LDES NODE WP2 - Techno-economic Analysis

Final Report

PREPARED FOR

Electricity North West

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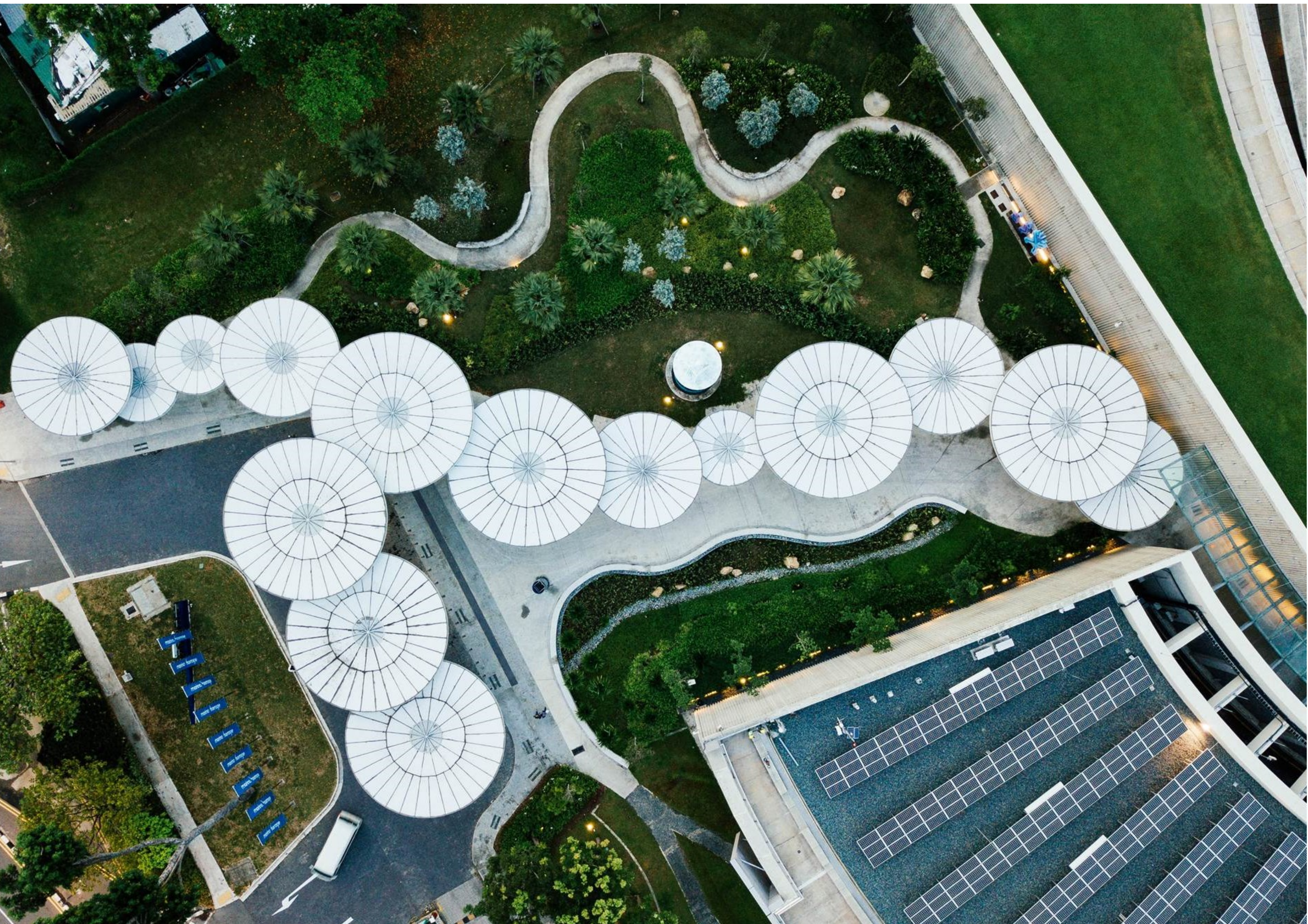

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

Acronyms	Description
A-CAES	Adiabatic compressed air energy storage
CAES	Compressed air energy storage
CSP	Concentrated solar power
COP	Coefficient of performance
DNO	Distribution network operator
GES	Gravitational energy storage
LAES	Liquid air energy storage
LAEP	Local area energy plans
LCOS	Levelized cost of storage
LDES	Long duration energy storage
Li-ion	Lithium-ion battery
TRL	Technology readiness level

Acronyms	Description
VRFB	Vanadium flow redox battery

EXECUTIVE SUMMARY

This report presents the findings of the techno-economic analysis of long duration energy storage (LDES) as part of the Discovery Phase of the Long Duration Energy Storage for Network Optimisation, Decarbonisation and Efficiency (LDES NODE) project, funded through the Strategic Innovation Fund.

The aim of the LDES NODE project is to create a proof-of-concept methodology for mapping LDES technologies to the Electricity North West (ENWL) network, with specified use cases and cost considerations. This is done to shed light on the benefits that LDES can bring to distribution networks operators (DNOs) and to local authorities in the UK. This is a step forward in further understanding the role of LDES technologies, the importance of which has been assessed at the national level but not yet at the local level. This report is, to our knowledge, the first detailed study of these more localised benefits at distribution network and local authority levels, and is intended to lay the groundwork for further exploration of the local impacts of LDES technologies, feeding into the development of local area action plans (LAEPs).

The techno-economic modelling undertaken in the Discovery Phase of the project has considered a total of 13 technologies, spanning across the 4 LDES categories: mechanical, thermal, electrochemical, and chemical. Technologies are compared against each other on the basis of their levelized cost of storage (LCOS), which is calculated in two ways to allow like for like comparisons:

- On an electricity output basis: in this comparison, which is the primary method used in this analysis, only technologies that discharge electricity are included.
- On a heat basis: in this comparison all technologies are included, but technologies that discharge electricity are assumed to be connected to a heat pump to allow us to compare electricity storage technologies to heat storage technologies.

The LCOS is calculated for each technology for a wide range of discharge durations and discharge frequencies. Services required by the distribution network have also been mapped to combinations of discharge durations and frequency, enabling the technologies to be linked to the services they are well placed to provide.

The results of the study showed that for longer duration energy storage, molten salt and adiabatic compressed air energy storage (A-CAES), are the most cost-effective technologies, with compressed air energy storage (CAES) being second most cost effective.

The absence of hydrogen as a cost-effective technology for longer duration energy storage is due to a combination of current cost and lifetime assumptions of hydrogen storage technologies as well as technology efficiencies. Indeed, we have found that the cost effectiveness of hydrogen is sensitive to changes in charging and discharging costs. In the future, these might reduce as the technology matures, up to the point where it is more cost-effective than CAES. This study considers current cost and performance estimates for LDES technologies, but technology development and cost reductions will be considered in further phases of work.

Several benefits that LDES technologies can offer the distribution network and local areas have been identified, including curtailment reduction and network management. Mapping these to the most cost-effective technology provides a basis for understanding how these technologies can help the grid and offers a starting point for more detailed analysis in the future. The results from this study can therefore inform which types and where LDES technologies can be deployed across the distribution network to meet network needs.

1. INTRODUCTION

As the UK transitions toward a low-carbon energy system, the importance of long duration energy storage (LDES) becomes increasingly evident. While to-date primarily considered a transmission grid asset, in this project LDES is reevaluated in the context of localized energy planning. Indeed, by addressing curtailment and network management issues, it may find a more prominent role within distribution networks. In addition, LDES technologies can become part of local area energy plans (LAEPs), which are expected to play a pivotal role in enabling UK grid decarbonisation by 2035.

This report presents a techno-economic analysis of a range of LDES technologies and maps them to the various services they can provide, with a focus on services to the distribution networks and the benefits provided to local areas where LDES technologies are deployed. Li-ion battery technology is also considered within the array of LDES technologies and used as counterfactual, due to its relevance in the UK energy landscape. This is, to our knowledge, the first such report in the UK and is intended to lay the groundwork for further exploration of the benefits that LDES technologies can deliver to distribution networks and the local areas they serve.

2. LDES TECHNOLOGIES

In this analysis 13 LDES technologies are considered, as seen in Table 1. These technologies can be classified into four broad categories, see below, as well as further into parent categories, where some of the technologies considered are different configurations of the same parent storage technology (i.e. using fuel cells and gas turbines to convert from hydrogen back to electricity are considered as separate technologies in the report, although they fall within the same parent technology of hydrogen storage).

2.1 LDES CATEGORIES

LDES technologies are generally separated into four broad categories:

- **Mechanical LDES technologies** – In mechanical LDES technologies, energy is stored by converting it to another form with the help of mechanical equipment such as compressors, flywheels, etc. Mechanical LDES technologies are the broadest range of LDES technologies, utilising a variety of methods and systems to store energy, such as: gravity (converting to potential energy), compression (increasing system energy by increasing pressure), motion (storing energy as kinetic energy), change of phase (using the latent energy of phase changing to store energy).

  Examples: pumped hydro energy storage, compressed air energy storage, liquid air energy storage, etc.

- **Thermal LDES technologies** – In thermal LDES technologies energy is stored as heat in a certain material, to be used when needed. Depending on the phase of the material, there are two categorisations:

- Sensible heat systems, in which there is no material phase change and the storage material's temperature increases.
- Latent heat systems, in which there is a phase change and the latent heat released during that change is utilized.

Examples: molten salt, district heating hot water storage, miscibility alloy, etc.

- **Electrochemical LDES technologies** – In electrochemical LDES technologies energy is stored as a chemical system by converting from one form of energy into chemical potential energy. There are two large classifications:
  - Metal anode systems, which are the traditional batteries where the energy is stored in the electrochemical difference between the metallic anode and cathode.
  - Flow battery systems, in which there are two electrolytic liquids that are pumped to enable ion exchange.

  Examples: Li-ion batteries, vanadium-redox flow batteries (VRFB).

- **Chemical LDES technologies** – In chemical LDES technologies energy is used to produce another chemical which can be stored, thus storing the embedded energy. The most relevant example of this is hydrogen storage, in which hydrogen is created using electricity through an electrolyser and is then stored to be used for energy production through fuel cells or turbines.

  Examples: Hydrogen

2.2 TECHNOLOGIES CONSIDERED

In this analysis only technologies with a technology readiness level (TRL) of at least 7 were considered, as defined by IEA [1]. The TRL index takes into account global technology updates and is commonly used as the reference when it comes to determining technology maturity levels. A TRL of 7 denotes pre-commercial demonstration. Technologies considered in this analysis are shown in Figure 1, alongside their corresponding TRL.

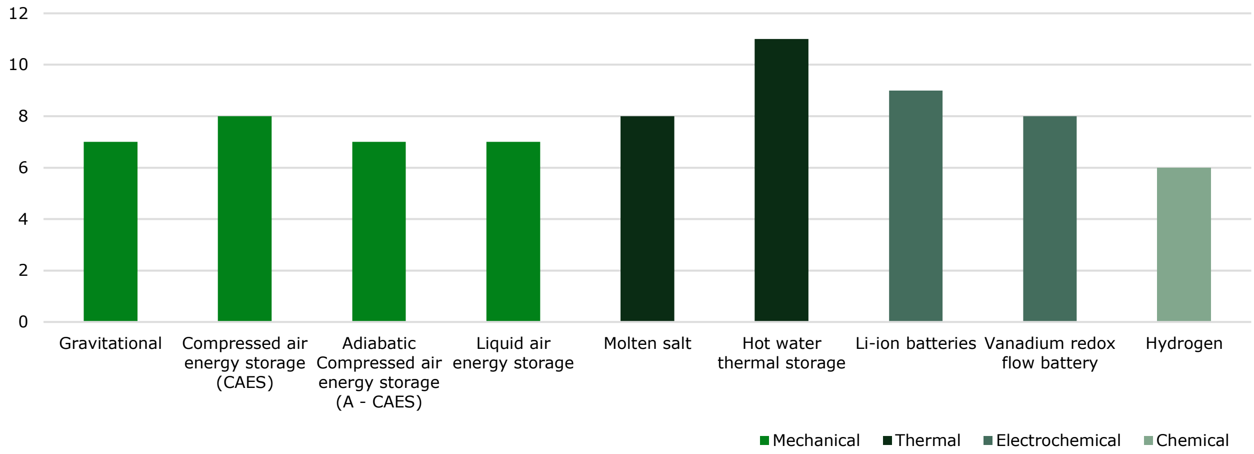

FIGURE 1: TRL LEVEL OF LDES TECHNOLOGIES CONSIDERED

Other storage technologies that were reviewed but not selected for the analysis are shown in Appendix A.

