Storage cost and technical assumptions for BEIS

Summary document

8 August 2018

Department for Business, Energy & Industrial Strategy

Mott MacDonald
Victory House
Trafalgar Place
Brighton BN1 4FY
United Kingdom

T +44 (0)1273 365000
F +44 (0)1273 365100
mottmac.com

Department for Business,
Energy & Industrial Strategy
1 Victoria St
Westminster
London
SW1H 0ET

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Mott MacDonald Limited. Registered in
England and Wales no. 1243967.
Registered office: Mott MacDonald House,
8-10 Sydenham Road, Croydon CR0 2EE,
United Kingdom

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Contents

Executive summary

In recent years the costs of electrical energy storage technologies have decreased, making their use more viable and increasing their appeal. This reduction in cost, coupled with the potential these technologies offer to mitigate issues (for both generation and networks) arising as a result of the growth in renewable, intermittent, and non-synchronous generation, electrification of heat & transport, and the resultant growing grid demands, means they are likely to be integrated into the grid more frequently in the future.

Mott MacDonald was appointed by the Department of Business, Energy, and Industrial Strategy (BEIS) to provide robust cost and technical assumptions on electricity storage technologies for BEIS's modelling and any future policy development.

There are a significant number of electricity storage technologies at different stages of development. From a system modelling perspective, given that some of these technologies have similar technical characteristics and would consequently be providing similar services to the system, this study sought to consider a subset of all of the storage technologies by assessing the technologies' commercial prospects in terms of their relative advantages/disadvantages.

Mott MacDonald's study provided BEIS with a consistent set of technical data and cost projections for representative electricity storage technologies that have been and will likely be commercially deployed in the future.

The first stage of the study was to consider the relevant technologies in scope, the study then identified the key existing and future use cases for storage technologies and the final stage of the study involved producing the final technical and cost projections out to 2050.

Mott MacDonald have used published resources as well as internal expertise to provide a robust independent assessment for BEIS that is also in-line with industry projections. High, medium and low-cost projection ranges have been provided to capture the variation in cost within technologies and assumptions for a break-through technology have also been provided to capture some of the more general uncertainty regarding the future state of the world.

However, it should still be noted that there is significant uncertainty regarding the future costs and technical characteristics of some of the storage technologies given that they are still nascent, hence these assumptions should be kept under review.

1 Introduction

Mott Macdonald was appointed by the Department of Business, Energy, and Industrial Strategy (BEIS) to provide a consistent set of technical data and cost projections for representative electricity storage technologies that have been and will likely be commercially deployed in the future. The findings from this study will be used in BEIS's models and to inform any future policy development.

1.1 Project Aims

The aim of the project is to provide data on electricity storage for BEIS's modelling and to inform any future policy development. The data provided includes current technical and costing data as well as cost projections up to and including 2050.

1.2 Report Structure

This report presents Mott MacDonald's methodology for collating and providing data on electricity storage to BEIS and the findings from the study. The report is structured as follows:

- Section 2: Electricity storage technologies
  - The first stage of improving the technical assumptions on energy storage was to consider the relevant technologies to include in the study. This section briefly describes the relevant technologies, their operation principles, advantages / disadvantages and possibility of future development discussed.
- Section 3: Electricity storage use cases
  - This section outlines how electricity storage may likely be used now and in the future. The section also details the most appropriate technologies for each use case.
- Section 4: Data collection methodology
  - This section outlines the methodology for data collection, the cost and technical assumptions that were considered for this study and the quality assurance that MM carried out for this study.
- Section 5: Use Case Results
  - This section presents the outcome of the modelling in determining the relative competitiveness of the different energy storage technologies in each use case each year out to 2050.
- Annex A: Final cost and technical assumptions
  - This section presents the final results of the study on the cost and technical assumptions for the relevant storage technologies out to 2050.

2 Electricity Storage Technologies

Mott MacDonald has carried out a literature review and evaluation to ensure that all relevant technologies are considered. After the initial evaluation, the inclusion of each technology was based on their potential viability as described in the literature. Thereafter they were evaluated in more depth.

2.1 Technology inclusion

The table below shows a list of the key technologies that are typically considered in the technical literature. We have shown which of these were included in this project and which are included in each of the named industry reports issued in the last two years which represent a readily available source of information. We used these criteria as the basis to select the technologies that were included in the scope. The technologies that were excluded are noted and their exclusion justified.

Table 1: Technology Inclusion Table

Technology	Lazard	IRENA (Electricity Storage)	USTDA	IRENA (Battery Storage)	ESMAP	Deloitte	The University of Warwick	Included in this Study (Y/N)?	Justification
Pumped Hydro Storage	Y	Y		Y		Y	Y	Y	
Flywheel Energy Storage	Y	Y	Y	Y		Y	Y		Only use case for which this technology is technically suitable is frequency management. Not price competitive with battery storage in this use case so is excluded (as presented in Lazard report 2.0.)
Compressed Air Energy Storage (CAES)	Y	Y	Y	Y	Y	Y	Y	Y	
Super Conducting Magnetic Energy Storage (SCMES)						Y	Y		Still in the research and development stage. When developed, the only use case for which this technology is technically suitable is frequency management. Future price projection will be complex to model. We proposed to allow for a low cost new technology by including the "new battery technologies" category.
Super Capacitors			Y			Y	Y		Still precommercial for grid scale applications. Supercapacitor most likely to be used in combination with other technologies (e.g. as part of advanced lead acid batteries). When developed, the only use case which this technology is technically suitable (as a stand-alone technology) is frequency management. Future price projection would be complex to model. We proposed to allow for a low cost new technology by including the "new battery technologies" technology.
Thermal Energy Storage						Y		Y	Still precommercial for grid scale applications. Has the potential to provide long duration storage - and hence meet a use case

Technology	Lazard	IRENA (Electricity Storage)	USTDA	IRENA (Battery Storage)	ESMAP	Deloitte	The University of Warwick	Included in this Study (Y/N)?	Justification
Lithium Ion Battery Storage	Y	Y	Y	Y	Y	Y	Y	Y	
Lead Based Battery Storage	Y	Y	Y	Y	Y		Y		Lead Acid and advanced lead acid battery cells will compete with Lithium Ion in all the use cases that they are suitable for. These include peak lopping domestic and industrial and commercial (I&C). The majority of price projections show Lead Acid as having comparable or higher LCOS than Li-ion for the use cases considered. As such Lead Acid batteries are likely to be chosen as a preferred technology for a use case only if the price reduction is significantly larger than Li-ion. To allow for new battery technologies having significant price reduction we have included the "new battery technologies" technology. As such rapid development of Lead Acids battery technologies will be allowed for in the new battery technology category.
Zinc Based Battery Storage	Y						Y	Y	
Flow Based Battery Storage	Y	Y	Y	Y	Y	Y	Y	Y	
Sodium Sulphur Battery Storage		Y	Y	Y		Y	Y	Y	Reviewing the literature (in particular IRENA), several projections showed molten salt NaS having the potential to be lower cost than Li-ion in future. As such, proposed to include this.
New Battery Storage Technology		Y			Y			Y	This category will be included to allow the impact of "game changing" technological developments in battery storage. This could include Metal Air, Sodium Ion or advanced Lead Acid.
Cryogenic Energy Storage	Y		Y				Y		Not included due to lack of diversity in information sources (1 UK manufacturer). Costs are anticipated to be similar or higher than competing technologies.

Technology	Lazard	IRENA (Electricity Storage)	USTDA	IRENA (Battery Storage)	ESMAP	Deloitte	The University of Warwick	Included in this Study (Y/N)?	Justification
Hydrogen Energy Storage			Y			Y	Y	Y	Still precommercial for grid scale applications. Has the potential to provide very long duration storage - and hence meet a use case
Synthetic Gas Generation						Y			Not included. Synthetic gas uses hydrogen production is the first stage in the gas production process. The hydrogen is then used as a feedstock which is turned into a Hydrocarbon. Due to the additional complexity this technology currently has significantly higher costs than hydrogen energy storage.

Source: Mott MacDonald analysis

The considered technologies were studied in more detail to understand their efficiency, response time, lifespan, locational constraints, operational hazards and technological maturity. This is summarised in Table 2 below:

Table 2: Technology Technical Summary

Technology	Efficiency (%)	Response Time (s)	Lifetime	Locational Constraints	Significant Operational Hazards	Technology Maturity
Pumped Hydro	65-87	< 60	30 years – (100 years with refurbishments)	Natural reservoirs and favourable geologies	No	Very mature technology with over 100 years of deployment globally.
CAES	50-89	< 60	25 years – (40 years with refurbishments)	Generally, only economic at locations with underground salt cavern	No	All components are technically mature. Two Projects in the USA and Germany have been operational for approx. 20 years. Adiabatic approach has not been installed in a large-scale project.
Thermal Energy Storage	65-70	10+	30 years	No	High operational temperature of thermal medium	The central design has been used within concentrated solar plants but no widespread use as a standalone storage technology.
Lithium Ion Battery	85-90	0.15-1	15 years – The duration is dependent on the energy capacity installed at the start of the project (overplanting at project start to account for degradation can extend life). The modelling has allowed for 15 years as this is in line with the duration of capacity market contracts.	No	No	Mature technology.
Zinc Battery	70-85	0.5-1	15 years. (With appropriate overplanting)	No	No	Commercially available with a small number of commercially deployed projects.
Flow Battery	70-80	0.5-1	15 years – (20 years with refurbishments)	No	Chemical Hazard within electrolyte tanks	Commercially available with a small number of commercially deployed projects.
Sodium Sulphur Battery	80-90	0.5-1	15 - 20 years	No	High operational temperature / fire risk	Until two years ago the most widely deployed Network Connected battery energy storage technology. The

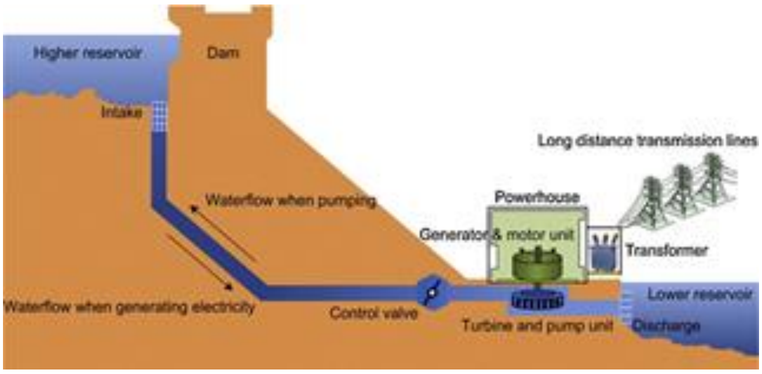
Technology	Efficiency (%)	Response Time (s)	Lifetime	Locational Constraints	Significant Operational Hazards	Technology Maturity
						technology is patented by one company and has been deployed commercially.
New Battery Technology	90-93	0.1-1	15 years – if sufficient capacity is installed at project start to account for degradation during operation	No	No	Pre-Commercial, still in R&D stage
Hydrogen Storage	32	0.5-10	10 years	No	Hazard zone due to presence of flammable gas	Limited deployment (e.g. public transport) but growing (e.g. German electrolysis plant) as the technology matures.

Source: Mott MacDonald analysis

Section 2.1 summarised the technologies that were considered in scope for this study. The following sections provide further detail on these technologies, including: technology descriptions, relative advantages/disadvantages, maximum technical potential build limits, and cost reduction potentials.

2.2 Pumped Hydro Storage

Figure 1: Pumped Hydro Diagram



Source: Luo, X., Wang, J., Dooner, M. and Clarke, J. (2014).

Pumped Hydro uses the upstream hydraulic potential of a water reservoir as a store of energy.

The water is held back until the pressurised pipe linked to the downstream area is opened, allowing the water to flow downwards, decreasing in potential energy and increasing in pressure as the column increases in vertical height. It then goes through a turbine which produces electrical energy.

During charging operation, the reverse occurs with the downstream water being pumped upwards, decreasing in pressure as it ascends to the reservoir. The grid electrical energy used to power the pump is stored as potential energy as the water sits in the reservoir.

The storage capacity may be increased by digging a bigger reservoir or building a higher dam. Historically Pumped Hydro has been used for daily load balancing and have typically had 6 to 8 hours of electricity storage, although some projects have a greater installed capacity. New projects are under development in the UK (Coire Glas and Balmacaan) with significantly more storage (20 hours plus).

In this report, costs are based on new pumped hydro sites using existing waterways (in a similar way to historically developed pumped hydro). Other technologies, such as developing new water storage or using underwater reservoirs is not considered.

2.2.1 Pumped Hydro Advantages

- Long project lifetimes.
- Technology does not require toxic or hazardous chemicals.
- Very mature technology that is well understood and has been built for over 100 years.
- If advantageous sites are available can provide very low-cost storage.
- Has the potential to also provide inertia to the system even when not generating (spinning the turbines in air). This has the potential to be useful in the future.

2.2.2 Pumped Hydro Disadvantages

- Relatively slow response time (when compared to battery storage); in general, more than 10 seconds due to physical construction.
- Dependant on natural reservoirs and favourable geographic sites to build. This limits the potential installed capacity.
- Has a high environmental impact and can take many years of planning approvals before it is installed.
- Long construction durations of many years.
- The connection to the grid is sometimes far from any connection point or load source, adding to the build complexity and cost.

2.2.3 Pumped Hydro Build Limits

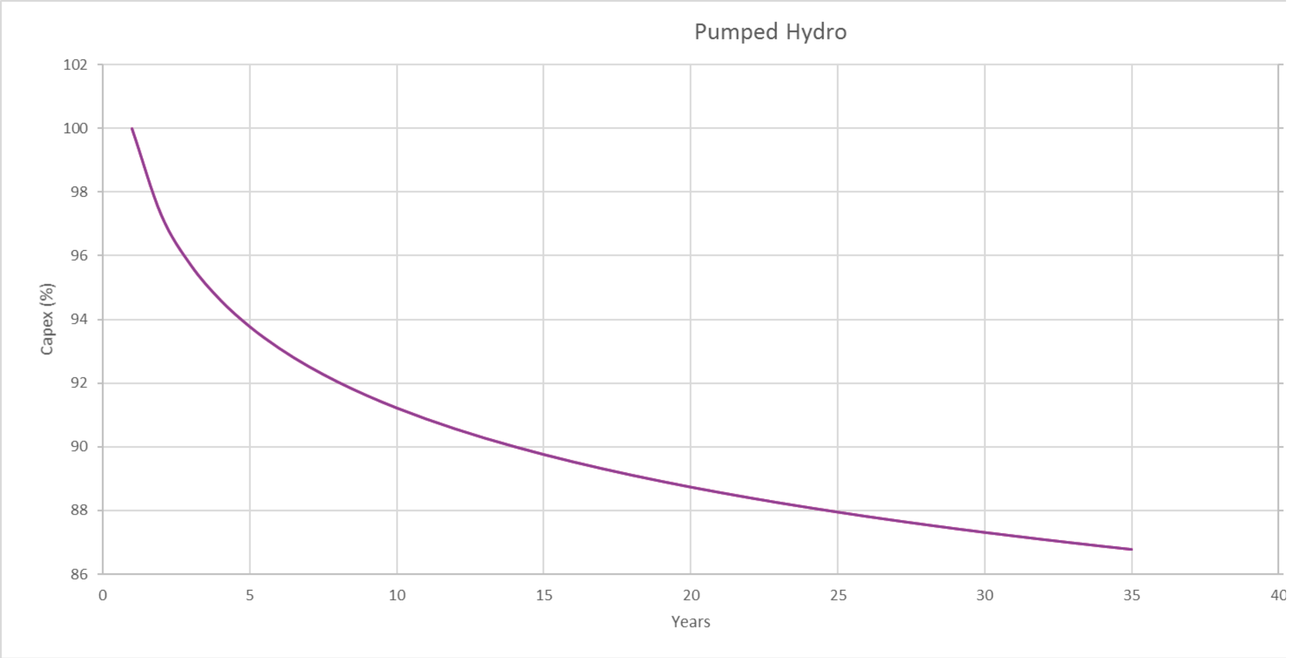
We have assumed a potential annual build limit of one project per year which would mean around 6GW of new pumped hydro could be theoretically be deployed between now and 2050.

The major constraint on the build limits is availability of sites for natural pumped storage. Due to economies of scale it is likely that GW scale pumped storage will be built, rather than 200 MW as assumed for this use case in this study. Dinorwig for example has 1728 MW installed capacity. As such we would expect it more likely that a 1GW project is built every 5 years, rather than one 200MW project each year.

2.2.4 Pumped Hydro Cost Reduction

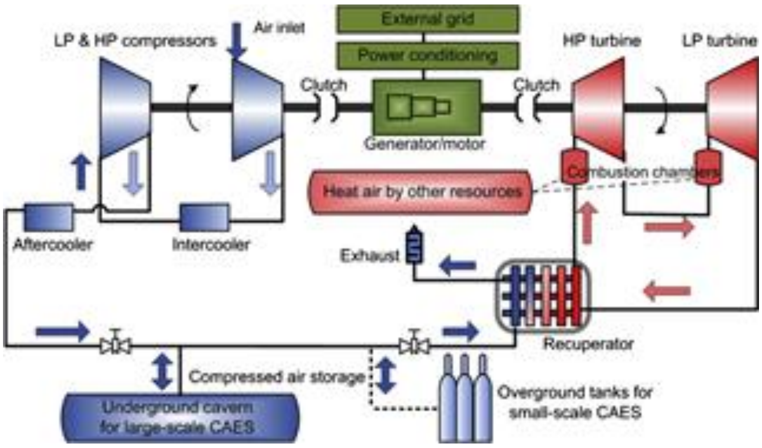
Pumped Hydro learning rates and associated cost reductions are limited by the small amount of development of the technology taking place mainly due to its maturity. Small incremental improvements in performance are expected along with advancements in reservoir construction methods (including more energy efficient forms of concrete and greater automation). Because of this we have modelled (in our medium time-based learning rate) a modest cost reduction over time. Details of the calculation methodology of the time-based learning rates are given in Section 4.2

Figure 2: Pumped Hydro Cost Reduction



2.3 Compressed Air Energy Storage (CAES)

Figure 3: Diagram of a CAES Plant



Source: Luo, X., Wang, J., Dooner, M. and Clarke, J. (2014).

CAES is based on the principle of pressurised air being used as an energy storage medium.

It comprises a pressurised reservoir (typically subsurface geological formation such as a salt cavern) being used to hold a pressurised medium, typically air, with the air whose flow out of or into the reservoir is the basis on generating or storing electrical energy to/from the grid.

During discharge the air is released from the reservoir into the atmosphere, going through a turbine which converts the piezometric (pressured) energy of the air into electrical energy for the grid. This is done by turning a turbine. The expansion of the air is endothermic (requires the absorption of heat) which necessitates the heating of the air.

During charge the air is pumped into the reservoir, decreasing in volume exothermically (pushes out heat). The air requires cooling to store this at suitable pressures. The electrical energy used to power the pump is converted into the compressed air' piezometric energy in the reservoir. In this study we will assume designs using an adiabatic cavern approach.

In the projects installed to date the heat released during compression is released to atmosphere (diabatic). The heat required during expansion is supplied by burning natural gas. A number of developers are seeking to improve the efficiency of CAES by developing an adiabatic (no heat added or taken away) system. In this system the heat released in compression would be stored and added to the air at expansion. This has the potential to improve the efficiency of CAES and eliminate the operational CO2 emissions.

2.3.1 CAES Advantages

- Potential to provide many hours of stored power.
- Technology does not require toxic or hazardous chemicals.
- The components of the technology are mature technology and well understood.

