# Clean Energy Superpower Mission (CESM) R&D Missions Accelerator Programme (R&D MAP)

## Final report for the Insight to Action Accelerator on long duration electricity storage (LDES) and low carbon dispatchable power (LCDP)

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AI methods have been used in the research methodology of this research. This is laid out in Section 3. Methodological framework. Any application of AI has been done with the permission of participants and with appropriate data approval and precautions against leaching. AI has not been used in the drafting of report text.

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The report focuses on technologies that could be supported through the R&D MAP process and within its definitions. The conclusions of this report are therefore specific to this context. This does not preclude that other LDES and LCDP technologies may be important to the future electricity system and may therefore be candidates for other sources of innovation support. Ultimately, there will be a difficult balance to be struck in innovation funding strategies between focussing on specific technologies, and applying a more technology agnostic approach, with the risk that available funding is spread too thin to have the necessary impact by 2030-2035.

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# List of Abbreviations

| | |
|---|---|
| A-CAES | Adiabatic-Compressed Air Energy Storage |
| AMR | Advanced Modular Reactor |
| AoI | Aspects of Integration |
| BECCS | Bioenergy with Carbon Capture and Storage |
| C&F | Cap & Floor Scheme |
| CAES | Compressed Air Energy Storage |
| CAPEX | Capital Expenditure |
| CCGT | Combined Cycle Gas Turbine |
| CCS | Carbon Capture and Storage |
| CESM | Clean Energy Superpower Mission |
| CHP | Combined Heat and Power |
| CP2030 | Clean Power 2030 |
| D-CAES | Diabatic Compressed Air Energy Storage |
| DESNZ | Department for Energy Security & Net Zero |
| ECAF | Eligibility Criteria Assessment Framework |
| ESME | Energy System Modelling Environment |
| EU | European Union |
| FES | Future Energy Scenario |
| $gCO_2e/kWh$ | Grams of Carbon Dioxide Equivalent per kilowatt-hour of Electricity |
| GW | Gigawatt |
| H2-ICE | Hydrogen Internal Combustion Engine |
| I-CAES | Isothermal Compressed Air Energy Storage |
| IGCC | Integrated Gasification Combined Cycle |
| kW | Kilowatt |
| LAES | Liquid Air Energy Storage |
| LCDP | Low Carbon Dispatchable Power |
| LCOE | Levelised Cost of Electricity |
| LCOS | Levelised Cost of Storage |
| LDES | Long Duration Electricity Storage |
| Li-ion | Lithium-ion |
| LRC | Lined Rock Caverns |
| MW | Megawatt |
| NED | Net Excess Demand |
| NESO | National Energy System Operator |
| O&M | Operation and Maintenance |
| OCGT | Open Cycle Gas Turbine |
| Ofgem | Office of Gas and Electricity Markets |
| OPEX | Operational Expenditure |
| PCM | Phase Change Material |
| PEMFC | Proton Exchange Membrane Fuel Cell |
| PHS | Pumped Hydro Storage |
| PV | Photovoltaic |
| R&D MAP | Research and Development Missions Accelerator Programme |
| R&D | Research and Development |
| R&I | Research and Innovation |
| RAG | Red/Amber/Green |
| REA | Rapid Evidence Assessment |
| RTE | Round Trip Efficiency |

| | |
|---|---|
| SMR | Small Modular Reactor |
| SOFC | Solid Oxide Fuel Cell |
| TES | Thermal Energy Storage |
| TRL | Technology Readiness Level |
| TW | Terawatt |
| UKERC | UK Energy Research Centre |
| UKRI | UK Research and Innovation |
| VRE | Variable Renewable Electricity Generation |

# Executive Summary

The rapid decarbonisation of the UK electricity system pursued under the Clean Power 2030 target creates an accelerated demand for electricity system supporting technologies such as Long Duration Electricity Storage (LDES) and Low Carbon Dispatchable Power (LCDP). This document examines the evidence on the innovation need for rapid deployment of these technologies and synthesises evidence from rapid evidence assessment, expert elicitation workshops, and whole-system modelling to identify priority technologies and innovation challenges for deployment by 2030–2035.

The report addresses two problem statements:

| **Long Duration Electricity Storage (LDES)** | **Low Carbon Dispatchable Power (LCDP)** |
|---|---|
| Can the UK deliver large-scale long duration (multi-week) storage via newer/innovative technologies in the period from 2030 to 2035? | To what extent could >500MW of innovative low carbon dispatchable power capacity be available for deployment in the UK by 2030–2035? |

Multi-week storage is likely necessary to ensure security of supply where high renewables penetration creates system vulnerability during extended periods of low renewables generation in winter low wind conditions. For ‘multi-week’ LDES, we will refer to ‘ultra LDES’ and assume this to be LDES technologies that can deliver 100+hrs of discharge duration at full discharge rate in line with The Faraday Institution definition. For LCDP, we assume technologies must be dispatchable (*schedulable, flexible* and *reliable*) and delivering electricity with a carbon intensity of 50g$CO_2$e/kWh or less in line with the CP2030 action plan. Where Research and Innovation (R&I) is referenced, we include a broad definition of innovation, including technological, market and policy/organisational innovation.

## Key Conclusions

- Storage duration: For LDES technologies, **hydrogen salt cavern storage** is the most capable of achieving ultra LDES (100hrs+). **Metal-air and flow battery** technologies are currently further from delivering ultra LDES, though there is commercial interest in innovation to support development and cost reduction towards long storage durations. These technologies offer modular design and a broader commercial application than just ultra LDES storage, which may have market advantages over larger scale technologies. There is therefore a strategic choice in terms of the technologies worth supporting currently at shorter durations and whether they can advance to the 100+ hrs durations by 2030-2035.

- Technologies that deliver shorter storage durations are better supported by current markets and policy arrangements, allowing stronger commercial opportunities, particularly for batteries. This includes well established technologies such as Li-ion, which is well represented in current LDES projects. Technologies delivering ultra LDES are fewer, and commercial avenues are less well supported by current markets. Innovation could therefore span both technical and market issues to address this relative lack of technologies.

- Salt cavern storage of hydrogen is a likely candidate for R&I support to help deliver ultra LDES quickly. R&I activity may include demonstrating integration of hydrogen salt caverns with hydrogen turbines to provide more options for seasonal, system-scale electricity storage. Hydrogen provides other benefits in terms of its use as LCDP, as the availability of external hydrogen supplies can increase its overall usefulness as a dispatchable generator. Current evidence suggests that innovation opportunities exist in:

  - Materials research to improve durability to embrittlement,
  - Demonstration of flexible fast cycle operation of caverns,
  - Supply-chain development to improve speed and reduce costs associated with rapid roll out,
  - System integration and optimisation research, and
  - Financial risk products, business models and market design issues may also be areas that R&I research could prioritise.

- Though electrochemical technologies currently struggle to provide ultralong duration storage, there are technology developers actively targeting this application, and there are opportunities to support that innovation journey in the UK. Working with electrochemical innovation specialists, such as The Faraday Institution, innovation funding may be able to support the leading technologies in this area. Areas of focus for R&I funding may include:
  - Support for MWh scale electrochemical ultra LDES demonstration,
  - Development of UK manufacturing capacity, and
  - The necessary supply chain support to underpin rapid rollout.
- Accelerated learning in system integration of technologies appears to be a key crosscutting opportunity for many LDES and LCDP technologies and could be served by further modelling analysis and testbed demonstration. Testbed approaches to innovation funding may help with innovation collaboration, and these facilities could be existing or newly developed, and could orientate around key collaboration areas, such as electricity system integration, subsurface knowledge development and supply chain cooperation.
- Modelling suggests that LDES and LCDP are not entirely interchangeable and in many cases, there are complementarities to their operation, so that in some modelled scenarios investing in both LCDP and LDES is likely to minimise system costs.
- For LCDP, gas fired generation with CCS emerges from the modelling as an important technology, with smaller but important roles for others. This raises strategic questions regarding the role in supporting this technology, given its relatively long history of innovation funding to date, albeit still without a strong commercial driver for investment. Opportunities around demonstration of flexible operation may be a specific innovation area that could benefit from R&I funding support.
- There are significant uncertainties and gaps in evidence, and strategies to mitigate these issues should be considered. For example, engagement with innovators and innovation financiers may be an important step to help bridge these evidence gaps and develop

confidence in future innovation funding strategies. Ultimately, investment decisions will need to be made in the absence of sufficient evidence.

# Methods

The methodology was designed to rapidly gather and build an extensive evidence base to support the development of findings. The following research activities were a significant undertaking and were conducted in parallel to deliver over a compressed timescale.