Below are short descriptions of the technologies.

2.2.1 GRAVITATIONAL ENERGY STORAGE

Technology Description: Gravitational energy storage works by using electric motors to lift solid weights when charging which are lowered under gravity when electricity discharge is needed. By controlling the height and velocity of the weights lowered, the power and energy output of the system can be controlled.

The system revolves around electric motors which can be used for both the charging and the discharging phases – charging when they are used to lift the blocks and discharging when the weights are lowered, and at this point the electric motor works as an electricity generator. The exact motor type used is not readily available information, but the ability to operate both as a generator and as a motor at larger scales will likely mean that it is a synchronous AC motor.

Two designs for gravitational energy storage projects are available based on the designs of two of the main technology developers:

- The first is an overground manmade structure, as seen in the G-VAULT design by Energy Vault (shown in Figure 2).

FIGURE 2: ENERGY VAULT DESIGN [2]

- The second utilizes existing mineshafts or other existing holes for the elevation needed with a modular system installed at the top. As seen in the GraviStore design by Gravitricity (shown in Figure 3).

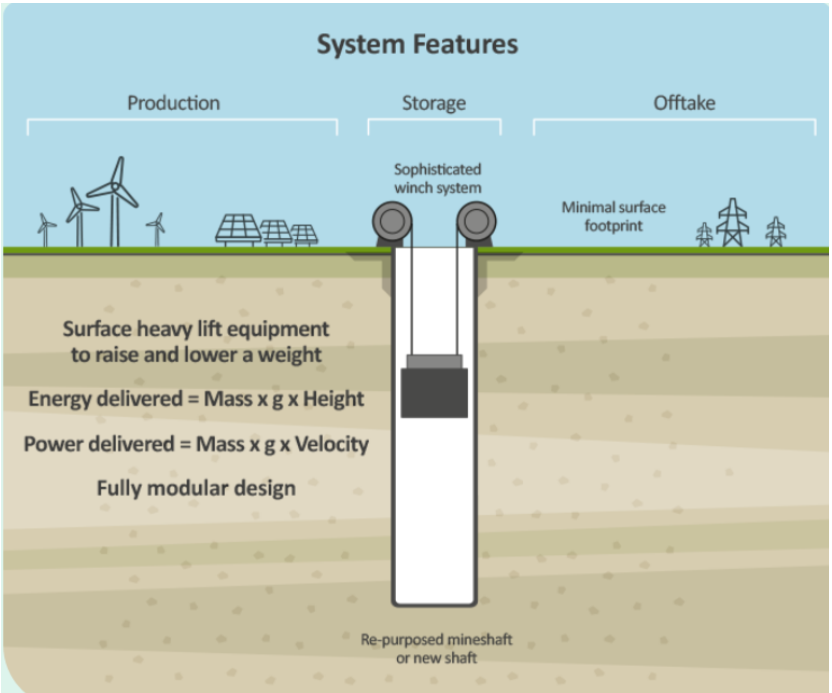

FIGURE 3: GRAVISTORE DESIGN [3]

Due to the limited publicly available information on the costs of these technologies, a single gravitational energy storage system is considered in this analysis that represents an overground gravitational energy storage system. This means that there are no geographical constraints to the system.

2.2.2 COMPRESSED AIR ENERGY STORAGE

Technology Description: Compressed air energy storage (CAES) works by using a compressor to compress air which is stored at an elevated pressure and temperature (typically underground but overground in pressure vessels is also possible) to be utilised for electricity generation through an air turbine when energy discharge is required.

Two main CAES technologies are considered:

- The first is diabatic CAES (shown in Figure 4) also referred to as simply CAES. In these systems the heat of compression is not stored and is lost to the environment. Because of this there is need for excess energy to re-heat the air after expansion in the turbine so that icing is prevented which decreases the efficiency of the process. In the system shown in Figure 4 this re-heating is provided by a natural gas heating system, but this can be electricity as well.

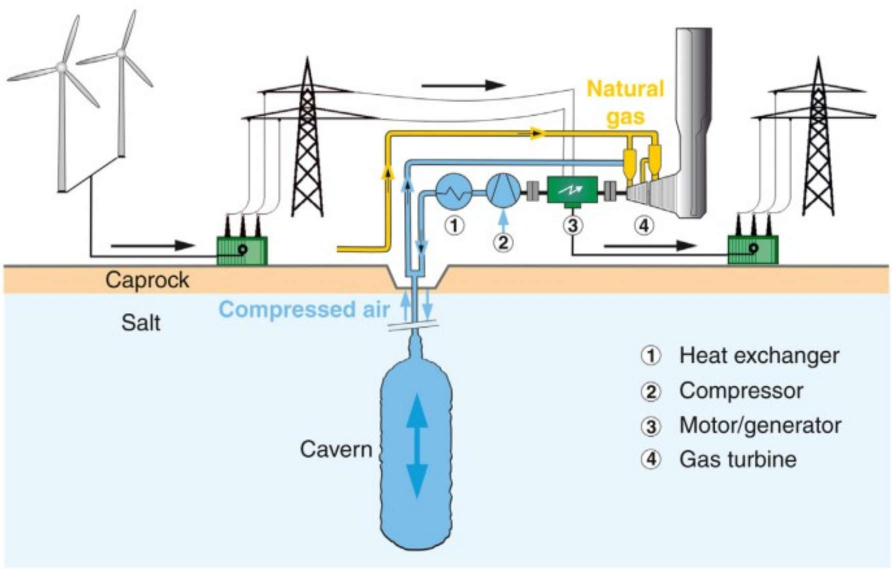

FIGURE 4: DIABATIC CAES SYSTEM, WITH NATURAL GAS USED FOR RE-HEATING AIR [4]

- The second is adiabatic or advanced CAES (shown in Figure 5) referred to as A-CAES. In these systems compression heat is stored and is used to re-heat the air, increasing the system efficiency.

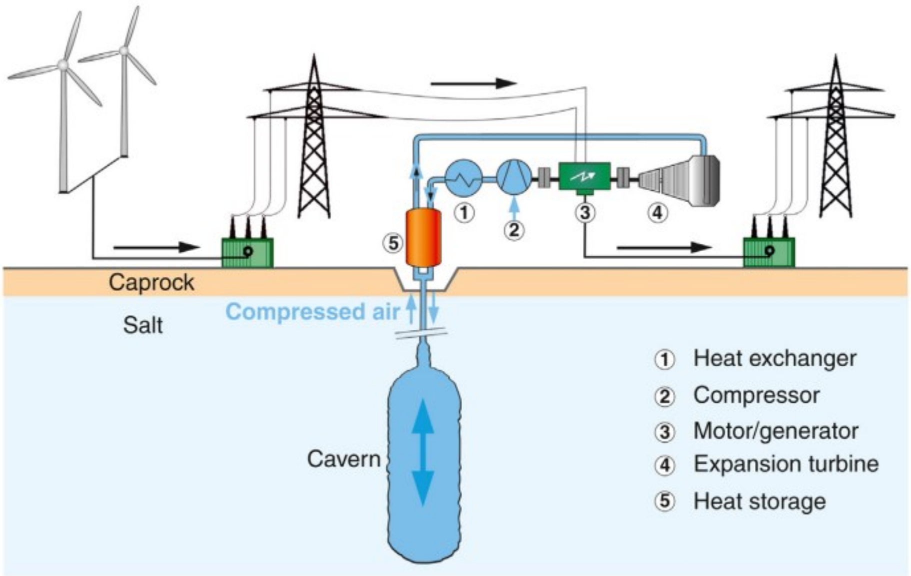

FIGURE 5: ADIABATIC CAES SYSTEM, STORED HEAT USED FOR RE-HEATING AIR [4]

Both the CAES and A-CAES systems considered in this analysis have salt-domes as the storage location of the compressed air. The reason for this is that some form of underground storage is needed for compressed air due to the low energy density which would require a large volume to store. This means that CAES and A-CAES systems are considered to have a geographical constraint in this analysis in the form of a salt cavern.

2.2.3 LIQUID AIR ENERGY STORAGE (LAES)

Technology description: Liquid air energy storage (LAES) works by using a compressor to compress air to high pressures and cools it so that it can liquify. The liquid air (cryogenic) is stored in a low-pressure vessel and is re-heated to high temperatures and pressures to run an air turbine for electricity generation.

There are multiple configurations of this technology with slight adjustments to the concept, but the working concept is similar between them – for this reason a single LAES setup is considered in this analysis to represent all configurations. The general schematic of one such system is shown in Figure 6.

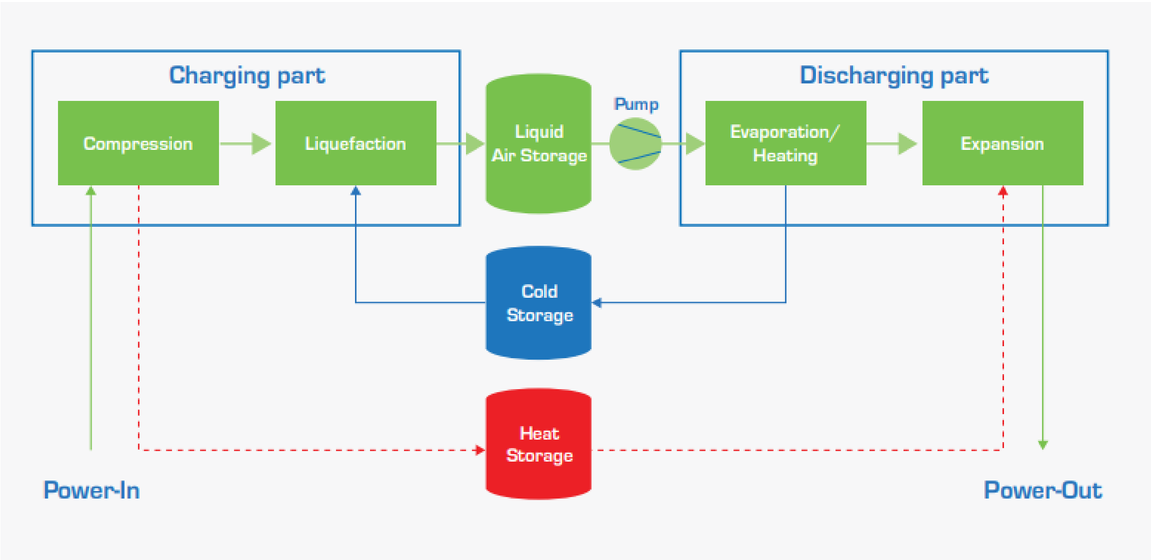

FIGURE 6: SIMPLIFIED WORKING SCHEMATIC OF A LAES SYSTEM [5]

Due to storing air in a liquid phase rather than in a gaseous phase, the storage volume needed is much lower than CAES (which is the most similar technology in terms of working concept), so LAES systems are mostly overground with no geographical constraints.

As can be seen in Figure 6, the heat of compression is stored and used further in the evaporation step. Depending on the size of the system, the heat storage system requirements might increase the system costs and might place minor geographical constrains on the system (a water reservoir might be needed to provide a heat sink for larger systems).

2.2.4 MOLTEN SALT ENERGY STORAGE

Technology description: Molten salt energy storage is a form of thermal energy storage, which works on the basis of using heat to increase the temperature of a molten salt mixture (charging) and using this energy to generate steam for electricity generation via a steam turbine (discharging).

Due to the nature of this technology, unlike the previous ones which are not very configurable, molten salt can very much be configured by changing the charging and/or discharging portion of the system.

FIGURE 7: CSP MOLTEN SALT SYSTEM, WITH RECEIVER TAKING CONCENTRATED SOLAR BEAMS REFLECTED BY HELIOSTATS. [6]

One of the most popular configurations is using concentrated solar power (CSP) to heat the molten salts (Figure 7), but since there is no conversion from electricity to another form of energy this setup is more akin to energy generation than it is to energy storage and thus hasn't been considered in this project.