2.3.2 CAES Disadvantages

- Theoretical efficiency is around 60 -70% for adiabatic storage which is on the low end compared to other storage technologies. This efficiency is theoretical as no adiabatic storage projects have been built. Diabatic projects typically have efficiencies of 30-45%.
- Relatively slow response time in the seconds to minutes range due to system component limitations including turbine response time.
- Underground CAES is location constrained to favourable geologies and suitable salt caverns. There are however, suitable sites in the UK. While location independent CAES with above ground tanks are under research, the cost of energy is between 6-50 times that of underground CAES.
- While component technologies are mature, the implementation of CAES is immature with very limited deployment in the USA and the EU. Only a few test projects have been built with further technological development still to come.

2.3.3 CAES Build limits

The most suitable location for CAES is at locations with access to salt caverns. In the UK this is concentrated in areas in the North East of England, Cheshire, and Northern Ireland (See Figure 4 below).

There is also a possibility to develop CAES within other rock formations and potentially offshore. However, this will increase risks and costs. The potential for CAES within the UK is potentially very high, some studies quoting TWhs of potential in the UK (albeit using soft rock formations and expanding offshore).

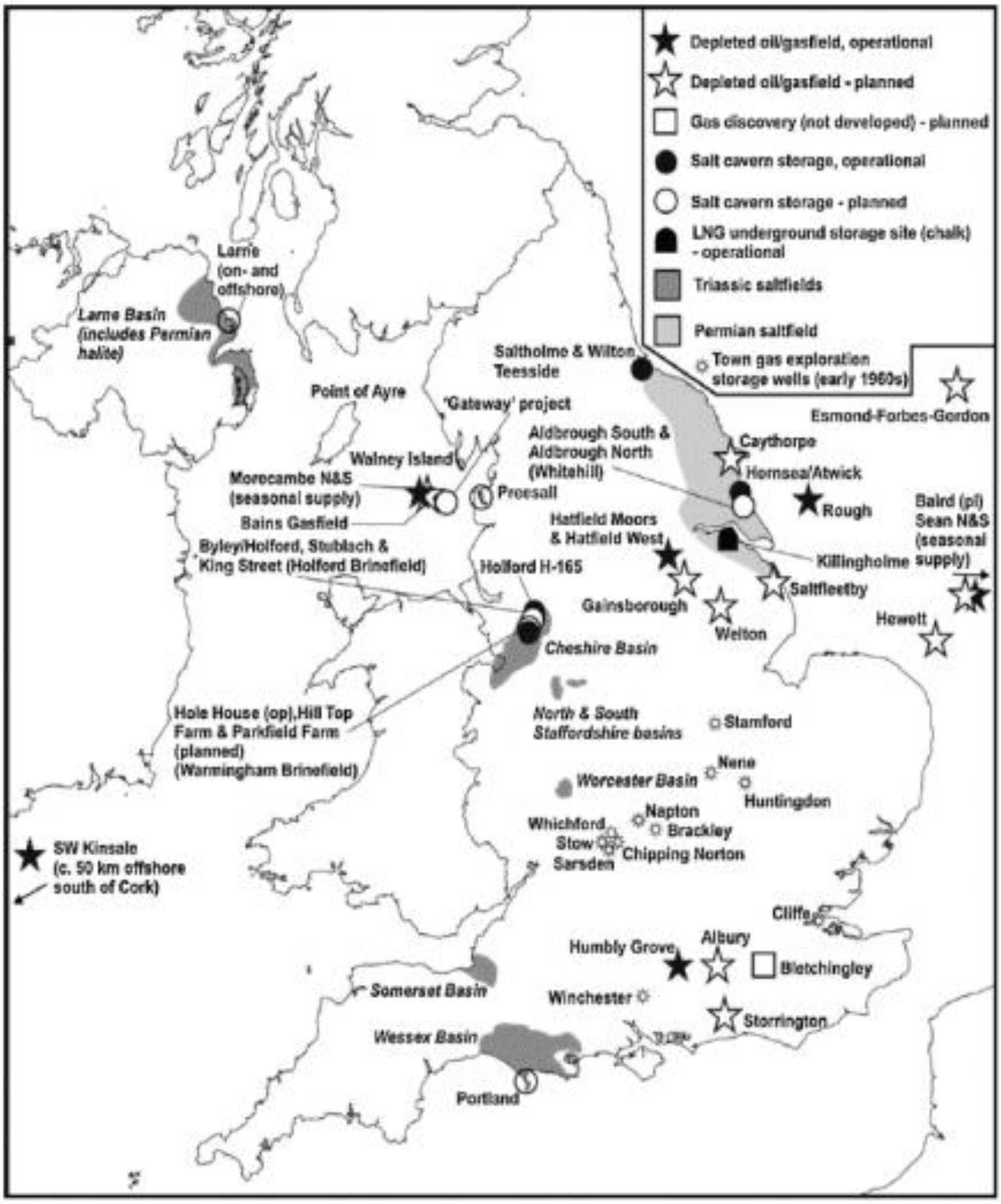
We have selected annual build limits based on suitable EPC contractors. As the skills and technologies used in CAES are comparable to CCGTs. We have made a high-level assumption that the capability within the UK is for 5 EPC projects of this type per year. This is in line with the rate of CCGTs built during the UK's early 1990's "dash for gas". For 200MW sized project this results in a build limit of 1000MW per year.

2.3.4 CAES Cost Reduction

Mott MacDonald has derived time-based learning rates for CAES based on projected costs from the IRENA Electricity Storage and Renewables – cost and markets to 2030 report. The main drivers for the cost reduction are likely to be increased utilisation of compression-phase heat that will result in improved system efficiencies and improvement in design made possible as the technology is rolled out.

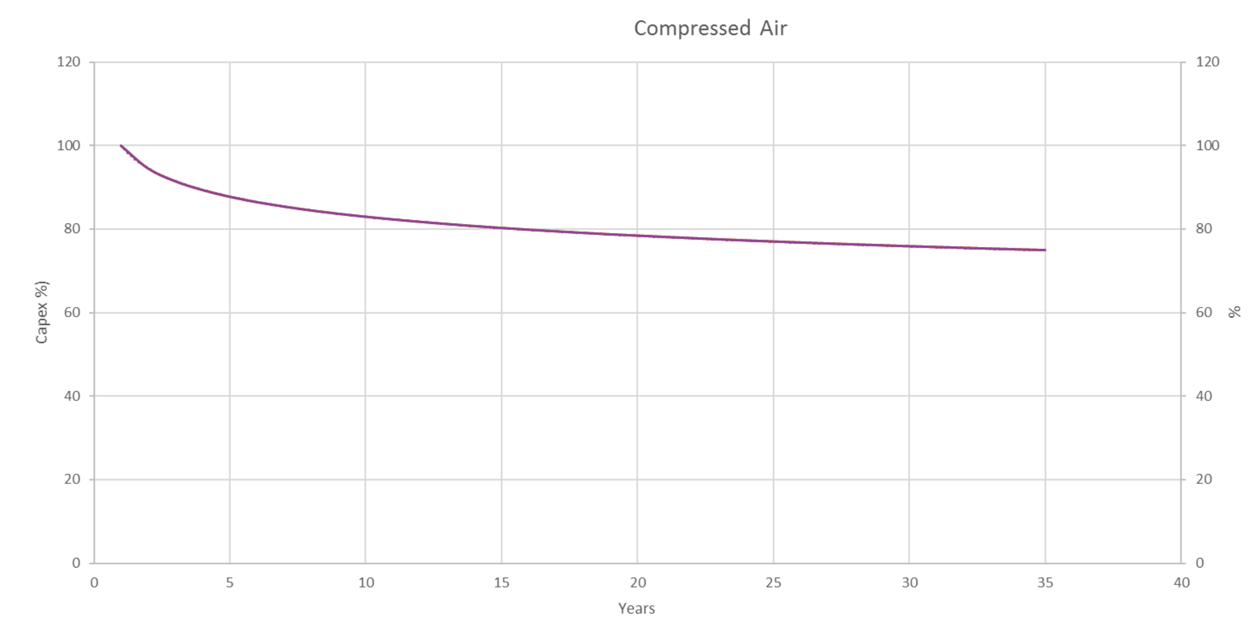
Details of the calculation methodology of the time-based learning rates are given in Section 4.2.

Figure 4: Map of possible CAES sites.



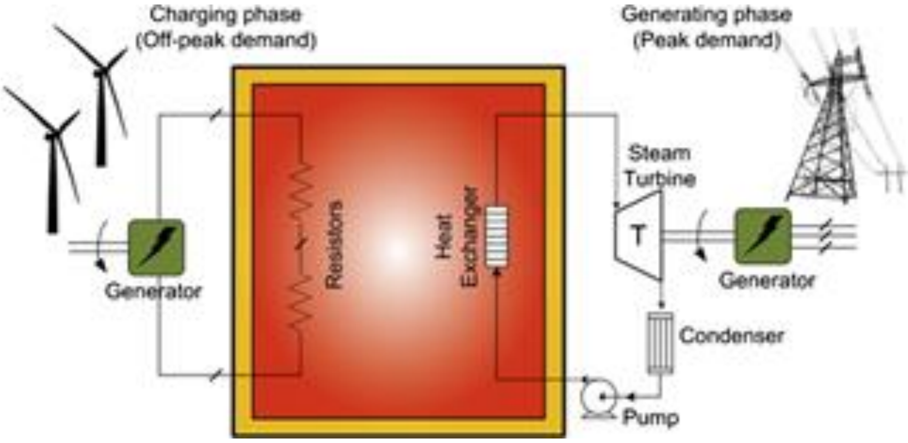
Source: EERA Overview of Current Development of CAES Technical Report, X Lou, J Wang University of Warwick 2013

Figure 5: CAES Cost Reduction



2.4 Thermal Energy Storage

Figure 6: Diagram of Thermal Energy Storage



Source: Luo, X., Wang, J., Dooner, M. and Clarke, J. (2014).

Thermal Energy Storage is based on high (and sometimes low) temperature materials used as energy storage mediums. In this report we have considered above ground (not using aquifers) thermal energy storage.

This comprises a heat store holding a thermal medium, e.g. molten salt, contained in a tank that is insulated to minimise thermal leakage. Energy is reclaimed either directly through a heat engine or through a heat exchanger, acting as a boiler in a conventional power plant cycle.

The basic concept of the technology is similar to concentrated solar power where molten salt is heated by reflected sunlight. The heat from the molten salt is then used to generate power using a steam turbine. The difference in thermal energy storage is that the heat comes from the electrical grid (either using resistors or heat pumps). Additional thermal energy may also come from waste heat. It is assumed this is the case in the data modelled in this report as this is likely to be required to make initial projects financially viable.

2.4.1 Thermal Energy Storage Advantages

- Potentially low capital cost.
- Potential to provide many hours of stored power.
- Technology does not require toxic or hazardous chemicals.
- The components of the technology are mature and well understood.
- High energy density.

2.4.2 Thermal Energy Storage Disadvantages

- Efficiency ranges between 35% and 50% for projects without waste heat reclamation, up to 65-70% for projects with waste heat reclamation.
- Response time is typically in the tens of seconds which is on the lower end for storage technologies.
- Self-discharge is comparatively higher to other technologies with a discharge rate between 1 and 3% per day.
- Requires high temperature operation with potential fire and safety concerns to be addressed.

2.4.3 Thermal Energy Storage Build Limits

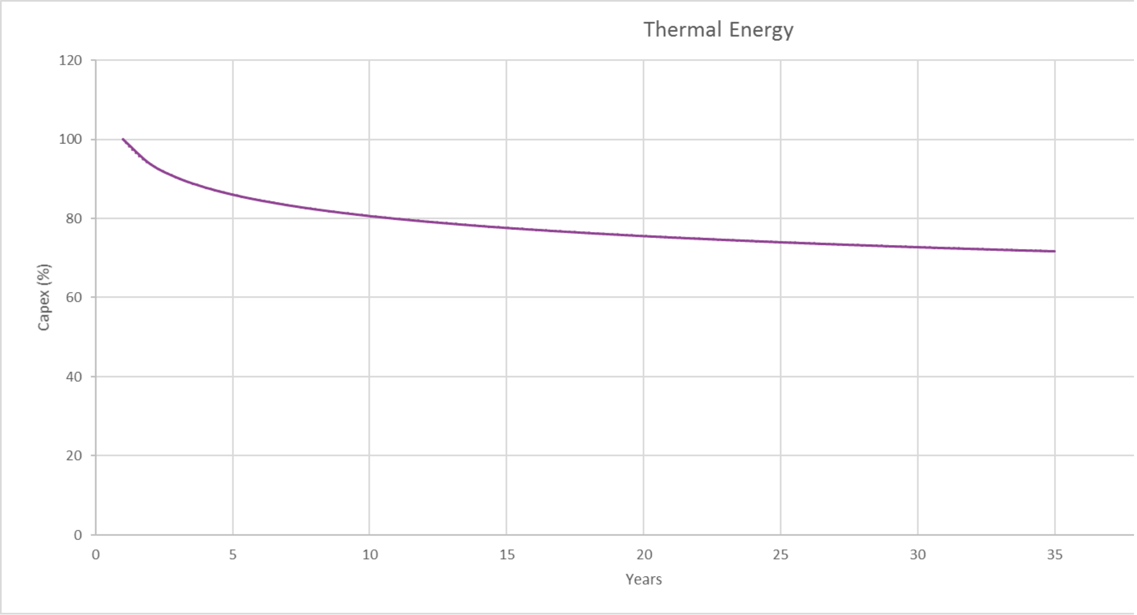
As with CAES we have selected annual build limits based on suitable EPC contractors. As the skills and technologies used in Thermal Energy Storage are comparable with closed cycle gas turbines (CCGTs). We have made a high-level assumption that the capability with the UK is for 5 EPC project of this type per year. This is in line with the rate of CCGTs built during the UK's early 1990's "dash for gas". For 200MW sized project this results in a build limit of 1000MW per year. This assumes that all the projects are sited at locations with low grade waste heat that is recoverable. The extent of available sites has not been considered in detail and this may provide another limitation on build limits.

2.4.4 Thermal Energy Storage Cost Reduction

Thermal Energy learning rates and associated cost reductions are driven by further development of the technology including the improvement of the specific energy of the storage mediums and increasing the insulation properties of the storage vessels that will lead to improved efficiencies. Further cost reduction is expected due to increased system roll-out and improvements in manufacturing, design and supply chain. Mott MacDonald has derived the time-based learning rates based on cost projections from the BEIS energy storage cost reduction competition and internal data.

Details of the calculation methodology of the time-based learning rates are given in Section 4.2.

Figure 7: Thermal Learning Rate



2.5 Lithium Ion Battery Storage

Figure 8: Diagram of a Cylindrical Lithium Ion Cell

Source: A. Akhil et al: DOE/EPRI 2013 electricity storage handbook in collaboration with NRECA

Lithium Battery storage stores electrical energy as chemical potential energy using lithium and carbon-based electrodes and is widespread in the consumer electronic sector as well as in the growing electric vehicle sector. While many variations of the cell chemistry exist, a standard cell is based on a planar or cylindrical design (as shown in Figure 8).

During discharge the battery supplies DC power to a power converter which converts it to AC. This is achieved by the lithium ions migrating through the porous separator to the anode where it is reduced (combined with electrons).

During battery charge the converter produces a slightly higher voltage, allowing power flow into the battery cells.

There are variations of Li-Ion chemistries of which the conventional types make use of a liquid electrolyte that assists with the transport of Li-ions to and from the cathode and anode.

A standard Li-Ion battery uses Lithium transitional metal oxides as the anodes and graphite carbon as the cathodes. The electrolyte is typically a non-aqueous organic liquid that contains dissolved lithium salts and transports the Li-ions between the electrodes. The anode and cathode are ionically connected and electrically separated by a micro-porous insulating membrane that acts as the separator. During the charging process, lithium ions are transported from the positive metal oxide host structure through the electrolyte and separator to the cathode electrode, with the reverse taking place during the discharge process. The chemical reactions are highly reversible and have led to its widespread commercial application in the portable electronics market.

Cost reductions make Lithium Ion likely to be attractive for installations where four hours or less of storage are required. For greater durations of storage, other technologies with lower MWh scaling may be more attractive.

2.5.1 Lithium Ion Advantages

- High efficiency ranging between 85 - 90%
- Commercially mature
- Sub-second response time of 0.15 - 0.25s
- Does not suffer from memory effect or severe depth of discharge limitations affecting Lead Acid and other battery technologies.
- High energy density
- No locational constraints
- Applications outside of grid connected storage (including electric vehicles) encouraging R&D and further cost reductions due to improvements in the supply chain.

2.5.2 Lithium Ion Disadvantages

- Limited cycle life due to degradation of the cell materials during operation (the exact limits will depend on the sub-chemistry and energy capacity and use),
- The technology has some safety and environmental issues that arise from the use of lithium and other materials such as cobalt.
  - Lithium is highly reactive and flammable and as such, the batteries can enter a state called thermal runaway during operation. The event occurs if the charge or discharge rate of the battery is not properly controlled by the battery management system and overcharge or an internal short circuit due to dendrite formation is generated. This causes a rapid increase in temperature. Once a critical temperature is reached, a chain of

exothermic reactions is triggered. This causes further temperature increase and an uncontrolled acceleration of the reaction kinetics that eventually leads to catastrophic failure. This phenomenon is usually detected by the battery management system but failures have been known to occur.

- Some cell designs incorporate the use of rare earth metals or metals with a limited supply chain such as cobalt, that might limit production capacity of the cells in future. Research into new cell designs aim to minimise or eliminate the use of such materials while maintaining performance.

2.5.3 Lithium Ion Build Limits

Lithium ion has a current and growing supply chain, this is being expanded significantly by Tesla/Panasonic, BYD and others. The global production capacity is approximately 150GWh and is expected to double over the next five years (as per BNEF). This is anticipated to continue to grow. The majority of grid connected lithium batteries are provided in containerised products. These require relatively little project specific engineering.

Due to the containerisation of engineering and the significant supply chain, we believe the major build limit will be the site-specific works of construction and planning. We propose to look to PV installations as a comparison. In 2015 (the peak year of installation prior to modifications in subsidies) nearly 4GW of solar generation was added to the UK network.

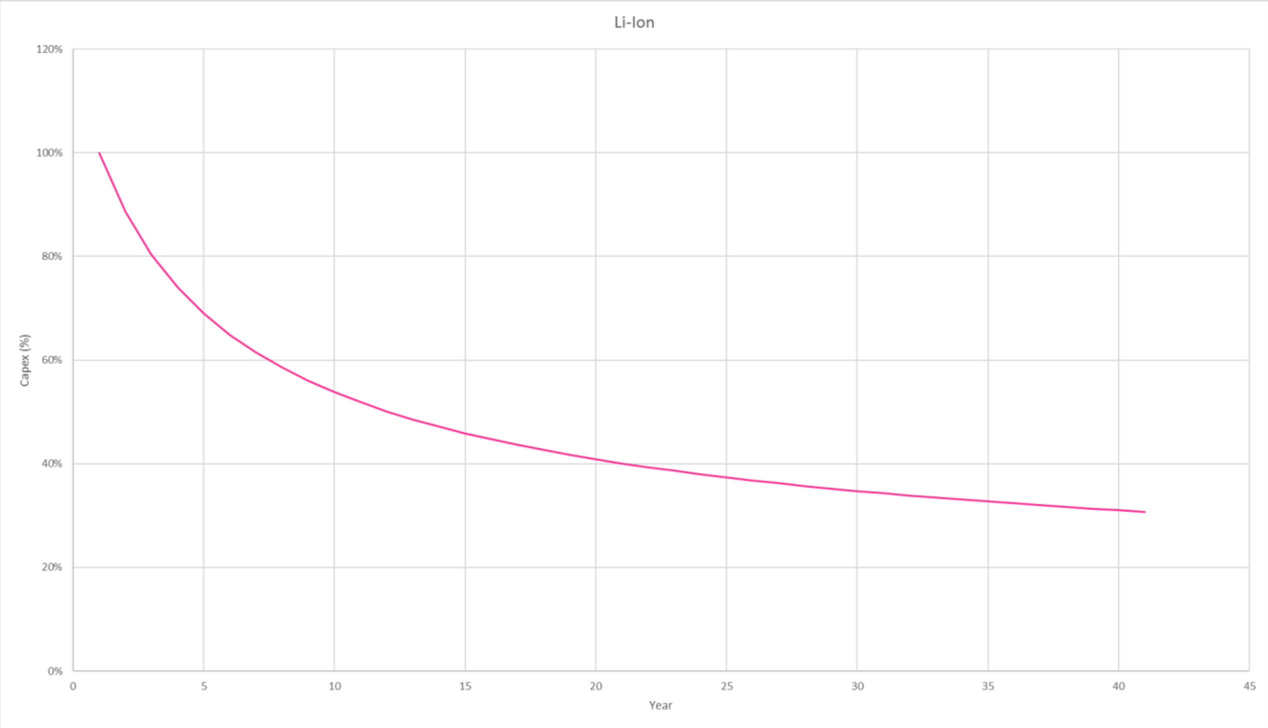
As such we could place a 4GW build limit on battery storage. For 4 hours duration projects this would represent approximately 10% of the current global production (or 5% of 2021 production).