- **Rapid evidence assessment** was used to gather a large amount of evidence from the existing literature on LDES and LCDP technology characteristics to allow for shortlisting. This used 42 search strings to gather more than 1,500 pieces of evidence, prioritising over 500 of these.
- **Expert elicitation** was used to obtain expert views on technology readiness and the key challenges facing technological innovation in this space. 25 workshops were conducted with over 100 participants.
- **Whole system energy modelling** augmented this evidence by generating insights on the system implications of different technology choices. This was conducted by Energy Systems Catapult using the ESME modelling framework.

# Technology Assessment: Shortlisted Technologies

The combined process of Rapid Evidence Assessment (REA) and expert elicitation gave rise to longlists of 17 options and 18 options for LDES and LCDP, respectively, which were then subject to Red/Amber/Green (RAG) analysis against key criteria. These are TRL, technical characteristics, current cost and learning potential, scalability, UK competitiveness, deliverability by 2030/2035 and focus and impact of innovation to 2035.

The comparative RAG evaluation was used to produce a priority technology shortlist for innovation funding. Five LDES and five LCDP technologies/technology groups were identified as the most promising for accelerated innovation into the electricity market by 2030-2035. These shortlisted technologies are shown in **Error! Reference source not found.**, with a brief rationale for their selection.

**ES Table 1: Summary table of shortlisted technologies most promising for accelerated innovation by 2030-2035**

| LDES Technology | | Rationale |
|---|---|---|
| $H_2$ | Salt cavern storage (Low cycle) | High TRL (9), Long storage/discharge durations, strong UK competitiveness |
| Electrochemical | Metal-air | Low cost, strong scalability potential, strong UK competitiveness |
| | Flow batteries (Vanadium/ Zinc bromine) | Strong scalability potential, relatively high TRL (7-8), relatively low cost |
| Mechanical | A-CAES | High TRL (8), intermediate duration, relatively low cost, strong UK competitiveness |
| | Pumped hydro energy storage | High TRL (9), intermediate duration, relatively low cost, strong UK competitiveness |

| LCDP Technology | | Rationale |
|---|---|---|
| $H_2$ | Reciprocating engines | High TRL (9), high dispatchability |

|  |  |  |
|---|---|---|
|  | Gas turbines | Relatively high TRL (7-9) (depending on natural gas/hydrogen blend ratio), high scalability |
| CCS | CCGT | High TRL (8), high scalability for core CCGT technology but dependant on available $CO_2$ storage market, strong UK competitiveness especially with vast carbon storage in North Sea |
|  | BECCS | High TRL (8-9), strong UK competitiveness especially with vast carbon storage in North Sea |
| Nuclear | SMR Nuclear (Gen III) | Relatively high TRL (7-8), scalability, strong UK competitiveness (Rolls Royce – UK led design) |

Of the LDES technologies shortlisted, hydrogen salt cavern storage and metal-air and flow battery technologies appear the most relevant to near term deployment for ultra LDES applications. Two mechanical storage technologies, adiabatic compressed air energy storage (A-CAES) and pumped hydro storage, are also shortlisted. Pumped hydro storage, A-CAES and flow batteries are currently in the intermediate discharge duration range of 12 to 24 hours, but all have potential to reach 100 hours. Adiabatic compressed air storage has relatively high technology readiness (TRL 8) and has cost benefits. There is also significant expertise in the UK relevant to different LDES technologies (fundamental science, geological data, supply chains, and skilled workforce). Pumped hydro energy storage is commercially mature, though innovation in novel types of dense fluid storage may open up wider geographical locations for deployment.

For LCDP, two hydrogen power generation technologies have been shortlisted. Reciprocating engines and hydrogen-fired combined-cycle gas turbines are both relevant options for power generation from hydrogen. For all hydrogen to power technologies, optimisation for flexible operation is an important area of technological innovation. Hydrogen technologies on both the LDES and LCDP shortlists present the possibility that this area could be supported by an innovation funding strategy that links these aspects of the whole hydrogen technology system. Carbon capture and storage (CCS) in association with natural gas-powered combined cycle gas turbines (CCGT) or biomass has also been shortlisted. The key rationale is the TRL (8-9) for CCGT with CCS and strong UK competitiveness, given UK $CO_2$ storage potential. Key technological innovation needs include flexible/dispatchable operation of these technologies, improving capture rates, particularly under ramp up/ramp down and CCS solvent development alongside energy penalty and cost reduction. Finally, Gen III small modular reactors (SMR) are shortlisted. Relative to conventional nuclear, their modular design, smaller size, and passive safety features enable reduced upfront capital costs, easier grid integration, and operational flexibility. There are, however, various challenges for SMRs, including high first-of-a-kind costs and regulatory and licensing hurdles.

## Insights from Whole System Energy Modelling

Whole energy systems modelling showed that achieving the least-cost energy system requires a mix of LDES and LCDP technologies to handle different types of energy imbalances over varying timescales. While some technologies compete with each other, a combination is needed – even during prolonged periods of energy imbalance. For instance, cycling batteries during a multi-week supply deficit can increase the utilisation rate of large, LCDP technologies by smoothing intra-day fluctuations. Similarly, during particularly large inter-day or intra-day supply deficits, fast LCDP technologies can supplement LDES technologies. This highlights the potential importance of investing in both LCDP and LDES to keep system costs low.

While the modelling did not explicitly represent markets, it illustrates why short-duration batteries are likely easier to commercialise, as they are used across a wider range of system services than just multi-day storage, providing broader commercial opportunity. Longer-duration technologies may only be needed for two or three of the four modelled services, with lower relative power capacity and being charged and discharged less frequently. To build a cost-effective low-carbon system, we may need ways to value longer duration storage capacities, less-utilised technologies which will likely need market, policy, regulatory and business model innovation.

By volume of energy delivered, carbon capture and storage (CCS)-based electricity generating technologies make up most LCDP by 2035, albeit operating in baseload for most of the time. Whilst this assumes high CCS efficiencies of 95% can be achieved, it could also lead to trade-offs in revenue as more energy and solvent could be demanded and operating cost could increase. Hydrogen is also key in all scenarios, with the highest LCDP and energy storage capacities. Removing hydrogen turbines or salt caverns increases total system costs between now and 2050 by 0.2-0.3% (£7-11bn). Without hydrogen salt caverns, CCGT with CCS capacity rises eightfold to offset an 82% drop in hydrogen turbines.

## Research and Innovation (R&I) Opportunities and Barriers

Combining the three methods used in the evidence collection, we identified six areas where there are potential opportunities for R&I to accelerate the development and deployment of LDES and LCDP technologies:

1. **Accessing investment** for organisations of all sizes across all parts of delivery, from small OEM to global developers. This could include quantitative tools that support risk minimisation or digital platforms that enhance cost and supply chain transparency, as well as innovative approaches to policy and market design.
2. **Getting to final investment decisions faster and cheaper**: even if the technology can be developed, other aspects of deployment could be on a lengthy critical path which could impact delivery by 2030-2035. For example, innovations that reduce time-intensive aspects of pre-final investment decisions or support parallelisation of activities.
3. **Overcoming technology and operational challenges**: investment is needed to both develop specific aspects of the technologies and demonstrate them.
4. **Bridging gaps in both investment and supply chains for mid-scale maturity technologies**: SMEs developing novel technology find that funding the valley of death is made more difficult when facing a gap in supply chain capability to deliver cost effectively at a medium scale. There are opportunities for clustering SME innovators in testbed organisations or innovative approaches to support maturing supply chains.
5. **Collaborating is important but difficult**: there are high profile examples of larger companies collaborating, but many companies and organisations still struggle to effectively collaborate for mutual benefit. Helping companies across the supply chain to effectively collaborate could support acceleration of deployment.
6. **Markets do not reward the system value that ultra LDES and LCDP provide**: whilst the UK has made inroads into market creation for storage technologies, e.g. through the cap and floor regime, current mechanisms are tailored towards technologies delivering in the order of eight hours discharge duration commensurate with common definitions of LDES. These market mechanisms are not sufficient to stimulate investment in large scale, lower utilisation assets providing ultra LDES discharge durations. Further research into novel market designs and incentive schemes that value ultra LDES is needed.

While the funding and investment landscape for technology innovation is a significant concern to experts and technology developers, this evidence indicates that wider system level innovation is needed to enable rapid deployment of these technologies by 2030-2035. There are common challenges across the end-to-end process, markets, collaboration and wider system integration to support the flow of private capital into these technologies. This suggests opportunities to facilitate rapid innovation that lie outside specific technology challenges.