For this analysis resistive heating will be used instead of CSP due to it being the most popular option when it comes to converting from electricity to the high enthalpy heat needed for increasing the temperature of the molten salt.

The discharge technology in most systems is a steam turbine, but in certain systems the heat may be used directly for long distance heat networks. In this project we are considering a steam turbine as the discharge technology. The working schematic of the system is shown in Figure 8.

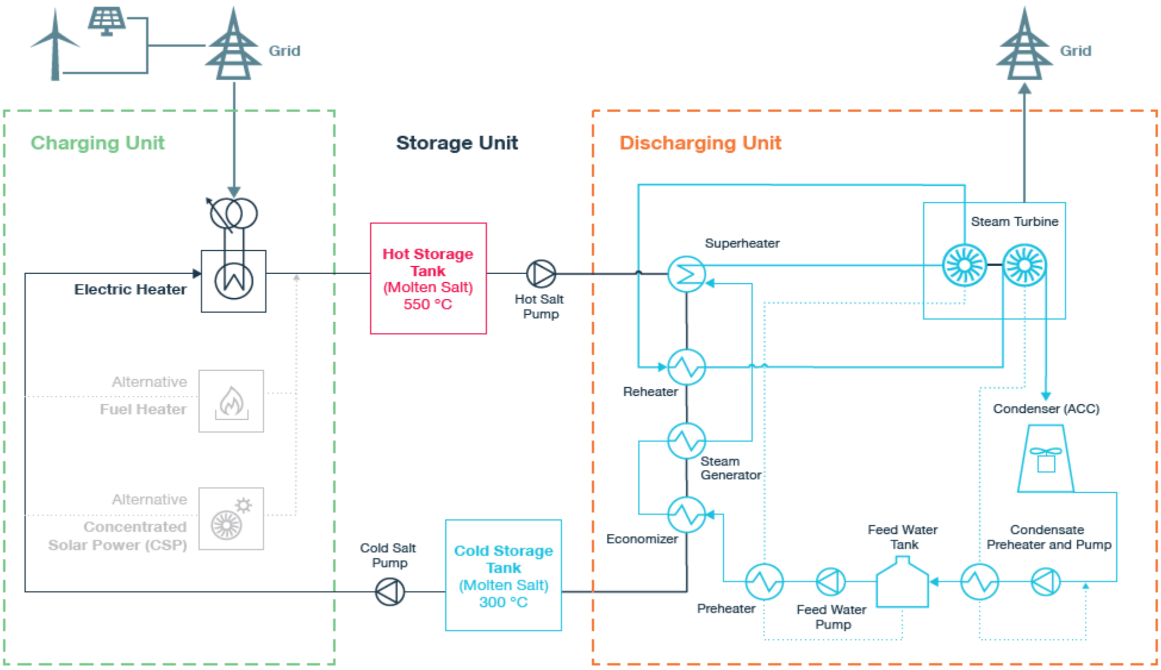

FIGURE 8: WORKING PRINCIPLE OF A MOLTEN SALT ENERGY STORAGE SYSTEM STEAM TURBINE AS THE DISCHARGING TECHNOLOGY [7]

2.2.5 VANADIUM FLOW REDOX FLOW BATTERIES

Technology description: Flow batteries are a type of electrochemical storage system, which consists of two chemical components dissolved in liquid separated by a membrane. Charging and discharging of batteries occur by ions transferring from one component to another component through the membrane, which is enabled through the liquids flowing by each other.

In this analysis we are only considering Vanadium redox flow batteries (VRFBs) which is the most popular flow battery chemistry. VRFBs are also the only flow battery with TRL 7 or above, which makes them the best technology to consider for this project.

VRFBs use only Vanadium in different oxidation states for both the anolyte and the catholyte. Despite this technology gaining more recognition, it remains an expensive option that operates in the same discharge duration and frequency region as Li-ion batteries and has poorer efficiency. There are no geographical constraints for this technology, and there is little that can be done in terms of different configurations so it will be analysed as a one-off technology. A working schematic of the technology is shown in Figure 9.

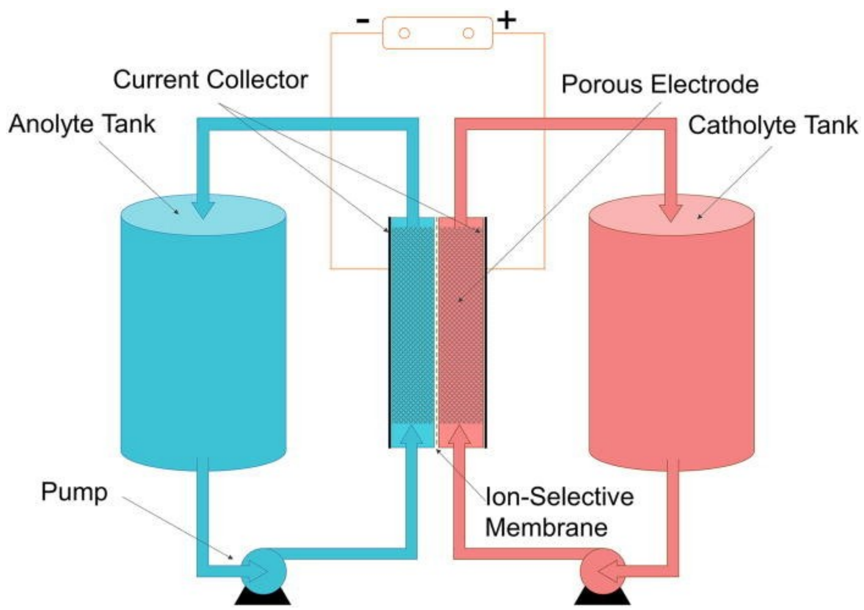

FIGURE 9: FLOW BATTERY DIAGRAM [8]

2.2.6 HOT WATER THERMAL STORAGE SYSTEMS

FIGURE 10: 3MW WATER HEAT PUMP AT CASTLE PARK IN BRISTOL, USED FOR DISTRICT HEATING [9]

Technology description: Hot water storage systems can be a convenient way to store energy as heat, usually where there is a nearby heating demand. Water is stored in well-insulated tanks and heated using heat generated by electricity (in this analysis), of from any alternative heat source.

Hot water energy storage is a well-established way of storing heat, and it is different from the other technologies considered in this analysis because it does not provide electricity as the output, but rather the heat stored in the hot water. An example of an installed system is shown in Figure 10.

These systems are applicable at large scale to heat distribution networks, which are normally installed in densely populated areas. In this analysis we are considering two energy input technologies for producing the thermal energy to heat up the water:

1. **Resistive heating** which can be easily installed to any hot water system regardless of geography.
2. **Heat pump** which is much more efficient compared to resistive heating but may require a large body of water in the case of water-source heat pumps.

In this project we are assuming a ground source heat pump, which for the purpose of this analysis we assume to have no geographical constraints.

2.2.7 LI-ION BATTERIES

Technology description: Li-ion batteries work on the basis of a solid Li-ion cathode and normally a graphite anode that are separated by an electrolyte, which only allows positively charged Lithium ions through. The direction of flow of the ions determines the charge or discharge of the battery.

Li-ion batteries are one of the most common forms of electrical energy storage, and present a number of advantages such as very high energy density, lower costs, scalability, etc.

While Li-ion batteries are very popular they are not yet used for longer duration energy storage, with discharge durations typically being <4 hours. For this reason, they are not considered as an LDES technology in this analysis but are used as a counterfactual. Li-ion batteries have no geographical constraints and there are no alternate charge/discharge configurations. With Li-ion there is a potential risk of supply issues in the future due to Lithium being a scarce metal, with deposits unevenly spread throughout the world.

A working schematic of this technology is given in Figure 11.

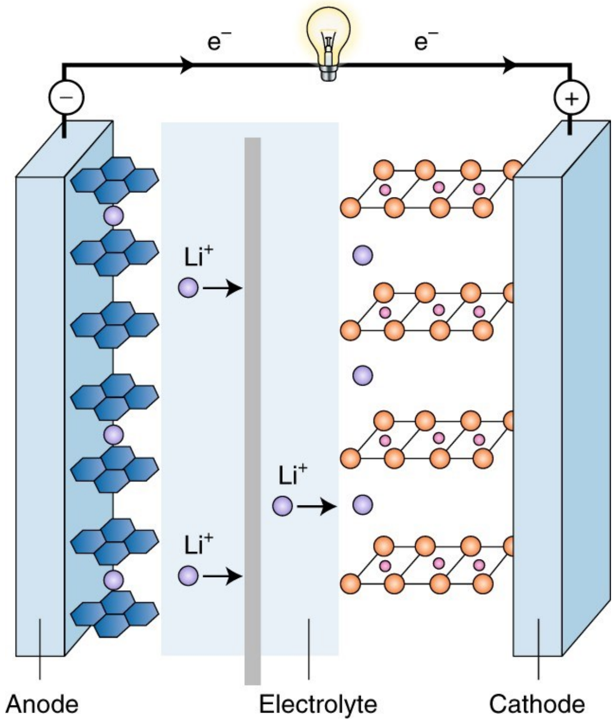

FIGURE 11: LI-ION CELL DIAGRAM [10]

2.2.8 HYDROGEN ENERGY STORAGE

Technology description: In this analysis we consider hydrogen produced by an electrolyser, which is stored at high pressure, ready to be converted back to electricity via either a fuel cell or gas turbine.

The hydrogen storage system can be separated into the charging side (the conversion to hydrogen and pressurisation stage), the actual hydrogen storage, and the discharge (the reconversion to electricity).

On the charging side we have only considered alkaline electrolysis as it is currently the lowest cost technology available to convert electricity to hydrogen.

For storage we consider two options:

1. Storing the hydrogen in naturally occurring underground salt caverns. This is the most cost-effective storage method but puts a geographical constraint on the system.
2. Storing in pressurised vessels, which can be above ground and are not constrained to locations where there are suitable geological formations.

On the discharge side we are also considering two options:

1. Using a PEM fuel cell to convert the hydrogen to electricity. This method has a higher upfront cost, but better efficiency compared to a gas turbine.
2. Using a gas turbine to convert to electricity, which is less efficient but cheaper.

The combination of the options above creates four hydrogen storage configurations that will be considered in this analysis.

2.3 TECHNOLOGY CONSIDERATIONS

Considering all the above there is a total of 13 combinations of 8 different technologies considered in this analysis, shown in Table 1.

TABLE 1: DIFFERENT TECHNOLOGIES AND COMBINATIONS CONSIDERED IN THIS ANALYSIS

Parent technology	Combinations	Geographical constraint	Discharge energy type
Gravitational energy storage (GES) (2.2.1)	Only one generic system		Electricity
Compressed air energy storage (CAES) (2.2.2)	Diabatic CAES (referred to as only CAES)	Requires salt cavern for storage	
	Adiabatic CAES (A-CAES)	Requires salt cavern for storage	
Liquid air energy storage (LAES) (2.2.3)	Only one combination – LAES	-	
Molten salt energy storage (2.2.4)	Resistive heating molten salt	-	
Flow batteries (2.2.5)	Vanadium redox flow battery (VRFB)	-	Electricity
Hot water thermal storage (2.2.6)	Hot water storage with heat pump	-	Hot water (thermal)
	Hot water storage with resistive heating	-	
Li-ion battery (2.2.7)	Only one combination – Li-ion	-	Electricity
Hydrogen (2.2.8)	Hydrogen (salt cavern + fuel cell)	Requires salt cavern for storage	Electricity
	Hydrogen (salt cavern + H2 GT)	Requires salt cavern for storage	
	Hydrogen (pressure vessel + fuel cell)	-	
	Hydrogen (pressure vessel + H2 GT)	-	

3. METHODOLOGY

This section gives details on the methodology used for the analysis, which involves a levelized cost of storage (LCOS) comparison of the technologies on a heat and electricity basis. More details are given below. A high-level explanation of the methodology is shown in Figure 12.

