency response provided by PHES in pumping mode is limited, while for 60 GW of wind, the value is significant
    - In the context of frequency regulation, variable speed does not bring much value, even with high penetration of wind.
    - Long-duration storage provides more valuable frequency support (additional benefit of about £400m/year from a 2-day duration PHES compared to a 5-h duration PHES, in the extreme case of absence of other flexibility technologies/systems), as the LD-PHES can keep pumping for a longer period and therefore provides ancillary services more frequently (particularly during low- inertia periods).
    - Increased wind generation capacity, combined with LD-PHES, can efficiently replace firm low carbon generation (such as nuclear, hydrogen-based generation, CCS): both system-operating costs and carbon intensity can be reduced.
    - In an extreme weather year, with two consecutive weeks without wind energy, LD-PHES could effectively provide firm capacity if enhanced wind-forecasting techniques are available: improved forecasting would allow charging the LD-PHES tank sufficiently before the periods with very low or no wind production.

- Large thermal storage reduces the value of long-duration electrical storage as it can be used to adjust heat-led electricity demand across a long period.

- There is cross-energy vector benefit of LD-PHES since it can reduce demand for H2 storage. It indicates a stronger coupling between a low-carbon electricity system with the hydrogen system.

- The development of market and policy frameworks for LD-PHES warrants further analysis.
    - The benefits of flexible technologies that allow more efficient investment in low-carbon generation technologies are not yet recognised fully. More than 75% of the benefits of LD-PHES are in this segment.
    - A CfD in its current form would not be the right instrument to support LD-PHES as it pays based on output, which is more suitable to generation technologies and not storage.

  - Approaches similar to "cap and floor" or regulated asset base (RAB) model would be more appropriate.
  - Real-time carbon price market may provide economic signal and incentive for LD-PHES to firm the output of variable RES.
- Moreover, there is also a need to investigate further how the cross-sector benefits of long-duration storage, e.g. the impact on hydrogen infrastructure, can be recognised and dealt with by suitable market frameworks.

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