## Risks to Technology Choice Conclusions

The technologies shortlisted in this project have the potential for swift deployment based on the evidence gathered. However, there are significant challenges associated with this technology selection approach to innovation funding, and these should be considered when designing the future LDES and LCDP innovation funding strategies.

- **The available evidence may be lacking:** Existing literature and academic evidence is behind the current knowledge within innovator communities and may not provide coverage across all criteria of interest. Innovators may not wish to divulge commercially relevant knowledge, and have bias related to commercial considerations.
- **Technological, policy and market uncertainties impact across all LDES and LCDP technologies:** Many of these are unpredictable, variable and contingent on global factors out of UK control. Supply chain factors, including fuels and manufacturing inputs, will influence technology costs. Policy decisions in the UK and in relevant international partners will also have impacts on the future competitiveness of different technology options.
- **Energy technology innovation is usually a multi-decadal process making the acceleration of LDES and LCDP innovation within ten years a particular challenge:** CCGT and nuclear took around 40 years to progress from invention to wider commercialisation; lithium-ion batteries have innovated more quickly. More rapid early commercialisation has been attained where innovations can readily substitute pre-existing technologies, compared to those which take longer to stimulate market demand and integrate with new institutions. There are also unpredictable aspects of the innovation process, including: technology response to innovation funding, innovation barriers may be relatively harder or easier to overcome, and global influences on innovation rates which are outside of UK control.
- **There is not a linear relationship between innovation funding and the speed of technological innovation:** Innovation does not proceed in a simple one directional journey from basic to applied research and subsequent diffusion. R&D continues beyond market introduction and can improve performance and reduce costs even in highly mature technologies. Approaches such as ‘technological innovation systems’ emphasise complex, systemic feedback between innovation funding and market pull, as well as the role of actors and institutions in developing and deploying technologies within a broader socio-technical landscape. This suggests that alongside innovation funding for technologies it is important to consider the wider policy, market and institutional landscape.
- **Innovation in LDES and LCDP also interrelates with wider systems challenges:** Key examples include understanding system value or uncertainties over utilisation/load factors in the future system. While the project is largely oriented around a technology-by-technology assessment, Aspects of Integration (AoI) framing and whole systems modelling were designed to identify and understand wider systems challenges. The questions surrounding future system challenges may require more attention.

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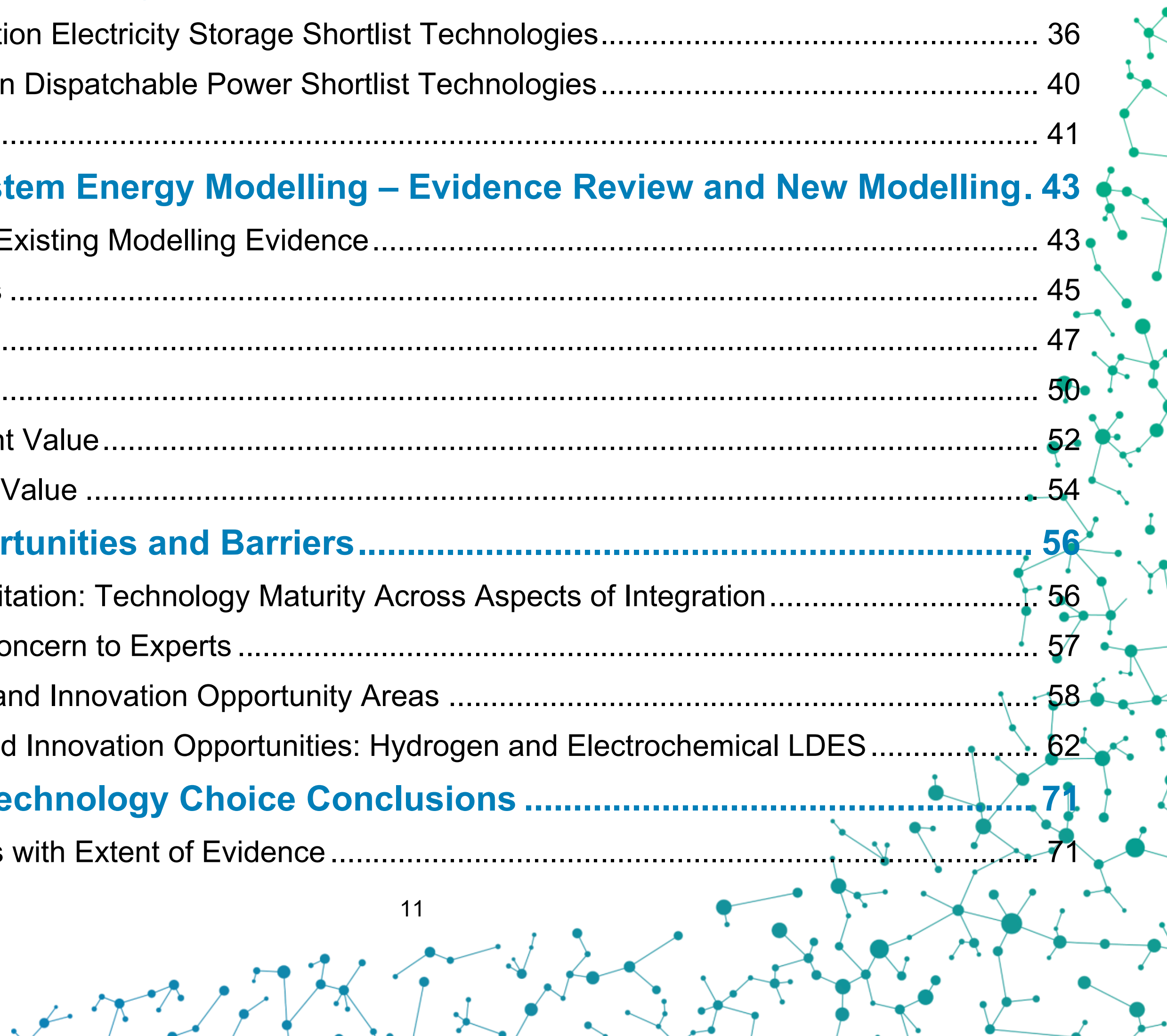

# 1. Introduction

The UK's ambitious Clean Power 2030 target requires a fundamental transformation of the electricity system, with renewables expected to provide the majority of generation. However, this transition creates significant challenges around system flexibility and reliability. As renewable energy sources replace traditional dispatchable fossil-fuel power stations, the system faces increasing variability and uncertainty that must be managed through alternative sources of low carbon flexibility. Substantial expansion of long duration electricity storage (LDES) and low carbon dispatchable power (LCDP) technologies will be critical to address the inherent intermittency challenges of variable renewable generation (House of Lords, 2024). Analysis from the 2030 Clean Power Action Plan (UK Government, 2024) indicates a requirement for 4-6 GW of LDES capacity and 2-7 GW of low carbon flexible generation by 2030.

UKRI has commissioned the UK Energy Research Centre (UKERC) and Energy Systems Catapult (the "Catapult") to deliver a project under the Clean Energy Superpower Mission (CESM) R&D Missions Accelerator Programme (R&D MAP). The commissioning document requests a project to gather evidence to inform R&D investment and accelerate LDES and LCDP deployment.

The Insight to Action Accelerator (ItAA) project was tasked to address the following two problem statements:

- Can the UK deliver large-scale long duration (multi-week) storage via newer / innovative technologies in the period from 2030 to 2035?
- To what extent could >500 MW of innovative low carbon dispatchable power capacity be available for deployment in the UK by 2030–2035?

This final report is the third deliverable agreed with UKRI and is designed to take stock of findings and support decision making for future potential innovation funding in this area. The scoping report was produced on 1 October 2025, and an interim report was presented to UKRI on 9 December 2025.

This report presents:

- A statement on definitions of LDES and LCDP for the purposes of this project
- A description of the components of the methodological framework
- Rapid Evidence Assessment (REA) and expert elicitation outcomes, informing comparative evaluation of LDES and LCDP technologies
- Evidence from whole system energy modelling
- Research and innovation opportunity areas
- Risks associated with technology choice
- Consolidated findings and R&I strategies

The report draws on the evidence gathered to identify a shortlist of technologies prioritised as most promising for funding to accelerate innovation into the electricity market by 2030-2035. The process and rationale for this is explained in Sections 3-5, and further details on all shortlisted technologies are in the Appendix at the end of this document.