2.5.4 Lithium Ion Cost Reduction

Lithium Ion learning rates and the associated cost reductions are driven by their suitability for the E.V and consumer market, due to the high specific energy of the cells, and use in utility scale energy storage systems. This promotes rather intensive research which in turn results in improvements in efficiencies, power and energy capacities, more competitive supply chains and simplified production techniques. Commercial factors such as increased competition and economies of scale with widespread deployment further stimulates the cost reduction.

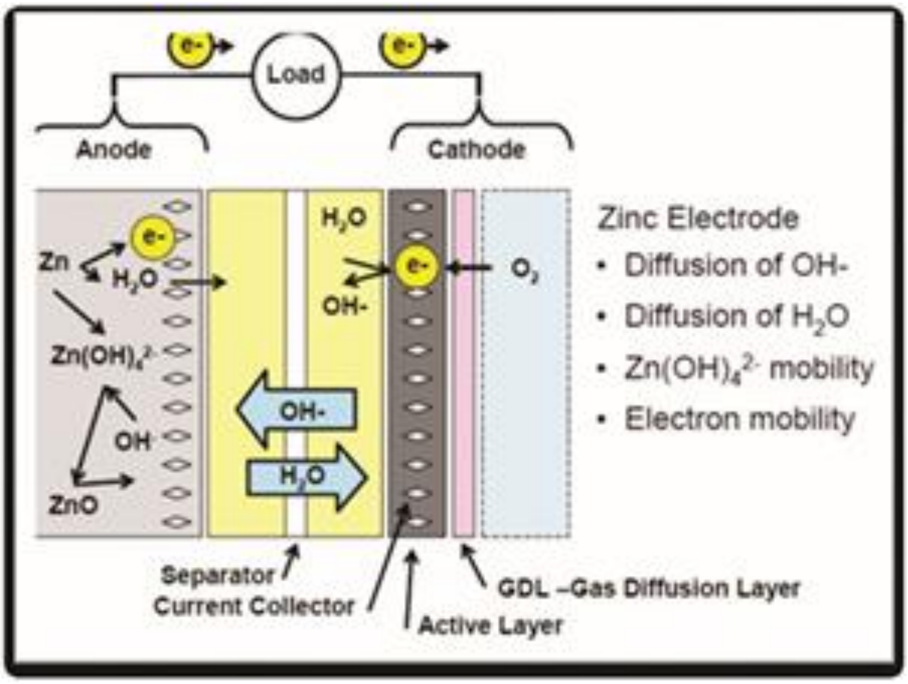
Mott MacDonald has derived learning rates for the cells based on published market projections of global sales figures for EVs. Separate time-based learning rates for each of the cost components as defined in Section 4.3 were calculated using projected costs in published reports from IRENA, DNV-GL and others. A final aggregate cost reduction curve was calculated based on a summation of the individual cost components for each projected year. Further advances such as the transition to solid-state electrolytes also promise greater energy density, as does improved electrode designs. These all combine to create further opportunities to reduce costs. The expected scale of deployment of Li-Ion batteries is considered to be orders of magnitude higher than the other commercial battery technologies considered in this investigation leading to significant cost reductions compared to the other technologies.

Figure 9: Lithium Ion Cost Reduction



2.6 Zinc Based Battery Storage

Figure 10: Diagram for a zinc air battery



Source: US Trade and Development Agency (2017). South Africa Energy Storage Technology and Market Assessment. Pasadena: Parsons, pp.Objective , Task 2.1, A-29.

Zinc Battery storage is based on storing energy in an electrochemical cell based on a zinc chemistry. There are different types, primarily Zinc air and Zinc Copper. Zinc battery work in a similar way to Lithium Ion with Zinc based ions replacing Lithium Ions.

2.6.1 Zinc Battery Advantages

- Sub second response time of 0.5 - 1 seconds
- No locational constraints
- Material used are non-hazardous and non-combustible.
- Lower CAPEX than Lithium Ion for high energy project (generally greater than 4 hours).

The technology has several advantages over other battery types such as sodium sulphur or lithium ion including the use of non-toxic and non-combustible materials. It also has a primary electrode metal of low cost.

2.6.2 Zinc Battery Disadvantages

- Relatively low efficiency of 75-85% compared to existing battery technology such as lithium ion.
- Generally, not suitable for installation of less than a 4:1 energy to power ratio. E.g. a 4-hour duration battery is minimum size. This is due to discharges at lower ratios than this damaging/aging the cells.
- High self-discharge rate ranging between 0.05 - 2% per day.
- No widespread deployment and relatively immature technology.

2.6.3 Zinc Battery Build Limits

The build limits are related to manufacturing capacity. This is presently very limited, however when the technology reaches maturity there is potential to commoditised production (like Li-ion) and as such produce large numbers of cells.

An assumption of 2GW is taken, this is half of the assumed build limit of Li-ion. This is made on the assumption that the supply chain will not reach the same maturity as Li-ion due to no EV or customer electronic applications however could be scaled up to multi GWh per year if this proves viable,

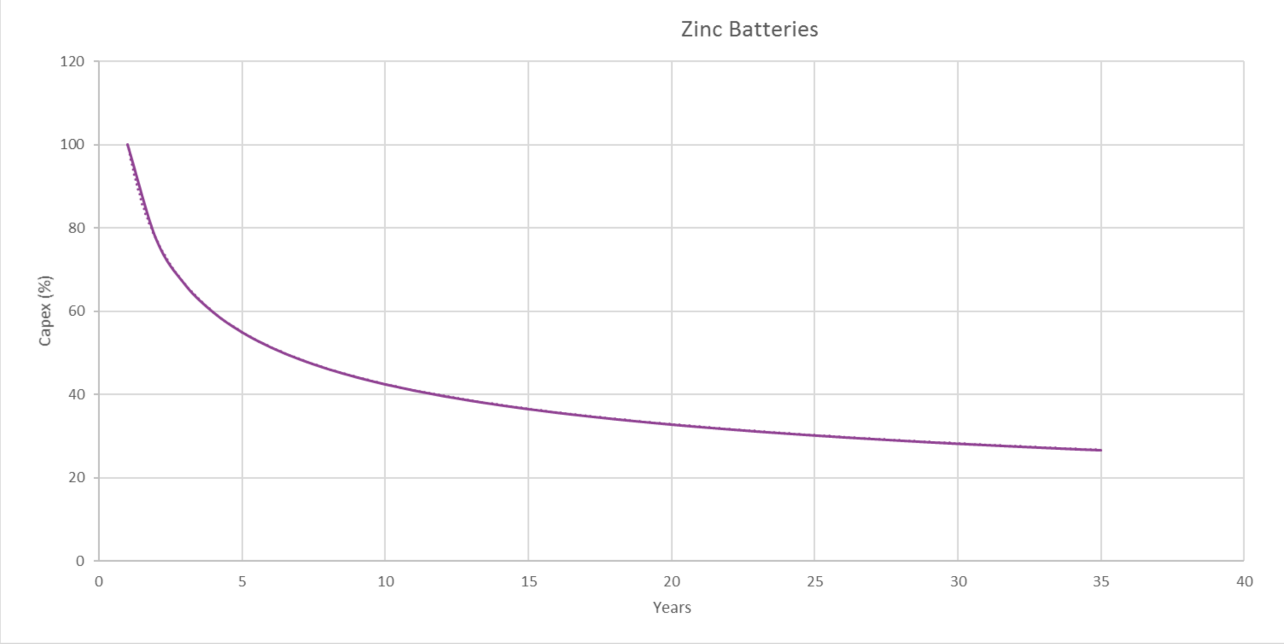
This figure will be very optimistic for the early years of battery installation.

2.6.4 Zinc Battery Learning Rates

The learning rates and associated cost reduction of zinc-based batteries are determined by the wide-spread adoption of the technology in the energy storage market. This will lead to increased production capacities and cost reduction through economies of scale. Further improvements in the cell designs will lead to increased efficiencies and lower self-discharge rates as well as improved the life cycles leading to lower levelized costs associated with these systems.

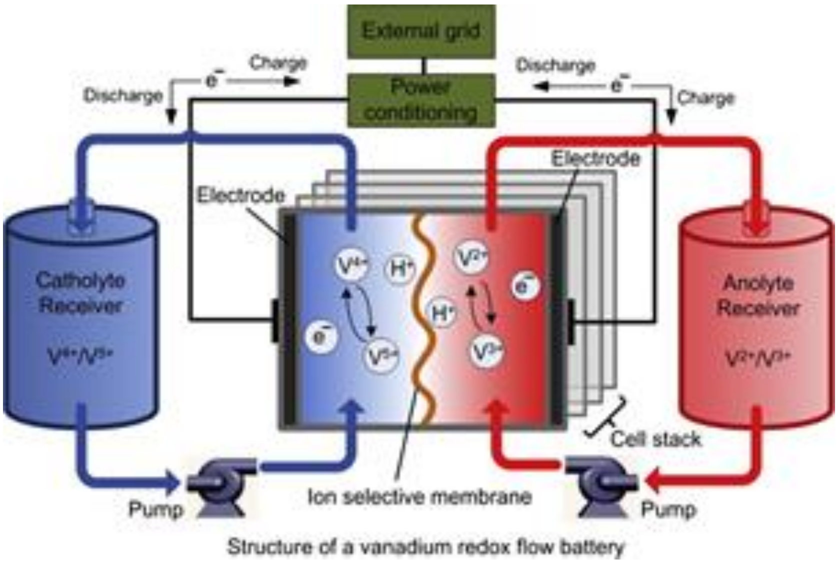
Mott MacDonald has based the calculation of time-based learning rates on projected costs published in reports from IRENA, DNV-GL and others. Details of the calculation methodology of the time-based learning rates are given in Section 4.2.

Figure 11: Zinc Learning Rates



2.7 Flow Battery Storage

Figure 12: Vanadium Type Flow Battery Diagram



Source: Luo, X., Wang, J., Dooner, M. and Clarke, J. (2014).

Flow Battery storage is based on storing energy in electrolytic tanks based on liquid electrolyte e.g. vanadium or zinc bromine. The approach effectively decouples the power and energy of the system. The energy rating can be changed by varying the capacity of the electrolyte tanks and the power rating can be changed by varying the size and number of cells in the stacks.

The storage system comprises two electrolyte tanks connected to a battery stack where a redox reaction occurs, producing DC power. The DC output of the stacks are connected to the grid via power converters and controllers.

During discharge the electrolytes are pumped to the cell where DC electrical power is produced from the electrochemical reaction and the electrolyte is spent. Electrolyte is continuously pumped into the battery stack to ensure adequate pressure is maintained and the reaction can be sustained. DC Power is converted to AC via converters and controllers.

During battery charge the converter supplies DC power to the battery stacks and while the pumps ensure continuous flow of electrolyte to the stacks to enable the electrolytic fluid to be regenerated. Electrical energy is stored as chemical potential energy in the electrolyte phase.

Future developments will produce enhanced cell and stack designs that improve performance and reliability and enables further commercialisation of the technology.

Due to the low cost of adding additional energy storage to a system (kWh), flow batteries are likely to be most suitable for long duration storage.

2.7.1 Vanadium Based Flow Storage

Vanadium based flow storage uses a vanadium-based electrolytes in the form of two vanadium redox couples.

2.7.2 Zinc Bromine Based Flow Storage

Zinc bromine-based flow battery storage makes use of zinc bromine solutions in two tanks with zinc as the active metallic element and is sometimes classified as a hybrid flow battery. This means not all the electroactive components have been dissolved, i.e. it’s a hybrid between a normal battery and a flow battery.

2.7.3 Flow Battery Advantages

- Sub second response time of between 0.5 - 1 seconds
- No locational constraints

Advantages include the ease of scaling the system, good cycle life and long lifespan (15 to 20 years).

2.7.3.1 Vanadium based Flow Battery Advantages

The technology has the benefits of quick response time, relatively high efficiencies and relative maturity compared to other flow battery technologies. It also features high electrolyte recyclability and cycle life.

2.7.3.2 Zinc Bromine Based Flow Battery Advantages

Advantages include relatively high energy density, good cell voltage and high depth of discharge.

2.7.4 Flow Battery Disadvantages

- Relatively low efficiency of between 70-80% compared to other battery systems such as lithium ion.
- Relatively high self-discharge ranging from 0.05% - 2%/day associated with continuous operation

- Operational hazard present with the electrolytic tank and corrosive elements
- Relatively low deployment with the technology still being quite immature with only a few test projects.

Disadvantages include high operating costs due to mechanical pumping elements, certain elements being expensive such as the membrane and possible chemical hazards due to the corrosive electrolyte.

2.7.4.1 Vanadium Based Flow Battery Disadvantages

Disadvantages include low electrolyte stability and solubility, low energy density as well as high vanadium cost.

2.7.4.2 Zinc Bromine Based Flow Storage Disadvantages

Disadvantages include corrosion of cell materials, dendrite formation, and relatively low efficiency. It also suffers from high self-discharge. Power and energy in the battery are also coupled to a degree.

2.7.5 Flow Battery Build Limits

The build limits are related to manufacturing capacity. This is presently very limited, however when the technology reaches maturity there is potential to commoditised production (similar to Li-ion) and as such produce large numbers of cells.

An assumption of 2GW is taken, this is half of the assumed build limit of Li-ion. This is made on the assumption that the supply chain will not reach the same maturity as Li-ion due to no EV or customer electronic applications however could be scaled up to multi GWh per year if this proves viable,

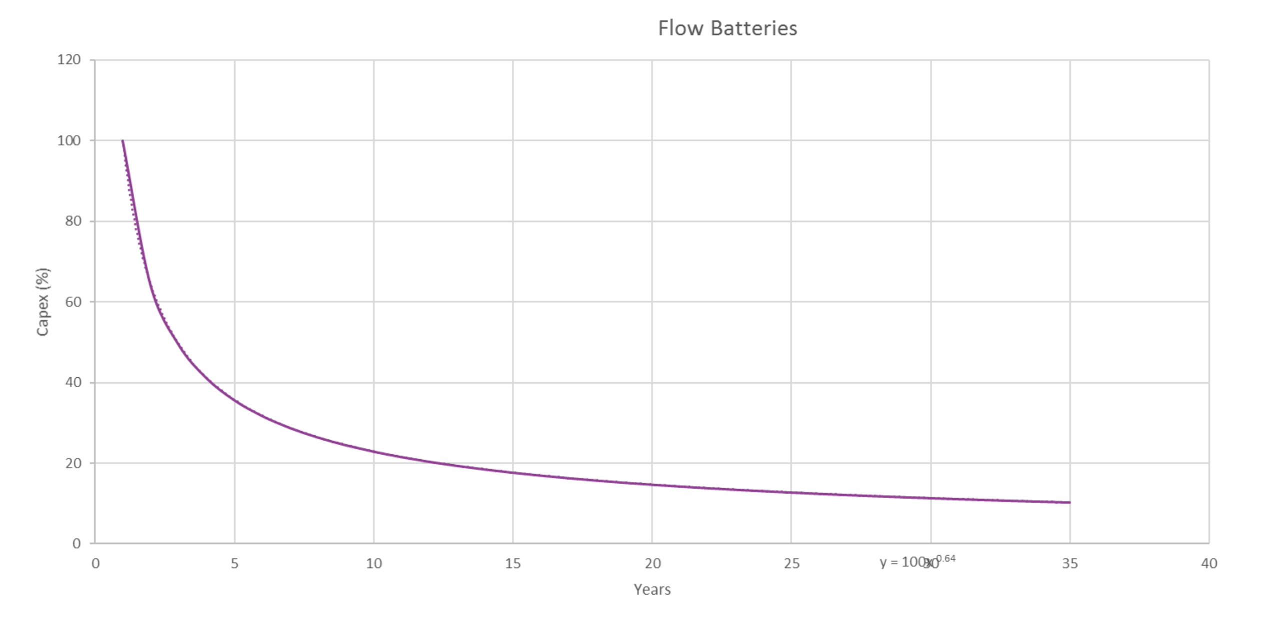
This figure will be very optimistic for the early years of installation.

2.7.6 Flow Battery Cost Reduction

The learning rate and associated cost reduction of flow batteries are driven by further development of the cells and stacks to increase system performance, particularly efficiencies by reducing balance of plant energy losses. Reduction in life cycle costs will be achieved by improving the chemical stability of the materials used in the membrane and electrodes. Improvements in the design of the electrodes, membranes and electrolytes will lead to greater conductivity and electrode kinetics allowing for higher power and energy densities that will in turn result in smaller system footprints and costs.

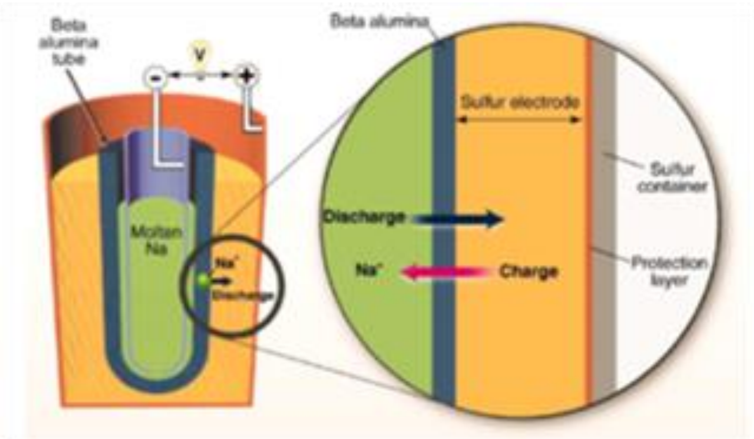
Mott MacDonald has based the calculation of time-based learning rates on projected costs published in reports from IRENA, DNV-GL and others. Details of the calculation methodology of the time-based learning rates are given in Section 4.2.

Figure 13: Flow Battery Cost Reduction



2.8 Sodium Sulphur Battery Storage

Figure 14: Picture of Tubular NaS Battery



Source: J. Cho et al: "Commercial and research battery technologies for electrical energy storage applications"

Sodium Sulphur (NaS) Battery storage is classified as a high temperature rechargeable battery and is based on storing energy in an electrochemical cell using a molten electrolyte e.g. sodium sulphur.

NaS batteries use molten sodium (Na) as the anode and molten sulphur (S) as the cathode, separated by a beta alumina tube as shown in Figure 14. During discharge, the positively charged sodium ions pass through the electrolyte into the molten sulphur where it reacts. The electrons that are released by the sodium pass through the external circuit and back into the battery at the positive electrode. To facilitate the ion transfer, the electrodes must be kept in a liquid molten state and requires the cells to be kept at an operating temperature in the range of 300°C to 360°C (572°F-680°F). The high operating temperatures lead to high reactivity and result in high rated capacities.