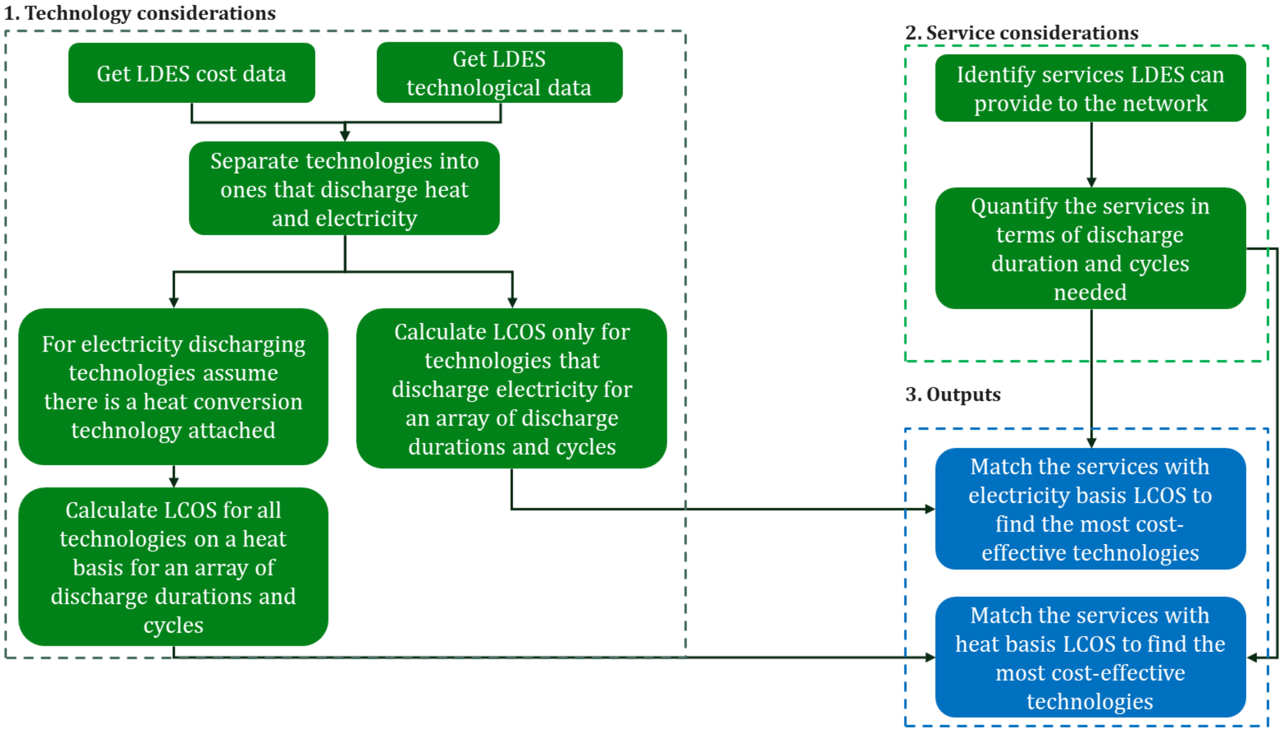

FIGURE 12: OVERVIEW OF TECHNO-ECONOMIC ANALYSIS

The technology cost and performance data can be found in Appendix B.

3.1 LEVELISED COST OF STORAGE

The LCOS is a cost indicator which considers both technical (efficiency, operation lifetimes, etc) and cost components of the technology. In doing so it allows for a more accurate and holistic comparison between different technologies, on an annualised and levelised basis.

Due to different storage technologies discharging different forms of energy, to compare between the technologies a unified vector of energy is needed. The only technology considered that produces heat instead of electricity is hot water storage – therefore we will compare the technologies based on their LCOS which will be calculated on both a heat and electricity discharge basis.

All technologies will be compared on a heat basis, whereas only the electricity discharging technologies will be compared on an electricity basis (this only excludes hot water storage).

To calculate the heat-basis LCOS for all technologies we are assuming that the electricity discharged is converted into heat using a heat pump. The addition of a heat pump for conversion to heat adds another CAPEX, OPEX, and a conversion efficiency to the calculation. The LCOS will be calculated for combinations of discharge durations and cycles per year, for some set installed capacity. So, for a given power (MW) capacity, the energy (MWh) capacity and the cycles per year will vary. The formula for calculating the LCOS is given below.

$$\text{LCOS}\left(\frac{£}{\text{MWh}}\right) = \frac{\text{Investment Cost} + \text{Operating Cost}}{\text{Energy discharged}}$$

Table 2 given the explanation for different component of the LCOS calculation shown in the formula above.

TABLE 2: FACTORS AFFECTING THE LCOS

LCOS Factors	Explanation
Investment cost	The investment costs include the annualised CAPEX of the storage, charge, and discharge equipment for each LDES technology.
Operating costs	The operating costs include charging costs, which in most cases will be the electricity cost as well as the O&M and other consumable costs.
Energy discharged	The annual energy discharged which is used to levelized the costs.

Assumptions used in the LCOS calculations are:

- An average electricity cost of 0.2 £/kWh is assumed. Note that this is almost the same as the current retail price in the UK (2024); in reality, electricity will likely be imported at times of lower prices, thus the average import price will be lower than this.
- A hurdle rate of 5% is assumed across all the technologies to annualise the capital costs.

More details on these calculations can be found in the Appendix C.

3.2 LDES SERVICE MAPPING

An integral part to the techno-economic modelling is identifying the services that LDES technologies can offer the network and quantifying their technical requirements in terms of the discharge duration and the cycles required. Using the technical requirements (discharge duration and cycles) for each service we are able to map between the services and the relevant LCOS for each technology, i.e. the LCOS when operated to meet the technical requirements of the service. This mapping is done by correlating the discharge duration and frequency range of each with the technologies that are cost-effective for that same range, thus presenting which technologies are best suited for each service.

The LCOS then serves as the basis for comparing the cost-effectiveness of the technologies for each of the services. For most of the services, electricity is required as the output, so we are only comparing LCOS on an electricity discharge basis, however, if the service requires heat as the output, then we can also compare the LCOS of technologies on a heat discharge basis.

This comparison will be the main output of the analysis, alongside the data gathered on each of the technologies, which will be used in subsequent phases of the project.

4. TECHNO-ECONOMIC RESULTS

In this section the results of the techno-economic analysis are presented. Please note that unless otherwise specified, the results refer to the electricity basis analysis. This means that only technologies that discharge electricity are taken into account for the analysis. The heat basis analysis is only done in Section 4.5.

4.1 MOST COST-EFFECTIVE TECHNOLOGIES

Figure 13 shows the most cost-effective technology (the technology with the lowest LCOS) for a range of discharge frequencies and durations. Please note that the N/A area is due to an impossible combination of discharge duration and cycling (when duration*cycles > 4380).

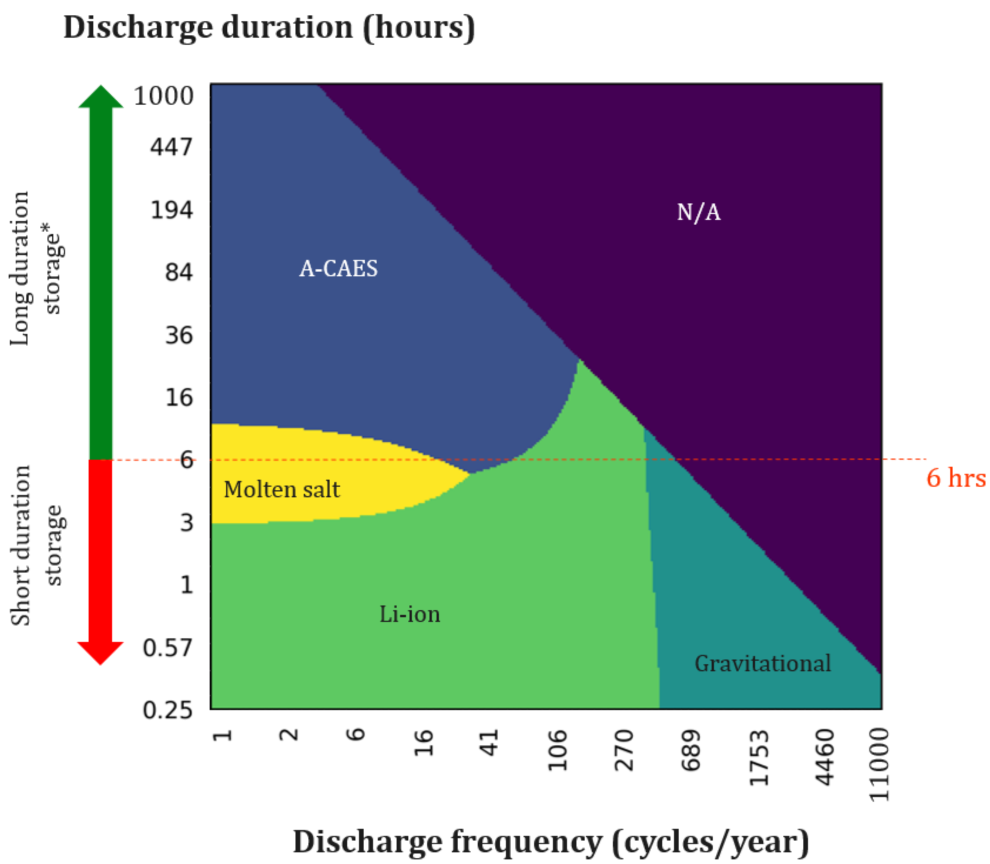

FIGURE 13: MOST COST-EFFECTIVE TECHNOLOGY FOR DIFFERENT DISCHARGE FREQUENCIES AND DURATIONS

The graph in Figure 13, presents the key outcome of the modelling as it shows how the most cost effective technology based on the lowest LCOS value for different discharge durations and cycles.

Although there is no strict definition of what constitutes long duration, in their latest LDES consultation DESNZ propose 6 hours as the cutoff point. In this analysis we have not used any cutoff point, but the 6 hours is used in the graph above to denote this convention. As can be seen in the longer duration region of the graph (>6 hrs), there are 3 technologies that prevail:

- For daily (6 – 24 hrs) discharge durations, molten salt, A-CAES and Li-ion are all cost-effective technologies depending on the discharge frequency, with Li-ion only being cost effective for frequent discharging (>100 cycles/year).
- For longer discharge durations A-CAES is the sole cost-effective technology for all frequencies.

In the shorter duration portion of the graph, Li-ion and molten salt are the most cost-effective for low to medium discharge frequencies, and gravitational energy storage is most cost effective for high-cycling storage.

Figures 14 and 15 show the costs associated with each of the technologies. These are the annualised costs (the annualised costs are the capex costs of the technology annualised using their lifetime and discount rate - more calculation details can be found in Appendix C), and they are helpful to understand the trends seen in Figure 13. Only technologies that are considered in the electricity basis analysis are shown. Annualised charge and discharge power costs (£/kW/y) have been added together to get this cost. The full breakdown for each technology is given in Appendix B.