# 2. Definitions of Long Duration Electricity Storage and Low Carbon Dispatchable Power

## 2.1. Long Duration Electricity Storage

**Long Duration Electricity Storage (LDES)** is often defined as storage which has a discharge duration of at least 8 hours (continuous at maximum power) and can be combined with charge and discharge from and to the electricity grid providing two-way flexibility to the system.[i] This definition allows for the inclusion of technologies from four categories of storage: Chemical, Thermal, Mechanical and Electrochemical. The focus of this project is to identify promising technologies that can provide discharge duration in the days to multi-week range, specifically 100 hours or more in line with the threshold set by The Faraday Institution for **ultra LDES** (The Faraday Institution, 2025).

Large scale LDES facilities (multiple GWs) can be characterised by several key attributes, namely power output, discharge duration and energy capacity (Box 1). Other common attributes of energy storage include round-trip efficiencies, scalability, response speeds and cycling limits. Discharge duration is not to be confused with the speed at which storage technologies can respond and start discharging into the electricity grid at their full rated power, which can vary from milliseconds to minutes for different LDES technologies. We use the following to distinguish between 'discharge' and 'storage' duration:

- **Discharge duration** – is the length of time a system can deliver power at its rated output.
- **Storage duration** – how long energy can be stored without significant losses or self-discharge.[ii]

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[i] In October 2024, the Government decided to use a Cap and Floor (C&F) scheme to encourage investment in LDES. It asked Ofgem to determine which projects should be offered a C&F regime. In April 2025, Ofgem published the Eligibility Criteria Assessment Framework (ECAF) for projects applying to window one of the LDES C&F regime. The ECAF set out the eligibility assessment framework and included seven criteria that the applicants were expected to meet in their applications. Among these, the minimum capacity requirement was emphasised: projects must demonstrate the ability to sustain a discharge capacity of at least 100 MW for Stream 1 (TRL 9 technologies) or 50 MW for Stream 2 (TRL 8 technologies). This threshold was established to ensure that supported projects deliver material system benefits, balancing accessibility for innovative technologies with the need for sufficient scale to contribute meaningfully to security of supply and decarbonisation objectives. The ECAF also clearly specified the requirement on duration, stating that "the scheme duration will be able to discharge power continuously at full discharge capacity for a minimum of 8 hours." For more details on C&F, see https://www.gov.uk/government/publications/long-duration-electricity-storage-technical-details-of-the-scheme-and-its-operation.

[ii] The Faraday Institution states, for example, that lithium-ion and sodium-ion batteries demonstrate relatively short self-discharge rates, typically losing around 5% of their charge within the first 24 hours and experiencing monthly self-discharge rates ranging from 0.5% to 3%. For more details see https://www.faraday.ac.uk/wp-content/uploads/2023/09/20230908_Rho_Motion_Faraday_Institution_UK_BESS_Report_Final.pdf

**Box 1 LDES Key Attributes**

**Power output (MW, GW):** This is the rate at which energy can be delivered by the storage system. This could be constant throughput or may change as the energy store depletes (for instance hydrogen storage).

**Discharge duration (hrs):** This is the length of time a system can provide energy at its rated power output.

**Energy Capacity (kWh, MWh, GWh):** This is the total amount of energy a system can store. This varies according to the type of storage technology (mechanical, electro-chemical, hydrogen etc). Based on the minimum capacity and duration requirements set out in the ECAF, the implied minimum energy capacity is 800 MWh for Stream 1 (TRL 9 technologies, 100 MW × 8 hours) and 400 MWh for Stream 2 (TRL 8 technologies, 50 MW × 8 hours). These thresholds ensure that projects possess both sufficient scale and operational duration to deliver meaningful system-level benefits.

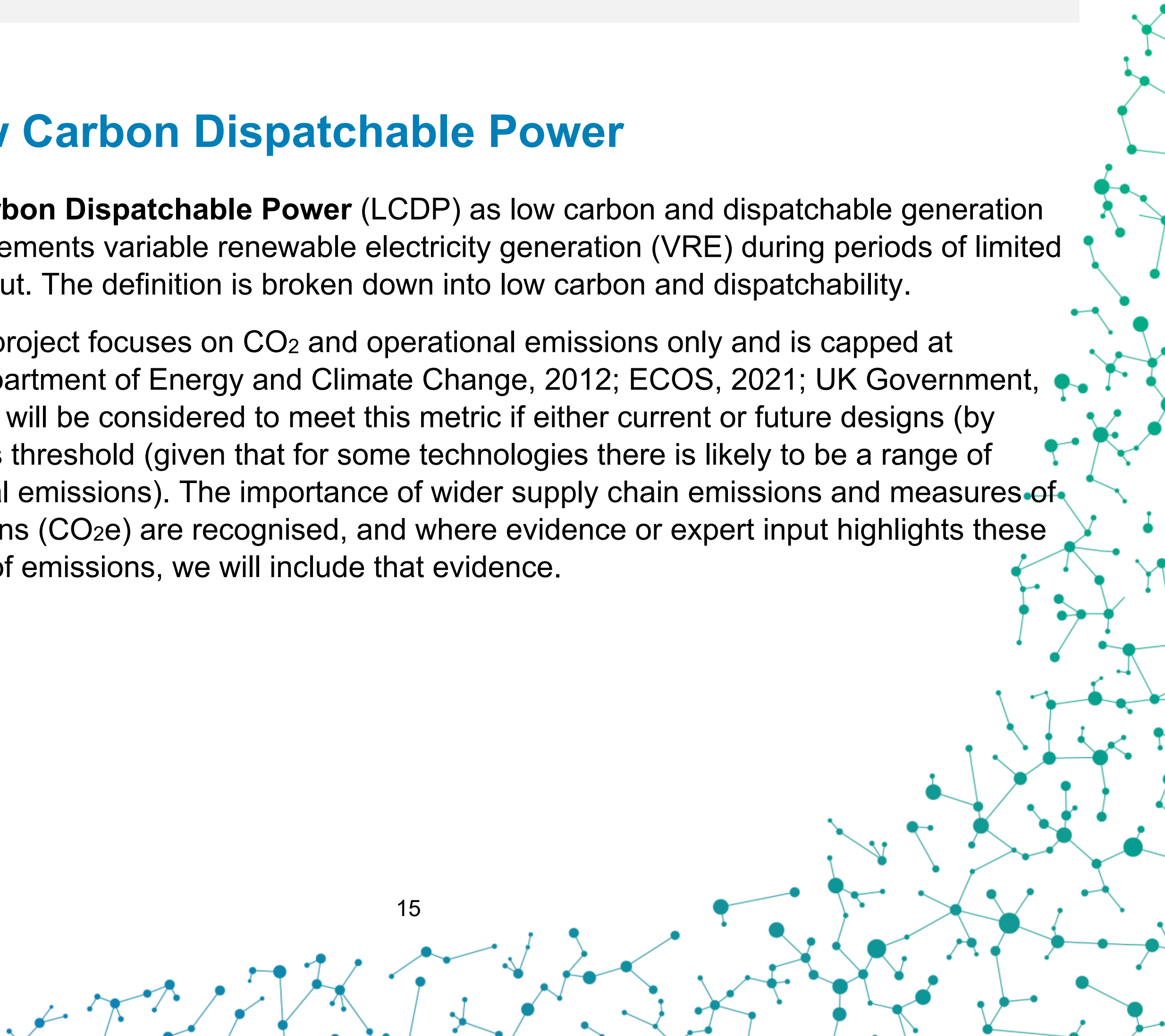
**Round-trip efficiency (RTE)** for energy storage is the ratio of electricity retrieved (discharged) compared to the electricity initially put into the system (charged) during a complete charging and discharging cycle. It measures the effectiveness of storing energy for later use, accounting for losses like heat or conversion."

**NOTE:** We exclusively looked at energy storage systems that have electricity in (charge) to electricity out (discharge)

## 2.2. Low Carbon Dispatchable Power

We define **Low Carbon Dispatchable Power** (LCDP) as low carbon and dispatchable generation capacity that complements variable renewable electricity generation (VRE) during periods of limited wind and solar output. The definition is broken down into low carbon and dispatchability.

**Low carbon**: This project focuses on $CO_2$ and operational emissions only and is capped at 50g$CO_2$e/kWh (Department of Energy and Climate Change, 2012; ECOS, 2021; UK Government, 2024) A technology will be considered to meet this metric if either current or future designs (by 2035) can meet this threshold (given that for some technologies there is likely to be a range of potential operational emissions). The importance of wider supply chain emissions and measures of wider GHG emissions ($CO_2$e) are recognised, and where evidence or expert input highlights these additional aspects of emissions, we will include that evidence.