The NaS battery is suited for power quality applications and can provide high rates of discharge. The manufacturer claims response times, from 0 - 100% rated load, in about 1 second and start up times for charging and discharging within 1ms. Initial start-up of the system requires that the battery modules be brought to operating temperatures. The bottom and side electric heaters can take up to 70 hours to heat the system from ambient to the required 300°C. During system operation, the thermal management system is required to maintain operating temperatures within a 25 and 20°C horizontal and vertical band and contributes to the parasitic loads of the system.

Existing installations have demonstrated their suitability for load shifting, peak shaving, power quality control and storage of renewable energy.

2.8.1 Sodium Sulphur Battery Advantages

- Good efficiency of 80-90%.
- Sub second response time of 0.5 - 1 seconds.
- Good self-discharge rate ranging between 0.05 - 0.1% per day.
- No locational constraints.

Advantages of the technology also include good energy density and being suitable for applications where energy needs to be stored for longer periods for time.

2.8.2 Sodium Sulphur Battery Disadvantages

- Operational hazard in high temperature operation of battery.
- Limited deployment in grid scale storage.

Additionally, the system has high operational costs and needs to maintain its temperature while idle.

2.8.3 Sodium Sulphur Battery Build Limits

The build limits are related to manufacturing capacity. This is presently limited to one manufacturer (NGK insulators), however when the technology reaches maturity there is potential to commoditised production (similar to Li-ion) and as such produce large numbers of cells.

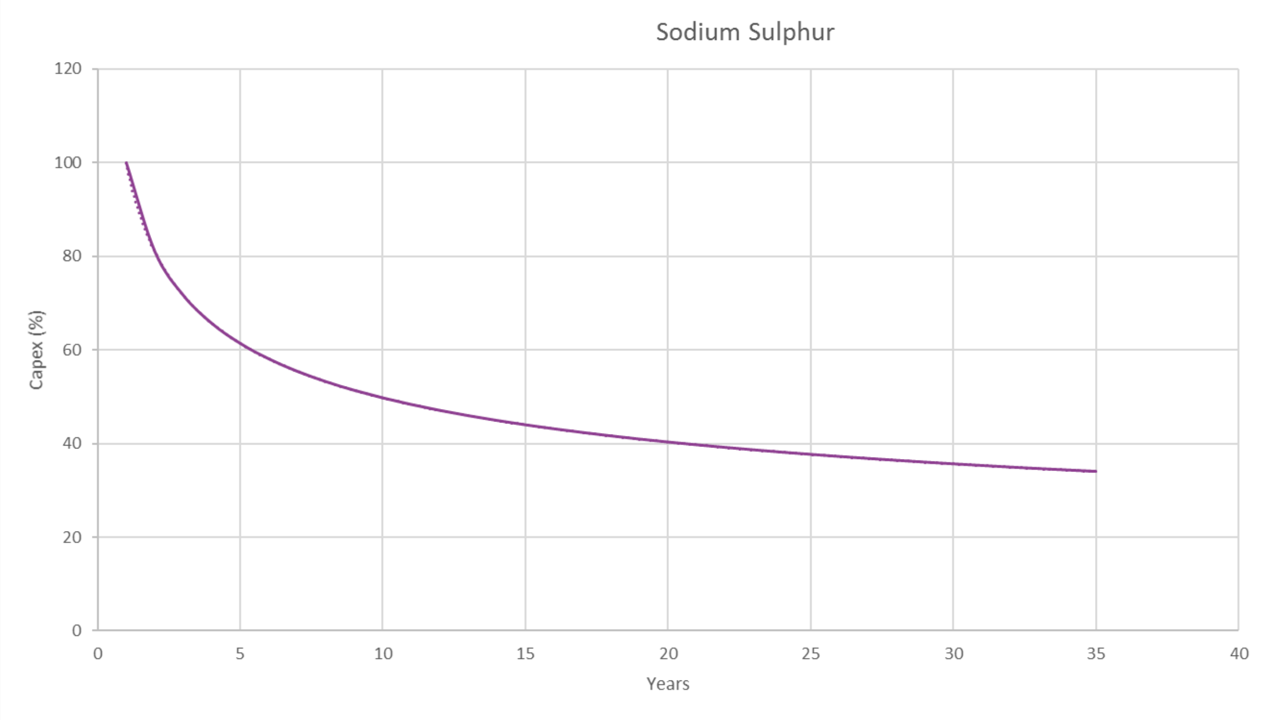
An assumption of 2GW is taken, this is half of the assumed build limit of Li-ion. This is made on the assumption that the supply chain will not reach the same maturity as Li-ion due to no EV or customer electronic applications however could be scaled up to multi GWh per year if this proves viable. This is also based on the assumption that NGK licences the technology and other manufacturers could enter the market.

2.8.4 Sodium Sulphur Battery Cost Reduction

The Sodium Sulphur learning rates and associated cost reduction relies on increased development of the materials and construction methods used to reduce operational expenditure. This will mainly be achieved by improving the corrosion resistance of the materials and lowering the operating temperature currently required to achieve the electrochemical activity in the sodium beta based systems. The main challenge is to improve the ion transfer capability of the electrolyte. Research is currently investigating replacing the ceramic electrolyte with an alternative material that will allow for a reduction in operating temperature, heating losses and therefore cost.

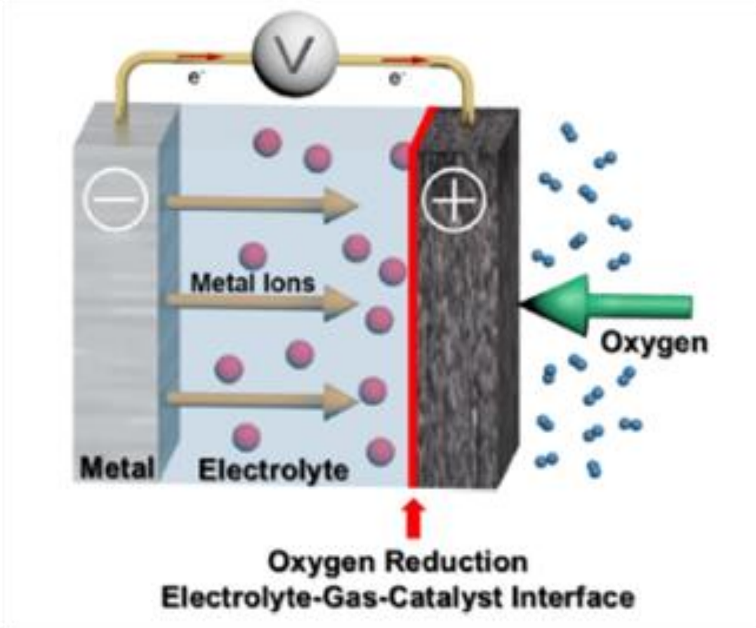
Mott MacDonald has based the calculation of time-based learning rates on projected costs published in reports from IRENA, DNV-GL and others. Details of the calculation methodology of the time-based learning rates are given in Section 4.3. It is important to note that the breakthroughs required in the electrolyte might not be achieved and therefore the projected cost reduction will have to be updated.

Figure 15: Sodium Sulphur Learning Rates



2.9 New Battery Storage

Figure 16: Diagram of a possible Metal Air Battery



Source: J. Cho et al: "Commercial and research battery technologies for electrical energy storage applications"

New battery designs are included in our assessment to allow for "game changing" new technologies. These included experimental new chemistries and compositions of the electrodes such as Lithium sulphur or Metal air e.g. Lithium air. All are based on storing electrical energy as electrochemical potential energy using electrode materials with high specific energy.

Metal air batteries generally consist of a metal anode, air cathode and metal ion conducting electrolyte. The air cathode consists of a nano-porous carbon network that is immersed in a liquid electrolyte with an interpenetrating gas phase. Depending on the state of the electrolyte, which can be aqueous or non-aqueous, the reaction pathways and products can vary.

During discharge the Lithium Air battery intakes atmospheric oxygen on the cathode and uses a redox reaction to complete the electrochemical cell, providing power.

During battery charge the reverse reaction occurs for the Lithium Sulphur battery while the Lithium Air battery type undergoes the opposite reaction, releasing oxygen.

Further R&D focuses on bringing them through preliminary research stages to a point where commercial trials can begin. These technologies require further development before commercial deployment can commence. As such, cost predictions require a breakthrough point in time before cost reduction can commence through large scale deployment and economies of scale.

2.9.1 New Battery Advantages

- Excellent efficiency of above 90%
- Sub-second response time of 0.1 - 0.3seconds
- Good self-discharge rate estimated at 0.1 - 0.3% per day
- No locational constraints

Advantages include the potential for higher energy densities than currently possible.

2.9.2 New Battery Disadvantages

- Operational hazard of thermal runaway if battery temperature is not managed.
- Technology is extremely immature and is still pre-commercial, as it is in the research and development phase

2.9.3 New Battery Build Limits

The build limits will be related to manufacturing capacity. This is presently experimental (and as such negligible), however when the technology reaches maturity there is potential to commoditised production (similar to Li-ion) and as such produce large numbers of cells.

An assumption of 2GW is taken, this is half of the assumed build limit of Li-ion. This is made on the assumption that the supply chain will not reach the same maturity as Li-ion due to no EV or customer electronic applications however could be scaled up to multi GWh per year if this proved viable,

This figure will be very optimistic for the early years of installation.

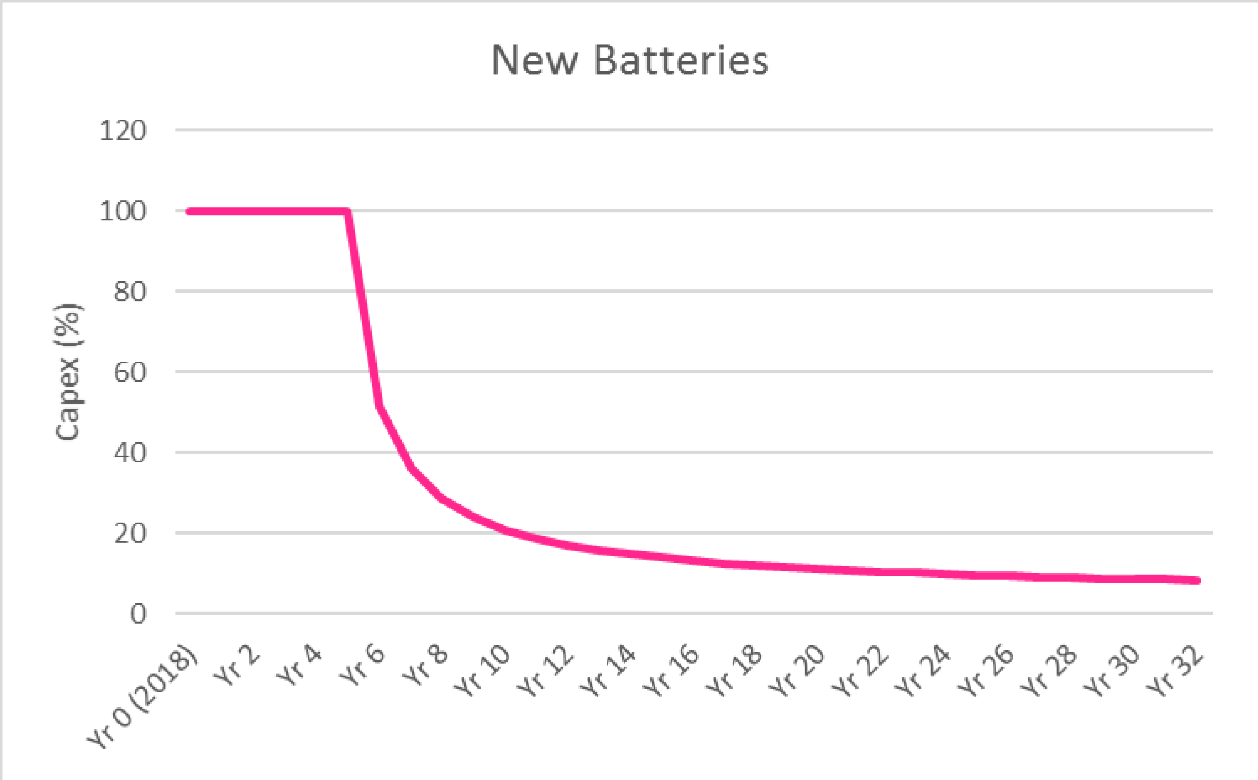
2.9.4 New Battery Cost Reduction

New Battery learning rates and associated cost reduction are mainly driven by the EV market who pay a premium for battery storage energy density. The nascent stage of current research usually precludes a “breakthrough” point, whereby the major technical challenges are solved and solving minor technical challenges, optimisation, commercialisation and standardisation follow rapidly. This gives the New Battery learning rate a fairy unique profile compared to other technologies. In the chart below this is modelled in year six.

Technologies such as Lithium Sulphur offer low cost materials and high energy densities, while Metal air batteries offer extraordinary potential energy densities all leading to aggressive cost reductions once introduced to the market.

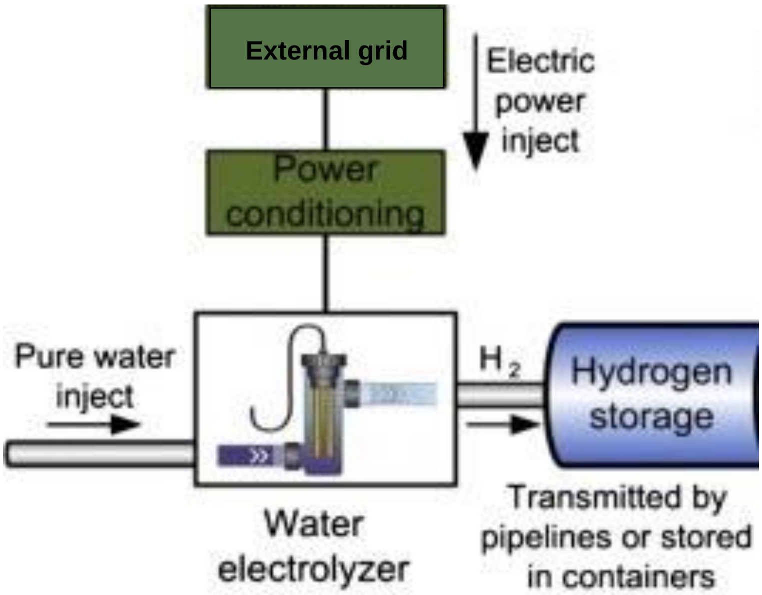
Mott MacDonald has derived time-based learning rates for the cells by reviewing research and development reports and publications in the field and estimating target cell prices in the future. Similar to Li-Ion, separate time-based learning rates for each of the cost components as defined in Section 4.3 were calculated using projected costs in published reports from IRENA, DNV-GL and others. A final aggregate cost reduction curve was calculated based on a summation of the individual cost components for each projected year.

Figure 17: New Battery Cost Reduction



2.10 Hydrogen Storage

Figure 18: Diagram of Hydrogen Storage Scheme



Source: Luo, X., Wang, J., Dooner, M. and Clarke, J. (2014).

Hydrogen Storage uses surplus electrical energy to generate hydrogen that acts as the energy carrier.

The operation consists of an electrolyser and a storage medium, typically a high-pressure vessel.

During discharge, the hydrogen can be combusted in boilers, turbines or reciprocating engines to produce electricity in conventional power plants along with natural gas or in a fuel cell can be used to directly convert the hydrogen into electricity and water.

During charge the electrolyser splits water molecules into oxygen and hydrogen. The hydrogen is then stored or can be injected into the gas network.

2.10.1 Hydrogen Storage Advantages

- Good response times ranging between 0.5 - 10 seconds
- Low self-discharge between 0.1 - 0.5% per day
- No locational constraints

Advantages include clean precursor (water) and output gases as well as high energy density. Another, if used to power a power plant, is large storage potential in the gas network.

2.10.2 Hydrogen Storage Disadvantages

- Very poor efficiency ranging between 32 - 40%
- Operational hazard in the form of a hazard zone due to the presence of hydrogen gas
- Technology is still quite immature and not widespread however, it is accelerating as seen in projects such as the plant being built in Rhineland, Germany by Shell

Disadvantages for hydrogen, regardless of how it is reconverted back to electricity, include high capital cost and relatively short life cycles of the electrolysers and fuel cells.

2.10.3 Hydrogen Storage Build Limits

The hydrogen storage build limits can be estimated by evaluating the electrolyser market deployments and forecasts. Estimated annual MWs of systems shipped for 2018 and 2020, according to industry reports, are 130MW and 450MW respectively. Assuming a constant linear market uptake, would estimate a global annual sales volume of close to 5.2GW by 2050.

When the technology reaches maturity, there is potential to commoditise production (similar to Li-ion) and as such produce large numbers of hydrogen production devices.

An assumption of 2GW is taken for the build limit, this is half of the assumed build limit of Li-ion and about 38% of the projected global sales volume for electrolysers. This is made on the assumption that the supply chain will not reach the same maturity as Li-ion due to no EV or customer electronic applications however could be scaled up to multi GW per year if this proved viable,

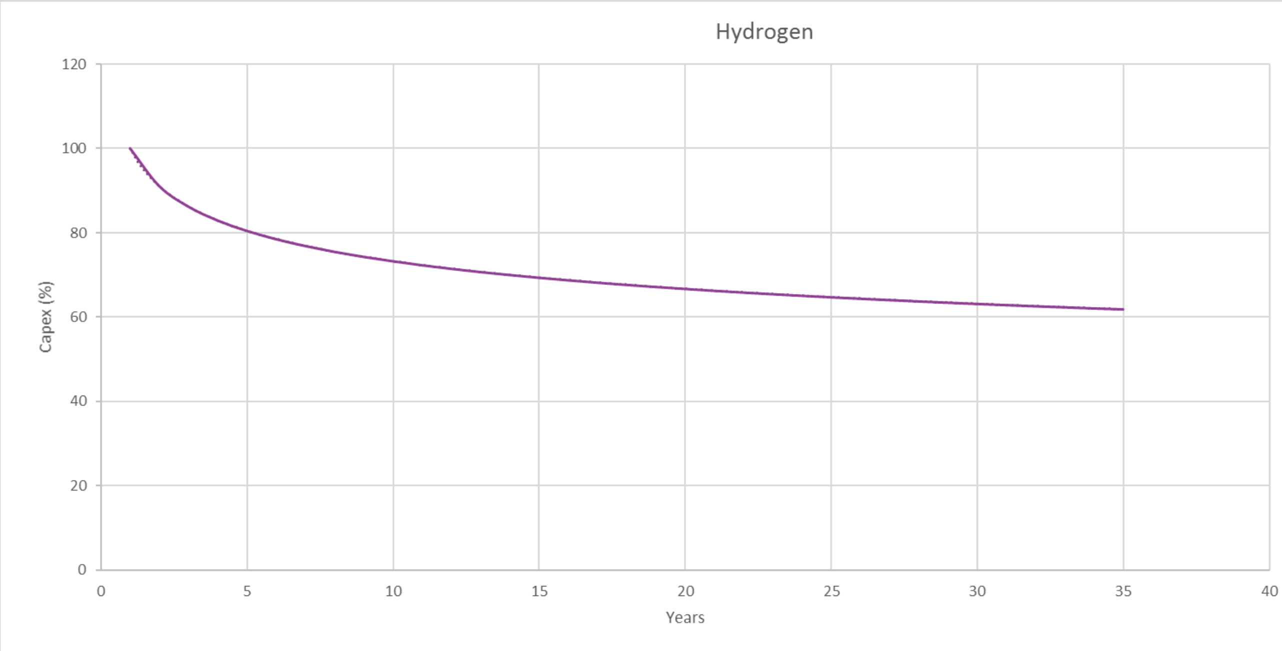
This figure will be very optimistic prior to 2030.