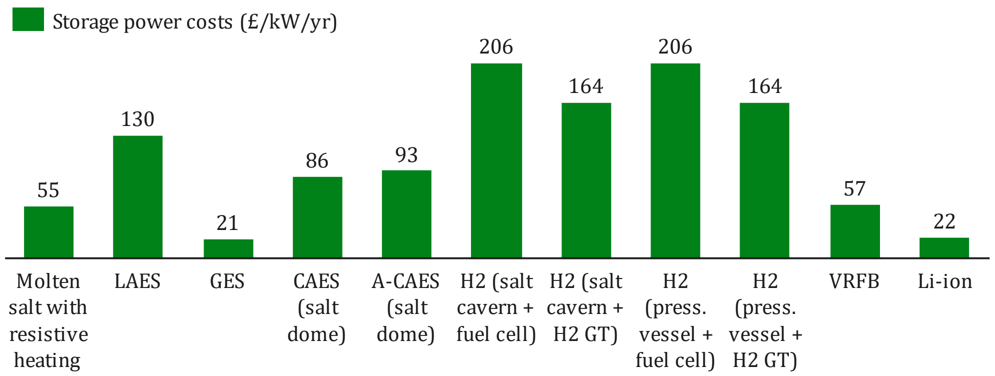

FIGURE 14: STORAGE POWER COSTS OF THE LDES TECHNOLOGIES CONSIDERED

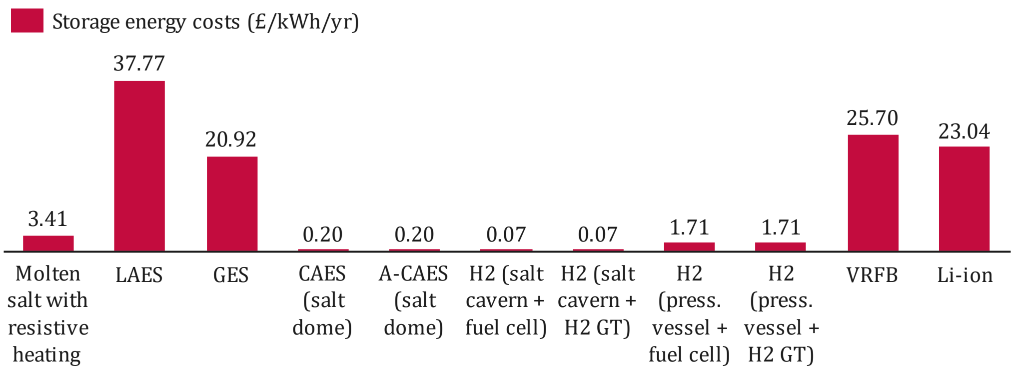

FIGURE 15: STORAGE ENERGY COSTS OF THE LDES TECHNOLOGIES CONSIDERED

For shorter discharge durations, the LCOS is dominated by the power costs (£/kW), since the energy storage capacity is low. This is why we see technologies with lower power costs such as Li-ion and gravitational energy storage (GES) come out as cost effective. For longer discharge durations on the other hand the LCOS is dominated by the storage energy costs (£/kWh) since a large energy capacity is required, for this reason we see technologies such as molten salt and A-CAES storage be most cost effective, with the latter being most optimal for seasonal storage.

While the power and energy costs play an important role, there are other factors that impact the LCOS, such as lifetime in years and cycles as well as the charge/discharge efficiency which determines the operating costs. The difference in efficiency (given in Appendix B) explains why A-CAES is preferred over CAES, despite CAES having a lower power cost.

4.2 FIRST AND SECOND MOST COST MOST COST-EFFECTIVE TECHNOLOGIES

Figure 16 gives a more nuanced view of the costs of the technologies by presenting the second most cost-effective technology as well as the LCOS relative difference between the most cost-effective and the second most cost-effective technology (meaning the ratio of the LCOS difference with the most cost-effective LCOS).

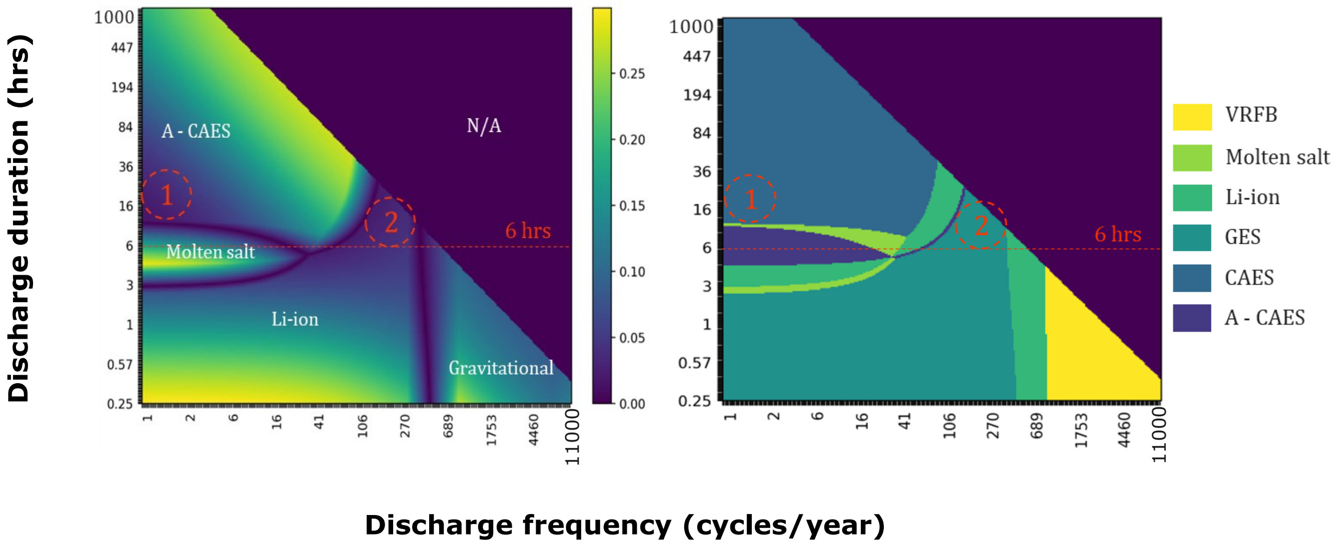

FIGURE 16: LEFT: RELATIVE DIFFERENCE BETWEEN THE TWO MOST COST-EFFECTIVE TECHNOLOGIES; RIGHT: SECOND MOST COST-EFFECTIVE TECHNOLOGY

Looking at both graphs for longer discharge durations (>6 hrs), there are 2 areas that are interesting, denoted in the graphs:

1. The first is in the inter-day (weekly) discharge duration zone where A-CAES is the most cost-effective technology, but the second most cost-effective (CAES) is <5% higher in LCOS. This means that depending on the cost assumptions, in this weekly discharge with low discharge frequency region there can be an opportunity for CAES.
2. The second is in the intra-day, high frequency discharge region, where gravitational energy storage is within 5% of Li-ion and can become a potential substitute.

For other durations/cycling the most cost-efficient technology is by far the most cost-efficient. In the identified areas the differences are small meaning that there is greater uncertainty regarding the most cost-effective technology, such that selection of the cost-effective technology is sensitive to small changes in the cost assumptions.

4.3 IMPACT OF GEOGRAPHICAL CONSTRAINTS

Figure 17 shows the impact that geographical formations such as salt caverns, which in this study are considered as geographical constraints, have on which technology is the most cost effective.

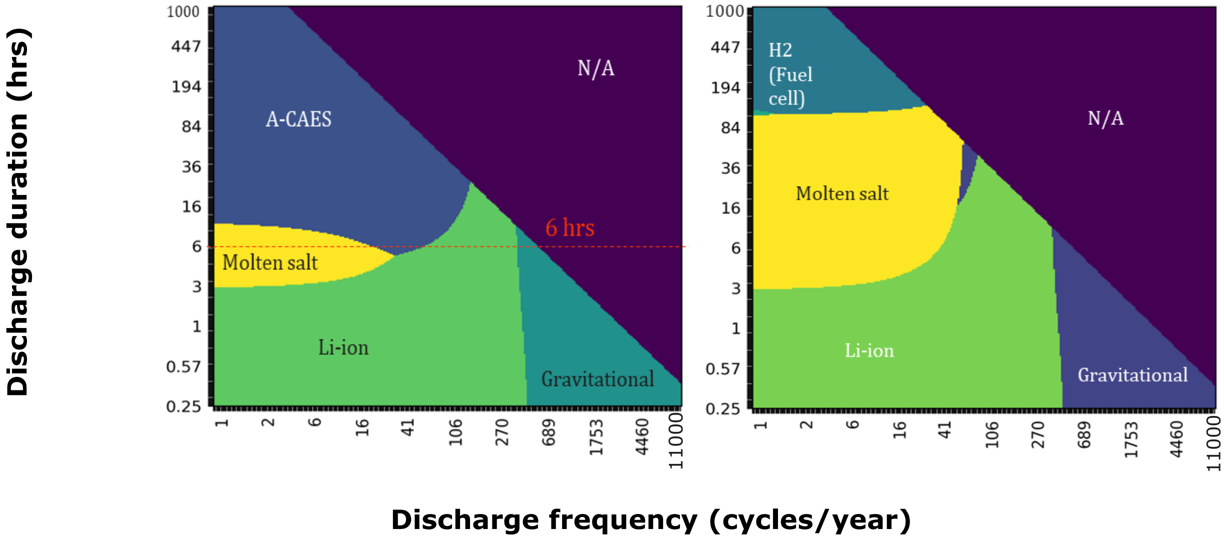

FIGURE 17: LEFT: ALL LDES WITHOUT ANY CONSTRAINT APPLIED (REPRINT OF FIGURE 13); RIGHT: CONSTRAINT OF NO SALT CAVERN APPLIED TO THE TECHNOLOGIES

On the left hand we have a reproduction of Figure 13 which shows the most cost-effective technology when all technologies are considered, whereas on the right are the most cost-effective technologies when only technologies with no geographical constraints (which in this analysis are salt caverns) are considered.

Comparing the two graphs there are two main differences:

- The low-cycling monthly storage region which was dominated by A-CAES earlier is now split between molten salt and hydrogen with a fuel cell. Note this is hydrogen stored in a pressure vessel.
- There is also a slight presence of hydrogen with gas turbine and gravitational in the long duration region of the graph, with the first being in the very infrequent cycling region and the second in the frequent cycling.

Figure 18 shows the LCOS for different technologies at discreet values of discharge durations, to show how the LCOS changes due to the presence of salt caverns. The grey lined technologies are ones that require a geographical formation (salt cavern), whereas technologies with green bars do not have geographical constraints. The red box shows the lowest LCOS for each.

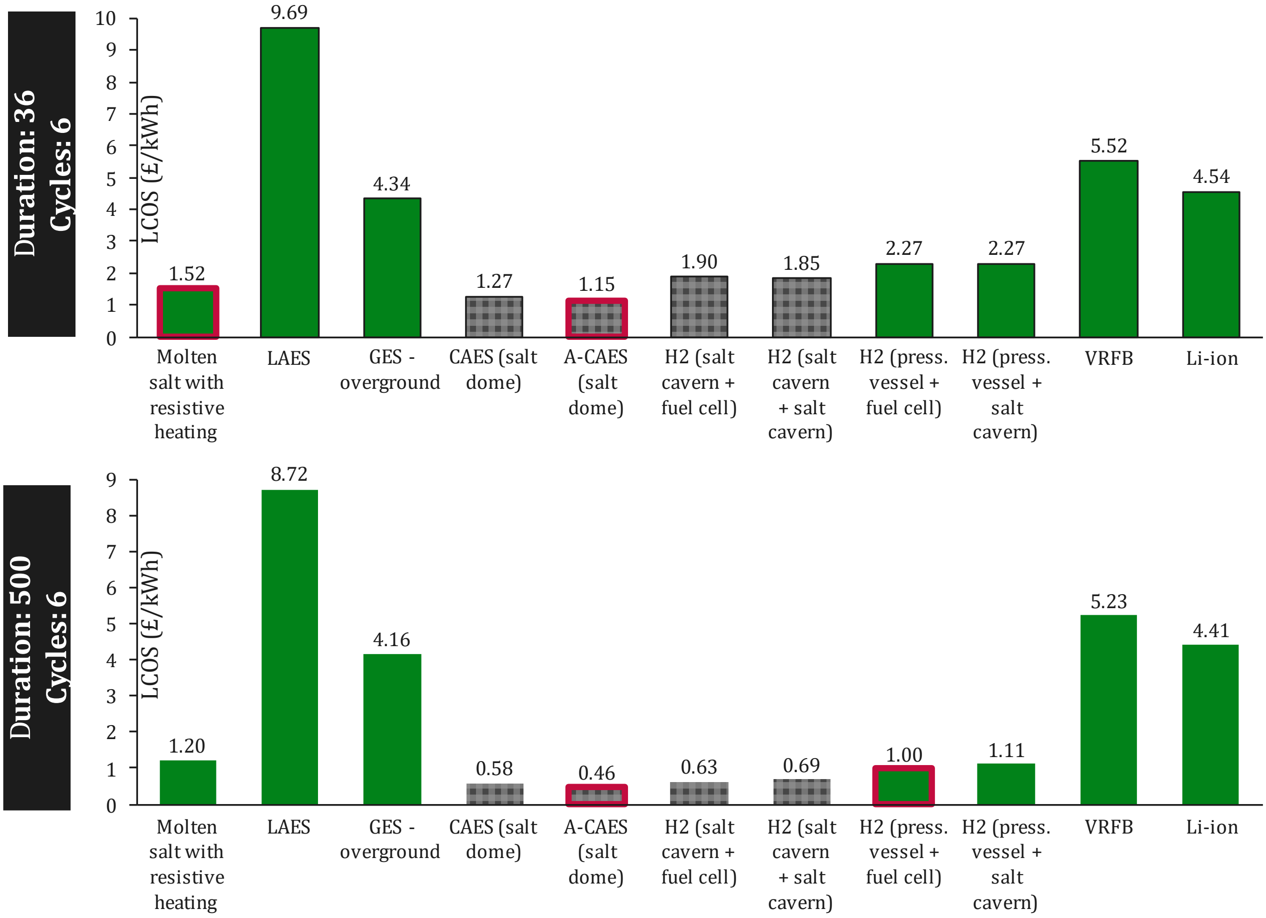

FIGURE 18: LCOS FOR DISCREET VALUES OF DURATION (HOURS) AND CYCLES

As can be seen in Figure 18, for lower durations (top graph) the LCOS increase between A-CAES and molten salt is only 32%, showing that the impact of the presence of the salt cavern is not too large, especially compared to the difference in the bottom graph in which Hydrogen is the most cost-effective technology with a LCOS that is twice higher than A-CAES. This means that having natural formations for storage makes an important difference and might impact the business case significantly, especially for longer duration storage.