### Box 2 LCDP Key Attributes

1. **Ramp rate:** This is the operational speed at which power output changes over time, expressed in MW/min or a percentage of nominal power output per unit time (% of MW/min)
2. **Ramp up time:** This is the total time that a power generator takes to reach a certain output from its *minimum stable load* and vice versa while in operation measured in hours or minutes (mins or hrs).
3. **Hot, warm and cold start up time**: Start up time is the time taken from the moment a generator is turned on to the moment it starts supplying power to the grid at its low operating level normally expressed in hours (h). The classification of hot, warm, and cold start-up times depends on the duration for which the power generating unit has been offline and this duration may be same across similar class of LCDP technologies such as turbines but may differ across different technologies such as between turbines and nuclear due to difference in their physical operating principles, thermal constraints, and system roles.
    a. A **hot start** typically refers to restarting the unit after a downtime of approximately ***8 hours or less***, when most residual heat is still retained.
    b. A **warm start** occurs after a shutdown period of ***roughly 8 to 48 hours***, during which partial cooling has taken place.
    c. A **cold start** is required when the unit has been offline for ***more than 48 hours***, by which time the plant has cooled to near ambient conditions and most of its stored heat has been lost.
4. **Minimum stable load**: This is the lowest level of power output at which a generating unit can operate safely and reliably, without causing damage or violating emissions standard expressed in percentage of rated power (%).
5. **Availability factor:** This is the percentage of time a power generation technology is ready to operate and produce electricity during a specific period. It is calculated by dividing the time the plant is available to generate power by the total time in that period, and it is not the same as the capacity factor, which measures how much energy is actually produced compared to the maximum possible.

**Dispatchability** means the power generation should combine '*schedulability*', '*flexibility*' and '*reliability*' on request by the grid operator to balance electricity supply with demand. However, different dispatchable power technologies will have these attributes to ***varying levels***.

The definitions we use are as follows:

- **Schedulability:** The ability of a power generation technology to be managed, allowing its output to be planned in advance to deliver the required power at a given time and meet grid's demand.
- **Flexibility:** The ability of a power generation technology to respond quickly to changes in electricity demand, variability in renewable generation, and real-time grid conditions.
- **Reliability:** The ability of a power generation technology to maintain output over time without interruption, even under adverse conditions such as extreme weather events, extended low-renewable output, prolonged periods of high system stress and fuel supply disruptions.

# 3. Methodological Framework

The methodology utilised in this project was designed to maximise rapidity, rigour and transparency. A key challenge for this project is the integration of several parallel activities that gather an extensive quantity of evidence over a significantly compressed time-period. The project methodology includes seven separate work activities, divided across three stages (data gathering and modelling, synthesis and analysis, and outcomes) as shown in Figure 1. This section describes the evidence gathering approach for the rapid evidence assessment, expert elicitation and modelling. The synthesis of this evidence informed the development of a longlist of technologies for comparative RAG rating and evaluation in order to produce a priority shortlist for possible innovation funding. All gathered evidence on the shortlisted technologies was then considered to identify key challenges to UK deployment at scale and develop a set of recommended options for R&I to accelerate the development and deployment of LDES and LCDP to 2035.

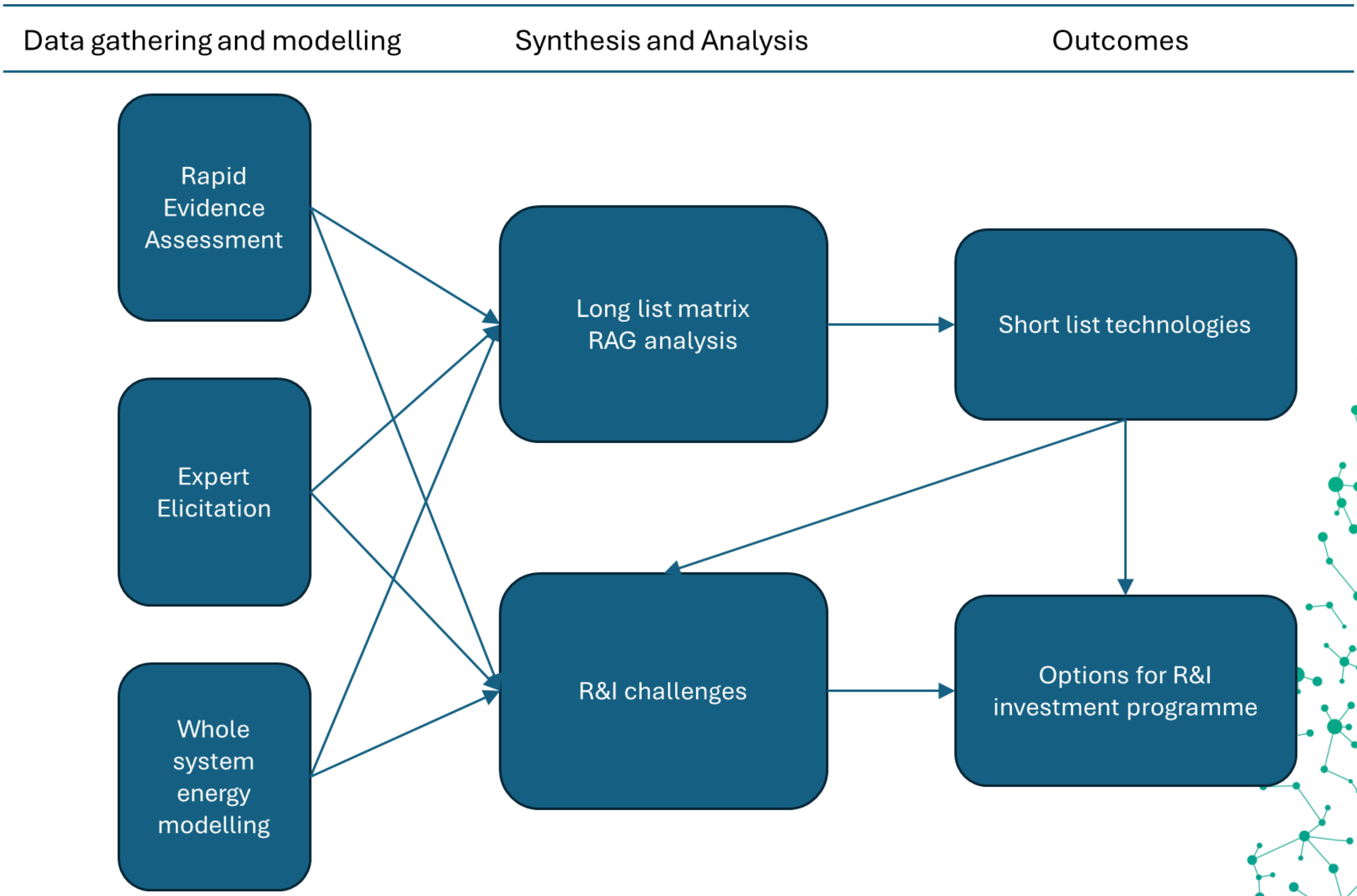


**Figure 1: Methodological framework**

## 3.1. Rapid Evidence Assessment

In order to deliver a thorough assessment of available evidence in a compressed timescale, parallel teams of subject-matter experts used conventional manual database searches, supplemented by AI-assisted search techniques to identify additional literature, overseen by evidence assessment experts. In addition to manual searches using conventional academic and grey literature databases, the REA made limited use of the AI tool Elicit exclusively to identify relevant literature beyond that extracted from the manual review. Elicit draws upon the Semantic Scholar AI discovery tool, which indexes over 200 million academic papers, including in the fields of engineering, economics and environmental science. Since Elicit focuses on academic publications, the Google Gemini AI research tool (Deep Research mode, 2.5 Pro model) was used to complement manual searches of Google and help identify the most up-to-date grey literature.

We then undertook a rigorous process of relevance rating, assessment and evaluation to move quickly from an initial set of over 1,500 documents to extract the most salient evidence. This expedited approach was assisted through the definition of a clear and tightly defined set of objectives and research questions as required for effectively carrying out a Rapid Evidence Assessment (REA) over a short period of time. An REA is a rapid systematic review on a constrained topic (Speirs et al., 2015; Warren, 2020), and as such searches have been confined to the last five years to capture the most recent evidence. As is standard practice in an REA (Sorrell, 2007), we have synthesised and evaluated currently available evidence and comparative reviews of primary research on relevant technologies. The review comprises three parallel REAs addressing LDES, LCDP and existing whole system modelling evidence:

- LDES REA: 21 search strings applied across four databases (Web of Science and Science Direct for academic literature; Google and Overton for grey literature). 813 documents published from 2020 to 2025 were gathered; 307 relevant documents were identified for systematic technology categorisation.
- LCDP REA: 12 search strings applied across four databases (Web of Science and Scopus for academic literature; Google and Overton for grey literature). 586 documents published from 2020 to 2025 were gathered; 184 relevant documents were identified for systematic technology categorisation.
- Modelling REA: nine search strings applied across four databases (Elicit and Google Scholar for academic literature; Google and Overton for grey literature). 22 recent modelling studies prioritised from 141 sources.