2.10.4 Hydrogen Storage Cost Reduction

The learning rates and associated cost reduction of hydrogen energy storage is mainly driven by the deployment and development of electrolyser and fuel cell systems. Increased interest in the production of zero carbon fuel using renewable energy has resulted in increased deployment rates of electrolysers as observed in annual reports of the top manufacturing companies. Further improvements in performance and a reduction in the use of noble metals are contributing factors to the cost reduction estimates.

Mott MacDonald has based the calculation of time-based learning rates on projected costs published in reports from hydrogen market research groups including E4Tech, 4thEnergyWave and others. Details of the calculation methodology of the time-based learning rates are given in Section 4.2.

Figure 19: Hydrogen Cost Reduction



3 Electricity Storage Use Case

3.1 Why "Use Cases"

BEIS requested cost and technical assumptions for around five electricity storage technologies or five storage technology types that were representative of storage currently deployed and likely to be deployed in the future to inform BEIS modelling and policy development.

To allow for a larger number of technologies to be considered, Mott MacDonald grouped technologies into use cases. Table 3 below, presents the list of the agreed use cases.

The use cases are based on existing proven applications in the UK, and on business cases put forward alongside more innovative storage types (e.g. CAES) which opens up new use cases such as weekly and seasonal energy balancing.

The use cases are presented with example plant sizes, technical requirements such as cycle life requirement, and the technologies suitable for the use case listed. This is determined by the technology capabilities being considered against the use case requirements.

The selected use cases are intended to reflect the current market for electricity storage and also the potential future markets. The use cases may be grouped into these three broad categories:

1. Frequency Response (short term duration)
2. Peak Lopping (4-6 hours response)
3. Long Term Energy Storage (20 hours +)

The frequency response use case is captured in the Frequency Management use case (FM). Peak Lopping (PL) has a number of sub-use cases. All the PL sub-cases incorporate Daily Arbitrage (DA) as an operating scenario. Long term energy storage use cases include Weekly Energy Balancing (WEB) and Seasonal Energy Storage (SES).

Table 3: Use Case Specifications

Category	Technical Requirement				Energy Storage Technologies	Total Requirement
	Deliverable Power (MW)	Energy Storage (MWh)	Time value (hours)	Response time		
Frequency Management (FM)	50	50	1	Response within 250ms	Lithium ion, New Battery Storage Technology	Constrained by the size of the frequency management market (demand side constraint).
Network Connected Peak Lopping / Daily Arbitrage (PL/DA)	200	800	4	Response within 20s	Pumped hydro storage, CAES, Thermal Energy Storage, Lithium ion Battery Storage, Zinc Based Battery Storage, Flow Battery Storage, Sodium Sulphur Battery Storage, New Battery Storage Technology	Constrained by the size of the arbitrage market (demand side constraint).
Domestic (Behind the Meter) Peak Lopping / Daily Arbitrage (DPA/DA)	0.005	0.02	4	Response within 1s	Lithium Ion Battery Storage, New Battery Storage Technology	Constrained by the size of BtM sites with interest in installing as well as arbitrage markets. Supply and demand side constraints.
Co-Located Renewables Peak Lopping / Daily Arbitrage (CPL DA)	10	40	4	Response within 1s	Lithium Ion Battery Storage, New Battery Storage Technology	Constrained by the size of renewable sites with interest in installing as well as arbitrage markets. Supply and demand side constraints.
Distribution Network Peak Lopping / Daily Arbitrage (DNPL DA)	2.5	10	4	Response within 1s	Lithium Ion Battery Storage, New Battery Storage Technology	Constrained by the size of distribution network need. Supply and demand side constraints.
I&C (Behind the Meter) Peak Lopping / Daily Arbitrage (BMPL /DA)	1	4	4	Response within 1s	Lithium ion, New Battery Storage Technology,	Constrained by the size of BtM sites with interest in installing as well as arbitrage markets. Supply and demand side constraints.
Weekly Energy Balancing (electricity to electricity) (WEB-EtoE)	200	4000	20	Response within 20s	Pumped Hydro Storage, CAES, Zinc Based battery storage, Flow Battery Storage, Sodium Sulphur Battery Storage, Thermal Energy Storage	Constrained by the size of the arbitrage market (demand side constraint).
Seasonal energy Storage (electricity to electricity) (SES-EtoE)	10	2500	250	Response within 20s	Hydrogen Energy Storage	Constrained by the size of the arbitrage market (demand side constraint).

3.2 Frequency Management

Frequency response is included as this has been the driver for the majority of battery electricity storage connected to the UK network in recent years.

However, as this service may be combined (for a number of technologies) with the provision of peak lopping, the prevalence of new dedicated frequency response projects may decline in the future. Frequency management has been modelled as requiring a one-hour battery storage. This is in line with typical project developed in the UK.

3.3 Peak Lopping

Peak lopping is medium duration storage used daily to remove either the peak load on a network or site. Or alternatively to move peak renewable generation from time of generation to time of need. This size of electricity storage (duration) is incentivised by Capacity Market Payments, Capacity Market avoidance, Distribution Use of System (DUoS) charges, Transmission Network Use of System (TNUoS) charges and high energy price avoidance (arbitrage). As mentioned in Section 3.1, where battery electricity storage (or other technologies with fast response) are used for peak lopping it is possible to stack this benefit with frequency response. Four hours has been selected as the electricity storage duration for these values as there are currently limited incentives to have storage of a duration in excess of this value. The direction of four hours may increase in the future, if the required duration of the capacity market increases and/or if longer duration peaks in energy prices occur.

We have provided many use cases for peak lopping e.g. Behind the Meter, or Network Connected. These reflect the location in the network that peak lopping can occur as well as whether the storage is co-located/ or standalone e.g. Co-located Renewable peak lopping. The intention of providing these different locations is to facilitate further modelling in the use of energy storage to reduce congestion in the distribution network. If both load and network connected generation are variable in time, the impact of where storage is connected will affect the required distribution network reinforcement works. One option that this could facilitate consideration, is if peak lopping storage is installed both behind the meter and at transmission level as it will make it possible to flatten power flows in the distribution network. This would minimise the costs of reinforcement on both the transmission and distribution levels.

3.3.1 Network Connected Peak Lopping

Network connected peak lopping refers to utility scale storage used for arbitrage at sub-transmission level (132kV).

This ensures the power produced by utility scale power plants can be stored and released as demand changes, reducing the need for peaking plants and the strain on slow response generation.

Network connected peak lopping storage at 200MW+ scale would require a grid connection at 132kV and would require large sites. Connection at higher (transmission) voltages (275kV to 400kV) may also be considered but this is likely to be less economic. The connection voltage of 132kV would be to the transmission networks in Scotland and Northern Ireland (132kV) and higher distribution (sub transmission) voltages in England and Wales (132kV).

In this document, higher voltage (275kW or 400kV) transmission connected energy storage is not considered as this would generally only be suitable for storage in excess of the largest capacity (200MW) we have considered in this project.

3.3.2 Domestic Peak Lopping

Domestic peak lopping refers to storage placed within a home. This provides arbitrage which reduces energy bills when combined with variable rate tariffs or domestic generation e.g. solar panels. While an individual domestic load is insignificant, the aggregate power consumed is worth consideration.

In this study we have only considered Li-ion and new battery storage technologies for this market, however in future other battery storage technologies such as flow batteries and zinc-based batteries may also enter this market.

3.3.3 Co-located Renewables Peak Lopping

Co-located renewable peak lopping refers to storage located with renewable energy sites.

This is generally done to ensure the intermittent renewable generation:

- Can export power to the grid at times of highest need
- Can export power to the grid for a greater percentage of the year (smooth out the power production to the grid)

This is particularly applicable for solar sites where the energy generation is predicable (with a mid-day peak) that can be moved in time to match peak load.

A major advantage of co-locating with renewables is the potential to use the existing electrical infrastructure on the generation site (e.g. 11 or 33kV substations) to connect the energy storage.

In addition, energy storage may allow for more renewable generation to be added to a site. Without storage, typically the renewable generation is limited by the largest export allowed from the site (agreed with the network owner). With storage additional generation may be added, by using the energy storage system to absorb energy at peak generation and export this later., This increases the site capacity factor (how much the renewables produce relative to the maximum export from site).

In this study we have only considered Li-ion and new battery storage technologies for this market, however in future other battery storage technologies such as flow batteries and zinc-based batteries may also enter this market.

3.3.4 Distribution Network Peak Lopping.

Distribution network peak lopping refers to distribution level storage that provides arbitrage to a more localised area than gird scale peak lopping. This would typically be connected to distribution networks at 11 or 33kV.

It is possible to combine the local benefit of removing grid constraints (by peak lopping the maximum local demand) with the national peak lopping as these peaks are generally coincident for the majority of loads. Exception to this would be exclusively business districts or some areas with particularly large industrial loads (e.g. smelters) dictating the local peak.

Use of energy storage in these areas will also reduce transmission/distribution losses and need for transmission/distribution infrastructure. This additional service has high value where it can be used to defer the requirement for a new distribution network equipment (Cables, overhead lines, substations) to be installed. It does however lose economies of scale in comparison.

In this study we have only considered Li-ion and new battery storage technologies for this market, however in future other battery storage technologies such as flow batteries and zinc-based batteries may also enter this market.

3.3.5 Industrial and Commercial Peak Lopping

Industrial and commercial peak lopping refers to storage located in and providing arbitrage to industrial sites. This has the potential to provide the same services as distribution network connected peak lopping (including reducing need for transmission/distribution infrastructure).

In addition to these incentives it provides the possibility for lower infrastructure costs (due to sharing connection infrastructure with the I&C sites) and provide greater revenues. The greater revenues are due to great incentives being in place, under the current regulatory arrangements, for reducing consumption has greater value than providing power to the grid.

We have chosen four hours duration for this use case for all the use cases the storage will be driven be the same commercial mechanisms (Capacity Market Payments, Capacity Market avoidance, Distribution Use of System (DUoS) charges, Transmission Network Use of System (TNUoS) charges and high energy price avoidance).

In this study we have only considered Li-ion and new battery storage technologies for this market, however in future other battery storage technologies such as flow batteries and zinc-based batteries may also enter this market.

3.4 Long Term Energy Storage

Long term (electrical) electricity storage is not currently incentivised or developed commercially in the UK or internationally. However, if the economy moves away from fossil fuels as an energy store (particularly for seasonal heating), it may become necessary to ensure energy security. Long term (weekly and seasonal) storage is included as a use case to facilitate the consideration of this with BEIS.

As these technologies are pre-commercial, the data quality and accuracy for the information on long term storage may be lower than that of more mature technologies.

3.4.1 Weekly Energy Storage

Weekly energy storage refers to storage over a medium length duration. This helps ensure that medium term variations in renewably generated power and in demand can be addressed. This helps prevent an over or undersupply of energy. This is particularly pertinent to balance daily variations in wind energy as well as variation from weekends to weekdays. We have considered this be transmission grid connected (132kV+) but could be installed at other locations in the network. We have chosen a value of 20 hours for the required duration of weekly balancing, this is approximately the load for the daily four-hour peak for a working week.

Another approach to sizing weekly storage would have been to size for longer duration weather events such as cold periods or wind droughts that can last for more than one week. This could potentially require energy storage of a greater duration than 20 hours. This has not been considered in this report

3.4.2 Seasonal Energy Storage

Seasonal Energy Storage refers to storage over a long-term duration to address the change of demand according to the time of the year. This is important within the UK where there is significantly greater energy consumption in winter (in particular heat) than in summer. This is negatively correlated to the availability of solar energy but positively correlated with wind energy[1].

Only hydrogen energy storage has been considered for this. Other potential viable technologies generally work on the principle of converting electricity into hydrocarbon fuels that can be stored and recovered. These other technologies, include synthetic natural gas and synthetic diesel. These require converting electricity to hydrogen, the combining the hydrogen with carbon dioxide to create a hydro carbon. As they require further steps (with the carbon dioxide using significantly more energy) these technologies are less efficient than using hydrogen as a fuel / energy vector.

Hydrogen can be used in a number of ways when generated. It can be burnt with or as a replacement for natural gas (for example in domestic boilers). Alternatively, hydrogen can generate electricity in either a gas turbine or a fuel cell.

In our model we have considered hydrogen stored and then combusted for electricity, as this gives an electricity to electricity cycle and so is comparable to the other technologies.

1 http://www.eci.ox.ac.uk/publications/downloads/sinden06-windresource.pdf

4 Data collection methodology

Mott Macdonald collected data on various cost and technical assumptions for the electricity storage technologies considered in this study.

This section covers the following:

1. Technical data
2. Cost data

4.1 Data Collected

The following key technical assumptions were collected for each electricity storage technology:

Table 4: Key attributes

Attribute	Definition
Round trip efficiency (%)	Defined as energy out/energy in at the point of connection to the grid. This is AC power to AC power.
Variable Cost (£/MWh)	Further detail on costs are included in Appendix A. The variable costs have been considered as zero all technologies. The only variable cost for energy storage is that of the input energy which is modelled in the DDM.
Maximum new builds by plant type each year (MW)	Technical build limit per annum (MW). This value is discussed in Section 2 for each technology.
Construction period (Years)	Length of time to construct the project
Lifetime (Years)	Lifetime of plant
Maximum deliverable power (MW)	To be defined by the deliverable power assumption for the use case see Section 3
Average availability (%)	This is the percentage of time during a year that plant is available. This will account for failures (unplanned) and maintenance (planned).
Energy Storage (MWh)	To be defined by the Electricity storage assumption for the use case see Section 3
Self-discharge rate	A standard measure of an energy storage technology's capability to 'keep' the stored energy. This is defined as the time elapsed before capacity is reduced to less than 80% by self-discharge.
Useable depth of discharge	% of electricity storage useable. (Some technologies will not allow all stored energy to be discharges).
Response time (seconds)	From signal to full power discharge
Footprint (m^2)	Physical footprint of the site required for the plant.
Operational environmental, safety limitations/ hazards (Y/N)	Note. if there are any environmental or safety hazards.
Provisions of Inertia (Y/N)	Whether or not the technology can provide synchronous generation to the network. This provides spinning mass on the network that acts to stabilise the system frequency.
Cycle Life	Cycle Life is a standard value used to give guidance on the number of full charges and discharges as technology can complete prior to end of life. Cycle life give an approximate view on the life of the technology. However, as most technologies will operate in partial cycles and at different discharge speeds this is not a complete indicator of life.
Infrastructure cost (£) (High, Medium and Low)	See Section 4.2.1 High, medium and low costs estimated to provide anticipated range of probable costs a project could pay. Details are provided on the phasing that costs will be incurred for each technology.
Pre-Development Costs (£)	See Section 4.2.2.

Attribute	Definition
Construction Period phasing (% of investment for each year of construction)	Time required to construct project. This time is from appointment of EPC contactor.
CAPEX (£) (High, Medium and Low)	See Section 4.2.3 . High, medium and low cost were estimated to provide anticipated range of probable costs a project could pay.
OPEX (£/year) (High, Medium and Low)	See Section 4.2.4 High, medium and low cost were estimated to provide anticipated range of probable costs a project could pay.

4.2 Costing Information

As noted above the cost data is broken down into four categories,

4.2.1 Infrastructure costs

The infrastructure costs considered within this document consider the electrical connections works required to connect the project. These include new switchgear (circuit breakers etc.) cables and Over Head Lines (OHL)

The requirement vary dependant on the use case (and hence MW value) as well as increasing for technologies that are location specific (Pumped Hydro and CAES). We have provided High, Medium and Low costs for infrastructure costs for each technology and use case. These are intended to reflect typical differences in connection costs project can incur based on distance to connecting substation and spare equipment at connection substation.

4.2.2 Pre-development costs

We have defined the pre-development costs to be the costs incurred prior to appointment of an EPC contractor. They include:

- Front End Engineering Design (including conceptual design)
- Studies Carried out (include electrical modelling, environmental surveys and ground investigations)
- Planning Approval process (including any licencing and enquires required)
- Grid connection approval works.

The costs for project has been estimated based on Mott MacDonald’s experience of performing FEED, grid connection application, system studies, ground investigation (specifying of) and planning approval processes.

The costs for these projects are proportionally higher for project with environmental or geological investigations required as well as potentially long planning approval works. As such, Pumped Hydro is allotted pre- development costs of approximately four times that of battery storage projects, with CAES around double.

4.2.3 Capital Expenditure (CAPEX)

CAPEX costs include the costs incurred by the project after appointment of the EPC contractor / financial close.

These include:

- Detailed design costs (carried out by EPC contractors)
- Capital Costs (including energy Storage System, electrical systems)
- Installation costs (including delivery, civil works, installation, commissioning and testing)

High, medium and low CAPEX costs are provided to give the anticipated range of probable costs a project could pay. The high and low cost will not be selected to accommodate all possible projects and will not include outlier values.

For battery storage products, the CAPEX is budgeted to ensure that there is sufficient capacity in the system to ensure the full energy capacity is available for project life time. This is in line with common industry practice. These figure also do not include consideration of embedded carbon.

4.2.4 Operational Expenditure (OPEX)

Operational Costs OPEX include the costs incurred on an annual basis.

These include:

- Operation
- Inspection
- Maintenance
- Replenishment / refurbishment of consumables
- Insurance
- Security

High, medium and low OPEX costs are provided to give the anticipated range of probable costs a project could pay. The high and low cost will not be selected to accommodate all possible projects and will not include outlier values.

These figures do not include

- Grid connection charges (TNUoS/DUoS/BSUoS),
- Operational CO_2 emissions. As none of the technologies involve significant fossil fuel use these will be dictated by the CO_2 used in the electricity lost in storage.

4.3 Learning Rates

The time-based learning rate (TBLR) used to determine the yearly costs of deployment associated with each technology and use case typically considers the primary technical and economic drivers. These are applied to CAPEX and OPEX. The OPEX has been modelled with the same TBLR as CAPEX. This is a simplified assumption for the technologies with significantly reduced costs over the lifetime such as Li-Ion. The reduction in O&M costs is likely to be consistent with the CAPEX in that the replacement parts will reduce in cost and insurance costs will be reduced. Operational costs will also be reduced with economies of scale. Some factors (such as security) will not scale with learning rates.

The infrastructure costs and predevelopment costs are not varied with learning rates as these are assumed to be constant with little cost reduction expected. For all the technologies considered we have considered the infrastructure costs to be dominated by electrical network connection costs. As such, the infrastructure costs only consider these values. Other potential infrastructure costs, such as roads, water supplies or gas supplies are not considered. Electrical network connections are a mature market and we don’t anticipate significant learning rate. The technical characteristics and build limits are not cost related data and thus not subject to a learning curve

Mott MacDonald has determined time-based learning rates for each technology and use case by performing curve fitting on yearly cost projections. The functions used were simplified polynomial or power expressions to minimise complexity of the analysis.

The curve fitting was performed on selected data points presented in literature, published reports where cost projections have been performed and our internal datasets. The cost estimates reported and used for the curve fitting were based on a number of drivers including volume of deployment and production capacity. For pre-commercial technologies that will only become viable for deployment in the future, cost data projections were based on internal knowledge of the industry and estimates in literature. The most recently available reference material was used for the analysis.

For ease of use, a time-based learning rate (TBLR) is calculated for all the technologies, as the projected cost data in published reports are typically presented for an equivalent year. The TBLR is calculated using an automated curve fitting approach using a standard learning curve approximation:

$$P_t = P_0 \left(\frac{X_t}{X_0}\right)^{-b}$$

Where P_t and P_0 are the price at the initial period and year t, X_t and X_0 are the respective times in years.