Figure 19 shows the LCOS for the technologies for discrete values of discharge duration and cycling in £/kWh. The technology in red is the technology with the lowest LCOS.

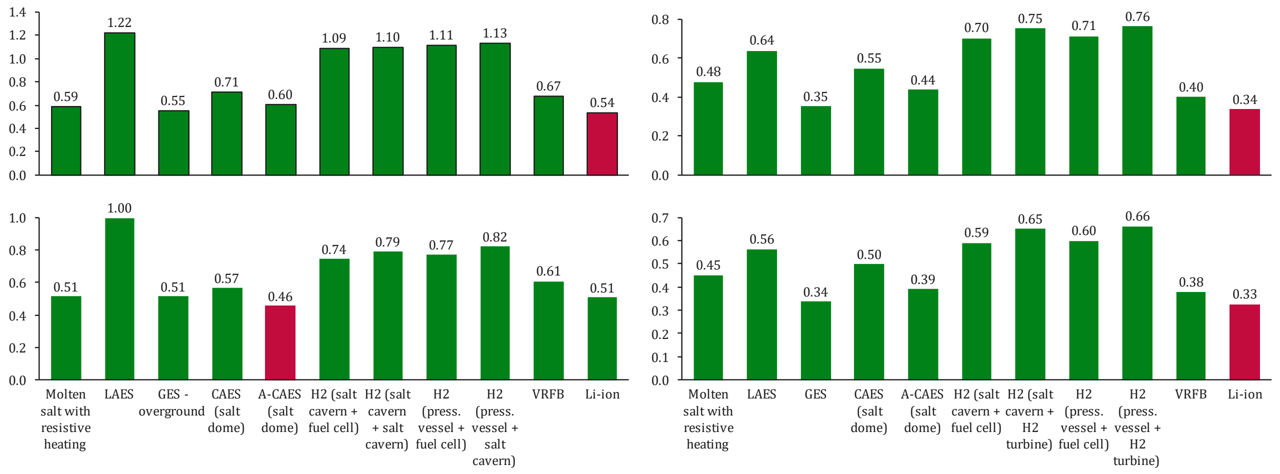

FIGURE 19: LCOS VALUES OF THE TECHNOLOGIES FOR DISCRETE VALUES OF DISCHARGE CYCLES AND DURATIONS

In Figure 19, starting from the top left in a clockwise direction the discharge duration (D) and frequency (F) are:

- **D:** 6 hrs **F:** 100 cycles
- **D:** 6 hrs **F:** 300 cycles
- **D:** 15 hrs **F:** 300 cycles
- **D:** 15 hrs **F:** 100 cycles

By comparing the graphs in the same row, the discharge duration remains the same and when the discharge frequency is increased the LCOS decreases for the same duration. This is to be expected since increasing the cycling means more energy output for a given investment in power and energy which drives the LCOS down. The effect of this decrease will vary between technologies, with technologies that have higher power cost seeing the largest relative decrease in LCOS as is expected due to the above reasoning.

Comparing the graphs in the same column shows the difference in the LCOS when the duration is increased for the same number of cycles. As can be seen increasing the discharge duration also decreases the LCOS for all the technologies, due to the throughput per kW increasing, causing the levelized power cost component to decrease which bring down the total LCOS.

4.4 ROLE OF HYDROGEN

An interesting result of this analysis is the absence of hydrogen as the most cost-effective or second most cost-effective technology, especially for storage applications with longer durations. Figure 20 illustrates the breakdown of the LCOS into different components for a high duration low cycling application (1000 hours, 2 cycles per year) for CAES, A-CAES, and salt cavern hydrogen storage (fuel cell and H2 turbine).

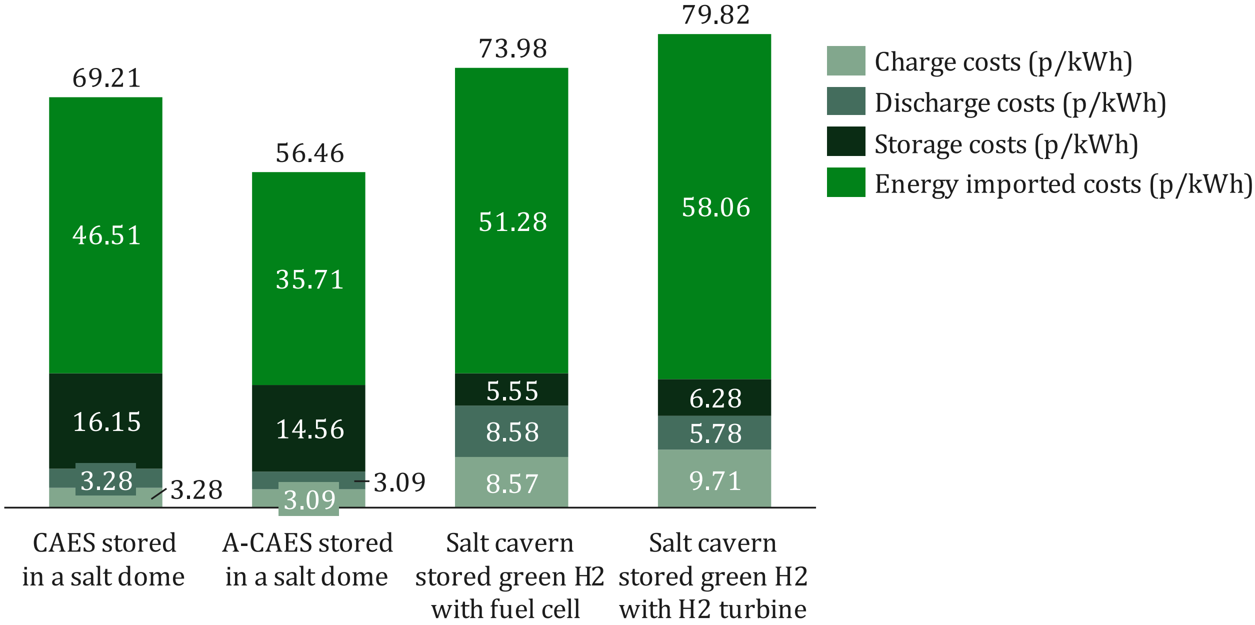

FIGURE 20: LCOS BREAKDOWN FOR CAES AND HYDROGEN TECHNOLOGIES

The explanation of the categories that make up the LCOS are:

- Charge costs – annualised costs of the charging technology.
- Discharge costs – annualised costs of the discharging technology.
- Storage costs – annualised costs for energy storage
- Energy imported costs – costs of the energy imported, based on the 0.2 £/kWh used in this analysis.

Comparing these different costs between the CAES technologies (CAES and A-CAES) and the hydrogen technologies, we notice that the CAES technologies have higher storage costs, but lower charge/discharge and energy imported costs compared to hydrogen, which leads to an overall lower LCOS.

The difference in energy imported costs is solely due to the difference in technology efficiency, with CAES and A-CAES being more efficient than the hydrogen systems with currently available technology, thus requiring less energy for each unit of energy discharged. While with technological improvements the efficiency of a hydrogen energy storage system will increase, there are limits to how much it can increase. Converting from hydrogen to electricity through fuel cells is already quite efficient (with little room for improvement) and converting using H2 GT is thermodynamically limited to about current efficiencies – the main scope for further improvements are electrolysers. . CAES systems are also not expected to change much in terms of efficiency, being already quite a mature technology.

The storage costs are lower for hydrogen compared to CAES due to the nature of the storage systems, despite using the same natural formations to store the gases in, and this is expected to be the case in the future as well. The reason for the difference in storage costs is that hydrogen is compressed only to make it easier to store larger volumes, but the compression does not impact the energy carried, whereas for CAES the energy is stored through compression, thus higher levels of compression are needed. Hydrogen also has a higher energy density compared to compressed air.

The charge/discharge annualised capex costs are currently more than three times lower for CAES systems compared to hydrogen systems, but if we look at the cost per kW of the technologies the difference is much smaller (within 10%, given in Appendix B), thus the large difference in the charge/discharge annualised capex costs is due to the lifetimes used in the analysis for the technologies, which is used for annualising the costs, as detailed in Appendix C. The CAES systems are assumed to have a lifetime of 40 years, whereas the hydrogen systems are assumed to have a lifetime of 20 years. These assumptions are in accordance with current literature (Appendix B). To test the sensitivity of the results to the technology lifetime, both technologies are assumed to have a lifetime of 30 years, and the LCOS results are shown in Figure 21.

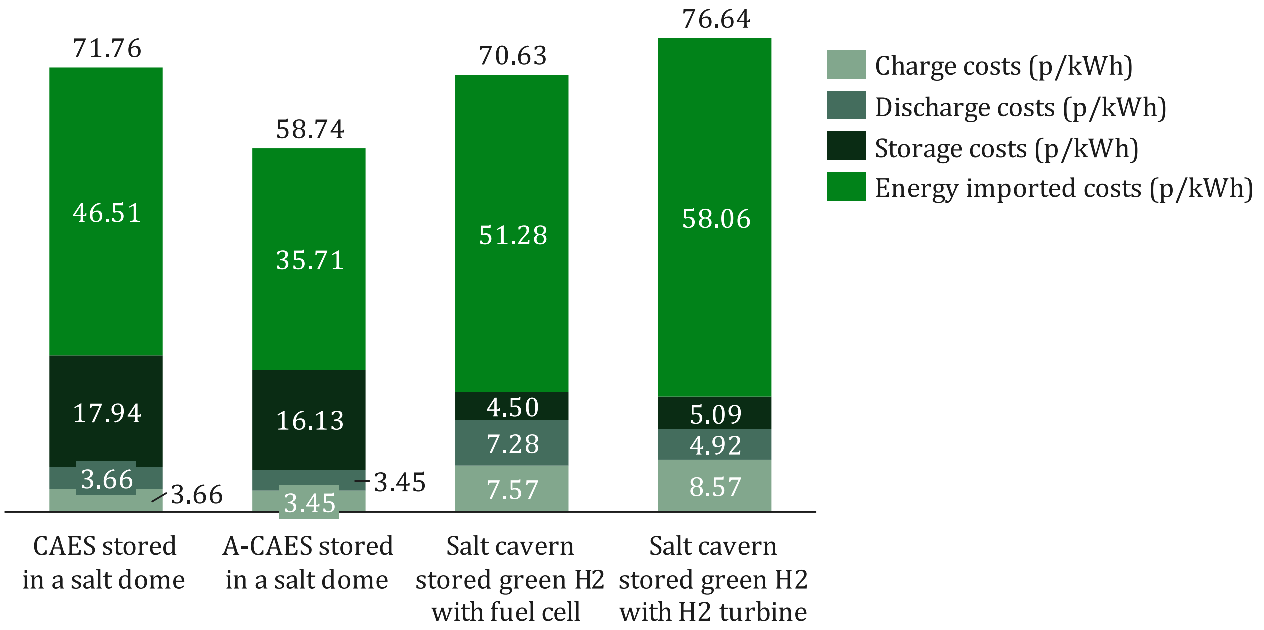

FIGURE 21: LCOS BREAKDOWN FOR CAES AND HYDROGEN SYSTEMS WHEN ASSUMING EQUAL LIFETIMES

As can be seen, the storage and charge/discharge costs decrease for the hydrogen technologies and increase for the CAES making hydrogen technologies more cost competitive with the CAES technologies in this scenario. This shows that these results are quite sensitive to the annualization lifetime, and depending on future technology trends it is possible that Hydrogen becomes the more cost-effective technology for these long duration situations. However, this analysis is focussed on current technology and, under current assumptions, CAES and A-CAES are more cost-effective technologies. This is not surprising considering Hydrogen is technologically less mature than these technologies (it has TRL 6). For shorter durations where the costs are more dominated by the charge/discharge costs as opposed to energy imports and storage costs, it might be hard for hydrogen to compete.