Search terms and categorisation of evidence were structured around Energy Systems Catapult's Aspects of Integration framework (see Appendix). Technologies that meet our definitions as laid out in Section 2 were targeted by the REA process and used to characterise a 'longlist' of technologies, presented in Section 4. A standardised flow diagram for the REA effort is in Figure 2.

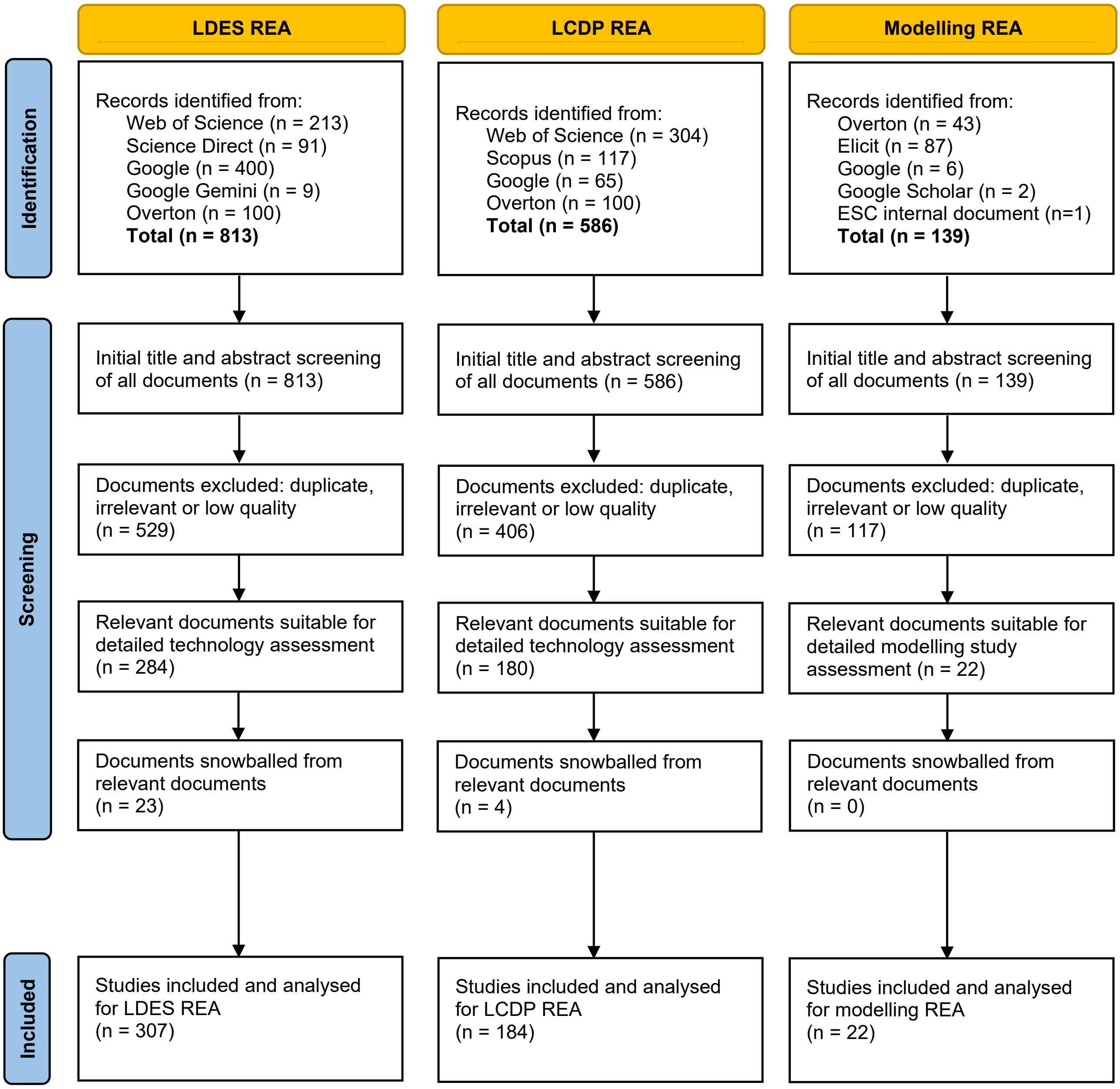


**Figure 2: PRISMA flow diagram of process for identification and inclusion of relevant evidence from the LDES and LCDP REAs**

## 3.2. Expert Elicitation

To gather views, expertise and intelligence from LDES and LCDP technology experts, an extensive programme of expert elicitation workshops was developed, and conducted over a compressed timeframe, across the key technologies meeting the definitions in Section 2. Overall, nineteen 2.5-hour expert workshops, one wider workshop and five shorter expert engagements were conducted by seven facilitators with over 110 participants (90 of which were targeted experts) across nine technologies from established large organisations, technology innovators, expert consultants, academics and government/public bodies.

Experts were identified through:

- Trade bodies: Long Duration Energy Storage Council, Energy UK and Thermal Storage UK
- The Catapult innovator database
- Innovation institutions including The Faraday Institution and other Catapults
- Catapult and UKERC networks
- Influential institutions and individuals identified via the Overton policy and grey literature database

The workshops were structured around the Catapult's Aspects of Integration (AoI) framework (see Appendix), complementing the findings of the REAs and the modelling analysis (see below), and split into two parts:

| Workshop objectives | Tools and approaches to be used |
|---|---|
| Establishing expert views on maturity of technologies against the AoI maturity scales | Virtually held sessions over Microsoft Teams, using a standardised Mural template synthesised across stakeholders using Mural AI and Microsoft Copilot. Each workshop was run using a bespoke facilitator pack with key questions defined to elicit insight from stakeholders relevant to the UKRI criteria defined in Table 1. |
| Eliciting expert views on key problem statements that, if addressed, would accelerate technology maturity towards deployment at scale | Using the Ideaonomy.ai[iii] platform, structured around the AoI framework. Problem statements elicited, with the option to up-vote problem statements defined in previous workshops. Ideaonomy.ai link provided to attendees to share with other experts. |

Each workshop produced a transcript, an AI-generated summary of the transcript, a Mural[iv] board and associated spreadsheet of the Mural, made possible by effective use of labels within the Mural design. These were processed in three stages:

1. **A two-page AI prompt was developed** and tested to ingest all workshop outputs and produce a summary of the workshop, structured by the Aspects of Integration framework and pulling out key barriers, UK strengths and key innovation opportunities
2. **Each workshop was summarised** using the AI prompt and subsequently reviewed and updated by the facilitators of the workshop to ensure all insights were captured effectively and accurately
3. **Eight technology summaries were produced**[v] by manually combining each of the workshops which related to each technology into a single technology summary. Information from these has been incorporated in the summaries for shortlisted technologies presented in the Appendix.

In total, over two thousand pages of workshop transcript, 5,000 rows of Mural data and additional notes have been synthesised to 56 pages of insight within the technology summaries, highlighting the expert perceptions of solution maturity, barriers to development and opportunities to overcome

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[iii] Ideaonomy is a collaborative problem-solving platform for organisations to prioritise problems match with solutions and solve unsolved problems together. It uses AI to support the development of detailed problem statements with lower effort from the participant.

[iv] As well as problem statements added to Ideaonomy.

[v] These technologies were shortlisted at the outset of the project before completion of the evidence review through discussions with UKRI. They comprised flow batteries, compressed air energy storage, gas CCUS, hydrogen salt caverns and turbines, liquid air energy storage, metal air batteries, pumped hydro and pumped heat storage.

them. These have been anonymised and, in some cases, redacted to ensure that sensitive information cannot be attributed to individual companies.

## 3.3. Modelling Analysis

Modelling analysis was conducted using two of the Catapult's whole energy system models: ESME and ESME Flex. These were used in accelerated mode to provide evidence within the timescales required and, the analysis builds on the Catapult's self-funded, modelling work for its flagship Innovating to Net Zero 2026 (ITNZ2026) event, providing additional value to the client.[vi] The modelling sought to provide new insights relative to existing modelling studies captured in the modelling evidence analysis, to support decision making within the R&D MAP ItAA project. Building on the findings of the Modelling REA and discussions with the R&D MAP team, the research questions we set out to address were:

1. **What are the relative costs and benefits of different LDES and LCDP technologies in future Net Zero energy systems and pathways?** Chosen to supplement existing literature that typically has low granularity of different LDES and LCDP technologies.
2. **How does LDES and LCDP availability impact upon operation of these technologies, including in Dunkelflaute events?** Chosen to providing insights on how operation of these technologies may, or may not, align with existing/planned market mechanisms.
3. **Could Li-ion battery stacking[vii] displace alternative innovative technologies in least cost systems?** Chosen to address a specific uncertainty on the relative value of innovating in LDES compared to leveraging the existing, established lithium-ion battery market.
4. **How could innovation that accelerates deployment[viii] impact upon optimal LDES and LCDP deployment in least cost energy system pathways?** Chosen to support decisions on how innovation funding could create impact.