The progress rate (PR) and time-based learning rate are calculated as follows:

$$PR = 2^{-b}$$

$$TBLR = 1 - PR$$

The TBLR represents the % cost reduction for each doubling of cumulative period of time and the PR provides a ratio of final to initial costs associated with a doubling of cumulative time. The TBLR and resulting cost reduction is a higher-level estimate compared to traditional learning rates based on production capacity of cumulative sales figures. The TBLR does not correlate the production and sales figures to price and then to the projected year but rather performs a direct yearly cost estimate. As such the underlying drivers for the cost reduction are only indirectly coupled to the TBLR.

In the modelling of the cost curves we have noted that the published data we are referring to is dated in either 2016 or 2017. While we are able to confirm from the market that the costs reductions (from 2016 to 2018) anticipated for Lithium Ion are accurate. For the other technologies (CAES, Pumped Hydro, Flow Batteries, Sodium Sulphur etc.) the market has not indicated large changes in the prices since 2016. In some cases, the price predicted were based on rapid develop due to large investment. Based on what we have seen in the market, this is yet to occur. As such we propose to keep the 2016 values as the year 0 (and hence 2018) values for learning rates. The fact that the price reductions have not necessarily happened does not make these curves incorrect for the next few years. Technologies (particularly flow batteries) are seeing large scale investment so the prices may reduce rapidly in line with the predicted price curves.

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4.4 Information Collection and Quality Assurance

Information collection and quality assurance underpins the work done and ensures that the information gathered is relevant, reliable and fit for purpose. This section details how this was achieved.

4.4.1 Quality Assurance

Mott MacDonald has worked in accordance with our own Business Management Systems (BMS) quality assurance procedures and BEIS's Quality Assurance requirements.

4.4.2 Attributes Considered

See Section 4.1 for details on a list of the attributes considered.

The attribute values were populated using publicly available reports (including reports published by Lazard, IRENA, USTDA, Deloitte and research groups), scientific papers, OEM data and from Mott MacDonald engineering knowledge. Recent publication of source material was preferred.

Appendices

A. Technology data

The key information collected on each technology is detailed below and covers both financial and technical data. All costs are presented in 2012 prices.

A.1 Frequency Management (FM) (50MW 50MWh)

A.1.1 Lithium Ion Battery Storage (50MW 50MWh)

Table 5: Lithium Ion Battery FM Data Table

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	85.0%
Variable Cost (£/MWh)	0
Maximum new builds by plant type each year (MW)	4000
Construction period (Years)	1
Lifetime (Years)	15
Maximum deliverable power (MW)	50
Average availability (%)	95.0%
Energy Storage (MWh)	50
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	1560
Useable depth of discharge (% of energy storage useable) (%)	80.0%
Response time (s)	0.15
Footprint (m^2)	907.5
Operational environmental, safety limitations/ hazards (Y/N)	N Generally but unsafe if overheated,
Provisions of Inertia (Y/N)	N
Cycle Life (Equivalent Complete Cycles)	5000
Pre-Development Costs (£)	£245,622
Construction Period phasing (% of investment for each year of construction)	100.0%
Infrastructure cost (High) (£)	£682,283
Infrastructure cost (Medium) (£)	£291,108
Infrastructure cost (Low) (£)	£109,165
CAPEX (High) (£)	£34,435,263
CAPEX (Medium) (£)	£29,515,939
CAPEX (Low) (£)	£24,596,616

Description of Attribute	Number or Truth Value
OPEX (High) (£/year)	£623,668
OPEX (Medium) (£/year)	£455,200
OPEX (Low) (£/year)	£257,433

Table 6: Lithium (FM) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	13.6	13.6	13.6	13.6	13.6
Infrastructure cost (Medium) (£/kW)	5.8	5.8	5.8	5.8	5.8
Infrastructure cost (Low) (£/kW)	2.2	2.2	2.2	2.2	2.2
CAPEX (high) (£/kW)	688.7	553.6	334.4	266.1	230.5
CAPEX (Medium) (£/kW)	590.3	474.5	286.6	228.1	197.6
CAPEX (Low) (£/kW)	491.9	395.4	238.8	190.1	164.6
OPEX (High) (£/kW/year)	12.5	10.0	6.1	4.8	4.2
OPEX (Medium) (£/kW/year)	9.1	7.3	4.4	3.5	3.0
OPEX (Low) (£/kW/year)	5.1	4.1	2.5	2.0	1.7

A.1.2 New Battery Storage (50MW 50MWh)

Table 7: New Battery Storage FM Data Table

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	90.0%
Variable Cost (£/MWh)	0
Maximum new builds by plant type each year (MW)	2000
Construction period (Years)	1
Lifetime (Years)	15
Maximum deliverable power (MW)	50
Average availability (%)	95.0%
Energy Storage (MWh)	50
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	1560
Useable depth of discharge (% of energy storage useable)	100.0%
Response time (s)	0.1
Footprint (m^2)	453.75

Description of Attribute	Number or Truth Value
Operational environmental, safety limitations/ hazards (Y/N)	N Generally but unsafe if overheated,
Provisions of Inertia (Y/N)	N
Cycle Life	1500
Pre-Development Costs (£)	£245,622
Construction Period phasing (% of investment for each year of construction)	100.0%
Infrastructure cost (High) (£)	£682,283
Infrastructure cost (Medium) (£)	£291,108
Infrastructure cost (Low) (£)	£109,165
CAPEX (High) (£)	£138,503,500
CAPEX (Medium) (£)	£118,717,286
CAPEX (Low) (£)	£98,931,071
OPEX (High) (£/year)	£1,875,142
OPEX (Medium) (£/year)	£1,335,001
OPEX (Low) (£/year)	£732,004

Table 8: New Battery Storage (FM) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	13.6	13.6	13.6	13.6	13.6
Infrastructure cost (Medium) (£/kW)	5.8	5.8	5.8	5.8	5.8
Infrastructure cost (Low) (£/kW)	2.2	2.2	2.2	2.2	2.2
CAPEX (high) (£/kW)	2770.1	2770.1	473.3	290.0	232.3
CAPEX (Medium) (£/kW)	2374.3	2374.3	405.7	248.6	199.1
CAPEX (Low) (£/kW)	1978.6	1978.6	338.1	207.2	165.9
OPEX (High) (£/kW/year)	37.5	37.5	6.4	3.9	3.1
OPEX (Medium) (£/kW/year)	26.7	26.7	4.6	2.8	2.2
OPEX (Low) (£/kW/year)	14.6	14.6	2.5	1.5	1.2

A.2 Network Connected Peak Lopping (PL-DA) (200MW 800MWh)

A.2.1 Pumped Hydro Storage (200MW 800MWh)

Table 9: Pumped Hydro Storage PL-DA Data Table

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	75.0%
Variable Cost (£/MWh)	0
Maximum new builds by plant type each year (MW)	200
Construction period (Years)	4
Lifetime (Years)	30
Maximum deliverable power (MW)	200
Average availability (%)	95.0%
Energy Storage (MWh)	800
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	87600
Useable depth of discharge (% of energy storage useable)	100.0%
Response time (s)	16
Footprint (m^2)	250,000
Operational environmental, safety limitations/ hazards (Y/N)	No
Provisions of Inertia (Y/N)	Yes
Cycle Life	100000
Pre-Development Costs (£)	£19,103,931
Construction Period phasing (% of investment for each year of construction)	25.0%
Infrastructure cost (High) (£)	£25,017,053
Infrastructure cost (Medium) (£)	£11,371,388
Infrastructure cost (Low) (£)	£3,183,989
CAPEX (High) (£)	£363,884,400
CAPEX (Medium) (£)	£272,913,300
CAPEX (Low) (£)	£218,330,640
OPEX (High) (£/year)	£4,965,445
OPEX (Medium) (£/year)	£3,724,083
OPEX (Low) (£/year)	£2,979,267

Table 10: Pumped Hydro Storage (PL-DA) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	125.1	125.1	125.1	125.1	125.1
Infrastructure cost (Medium) (£/kW)	56.9	56.9	56.9	56.9	56.9
Infrastructure cost (Low) (£/kW)	15.9	15.9	15.9	15.9	15.9

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
CAPEX (high) (£/kW)	1819.4	1741.3	1642.3	1605.3	1582.4
CAPEX (Medium) (£/kW)	1364.6	1306.0	1231.7	1204.0	1186.8
CAPEX (Low) (£/kW)	1091.7	1044.8	985.4	963.2	949.4
OPEX (High) (£/kW/year)	24.8	23.8	22.4	21.9	21.6
OPEX (Medium) (£/kW/year)	18.6	17.8	16.8	16.4	16.2
OPEX (Low) (£/kW/year)	14.9	14.3	13.4	13.1	13.0

A.2.2 CAES (200MW 800MWh)

Table 11: CAES PL-DA Data Table

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	65.0%
Variable Cost (£/MWh)	0
Maximum new builds by plant type each year (MW)	1000
Construction period (Years)	3
Lifetime (Years)	25
Maximum deliverable power (MW)	200
Average availability (%)	92.0%
Energy Storage (MWh)	800
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	9600
Useable depth of discharge (% of energy storage useable)	100.0%
Response time (s)	30
Footprint (m^2)	22500
Operational environmental, safety limitations/ hazards (Y/N)	No
Provisions of Inertia (Y/N)	Y
Cycle Life	50000
Pre-Development Costs (£)	£2,547,191
Construction Period phasing (% of investment for each year of construction)	50.0%
Infrastructure cost (High) (£)	£25,017,053
Infrastructure cost (Medium) (£)	£6,822,833
Infrastructure cost (Low) (£)	£1,591,994
CAPEX (High) (£)	£218,330,640
CAPEX (Medium) (£)	£200,136,420
CAPEX (Low) (£)	£181,942,200
OPEX (High) (£/year)	£3,638,844
OPEX (Medium) (£/year)	£2,729,133

Description of Attribute	Number or Truth Value
OPEX (Low) (£/year)	£2,274,278

Table 12: CAES (PL-DA) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	125.1	125.1	125.1	125.1	125.1
Infrastructure cost (Medium) (£/kW)	34.1	34.1	34.1	34.1	34.1
Infrastructure cost (Low) (£/kW)	8.0	8.0	8.0	8.0	8.0
CAPEX (high) (£/kW)	1091.7	1010.3	911.0	875.1	853.1
CAPEX (Medium) (£/kW)	1000.7	926.1	835.1	802.2	782.0
CAPEX (Low) (£/kW)	909.7	841.9	759.2	729.3	710.9
OPEX (High) (£/kW/year)	18.2	16.8	15.2	14.6	14.2
OPEX (Medium) (£/kW/year)	13.6	12.6	11.4	10.9	10.7
OPEX (Low) (£/kW/year)	11.4	10.5	9.5	9.1	8.9

A.2.3 Thermal Energy Storage (200MW 800MWh)

Table 13: Thermal Energy Storage PL-DA Data Table

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	65.0%
Variable Cost (£/MWh)	0
Maximum new builds by plant type each year (MW)	1000
Construction period (Years)	2
Lifetime (Years)	20
Maximum deliverable power (MW)	200
Average availability (%)	92.0%
Energy Storage (MWh)	800
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	480
Useable depth of discharge (% of energy storage useable)	90.0%
Response time (s)	10+
Footprint (m^2)	25000
Operational environmental, safety limitations/ hazards (Y/N)	N

Description of Attribute	Number or Truth Value
Provisions of Inertia (Y/N)	Yes
Cycle Life	50000
Pre-Development Costs (£)	£1,273,595
Construction Period phasing (% of investment for each year of construction)	50.0%
Infrastructure cost (High) (£)	£25,017,053
Infrastructure cost (Medium) (£)	£4,548,555
Infrastructure cost (Low) (£)	£1,591,994
CAPEX (High) (£)	£227,427,750
CAPEX (Medium) (£)	£204,684,975
CAPEX (Low) (£)	£181,942,200
OPEX (High) (£/year)	£8,187,399
OPEX (Medium) (£/year)	£6,822,833
OPEX (Low) (£/year)	£5,458,266

Table 14: Thermal Energy Storage (PL-DA) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	125.1	125.1	125.1	125.1	125.1
Infrastructure cost (Medium) (£/kW)	22.7	22.7	22.7	22.7	22.7
Infrastructure cost (Low) (£/kW)	8.0	8.0	8.0	8.0	8.0
CAPEX (high) (£/kW)	1137.1	1008.8	859.8	807.9	776.7
CAPEX (Medium) (£/kW)	1023.4	907.9	773.8	727.1	699.1
CAPEX (Low) (£/kW)	909.7	807.0	687.8	646.3	621.4
OPEX (High) (£/kW/year)	40.9	36.3	31.0	29.1	28.0
OPEX (Medium) (£/kW/year)	34.1	30.3	25.8	24.2	23.3
OPEX (Low) (£/kW/year)	27.3	24.2	20.6	19.4	18.6

A.2.4 Lithium Ion Battery Storage (200MW 800MWh)

Table 15: Lithium Ion Battery Storage PL-DA Data Table

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	85.0%
Variable Cost (£/MWh)	0

Description of Attribute	Number or Truth Value
Maximum new builds by plant type each year (MW)	4000
Construction period (Years)	2
Lifetime (Years)	15
Maximum deliverable power (MW)	200
Average availability (%)	95.0%
Energy Storage (MWh)	800
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	1560
Useable depth of discharge (% of energy storage useable)	80.0%
Response time (s)	0.15
Footprint (m^2)	7260
Operational environmental, safety limitations/ hazards (Y/N)	N Generally but unsafe if overheated,
Provisions of Inertia (Y/N)	N
Cycle Life	5000
Pre-Development Costs (£)	£1,182,624
Construction Period phasing (% of investment for each year of construction)	100.0%
Infrastructure cost (High) (£)	£25,017,053
Infrastructure cost (Medium) (£)	£6,822,833
Infrastructure cost (Low) (£)	£1,591,994
CAPEX (High) (£)	£341,166,490
CAPEX (Medium) (£)	£292,428,420
CAPEX (Low) (£)	£243,690,350
OPEX (High) (£/year)	£6,066,089
OPEX (Medium) (£/year)	£4,674,793
OPEX (Low) (£/year)	£3,337,231

Table 16: Lithium Ion Battery Storage (PL-DA) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	125.1	125.1	125.1	125.1	125.1
Infrastructure cost (Medium) (£/kW)	34.1	34.1	34.1	34.1	34.1
Infrastructure cost (Low) (£/kW)	8.0	8.0	8.0	8.0	8.0
CAPEX (high) (£/kW)	1705.8	1309.9	676.3	491.5	400.1
CAPEX (Medium) (£/kW)	1462.1	1122.8	579.7	421.3	342.9
CAPEX (Low) (£/kW)	1218.5	935.7	483.1	351.1	285.8
OPEX (High) (£/kW/year)	30.3	23.3	12.0	8.7	7.1

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
OPEX (Medium) (£/kW/year)	23.4	17.9	9.3	6.7	5.5
OPEX (Low) (£/kW/year)	16.7	12.8	6.6	4.8	3.9

A.2.5 Zinc Based Battery Storage (200MW 800MWh)

Table 17: Zinc Based Battery Storage PL-DA Data Table

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	75.0%
Variable Cost (£/MWh)	0
Maximum new builds by plant type each year (MW)	2000
Construction period (Years)	2
Lifetime (Years)	15
Maximum deliverable power (MW)	200
Average availability (%)	95.0%
Energy Storage (MWh)	800
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	480
Useable depth of discharge (% of energy storage useable)	100.0%
Response time (s)	0.5
Footprint (m^2)	6000
Operational environmental, safety limitations/ hazards (Y/N)	Yes
Provisions of Inertia (Y/N)	N
Cycle Life	5000
Pre-Development Costs (£)	£1,182,624
Construction Period phasing (% of investment for each year of construction)	100.0%
Infrastructure cost (High) (£)	£25,017,053
Infrastructure cost (Medium) (£)	£4,548,555
Infrastructure cost (Low) (£)	£1,591,994
CAPEX (High) (£)	£363,884,400
CAPEX (Medium) (£)	£304,184,616
CAPEX (Low) (£)	£244,484,831
OPEX (High) (£/year)	£9,168,181
OPEX (Medium) (£/year)	£7,640,151
OPEX (Low) (£/year)	£6,112,121

Table 18: Zinc Based Battery Storage (PL-DA) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	125.1	125.1	125.1	125.1	125.1
Infrastructure cost (Medium) (£/kW)	22.7	22.7	22.7	22.7	22.7
Infrastructure cost (Low) (£/kW)	8.0	8.0	8.0	8.0	8.0
CAPEX (high) (£/kW)	1819.4	1209.6	701.4	567.4	496.2
CAPEX (Medium) (£/kW)	1520.9	1011.1	586.3	474.3	414.8
CAPEX (Low) (£/kW)	1222.4	812.7	471.3	381.2	333.4
OPEX (High) (£/kW/year)	45.8	30.5	17.7	14.3	12.5
OPEX (Medium) (£/kW/year)	38.2	25.4	14.7	11.9	10.4
OPEX (Low) (£/kW/year)	30.6	20.3	11.8	9.5	8.3

A.2.6 Flow Battery Storage (200MW 800MWh)

Table 19: Flow Storage PL-DA Data Table

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	70.0%
Variable Cost (£/MWh)	0
Maximum new builds by plant type each year (MW)	2000
Construction period (Years)	2
Lifetime (Years)	15
Maximum deliverable power (MW)	200
Average availability (%)	95.0%
Energy Storage (MWh)	800
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	480
Useable depth of discharge (% of energy storage useable)	100.0%
Response time (s)	0.5
Footprint (m^2)	76800
Operational environmental, safety limitations/ hazards (Y/N)	Y
Provisions of Inertia (Y/N)	N
Cycle Life	10000
Pre-Development Costs (£)	£1,364,567
Construction Period phasing (% of investment for each year of construction)	100.0%
Infrastructure cost (High) (£)	£25,017,053
Infrastructure cost (Medium) (£)	£4,548,555
Infrastructure cost (Low) (£)	£1,591,994

Description of Attribute	Number or Truth Value
CAPEX (High) (£)	£764,157,240
CAPEX (Medium) (£)	£654,991,920
CAPEX (Low) (£)	£545,826,600
OPEX (High) (£/year)	£20,468,498
OPEX (Medium) (£/year)	£17,057,081
OPEX (Low) (£/year)	£13,645,665

Table 20: Flow Storage (PL-DA) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	125.1	125.1	125.1	125.1	125.1
Infrastructure cost (Medium) (£/kW)	22.7	22.7	22.7	22.7	22.7
Infrastructure cost (Low) (£/kW)	8.0	8.0	8.0	8.0	8.0
CAPEX (high) (£/kW)	3820.8	1891.1	739.6	513.3	407.4
CAPEX (Medium) (£/kW)	3275.0	1620.9	634.0	440.0	349.2
CAPEX (Low) (£/kW)	2729.1	1350.8	528.3	366.7	291.0
OPEX (High) (£/kW/year)	102.3	50.7	19.8	13.7	10.9
OPEX (Medium) (£/kW/year)	85.3	42.2	16.5	11.5	9.1
OPEX (Low) (£/kW/year)	68.2	33.8	13.2	9.2	7.3

A.2.7 Sodium Sulphur Battery Storage (200MW 800MWh)

Table 21: Sodium Sulphur Battery Storage PL-DA Data Table

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	80.0%
Variable Cost (£/MWh)	0
Maximum new builds by plant type each year (MW)	2000
Construction period (Years)	2
Lifetime (Years)	15
Maximum deliverable power (MW)	200
Average availability (%)	90.0%
Energy Storage (MWh)	800
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	9600