4.5 HEAT BASIS RESULTS

For the heat basis comparison, as detailed in the methodology a heat pump is added to the electricity discharging technologies to unify the energy vector throughout the technologies. The heat pump is assumed to have a COP of 4 (chosen as a good representative value for ground-source/water-source COP value) [11], and the cost data is given in the Appendix B. Figure 22 gives the most cost-effective technology for different discharge durations and frequencies, similar to the approach taken for the electricity basis comparison. The difference here is that hot water storage technologies are also included in the analysis.

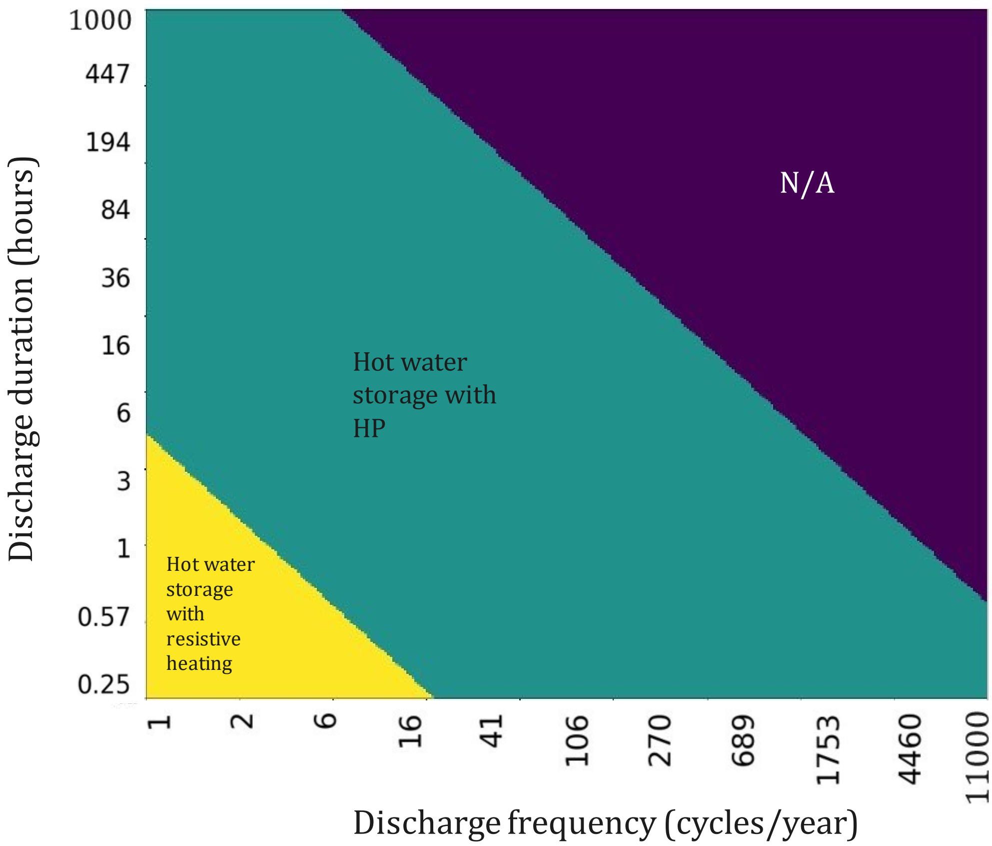

FIGURE 22: HEAT-BASIS MOST COST-EFFECTIVE TECHNOLOGIES

As can be seen in Figure 22 the most cost-effective technologies in the heat-basis comparison are hot water storage technologies, with resistive heating being more cost effective in the lower duration/frequency range (due to its lower efficiency but also lower cost), with heat pump hot water storage being the most cost effective for the rest of the ranges. This result shows that for applications where heat is needed as the final outputs (e.g. district heating), hot water storage is by far the most cost-effective option.

5. OPPORTUNITY SPACE

5.1 LDES SERVICES AND LAEP BENEFITS

LDES technologies can provide several services to the network which vary with duration and cycling. They are shown in Table 3 where they are also mapped to different LDES discharge durations and frequencies.

TABLE 3: LDES SERVICES MAPPED TO LDES CYCLING AND DURATIONS

<table>
<tr><th>Cycling / Discharge duration</th><th>~Daily (1-24 hrs)</th><th>~Weekly (24 – 300 hrs)</th><th>~Monthly (>300 hrs)</th></tr>
<tr><td rowspan="2">Frequent / regular cycling</td><td>• Increase renewable utilisation for regular load e.g. the NW industrial cluster (1)
• Increase new connection capacity on constrained DN (2)
• Assist in demand management and midday peak demand reduction (4)
• Absorb excess PV and help smooth PV generation profiles (5)</td><td></td><td rowspan="2"></td></tr>
<tr><td colspan="2">• Active network management (ANM) (3)</td></tr>
<tr><td>Infrequent cycling</td><td colspan="2">• Absorb DN zone level wind oversupply– reduce curtailment (6)</td><td>• Inter-seasonal renewable storage which reduces curtailment (7)
• Store excess generation as heat for district heat scheme (8)</td></tr>
</table>

DN = Distribution Network | NW = North West

In Table 3 the services in red are applicable to heat-discharging technologies, whereas the ones in black to electricity discharging technologies. Furthermore, the below definitions on frequency are used:

- Frequent cycling: >100 cycles/year
- Regular cycling: 30 – 100 cycles/year
- Infrequent cycling: <30 cycles/year

This mapping allows for each service to be further mapped to the LDES technologies that were found to be cost effective within that range. This is done in Table 4 (note that in Table 4 the numbers on the top correspond to the number in parentheses next to each service in Table 3 to denote the service).

TABLE 4: MAPPING LDES SERVICES TO LDES TECHNOLOGIES

Technology / Service	1	2	3	4	5	6	7	8
Molten salt with resistive heating								
LAES								
Gravitational								
CAES (salt dome)								
A-CAES (salt dome)								
H2 (salt cavern + fuel cell)								
H2 (salt cavern + H2 turbine)								
H2 (press. vessel + fuel cell)								
H2 (press. vessel + H2 turbine)								
VRFB								
Li-ion								
Hot water storage with heat pump								
Hot water storage with resistive heater								

Most cost-effective technology

Second most cost-effective technology (within 10% LCOS)

Due to the broad range of the discharge duration and cycling that these services span, a single technology cannot be specified as the most cost effective, thus in the table above all possible options are denoted. This suggests there is some diversity in the range of LDES technologies that can be used.

The exceptions to the above are the district heating services, which we established are much more cost effective when using hot water storage, and the inter-seasonal storage, which we also established is dominated by A-CAES, and these are reflected in the mapping above. The actual LCOS values from the report are given in Appendix D for a range of durations and cycles.

Values that LDES technologies offer to LAEP practitioners broadly come as a derivative of the above distribution network benefits by ways of cost reductions that are associated with them. The main benefit of having LDES technologies within proximity is the avoidance of costs associated with network reinforcements if they were located elsewhere, which ultimately finds its way to the consumers. In this sense the DNO benefits that LDES technologies can offer are also benefits to the consumers and therefore of interest to local energy planners. Furthermore, LDES technologies can be beneficial to rural communities with unreliable grid connections to provide energy when needed, as well as be a source of backup power in cases of prolonged connection issues. In these communities they can substitute traditional means such as diesel generators, thus contributing simultaneously to decarbonisation of these areas which otherwise would be harder to decarbonise.

5.2 LDES INVESTMENT CASE

Despite their benefits, LDES technologies face financial hurdles to market entry, which will likely require both a diversified revenue stack and policy support to overcome. The revenue stack for LDES technologies can be formed by 4 main sources:

- Wholesale market
- Capacity market
- Balancing Mechanism
- System services

Alongside these there are revenue that can come from the services that these technologies can offer the Distribution Network Operator (DNO). The system services that these technologies can provide are shown in Table 5.

TABLE 5: SYSTEM SERVICES LDES TECHNOLOGIES CAN PROVIDE

Technology / Service	Reserve	Frequency	Inertia	Reactive Power	SCL	Black Start
Gravitational	✓	✓				✓
CAES	✓		✓	✓	✓	✓
A-CAES	✓		✓	✓	✓	✓
LAES			✓	✓	✓	✓
Molten salt	✓	✓		✓		✓
Li – ion battery		✓	✓	✓	✓	
Flow battery	✓	✓	✓	✓		
Hydrogen (to power)	✓		✓	✓	✓	✓

The above services are also very important to the network, as there are services such as black start and reserve that aren't offered by Li-ion batteries.

Progress is also being made on policy support, as DESNZ has identified the importance of LDES technologies, as well as their barriers for entering the market. As a result, in January 2024, they opened a consultation on their intention to implement a cap & floor scheme. This scheme will guarantee investors a return on their investment which will at the very least be the floor price (£/MWh) agreed while preventing windfall revenue through the price cap. DESNZ is also proposing to offer financial support to LDES projects in the UK through two funding streams that support novel and established technologies:

Stream 1: for technologies with TRL 9, discharge duration of at least 6 hrs and minimum capacity of 100MW.

Stream 2: for technologies with TRL 8, discharge duration of at least 6 hrs and minimum capacity of 50MW.

Consideration of the full revenue stack available to LDES technologies and the impact of policy support on the overall investment case will be considered in more detail in subsequent phases of this project.

6. SUMMARY

In this study a techno-economic analysis of the current status of LDES technologies was performed as well as a mapping between these technologies and the services that they can offer the DNO and considerations for local area energy planners. The main conclusions are:

- A-CAES, molten salt and Li-ion storage are all cost effective for long durations (>6 hrs), with A-CAES dominating most of the space, especially in the daily and weekly discharge durations.
- Natural storage formations such as salt caverns play an important role in the business case for LDES, as they lower the costs of storage. In their absence the cheapest technologies such as CAES and A-CAES are no longer available and are replaced by technologies such as molten salt and pressure-vessel stored hydrogen. This comes with a substantial increase in costs, especially for longer durations.
- Salt cavern hydrogen storage is currently not cost-competitive with A-CAES due to a combination of costs, assumed asset lifetime and efficiency, but with future hydrogen costs expected to decrease and technological improvements which can increase the efficiencies, hydrogen can be more competitive with CAES and A-CAES on a levelised cost basis.
- A number of services including curtailment reduction and distribution network management were identified and mapped to the most cost-effective technologies. Services to the DNOs can also provide localised benefits and ultimately benefit consumers.

This report is intended to lay the groundwork for future work in the LDES space. There are multiple directions that future work can steer in, some of the most important ones being:

- Investigating the effects of future cost reductions and technology improvements on the analysis, especially in the hydrogen space.
- Further investigating technological limitations of these technologies, especially when it comes to mapping to a certain network while considering geographical constraints. The importance of geographical formations such as salt caverns was investigated in this report, but other geographical considerations can also be very important.
- Conducting a more thorough technical analysis, by considering hourly generation and demand profiles in local areas or case studies, which can be used to better understand and quantify the services and benefits offered by LDES.
- An investigation into the full revenue stack of these technologies, which can complement more detailed analysis of the services already identified, in order to develop a more complete assessment of the business case for investors.