Four specific modelling approaches were taken to explore a range of systems issues of interest to LDES and LCDP:

- **"Peak Gap" analysis** – building upon the Catapult's established methodology for their Innovating to Net Zero 2026 event, we defined four "Peak Gaps", representing four fundamental needs for LCDP and LDES, where there are imbalances to energy supply and demand. This aimed to demonstrate the scale of the challenge that LCDP and LDES are expected to meet as part of a system transitioning to Net Zero. The outputs were used alongside other areas of modelling.
- **Techno-economic system design and hierarchy sensitivities** – using ESME, we designed least cost energy systems across four scenarios which all met Net Zero and Carbon Budget 6. Three also met clean power 2030, with varying alignment with NESO projections. We then systematically removed different LCDP and LDES technologies to understand the system impacts and provide an indication of the value of that innovation existing.
- **Techno-economic sensitivities to understand innovation impacts** – using ESME, we tested the impacts of potential innovation interventions on least cost system design, including accelerating deployments, improving efficiencies and lowering technology costs. We also

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[vi] Innovating to Net Zero 2026 had been running for 7 months prior to this project, with extensive model preparation, dataset and scenario development and model debugging, all of which did not have to be done to the same extent here. The final ITNZ 2026 report can be found here: https://es.catapult.org.uk/project/innovating-to-net-zero-2026/

[vii] Battery stacking refers to the sequential dispatch of multiple batteries that have a shorter nominal duration to 'act like' a longer duration storage technology.

[viii] In this study, we assume innovation could accelerate deployment by 5 years compared to our counterfactual.

tested the inclusion of generic low-cost battery technologies, informed by the ambitions of The Faraday Institution's Ultrastore Challenge.[ix]

- **Techno-economic whole system dispatch analysis** – using ESME Flex, we tested how the system designs from ESME scenarios are dispatched, and how different technologies interact to meet the 'Peak Gaps'.

Together, these modelling approaches were used to inform the scale of the innovation challenges needed to support delivery of the whole energy system at lowest cost.

## 3.4. Synthesis and Analysis

### Technology Shortlisting

The evidence gathering process was complemented by the expert elicitation and modelling analysis to capture information not accessible in the literature and validate findings from the REAs. The outcome of this process was a longlist of LDES and LCDP technologies, which set out to include technologies predominantly but not exclusively at TRLs 6-9, selected based on alignment with our definitions in Section 2, and for which the evidence suggests there is a plausible innovation journey making these technologies commercially available by 2030-2035. Evidence collection was structured around the Catapult's Aspects of Integration framework (see Appendix), and key criteria identified with UKRI (Table 1). Technologies were included in the longlist if they were identified in either the REAs or the expert elicitation, and if sufficient evidence on given technologies was available to permit meaningful evaluation and comparison using these criteria.

Using a Red/Amber/Green (RAG) analytical approach, technologies were shortlisted and prioritised for possible innovation funding on the basis of their potential to provide storage or dispatchable power services to the electricity grid by 2030-2035. The longlist LDES and LCDP technologies were assessed against seven key quantitative and qualitative criteria (Table 1), agreed with UKRI as of most interest for further evidence. Assessment of these longlist technologies in relation to the seven criteria, which informed the shortlisting and technology prioritisation, is presented in the longlist matrix analysis in Section 4. Technological Readiness Levels (TRLs) are generally specified for technologies in this report, but are also referred to in terms of low (TRLs 1-5, basic principles to basic validation), medium (TRLs 6-7, prototype demonstration) and high (TRLs 8-9, actual system demonstrated and /or successfully proven in its operational environment).

**Table 1: Seven key criteria identified with UKRI for analysis of LDES and LCDP technologies**

| | |
|---|---|
| **Technological Readiness Level (TRL)** | Including whole technologies and separate system components |
| **Technical characteristics** | Capacity / potential output, energy density, storage duration, discharge duration, dispatchability, ramp rates |
| **Costs** | Current and future cost reduction |
| **Scalability** | Technological, economic, geographical specificity and environmental impact / availability of critical components or materials |
| **UK competitive advantage** | Technological, supply chains, environmental resources, legislation and regulatory framework |

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[ix] The Faradays Institution's Ultrastrore Transformational Challenge Research Programme focuses to develop new ultra-low-cost batteries with the underlying cost of the cell's active material of <£3.8/kWh($5/kWh). For more details about the programme, see https://www.faraday.ac.uk/wp-content/uploads/2026/03/UltraStore-Aluminium-call-document.pdf

| | |
|---|---|
| **Potential deliverability** | To 2030 and/or 2035 including current or planned policies |
| **Potential focus of innovation spend** | The R&I challenges offer opportunities that future innovation initiatives may be able to fund |

## Development of R&I opportunities

The extensive evidence base gathered through the REAs, expert elicitation and modelling was designed to highlight, where available, the key challenges facing the technologies examined. Details of these can be found in the technology summaries in Section 10.. By combining these sources of evidence, the challenges of most concern to specific technologies were identified. The expert elicitation workshops also provided a comprehensive set of perspectives on the maturity of LDES and LCDP technologies, as well as a clear set of barriers faced to scaling those technologies, framed through the Aspects of Integration framework. The AI tool Ideaonomy was then used to elicit a set of more detailed 'problem statements' that most concerned experts in terms of inhibiting the technologies' ability to scale. By synthesising all the gathered evidence, areas with opportunities to benefit from R&I to accelerate development and deployment of LDES and LCDP technologies were identified. These areas were then assessed against the following four challenge areas:

- Technical innovation challenges: primarily relating to the technical aspect
- Market, policy and regulatory innovation challenges: primarily related to market area of commercial and legislation aspects
- System innovation challenges: primarily related to people, information, infrastructure and interoperability aspects
- Financial and business model innovation challenges: primarily related to the non-market areas of the commercial aspect such as investment and business models

These outcomes are presented in Section 7.

# 4. Longlist Matrix and Priority List of LDES and LCDP Technologies

The results of the REAs and expert elicitation were used to extract a longlist of technologies that fell within the scope of the project and met our definitions for LDES and LCDP as set out in Section 2. Technologies were then shortlisted for possible innovation funding based on their deployment potential to 2035 and the criteria in Section 3.4. The detailed rationale for prioritising and excluding technologies from shortlists for LDES and LCDP is explained below.

## 4.1. Longlist Extraction and Technology Exclusions

Technologies were included on the longlist if the quality and quantity of evidence on each technology permitted a reasonably holistic and reliable assessment against the criteria presented in Table 1. The longlist is therefore not exhaustive as it depends on the extent and reliability of sufficient evidence from the REAs or expert elicitation. In certain cases, specific technologies were provisionally considered for inclusion in the longlist, but judged to be unsuitable for eventual inclusion, for example sodium–sulphur batteries, lined rock caverns for hydrogen storage and Phase Change Materials (PCMs) thermal energy storage. The rationale for these decisions was based on the balance of evidence gathered on these technologies and is set out below.

Room-temperature sodium–sulphur batteries were not included because recent progress towards room/ambient-temperature operation remains largely lab-scale (TRL 3-4), there are significant safety concerns, and large-scale deployment by ~2035 is not yet considered deliverable. The technologies are physically stackable to reduce land-use, though costs are a challenge for low load factor applications.

Lined Rock Caverns (LRCs) were also excluded from the longlist. LRCs are engineered underground hydrogen storage solutions, featuring a steel-lined, concrete-reinforced chamber designed for high-pressure, large-scale storage of gases such as hydrogen. LRCs are not constrained by local salt geology, and their technology readiness is broadly in the TRL 4-5 range, although progress has been reported by the Swedish HYBRIT demo which suggests a higher readiness level of up to TRL 7 (Vattenfall, 2025). However, compared with depleted gas reservoirs, LRCs typically offer lower storage capacity potential and higher capital and operational costs. Given these trade-offs - and the limited evidence base identified in the REA searches - LRCs were not included.