Description of Attribute	Number or Truth Value
Useable depth of discharge (% of energy storage useable)	80.0%
Response time (s)	0.5
Footprint (m^2)	10670
Operational environmental, safety limitations/ hazards (Y/N)	Yes
Provisions of Inertia (Y/N)	N
Cycle Life	4500
Pre-Development Costs (£)	£1,364,567
Construction Period phasing (% of investment for each year of construction)	100.0%
Infrastructure cost (High) (£)	£25,017,053
Infrastructure cost (Medium) (£)	£6,822,833
Infrastructure cost (Low) (£)	£1,591,994
CAPEX (High) (£)	£764,157,240
CAPEX (Medium) (£)	£654,991,920
CAPEX (Low) (£)	£545,826,600
OPEX (High) (£/year)	£12,281,099
OPEX (Medium) (£/year)	£10,234,249
OPEX (Low) (£/year)	£8,187,399

Table 22: Sodium Sulphur Battery Storage (PL-DA) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	125.1	125.1	125.1	125.1	125.1
Infrastructure cost (Medium) (£/kW)	34.1	34.1	34.1	34.1	34.1
Infrastructure cost (Low) (£/kW)	8.0	8.0	8.0	8.0	8.0
CAPEX (high) (£/kW)	3820.8	2740.2	1758.3	1479.6	1326.5
CAPEX (Medium) (£/kW)	3275.0	2348.8	1507.2	1268.2	1137.0
CAPEX (Low) (£/kW)	2729.1	1957.3	1256.0	1056.8	947.5
OPEX (High) (£/kW/year)	61.4	44.0	28.3	23.8	21.3
OPEX (Medium) (£/kW/year)	51.2	36.7	23.5	19.8	17.8
OPEX (Low) (£/kW/year)	40.9	29.4	18.8	15.9	14.2

A.2.8 New Battery Storage (200MW 800MWh)

Table 23: New Battery Storage PL-DA Data Table

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	90.0%
Variable Cost (£/MWh)	0
Maximum new builds by plant type each year (MW)	2000
Construction period (Years)	2
Lifetime (Years)	15
Maximum deliverable power (MW)	200
Average availability (%)	95.0%
Energy Storage (MWh)	800
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	1560
Useable depth of discharge (% of energy storage useable)	100.0%
Response time (s)	0.1
Footprint (m^2)	3630
Operational environmental, safety limitations/ hazards (Y/N)	N Generally but unsafe if overheated,
Provisions of Inertia (Y/N)	N
Cycle Life	1500
Pre-Development Costs (£)	£1,182,624
Construction Period phasing (% of investment for each year of construction)	100.0%
Infrastructure cost (High) (£)	£25,017,053
Infrastructure cost (Medium) (£)	£6,822,833
Infrastructure cost (Low) (£)	£1,591,994
CAPEX (High) (£)	£1,929,497,031
CAPEX (Medium) (£)	£1,653,854,598
CAPEX (Low) (£)	£1,378,212,165
OPEX (High) (£/year)	£25,267,223
OPEX (Medium) (£/year)	£18,203,317
OPEX (Low) (£/year)	£10,680,972

Table 24: New Battery Storage (PL-DA) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	125.1	125.1	125.1	125.1	125.1
Infrastructure cost (Medium) (£/kW)	34.1	34.1	34.1	34.1	34.1
Infrastructure cost (Low) (£/kW)	8.0	8.0	8.0	8.0	8.0
CAPEX (high) (£/kW)	9647.5	9647.5	1122.3	548.6	388.9

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
CAPEX (Medium) (£/kW)	8269.3	8269.3	962.0	470.2	333.3
CAPEX (Low) (£/kW)	6891.1	6891.1	801.7	391.8	277.8
OPEX (High) (£/kW/year)	126.3	126.3	14.7	7.2	5.1
OPEX (Medium) (£/kW/year)	91.0	91.0	10.6	5.2	3.7
OPEX (Low) (£/kW/year)	53.4	53.4	6.2	3.0	2.2

A.3 Domestic Peak Lopping (DPA-DA) (5kW, 20kWh)

A.3.1 Lithium Ion Battery Storage (5kW, 20kWh)

Table 25: Lithium Ion Battery Storage DPA-DA Data Sheet

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	85.0%
Variable Cost (£/MWh)	0
Maximum new builds by plant type each year (MW)	4000
Construction period (Years)	1
Lifetime (Years)	15
Maximum deliverable power (MW)	0.005
Average availability (%)	95.0%
Energy Storage (MWh)	0.02
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	1560
Useable depth of discharge (% of energy storage useable)	80.0%
Response time (s)	0.15
Footprint (m^2)	0.15
Operational environmental, safety limitations/ hazards (Y/N)	N Generally but unsafe if overheated,
Provisions of Inertia (Y/N)	N
Cycle Life	5000
Pre-Development Costs (£)	0
Construction Period phasing (% of investment for each year of construction)	100.0%
Infrastructure cost (High) (£)	£227
Infrastructure cost (Medium) (£)	£136
Infrastructure cost (Low) (£)	£68
CAPEX (High) (£)	£8,529
CAPEX (Medium) (£)	£7,311
CAPEX (Low) (£)	£6,092
OPEX (High) (£/year)	£182

Description of Attribute	Number or Truth Value
OPEX (Medium) (£/year)	£23
OPEX (Low) (£/year)	£0

Table 26: Lithium Ion Battery Storage (DPA-DA) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	45.5	45.5	45.5	45.5	45.5
Infrastructure cost (Medium) (£/kW)	27.3	27.3	27.3	27.3	27.3
Infrastructure cost (Low) (£/kW)	13.6	13.6	13.6	13.6	13.6
CAPEX (high) (£/kW)	1705.8	1309.9	676.3	491.5	400.1
CAPEX (Medium) (£/kW)	1462.1	1122.8	579.7	421.3	342.9
CAPEX (Low) (£/kW)	1218.5	935.7	483.1	351.1	285.8
OPEX (High) (£/kW/year)	36.4	27.9	14.4	10.5	8.5
OPEX (Medium) (£/kW/year)	4.5	3.5	1.8	1.3	1.1
OPEX (Low) (£/kW/year)	0.0	0.0	0.0	0.0	0.0

A.3.2 New Battery Storage (5kW, 20kWh)

Table 27: New Battery Storage DPA-DA Data Sheet

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	90.0%
Variable Cost (£/MWh)	0
Maximum new builds by plant type each year (MW)	2000
Construction period (Years)	1
Lifetime (Years)	15
Maximum deliverable power (MW)	0.005
Average availability (%)	95.0%
Energy Storage (MWh)	0.02
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	1560
Useable depth of discharge (% of energy storage useable)	100.0%
Response time (s)	0.1
Footprint (m^2)	0.15

Description of Attribute	Number or Truth Value
Operational environmental, safety limitations/ hazards (Y/N)	N Generally but unsafe if overheated,
Provisions of Inertia (Y/N)	N
Cycle Life	1500
Pre-Development Costs (£)	0
Construction Period phasing (% of investment for each year of construction)	100.0%
Infrastructure cost (High) (£)	£227
Infrastructure cost (Medium) (£)	£136
Infrastructure cost (Low) (£)	£68
CAPEX (High) (£)	£48,237
CAPEX (Medium) (£)	£41,346
CAPEX (Low) (£)	£34,455
OPEX (High) (£/year)	£910
OPEX (Medium) (£/year)	£91
OPEX (Low) (£/year)	£0

Table 28: New Battery Storage (DPA DA) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	45.5	45.5	45.5	45.5	45.5
Infrastructure cost (Medium) (£/kW)	27.3	27.3	27.3	27.3	27.3
Infrastructure cost (Low) (£/kW)	13.6	13.6	13.6	13.6	13.6
CAPEX (high) (£/kW)	9647.5	9647.5	1122.3	548.6	388.9
CAPEX (Medium) (£/kW)	8269.3	8269.3	962.0	470.2	333.3
CAPEX (Low) (£/kW)	6891.1	6891.1	801.7	391.8	277.8
OPEX (High) (£/kW/year)	181.9	181.9	21.2	10.3	7.3
OPEX (Medium) (£/kW/year)	18.2	18.2	2.1	1.0	0.7
OPEX (Low) (£/kW/year)	0.0	0.0	0.0	0.0	0.0

A.4 Co-Located Peak Lopping (CPL-DA) (10MW, 40MWh)

A.4.1 Lithium Ion Battery Storage (10MW, 40MWh)

Table 29: Lithium Ion Battery Storage CPL-DA Data Table

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	85.0%
Variable Cost (£/MWh)	0
Maximum new builds by plant type each year (MW)	4000
Construction period (Years)	1
Lifetime (Years)	15
Maximum deliverable power (MW)	10
Average availability (%)	95.0%
Energy Storage (MWh)	40
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	1560
Useable depth of discharge (% of energy storage useable)	80.0%
Response time (s)	0.15
Footprint (m^2)	363
Operational environmental, safety limitations/ hazards (Y/N)	N Generally but unsafe if overheated,
Provisions of Inertia (Y/N)	N
Cycle Life	5000
Pre-Development Costs (£)	£81,874
Construction Period phasing (% of investment for each year of construction)	100.0%
Infrastructure cost (High) (£)	£109,165
Infrastructure cost (Medium) (£)	£45,486
Infrastructure cost (Low) (£)	£18,194
CAPEX (High) (£)	£17,058,324
CAPEX (Medium) (£)	£14,621,421
CAPEX (Low) (£)	£12,184,517
OPEX (High) (£/year)	£328,322
OPEX (Medium) (£/year)	£221,913
OPEX (Low) (£/year)	£91,810

Table 30: Lithium Ion Battery Storage (CPL-DA) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	10.9	10.9	10.9	10.9	10.9
Infrastructure cost (Medium) (£/kW)	4.5	4.5	4.5	4.5	4.5

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (Low) (£/kW)	1.8	1.8	1.8	1.8	1.8
CAPEX (high) (£/kW)	1705.8	1309.9	676.3	491.5	400.1
CAPEX (Medium) (£/kW)	1462.1	1122.8	579.7	421.3	342.9
CAPEX (Low) (£/kW)	1218.5	935.7	483.1	351.1	285.8
OPEX (High) (£/kW/year)	32.8	25.2	13.0	9.5	7.7
OPEX (Medium) (£/kW/year)	22.2	17.0	8.8	6.4	5.2
OPEX (Low) (£/kW/year)	9.2	7.1	3.6	2.6	2.2

A.4.2 New Battery Storage (10MW, 40MWh)

Table 31: New Battery Storage CPL-DA Data Table

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	90.0%
Variable Cost (£/MWh)	0
Maximum new builds by plant type each year (MW)	2000
Construction period (Years)	1
Lifetime (Years)	15
Maximum deliverable power (MW)	10
Average availability (%)	95.0%
Energy Storage (MWh)	40
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	1560
Useable depth of discharge (% of energy storage useable)	100.0%
Response time (s)	0.1
Footprint (m^2)	181.5
Operational environmental, safety limitations/ hazards (Y/N)	N Generally but unsafe if overheated,
Provisions of Inertia (Y/N)	N
Cycle Life	1500
Pre-Development Costs (£)	£81,874
Construction Period phasing (% of investment for each year of construction)	100.0%
Infrastructure cost (High) (£)	£109,165
Infrastructure cost (Medium) (£)	£45,486
Infrastructure cost (Low) (£)	£18,194
CAPEX (High) (£)	£96,474,852
CAPEX (Medium) (£)	£82,692,730
CAPEX (Low) (£)	£68,910,608

Description of Attribute	Number or Truth Value
OPEX (High) (£/year)	£1,206,504
OPEX (Medium) (£/year)	£816,466
OPEX (Low) (£/year)	£377,123

Table 32: New Battery Storage (CPL-DA) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	10.9	10.9	10.9	10.9	10.9
Infrastructure cost (Medium) (£/kW)	4.5	4.5	4.5	4.5	4.5
Infrastructure cost (Low) (£/kW)	1.8	1.8	1.8	1.8	1.8
CAPEX (high) (£/kW)	9647.5	9647.5	1122.3	548.6	388.9
CAPEX (Medium) (£/kW)	8269.3	8269.3	962.0	470.2	333.3
CAPEX (Low) (£/kW)	6891.1	6891.1	801.7	391.8	277.8
OPEX (High) (£/kW/year)	120.7	120.7	14.0	6.9	4.9
OPEX (Medium) (£/kW/year)	81.6	81.6	9.5	4.6	3.3
OPEX (Low) (£/kW/year)	37.7	37.7	4.4	2.1	1.5

A.5 Distribution Peak Lopping (DNPL-DA) (2.5MW, 10MWh)

A.5.1 Lithium Ion Battery Storage (2.5MW, 10MWh)

Table 33: Lithium Ion Battery Storage DNPL-DA Data Table

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	85.0%
Variable Cost (£/MWh)	0
Maximum new builds by plant type each year (MW)	4000
Construction period (Years)	1
Lifetime (Years)	15
Maximum deliverable power (MW)	2.5
Average availability (%)	95.0%
Energy Storage (MWh)	10
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	1560
Useable depth of discharge (% of energy storage useable)	80.0%

Description of Attribute	Number or Truth Value
Response time (s)	0.15
Footprint (m^2)	90.75
Operational environmental, safety limitations/ hazards (Y/N)	N Generally but unsafe if overheated,
Provisions of Inertia (Y/N)	N
Cycle Life	5000
Pre-Development Costs (£)	£81,874
Construction Period phasing (% of investment for each year of construction)	100.0%
Infrastructure cost (High) (£)	£209,234
Infrastructure cost (Medium) (£)	£118,262
Infrastructure cost (Low) (£)	£45,486
CAPEX (High) (£)	£4,264,581
CAPEX (Medium) (£)	£3,655,355
CAPEX (Low) (£)	£3,046,129
OPEX (High) (£/year)	£154,857
OPEX (Medium) (£/year)	£94,141
OPEX (Low) (£/year)	£50,244

Table 34: Lithium Ion Battery Storage (DNPL-DA) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	83.7	83.7	83.7	83.7	83.7
Infrastructure cost (Medium) (£/kW)	47.3	47.3	47.3	47.3	47.3
Infrastructure cost (Low) (£/kW)	18.2	18.2	18.2	18.2	18.2
CAPEX (high) (£/kW)	1705.8	1309.9	676.3	491.5	400.1
CAPEX (Medium) (£/kW)	1462.1	1122.8	579.7	421.3	342.9
CAPEX (Low) (£/kW)	1218.5	935.7	483.1	351.1	285.8
OPEX (High) (£/kW/year)	61.9	47.6	24.6	17.8	14.5
OPEX (Medium) (£/kW/year)	37.7	28.9	14.9	10.8	8.8
OPEX (Low) (£/kW/year)	20.1	15.4	8.0	5.8	4.7

A.5.2 New Battery Storage (2.5MW, 10MWh)

Table 35: New Battery Storage DNPL-DA Data Table

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	90.0%
Variable Cost (£/MWh)	0
Maximum new builds by plant type each year (MW)	2000
Construction period (Years)	1
Lifetime (Years)	15
Maximum deliverable power (MW)	2.5
Average availability (%)	95.0%
Energy Storage (MWh)	10
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	1560
Useable depth of discharge (% of energy storage useable)	100.0%
Response time (s)	0.1
Footprint (m^2)	45.375
Operational environmental, safety limitations/ hazards (Y/N)	N Generally but unsafe if overheated,
Provisions of Inertia (Y/N)	N
Cycle Life	1500
Pre-Development Costs (£)	£81,874
Construction Period phasing (% of investment for each year of construction)	100.0%
Infrastructure cost (High) (£)	£209,234
Infrastructure cost (Medium) (£)	£118,262
Infrastructure cost (Low) (£)	£45,486
CAPEX (High) (£)	£24,118,713
CAPEX (Medium) (£)	£20,673,182
CAPEX (Low) (£)	£17,227,652
OPEX (High) (£/year)	£394,871
OPEX (Medium) (£/year)	£263,248
OPEX (Low) (£/year)	£142,041

Table 36: New Battery Storage (DNPL-DA) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	83.7	83.7	83.7	83.7	83.7
Infrastructure cost (Medium) (£/kW)	47.3	47.3	47.3	47.3	47.3
Infrastructure cost (Low) (£/kW)	18.2	18.2	18.2	18.2	18.2
CAPEX (high) (£/kW)	9647.5	9647.5	1122.3	548.6	388.9

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
CAPEX (Medium) (£/kW)	8269.3	8269.3	962.0	470.2	333.3
CAPEX (Low) (£/kW)	6891.1	6891.1	801.7	391.8	277.8
OPEX (High) (£/kW/year)	157.9	157.9	18.4	9.0	6.4
OPEX (Medium) (£/kW/year)	105.3	105.3	12.2	6.0	4.2
OPEX (Low) (£/kW/year)	56.8	56.8	6.6	3.2	2.3

A.6 Industrial and Commercial Peak Lopping (BMPL-DA) (1MW, 2.5MWh)

A.6.1 Lithium Ion Battery Storage (1MW, 2.5MWh)

Table 37: Lithium Ion Battery Storage BMPL-DA Data Table

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	85.0%
Variable Cost (£/MWh)	0
Maximum new builds by plant type each year (MW)	4000
Construction period (Years)	1
Lifetime (Years)	15
Maximum deliverable power (MW)	1
Average availability (%)	95.0%
Energy Storage (MWh)	4
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	1560
Useable depth of discharge (% of energy storage useable)	80.0%
Response time (s)	0.15
Footprint (m^2)	36.3
Operational environmental, safety limitations/ hazards (Y/N)	N Generally but unsafe if overheated,
Provisions of Inertia (Y/N)	N
Cycle Life	5000
Pre-Development Costs (£)	£20,923
Construction Period phasing (% of investment for each year of construction)	100.0%
Infrastructure cost (High) (£)	£72,777
Infrastructure cost (Medium) (£)	£45,486
Infrastructure cost (Low) (£)	£18,194
CAPEX (High) (£)	£1,356,170
CAPEX (Medium) (£)	£1,162,431
CAPEX (Low) (£)	£968,693
OPEX (High) (£/year)	£89,127

Description of Attribute	Number or Truth Value
OPEX (Medium) (£/year)	£47,895
OPEX (Low) (£/year)	£24,420

Table 38: Lithium Ion Battery Storage (BMPL-DA) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	72.8	72.8	72.8	72.8	72.8
Infrastructure cost (Medium) (£/kW)	45.5	45.5	45.5	45.5	45.5
Infrastructure cost (Low) (£/kW)	18.2	18.2	18.2	18.2	18.2
CAPEX (high) (£/kW)	1356.2	1008.5	455.9	300.5	226.1
CAPEX (Medium) (£/kW)	1162.4	864.4	390.8	257.5	193.8
CAPEX (Low) (£/kW)	968.7	720.3	325.6	214.6	161.5
OPEX (High) (£/kW/year)	89.1	66.3	30.0	19.7	14.9
OPEX (Medium) (£/kW/year)	47.9	35.6	16.1	10.6	8.0
OPEX (Low) (£/kW/year)	24.4	18.2	8.2	5.4	4.1

A.6.2 New Battery Storage (1MW, 2.5MWh)

Table 39: New Battery Storage BMPL-DA Data Table

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	90.0%
Variable Cost (£/MWh)	0
Maximum new builds by plant type each year (MW)	2000
Construction period (Years)	1
Lifetime (Years)	15
Maximum deliverable power (MW)	1
Average availability (%)	95.0%
Energy Storage (MWh)	4
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	1560
Useable depth of discharge (% of energy storage useable)	100.0%
Response time (s)	0.1
Footprint (m^2)	36