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APPENDIX A LDES TECHNOLOGIES NOT CONISDERED IN THE ANALYSIS

Technology	Principle	TRL	Grounds for Exclusion
Phase change thermal storage	The phase-change temperatures of smart materials are tuned to a particular temperature range, allowing large amounts of heat to be stored without rise in temperature.	<6	Low TRL. Does not currently substantially reduce the cost of thermal storage at scale.
Miscibillity alloy technology	Similar to above; heat is stored at high temperature as latent heat using a smart metal alloy.	<5	
Pumped Hydro (PHS)	Water is pumped into a high reservoir during times of high- or over-supply, and released through a turbine at times of under-supply.	11	Project scale >> DNO requirements. Lack of suitable available geography in the UK.
Closed loop PHS	Similar to above; water, or bespoke high density fluids, are pumped through bespoke flow/return loop, often built on brownfield sites.	6	Insufficiently mature technology. Project development subject to significant planning requirements.
Power-to-gas	Electrolytic hydrogen is further processed to create other fuel gases, e.g. synthetic methane, ammonia.	<5	Insufficient mature technology. Builds on the case for power-to-H2, (though with increased losses).
Supercapacitors	Positive and negative charges are stored in reservoirs	<7	Insufficient mature technology. Technology better suited to

	separated by a porous electrode.	applications involving rapid charge/discharge cycling.

APPENDIX B TECHNOLOGY DATA

A. TECHNOLOGY COST DATA

Technology	Storage Power CAPEX [GBP/kW]	Storage Energy CAPEX [GBP/kWh]	Storage energy OPEX [GBP/kWh]	Fixed storage OPEX [GBP/kW/yr]	Charge technology	Charge CAPEX [GBP/kW]	Charge OPEX [GBP/kW/yr]	Discharge technology	Discharge CAPEX [GBP/kW]	Discharge OPEX [GBP/kW/yr]
Molten salt with resistive heating [12]	-	47.40	0.66	-	Resistive heating [13]	145.07	2.06	Steam turbine [14]	526.14	5.26
Liquid air energy storage [15]	1996	580.57	-	39.93	Compressor, but it is included in the storage facility	-	-	Gas turbine, but it is included in the storage facility	-	-
Gravitational energy storage [16]	339	326.20	16.31	16.99	Electric motor lifting blocks, included in storage cost	-	-	Electric motor operated in reverse	-	-
CAES stored in a salt dome [17]	1474	3.47	-	9.76	Compressor, but it is included in the storage facility	-	-	Turbine, but it is included in the storage facility	-	-
A-CAES stored in a salt dome [16]	1588	3.47*	-	15.88	Compressor, but it is included in the storage facility	-	-	Turbine, but it is included in the storage facility	-	-
Salt cavern stored green H2 with fuel cell	-	0.83 [18]	-	-	Alkaline Electrolyser [19]	790	39.50	PEM Fuel cell [20]	1400	14
Salt cavern stored green H2 with H2 turbine	-	0.83 [18]	-	-	Alkaline Electrolyser [19]	790	39.50	H2 turbine [21]	600	13.10
Pressure vessel stored green H2 with fuel cell	-	21.33 [18]	-	-	Alkaline Electrolyser [19]	790	39.50	PEM Fuel cell [20]	1400	2.83
Pressure vessel stored green H2 with H2 turbine	-	21.33 [17]	-	-	Alkaline Electrolyser [19]	790	39.50	H2 turbine [21]	600	14
VRFB [17]	710	319.79	0.49	-	N/A	-	-	N/A	-	-
Li-ion [22]	233	239.18	-	5.83	N/A	-	-	N/A	-	-

Hot water storage with heat pump [23]	-	22.49	9.26	-	Heat pump [14]	141	3.27	District heating	-	-
Hot water storage with resistive heater [23]	-	22.49	9.26	-	Resistive heater [14]	145	2.06	District heating	-	-

The number in square brackets shows the reference number for the data.

* Assuming the storage costs are the same as for CAES.

B. TECHNOLOGY TECHNICAL CONSIDERATIONS

Technology	**Charge efficiency***	**Discharge efficiency***	**Roundtrip efficiency**	**Lifetime [years]**	**Lifetime [cycles]****	**Storage loss rate [%/hr]*****	**Geographical constraint**
Molten salt with resistive heating	-	-	0.4 [24]	25 [23]	-	0.083 [24]	None to note
LAES	-	-	0.575 [25]	30 [25]	-	-	None to note
Gravity energy storage	-	-	0.8 [26]	35 [26]	-	-	Potentially, see slide 6
CAES stored in a salt dome	-	-	0.43 [27]	40 [27]	13000 [28]	-	Salt dome
A-CAES stored in a salt dome	-	-	0.56 [27]	40 [27]	13000 [28]	-	Salt dome
Salt cavern stored green H2 with fuel cell	0.65 [28]	0.6 [29]	0.39	20 [29]	-	-	Salt cavern
Salt cavern stored green H2 with H2 turbine	0.65 [6]	0.53 [30]	0.34	20 [29]	-	-	Salt cavern
Pressure vessel stored green H2 with fuel cell	0.65 [6]	0.6 [30]	0.39	20 [29]	-	-	None to note
Pressure vessel stored green H2 with H2 turbine	0.65 [6]	0.53 [31]	0.34	20 [29]	-	-	None to note

VFRB	-	-	0.75 [32]	20 [33]	150000 [33]	0.625 [32]	None to note
Li-ion	-	-	0.85 [34]	15 [33]	4800 [34]	0.0125 [32]	None to note
Hot water storage with heat pump	4 [11]	1	4	25 [11]	-	-	District network needed
Hot water storage with resistive heater	1	1	1	25 [11]	-	-	District heat network needed

The number in square brackets shows the reference number for the data.

* Where charge/discharge efficiency not shown they are calculated from the roundtrip efficiency as the square root of the roundtrip efficiency.

** A cycle lifetime could not be found for all technologies. For technologies that have a defined cycle lifetime the annualization period (or lifetime) will be the minimum between the per year lifetime and the cycle lifetime.

*** This was not used in the analysis due to it being negligible and not readily available in literature for all technologies.

C. OTHER TECHNOLOGY CONSIDERATIONS

Technology	Construction time [years]*	Material shortages	Commercial readiness level [CRL]	TRL [1]	Energy density [kWh/m^3]*	Land usage [m^2/kW]**	Modularity
Molten salt with resistive heating	-	None to note, all materials are readily available.	Commercial	8	70 – 210 [35]	~0.05	No
LAES	<18 months [37]	None to note, all materials are readily available.	Pilot projects	7	50 – 200 [24]	~0.05	No
Gravity energy storage	Varies by geography. Modular units are much quicker to construct	None to note, all materials are readily available.	Pilot projects	7	-	0.08 – 0.12	Can be modular – depends on design.
CAES stored in a salt dome	Varies by geography	None to note, all materials are readily available.	Commercial	8	2 – 6 [35]	0.8	No
A-CAES stored in a salt dome		None to note, all materials are readily available.	Pilot/Commercial	7			Typically not, but some modern designs such as Hydrostor are more modular.
Salt cavern stored green H_2 with fuel cell	Varies by geography	None to note, all materials are readily available.	Pilot	6	600 [35]	Modest, though does not scale as a function of store size. Only specific locations are suitable. [36]	No
Salt cavern stored green H_2 with H_2 turbine		None to note, all materials are readily available.	Pilot	6			No

Pressure vessel stored green H_2 with fuel cell	< 12 months	None to note, all materials are readily available.	Pilot	6	1000 [35]	0.004 – 0.01	No
Pressure vessel stored green H_2 with H_2 turbine		None to note, all materials are readily available.	Pilot	6	1000 [35]		No
VFRB	<3 months	Vanadium is common in the earth's crust but expensive to recover, so there is potential for shortages.	Commercial	8	20 – 70 [35]	0.1 – 0.4***	Yes
Li-ion	<3 months	Lithium is a rare element with limited sources in the world, so there is potential for shortages	Commercial	9	200 – 400 [35]	0.01 – 0.04	Yes
Hot water storage with heat pump	-	None to note, all materials are readily available	Commercial	11	-	-	No
Hot water storage with resistive heater	-	None to note, all materials are readily available	Commercial	11	-	-	No

The number in square brackets shows the reference number for the data. CRL is determined from subject matter research.

* Where no value given do public domain data were found.

** Estimates and assumptions have been used have been used based on publicly available data.

*** VFRB assumed to be 10 times more than Li-ion based on their energy densities. Vertical stacking may complicate this assumption.

APPENDIX C LCOS CALCULATIONS

The basis for the LCOS calculations is the formula below:

$$\text{LCOS}\left(\frac{£}{\text{MWh}}\right) = \frac{\text{Investment Cost} + \text{Operating Cost}}{\text{Energy discharged}}$$

The formula above calculated the Levelized Cost of Storage (LCOS) for a single year. Looking at the individual components from the formula, for a given technology we have:

1. Investment costs

$$\text{Investment Cost} = \sum_i -PMT(n, L, C_i)$$

Where:

- PMT = PMT function which calculates the annualised cost of the asset.
- n = interest rate, which for this analysis is 5%

- L = operational lifetime of the asset which is the minimum of the asset lifetime in years and the number of years to reach the maximum cycle lifetime if that is applicable to the asset.
- C_i = Investment costs of the asset, which are:
    - Storage power CAPEX (£/kW)
    - Charging CAPEX (£/kW)
    - Discharging CAPEX (£/kW)

2. Operating costs. These are similar to the investment costs in terms of formula, but they deal with the OPEX instead of CAPEX. Because their costs are already on an annum basis there is no need to annualise them. These costs are:
    - Charge OPEX (£/kW/yr)
    - Discharge OPEX (£/kW/yr)
    - Fixed storage OPEX (£/kW/yr)

   Costs that need to be annualised are:

   - Storage energy CAPEX (£/kWh)
   - Storage energy OPEX (£/kWh)

   The above costs are given for each technology in Appendix B, whereas there are also costs that need to be calculated:

   - Energy import costs (£/kWh). These are the costs of the energy imported for charging. This is calculated by taking into account the charge and discharge efficiency for each technology, and a electricity price of 0.2 p/kWh is used.

3. Energy discharged is the total energy discharged per annum. This is calculated as discharge duration * cycles per year.

APPENDIX D LCOS VALUES

Technology / Service	1	2	3	4	5	6	7	8
Molten salt with resistive heating	0.499	0.590	0.461	0.476	0.699	1.216	1.981	N/A
LAES	0.829	1.379	0.653	0.638	1.800	7.273	17.099	N/A
Gravitational	0.434	0.644	0.377	0.351	0.757	3.305	8.074	N/A
CAES (salt dome)	0.575	0.700	0.507	0.556	0.918	1.012	0.687	N/A
A-CAES (salt dome)	0.465	0.589	0.398	0.447	0.805	0.893	0.564	N/A
H2 (salt cavern + fuel cell)	0.711	0.938	0.588	0.678	1.339	1.452	0.741	N/A
H2 (salt cavern + H2 turbine)	0.761	0.968	0.649	0.731	1.332	1.437	0.794	N/A
H2 (press. vessel + fuel cell)	0.726	0.970	0.599	0.686	1.377	1.730	1.482	N/A
H2 (press. vessel + H2 turbine)	0.778	1.003	0.661	0.739	1.374	1.751	1.633	N/A
VRFB	0.508	0.785	0.431	0.402	0.944	4.182	10.202	N/A
Li-ion	0.422	0.636	0.368	0.336	0.737	3.456	8.587	N/A
Hot water storage with heat pump	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.810
Hot water storage with resistive heater	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.959

The table above show the LCOS values in £/kWh for discrete discharge duration and frequency values that are meant to represent the services identified. Note that the selected values are for illustration purposes and can vary. The discreet values selected for each service are given in the "Selected duration" and "Selected frequency" columns in the table below.

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Service	Number	Duration	Cycles	Selected duration (hrs)	Selected frequency (cycles)
Increase renewable utilisation for regular load e.g. the NW industrial cluster	1	~Daily	>100	10	150
Increase new connection capacity on constrained DN	2	~Daily	30-100	10	70
Active network management	3	Daily/Weekly	>100	20	200
Assist in demand management and midday peak demand reduction	4	~Daily	>100	6	300
Absorb excess PV and help smooth PV generation profiles	5	~Daily	30-100	6	60
Absorb DN zone level wind oversupply– reduce curtailment	6	Daily/Weekly	<30	40	8
Interseasonal renewable storage which reduces curtailment	7	~Monthly	<30	500	3
Store excess generation as heat for district heat scheme	8	~Monthly	<30	500	3

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