Description of Attribute	Number or Truth Value
Operational environmental, safety limitations/ hazards (Y/N)	"N Generally, but unsafe if overheated,"
Provisions of Inertia (Y/N)	N
Cycle Life	1500
Pre-Development Costs (£)	£20,923
Construction Period phasing (% of investment for each year of construction)	100.0%
Infrastructure cost (High) (£)	£72,777
Infrastructure cost (Medium) (£)	£45,486
Infrastructure cost (Low) (£)	£18,194
CAPEX (High) (£)	£9,647,485
CAPEX (Medium) (£)	£8,269,273
CAPEX (Low) (£)	£6,891,061
OPEX (High) (£/year)	£188,879
OPEX (Medium) (£/year)	£118,035
OPEX (Low) (£/year)	£62,275

Table 40: New Battery Storage (BMPL-DA) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	72.8	72.8	72.8	72.8	72.8
Infrastructure cost (Medium) (£/kW)	45.5	45.5	45.5	45.5	45.5
Infrastructure cost (Low) (£/kW)	18.2	18.2	18.2	18.2	18.2
CAPEX (high) (£/kW)	9647.5	9647.5	1122.3	548.6	388.9
CAPEX (Medium) (£/kW)	8269.3	8269.3	962.0	470.2	333.3
CAPEX (Low) (£/kW)	6891.1	6891.1	801.7	391.8	277.8
OPEX (High) (£/kW/year)	188.9	188.9	22.0	10.7	7.6
OPEX (Medium) (£/kW/year)	118.0	118.0	13.7	6.7	4.8
OPEX (Low) (£/kW/year)	62.3	62.3	7.2	3.5	2.5

A.7 Weekly Energy Balancing (WEB-EtoE) (200MW, 800MWh)

A.7.1 Pumped Hydro Storage (200MW, 800MWh)

Table 41: Pumped Hydro Storage WEB-EtoE Data Table

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	75.0%
Variable Cost (£/MWh)	0
Maximum new builds by plant type each year (MW)	200
Construction period (Years)	4
Lifetime (Years)	30
Maximum deliverable power (MW)	200
Average availability (%)	95.0%
Energy Storage (MWh)	4000
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	87600
Useable depth of discharge (% of energy storage useable)	100.0%
Response time (s)	16
Footprint (m^2)	1,250,000
Operational environmental, safety limitations/ hazards (Y/N)	No
Provisions of Inertia (Y/N)	Yes
Cycle Life	100000
Pre-Development Costs (£)	£19,103,931
Construction Period phasing (% of investment for each year of construction)	25.0%
Infrastructure cost (High) (£)	£25,017,053
Infrastructure cost (Medium) (£)	£11,371,388
Infrastructure cost (Low) (£)	£3,183,989
CAPEX (High) (£)	£582,215,040
CAPEX (Medium) (£)	£316,579,428
CAPEX (Low) (£)	£240,163,704
OPEX (High) (£/year)	£7,944,711
OPEX (Medium) (£/year)	£4,319,937
OPEX (Low) (£/year)	£3,277,193

Table 42: Pumped Hydro Storage (WEB-EtoE) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	125.1	125.1	125.1	125.1	125.1
Infrastructure cost (Medium) (£/kW)	56.9	56.9	56.9	56.9	56.9
Infrastructure cost (Low) (£/kW)	15.9	15.9	15.9	15.9	15.9
CAPEX (high) (£/kW)	2911.1	2786.2	2627.7	2568.6	2531.8
CAPEX (Medium) (£/kW)	1582.9	1515.0	1428.8	1396.7	1376.7
CAPEX (Low) (£/kW)	1200.8	1149.3	1083.9	1059.5	1044.4

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
OPEX (High) (£/kW/year)	39.7	38.0	35.9	35.0	34.5
OPEX (Medium) (£/kW/year)	21.6	20.7	19.5	19.1	18.8
OPEX (Low) (£/kW/year)	16.4	15.7	14.8	14.5	14.3

A.7.2 CAES (200MW, 800MWh)

Table 43: CAES WEB-EtoE Data Table

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	65.0%
Variable Cost (£/MWh)	0
Maximum new builds by plant type each year (MW)	1000
Construction period (Years)	3
Lifetime (Years)	25
Maximum deliverable power (MW)	200
Average availability (%)	92.0%
Energy Storage (MWh)	4000
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	9600
Useable depth of discharge (% of energy storage useable)	100.0%
Response time (s)	30
Footprint (m^2)	90000
Operational environmental, safety limitations/ hazards (Y/N)	No
Provisions of Inertia (Y/N)	Y
Cycle Life	50000
Pre-Development Costs (£)	£2,547,191
Construction Period phasing (% of investment for each year of construction)	50.0%
Infrastructure cost (High) (£)	£25,017,053
Infrastructure cost (Medium) (£)	£4,548,555
Infrastructure cost (Low) (£)	£1,591,994
CAPEX (High) (£)	£363,884,400
CAPEX (Medium) (£)	£287,468,676
CAPEX (Low) (£)	£211,052,952
OPEX (High) (£/year)	£3,638,844
OPEX (Medium) (£/year)	£2,729,133
OPEX (Low) (£/year)	£2,274,278

Table 44: CAES (WEB-EtoE) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	125.1	125.1	125.1	125.1	125.1
Infrastructure cost (Medium) (£/kW)	22.7	22.7	22.7	22.7	22.7
Infrastructure cost (Low) (£/kW)	8.0	8.0	8.0	8.0	8.0
CAPEX (high) (£/kW)	1819.4	1683.8	1518.4	1458.5	1421.8
CAPEX (Medium) (£/kW)	1437.3	1330.2	1199.5	1152.2	1123.3
CAPEX (Low) (£/kW)	1055.3	976.6	880.7	845.9	824.7
OPEX (High) (£/kW/year)	18.2	16.8	15.2	14.6	14.2
OPEX (Medium) (£/kW/year)	13.6	12.6	11.4	10.9	10.7
OPEX (Low) (£/kW/year)	11.4	10.5	9.5	9.1	8.9

A.7.3 Zinc Based Battery Storage (200MW, 800MWh)

Table 45: Zinc Based Battery Storage WEB-EtoE Data Table

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	75.0%
Variable Cost (£/MWh)	0
Maximum new builds by plant type each year (MW)	2000
Construction period (Years)	2
Lifetime (Years)	10
Maximum deliverable power (MW)	200
Average availability (%)	95.0%
Energy Storage (MWh)	4000
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	480
Useable depth of discharge (% of energy storage useable)	100.0%
Response time (s)	0.5
Footprint (m^2)	30000
Operational environmental, safety limitations/ hazards (Y/N)	Yes
Provisions of Inertia (Y/N)	N
Cycle Life	5000
Pre-Development Costs (£)	£1,182,624
Construction Period phasing (% of investment for each year of construction)	100.0%

Description of Attribute	Number or Truth Value
Infrastructure cost (High) (£)	£25,017,053
Infrastructure cost (Medium) (£)	£6,822,833
Infrastructure cost (Low) (£)	£1,591,994
CAPEX (High) (£)	£654,991,920
CAPEX (Medium) (£)	£491,243,940
CAPEX (Low) (£)	£327,495,960
OPEX (High) (£/year)	£16,374,798
OPEX (Medium) (£/year)	£12,281,099
OPEX (Low) (£/year)	£8,187,399

Table 46: Zinc Based Battery Storage (WEB-EtoE) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	125.1	125.1	125.1	125.1	125.1
Infrastructure cost (Medium) (£/kW)	34.1	34.1	34.1	34.1	34.1
Infrastructure cost (Low) (£/kW)	8.0	8.0	8.0	8.0	8.0
CAPEX (high) (£/kW)	3275.0	2177.2	1262.6	1021.3	893.1
CAPEX (Medium) (£/kW)	2456.2	1632.9	946.9	766.0	669.8
CAPEX (Low) (£/kW)	1637.5	1088.6	631.3	510.7	446.6
OPEX (High) (£/kW/year)	81.9	54.4	31.6	25.5	22.3
OPEX (Medium) (£/kW/year)	61.4	40.8	23.7	19.2	16.7
OPEX (Low) (£/kW/year)	40.9	27.2	15.8	12.8	11.2

A.7.4 Flow Battery Storage (200MW, 800MWh)

Table 47: Flow Storage WEB-EtoE Data Table

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	70.0%
Variable Cost (£/MWh)	0
Maximum new builds by plant type each year (MW)	2000
Construction period (Years)	2
Lifetime (Years)	10
Maximum deliverable power (MW)	200

Description of Attribute	Number or Truth Value
Average availability (%)	95.0%
Energy Storage (MWh)	4000
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	480
Useable depth of discharge (% of energy storage useable)	100.0%
Response time (s)	0.5
Footprint (m^2)	76800
Operational environmental, safety limitations/ hazards (Y/N)	Y
Provisions of Inertia (Y/N)	N
Cycle Life	10000
Pre-Development Costs (£)	£1,364,567
Construction Period phasing (% of investment for each year of construction)	100.0%
Infrastructure cost (High) (£)	£25,017,053
Infrastructure cost (Medium) (£)	£6,822,833
Infrastructure cost (Low) (£)	£1,591,994
CAPEX (High) (£)	£1,171,707,768
CAPEX (Medium) (£)	£1,004,320,944
CAPEX (Low) (£)	£836,934,120
OPEX (High) (£/year)	£31,385,030
OPEX (Medium) (£/year)	£26,154,191
OPEX (Low) (£/year)	£20,923,353

Table 48: Flow Storage (WEB-EtoE) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	125.1	125.1	125.1	125.1	125.1
Infrastructure cost (Medium) (£/kW)	34.1	34.1	34.1	34.1	34.1
Infrastructure cost (Low) (£/kW)	8.0	8.0	8.0	8.0	8.0
CAPEX (high) (£/kW)	5858.5	2899.6	1134.1	787.1	624.7
CAPEX (Medium) (£/kW)	5021.6	2485.4	972.1	674.7	535.4
CAPEX (Low) (£/kW)	4184.7	2071.2	810.1	562.2	446.2
OPEX (High) (£/kW/year)	156.9	77.7	30.4	21.1	16.7

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
OPEX (Medium) (£/kW/year)	130.8	64.7	25.3	17.6	13.9
OPEX (Low) (£/kW/year)	104.6	51.8	20.3	14.1	11.2

A.7.5 Sodium Sulphur Battery Storage (200MW, 800MWh)

Table 49: Sodium Sulphur Battery Storage WEB-EtoE Data Table

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	80.0%
Variable Cost (£/MWh)	0
Maximum new builds by plant type each year (MW)	2000
Construction period (Years)	2
Lifetime (Years)	15
Maximum deliverable power (MW)	200
Average availability (%)	90.0%
Energy Storage (MWh)	4000
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	9600
Useable depth of discharge (% of energy storage useable)	80.0%
Response time (s)	0.5
Footprint (m^2)	50000
Operational environmental, safety limitations/ hazards (Y/N)	Yes
Provisions of Inertia (Y/N)	N
Cycle Life	4500
Pre-Development Costs (£)	£1,364,567
Construction Period phasing (% of investment for each year of construction)	100.0%
Infrastructure cost (High) (£)	£25,017,053
Infrastructure cost (Medium) (£)	£4,548,555
Infrastructure cost (Low) (£)	£1,591,994
CAPEX (High) (£)	£1,375,483,032
CAPEX (Medium) (£)	£1,178,985,456
CAPEX (Low) (£)	£982,487,880
OPEX (High) (£/year)	£12,281,099
OPEX (Medium) (£/year)	£10,234,249
OPEX (Low) (£/year)	£8,187,399

Table 50: Sodium Sulphur Battery Storage (WEB-EtoE) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	125.1	125.1	125.1	125.1	125.1
Infrastructure cost (Medium) (£/kW)	22.7	22.7	22.7	22.7	22.7
Infrastructure cost (Low) (£/kW)	8.0	8.0	8.0	8.0	8.0
CAPEX (high) (£/kW)	6877.4	4932.4	3165.0	2663.2	2387.6
CAPEX (Medium) (£/kW)	5894.9	4227.8	2712.9	2282.7	2046.5
CAPEX (Low) (£/kW)	4912.4	3523.2	2260.7	1902.3	1705.4
OPEX (High) (£/kW/year)	61.4	44.0	28.3	23.8	21.3
OPEX (Medium) (£/kW/year)	51.2	36.7	23.5	19.8	17.8
OPEX (Low) (£/kW/year)	40.9	29.4	18.8	15.9	14.2

A.7.6 Thermal Energy Storage (200MW, 800MWh)

Table 51: Thermal Energy Storage WEB-EtoE Data Table

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	65.0%
Variable Cost (£/MWh)	0
Maximum new builds by plant type each year (MW)	1000
Construction period (Years)	2
Lifetime (Years)	20
Maximum deliverable power (MW)	200
Average availability (%)	92.0%
Energy Storage (MWh)	4000
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	480
Useable depth of discharge (% of energy storage useable)	90.0%
Response time (s)	10
Footprint (m^2)	70000
Operational environmental, safety limitations/ hazards (Y/N)	N
Provisions of Inertia (Y/N)	Yes
Cycle Life	50000
Pre-Development Costs (£)	£1,273,595
Construction Period phasing (% of investment for each year of construction)	50.0%

Description of Attribute	Number or Truth Value
Infrastructure cost (High) (£)	£25,017,053
Infrastructure cost (Medium) (£)	£6,822,833
Infrastructure cost (Low) (£)	£1,591,994
CAPEX (High) (£)	£372,981,510
CAPEX (Medium) (£)	£292,017,231
CAPEX (Low) (£)	£211,052,952
OPEX (High) (£/year)	£9,497,383
OPEX (Medium) (£/year)	£7,914,486
OPEX (Low) (£/year)	£6,331,589

Table 52: Thermal Energy Storage (WEB-EtoE) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	125.1	125.1	125.1	125.1	125.1
Infrastructure cost (Medium) (£/kW)	34.1	34.1	34.1	34.1	34.1
Infrastructure cost (Low) (£/kW)	8.0	8.0	8.0	8.0	8.0
CAPEX (high) (£/kW)	1864.9	1654.4	1410.0	1325.0	1273.9
CAPEX (Medium) (£/kW)	1460.1	1295.3	1103.9	1037.4	997.3
CAPEX (Low) (£/kW)	1055.3	936.2	797.9	749.8	720.8
OPEX (High) (£/kW/year)	47.5	42.1	35.9	33.7	32.4
OPEX (Medium) (£/kW/year)	39.6	35.1	29.9	28.1	27.0
OPEX (Low) (£/kW/year)	31.7	28.1	23.9	22.5	21.6

A.8 Seasonal Energy Balancing (SES-EtoE) (10MW, 2500MWh)

A.8.1 Hydrogen Energy Storage (10MW, 2500MWh)

Table 53: Hydrogen Energy Storage SES-EtoE Data Table

Description of Attribute	Number or Truth Value
Round trip efficiency (%)	32.0%
Variable Cost (£/MWh)	100
Maximum new builds by plant type each year (MW)	2000
Construction period (Years)	1

Description of Attribute	Number or Truth Value	
Lifetime (Years)	10.0	
Maximum deliverable power (MW)	10	
Average availability (%)	90.0%	
Energy Storage (MWh)	2500	
Self-discharge time (i.e. time elapsed before capacity is reduced to less than 80% by self-discharge) (hours)	2500	
Useable depth of discharge (% of energy storage useable)	100.0%	
Response time (s)	0.5	
Footprint (m^2)	80	
Operational environmental, safety limitations/ hazards (Y/N)	Y Limited Cycle life, hazard zone due to presence of hydrogen, flammable gas.	
Provisions of Inertia (Y/N)	N	
Cycle Life	1000	
Pre-Development Costs (£)	£	1,091,653.20
Construction Period phasing (% of investment for each year of construction)	100.0%	
Infrastructure cost (High) (£)	£	800,545.68
Infrastructure cost (Medium) (£)	£	727,768.80
Infrastructure cost (Low) (£)	£	654,991.92
CAPEX (High) (£)	£	12,508,526.25
CAPEX (Medium) (£)	£	11,371,388
CAPEX (Low) (£)	£	10,234,249
OPEX (High) (£/year)	£	341,374.32
OPEX (Medium) (£/year)	£	310,340.29
OPEX (Low) (£/year)	£	279,306.26

Table 54: Hydrogen Energy Storage (SES-EtoE) Cost Projections

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
Infrastructure cost (High) (£/kW)	80.1	80.1	80.1	80.1	80.1
Infrastructure cost (Medium) (£/kW)	72.8	72.8	72.8	72.8	72.8
Infrastructure cost (Low) (£/kW)	65.5	65.5	65.5	65.5	65.5
CAPEX (high) (£/kW)	1250.9	1078.3	884.4	818.8	779.8
CAPEX (Medium) (£/kW)	1137.1	980.2	804.0	744.3	708.9
CAPEX (Low) (£/kW)	1023.4	882.2	723.6	669.9	638.0

	Yr 0 (2018)	Yr 2 (2020)	Yr 12 (2030)	Yr 22 (2040)	Yr 32 (2050)
OPEX (High) (£/kW/year)	34.1	29.4	24.1	22.3	21.3
OPEX (Medium) (£/kW/year)	31.0	26.8	21.9	20.3	19.3
OPEX (Low) (£/kW/year)	27.9	24.1	19.7	18.3	17.4

B. Project source material

- [Lazard] Lazard Ltd. 2017. *Lazard's Levelized Cost Of Storage Analysis—Version 3.0*. Ebook. 3rd ed. Lazard. https://www.lazard.com/media/450338/lazard-levelized-cost-of-storage-version-30.pdf.
- [IRENA] Ralon, Pablo, Michael Taylor, and Andrei Ilas. 2017. *Electricity Storage and Renewables: Costs and Markets To 2030*. Ebook. Abu Dhabi: International Renewable Energy Agency. http://www.climateactionprogramme.org/images/uploads/documents/IRENA_Electricity_Storage_Costs_2017.pdf.
- [USTDA] *South Africa Energy Storage Technology and Market Assessment*. 2017. Ebook. Pasadena: Parsons. https://www.researchgate.net/profile/Karin_Kritzinger/publication/318562746_South_Africa_Energy_Storage_Technology_and_Market_Assessment/links/597086020f7e9b44173e035c/South-Africa-Energy-Storage-Technology-and-Market-Assessment.pdf.
- [University of Warwick] Luo, Xing, Jihong Wang, Mark Dooner, and Jonathan Clarke. 2015. *Overview of Current Development In Electrical Energy Storage Technologies And The Application Potential In Power System Operation*. Ebook. Coventry: Elsevier. https://ac.els-cdn.com/S0306261914010290/1-s2.0-S0306261914010290-main.pdf?_tid=15344186-a087-43b4-a563-3bb6b0d8204e&acdnat=1524840125_ea4a0f4365979167b8ae289f7379abf2.
- [Deloitte] Slaughter, Andrew. 2015. *Electricity Storage Technologies, Impacts, And Prospects*. Ebook. Houston: Deloitte. https://www2.deloitte.com/content/dam/Deloitte/us/Documents/energy-resources/us-er-electric-storage-paper.pdf.
- [Scientific Paper 1, Gallo et al] Gallo, A.B., J.R. Simoes-Moreira, H.K.M. Costa, M.M. Santos, and E.Moutinho dos Santos. 2016. *Energy Storage In The Energy Transition Context: A Technology Review*. Ebook. Sao Paulo: Elsevier. https://www.sciencedirect.com/science/article/pii/S1364032116303562.
- [Scientific Paper 2, Aneke et all] Aneke, Matthew, and Meihong Wang. 2016. *Energy Storage Technologies and Real Life Applications – A State Of The Art Review*. Ebook. Hull: Elsevier. https://www.sciencedirect.com/science/article/pii/S0306261916308728.
- [Scientific Paper 3, Amirante et all] Amirante, Riccardo, Egidio Cassone, and Paolo Tamburrano. 2017. *Overview on Recent Developments In Energy Storage: Mechanical, Electrochemical And Hydrogen Technologies*. Ebook. Bari: Elsevier. https://www.sciencedirect.com/science/article/pii/S019689041631055X.

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