Phase Change Materials (PCMs) thermal energy storage was also omitted from the longlist, since identified literature was mainly focussed on their use for heating in buildings (at higher TRLs 7-9), whereas evidence with respect to LDES applications and potential use of PCMs in re-conversion back to electricity is limited and indicates low TRLs (TRL 2).

## 4.2. Long Duration Electricity Storage: Priority Technologies and Longlist Matrix

The longlist matrix for LDES technologies represents all LDES technologies evaluated against the seven criteria set out in the methodology Section 3, based on collated evidence from the REA, expert elicitation and modelling. In order to clearly indicate the technologies prioritised for potential innovation funding, we present the matrix split by shortlisted technologies and those on the longer list which were excluded from this prioritisation. All technologies are rated according to the RAG analysis for each criterion, and the key justifications for including or excluding technologies from the shortlist are set out below. Cells are shaded red, amber or green to represent the extent to which a criterion may indicate the suitability of a technology for possible innovation investment and the potential of the technology being available to the energy system in 2030 to 2035. Grey shading indicates where there was insufficient evidence from the REA, expert elicitation or modelling to inform a RAG rating.

In some cases, the RAG colour for key criteria shown in Table 2 represents an overall or average rating arrived at by assessing several sub-criteria in turn, which includes the use of quantitative metric ranges to inform the RAG analysis.

The TRL rating is a relative rating reflecting the distribution of TRL values across the LDES longlist (where minimum TRL values are lower than those for LCDP), and therefore the thresholds used to determine particular colours do not align precisely with those used for the LCDP matrix below. TRL values shown represent our overall assessment for each LDES technology at the time of collecting all relevant evidence, expressed as a single figure or a range in cases where the TRL varies across component technologies. A red rating applies where the TRL ranges have a minimum value of 5 or below. A green colour represents TRLs of 9 or 8-9, with amber ratings covering TRL values and ranges which fall between these criteria. Where a technology has a TRL of 9 exclusively it is rated as green even though its technological readiness is mature overall, because there are still niche innovation opportunities for potential R&I investment. In general we prioritise technologies that have ability to deliver at grid scale. They therefore need to be available, commercially and technically viable, either now or by 2035. We further discuss innovation opportunities for shortlisted technologies in Section 5.

The technical characteristics RAG rating is an average of individual ratings against quantitative metrics for capacity / power output, storage duration, discharge duration, round trip efficiency (%), lifetime cycling and energy density.

Reliable or comparable data on current costs and learning potential of LDES technologies was difficult to obtain through the REAs, therefore authoritative sources of cost data were combined with data points from the modelling analysis as a basis for this assessment. The process and rationale for the cost RAG rating is explained below.

The remaining indicators are based on qualitative evaluations of the evidence, drawing on detailed assessments for each technology, including the technology summaries presented in the Appendix. Scalability represents an average of individual RAG ratings for the following dimensions: technological, economic, co-location / integration advantage, geographical specificity, environmental impact, available critical components / materials. UK competitiveness averages separate ratings relating to whether there are existing / planned projects, an established supply chain, an existing policy / legal framework, available natural resources and world leading R&D capacity / companies in the UK.

**Table 2: Longlist matrix for LDES ranked by RAG analysis**

**Shortlist technologies**

**Shortlisted technologies have to be green or amber for deliverability and TRL and focus / impact of innovation**

| Groupings | LDES technologies | TRL | Technical characteristics | Current cost and learning potential to 2035 | Scalability | UK competitiveness | 2030/2035 potential deliverability including current or planned policies | Potential focus areas and impact of innovation to 2035 |
|---|---|---|---|---|---|---|---|---|
| Mechanical | A-CAES | 🟨 8 | 🟩 | 🟩 | 🟨 | 🟨 | 🟩 | 🟩 |
|  | PHS | 🟩 9 | 🟩 | 🟩 | 🟥 | 🟨 | 🟩 | 🟨 |
| Chemical | Hydrogen salt cavern storage (low cycle) | 🟩 9 | 🟩 | 🟩 | 🟨 | 🟩 | 🟩 | 🟩 |
| Electro-chemical | Metal air batteries | 🟨 6-8 | 🟩 | 🟨 | 🟨 | 🟨 | 🟨 ` | 🟨 |
|  | Flow batteries | 🟨 7-8 | 🟩 | 🟨 | 🟩 | 🟩 | 🟩 | 🟨 ` |

**Longlist (technologies not shortlisted)**

| Groupings | LDES technologies | TRL | Technical characteristics | Current cost and learning potential to 2035 | Scalability | UK competitiveness | 2030/2035 potential deliverability including current or planned policies | Potential focus areas and impact of innovation to 2035 |
|---|---|---|---|---|---|---|---|---|
| Mechanical | LAES | 🟨 8 | 🟨 | 🟨 | 🟩 | 🟩 | 🟩 | 🟩 |
|  | D-CAES | 🟩 9 | 🟩 | 🟩 | 🟨 | 🟥 | 🟥 | 🟥 |
|  | I-CAES | 🟥 5-7 | 🟨 | 🟥 | 🟥 | 🟥 | 🟥 | 🟨 |
| Chemical | Ammonia storage | 🟨 4-9 | 🟩 | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 |
|  | Methanol storage | 🟨 6-9 | 🟩 | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 |
|  | Hydrogen: Depleted gas fields/reservoirs | 🟥 3-5 | 🟩 | 🟩 | 🟨 | 🟩 | 🟥 | 🟨 |
| Electro-chemical | Lithium-ion batteries | 🟩 9 | 🟩 | 🟨 | 🟩 | 🟩 | 🟩 | 🟩 |
|  | Sodium-ion batteries | 🟨 7 | 🟨 | 🟥 | 🟨 | 🟨 | 🟨 ` | 🟨 |
|  | Sodium-sulfur batteries (high temperature) | 🟩 8-9 | 🟨 | 🟨 | 🟥 | 🟥 | 🟥 | 🟥 |
| Thermal | Molten salt TES | 🟥 5-9 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 |
|  | Pumped TES | 🟥 4-6 | 🟨 | 🟨 | 🟩 | 🟩 | 🟥 | 🟨 |

## LDES Technology Shortlisting: Justifications for Inclusion and Exclusion

LDES technologies were prioritised for their relatively high TRLs (predominantly 7-9), low costs and present or future potential to provide longer discharge durations, as well as their potential deliverability to 2035 (see also Table 4). Pumped hydro storage (PHS), adiabatic-compressed air energy storage (A-CAES) and flow batteries are currently in the intermediate discharge duration range of 12 to 24 hours, but all in the future have the potential to reach 100 hours (McIlroy, 2025; Yang et al., 2025). Hydrogen and to a lesser degree metal-air batteries (at much lower storage capacity) can achieve a discharge duration of 100 hours or greater. Section 5 elaborates further on specific shortlisted technologies.

Shortlisted technologies were required to be green or amber for potential focus areas and impact of innovation, potential deliverability to 2030 and/or 2035 including current or planned policies, and TRL. There were some instances where specific LDES technologies met these criteria and were otherwise rated quite favourably but were not prioritised. The rationale for decisions relating to marginal cases where technologies were close to making the shortlist is set out below.

Lithium-ion batteries were excluded from the shortlist based on their inability to meet 100+ hours discharge duration as a stand-alone technology. In the future there is potential to stack or aggregate lithium-ion batteries to achieve these longer durations, but this is a highly unlikely aspiration for 2030/2035. High potential costs and land use issues associated with such battery stacking are particular challenges, ameliorated by the capability of lithium-ion batteries to access short-term revenues (e.g. fast-start ancillary services). However, there is a lack of evidence in the literature on the potential for lithium-ion battery aggregation to provide multi-day discharge durations.

Similarly, sodium-ion batteries and liquid air energy storage (LAES, which otherwise rates quite favourably across the criteria) were not shortlisted because they do not have current or potential capability by 2035 to provide 100+ hours discharge durations (Rabi et al., 2023; She et al., 2025).

Existing diabatic CAES is already commercially available, but it was not shortlisted because it is fossil fuel-coupled and emissions-linked; isothermal CAES was also not prioritised given low maturity (TRL 2-3, see e.g. (Mahmoudi Larimi, 2024) and has scale-up/control uncertainties.

## Further Explanation of LDES Technology Cost Justifications

The REA uncovered a range of cost estimates represented in the literature for LDES technologies. The levelised cost of storage (LCOS) calculation had to take into consideration the range of numbers, including CAPEX and OPEX where available. Another challenge in providing the cost calculations was that there is no one source that represents all LDES technologies for the UK. Therefore, several UK and international sources were used[x] alongside cost estimates for 2030-2035 from the Catapult's whole system energy modelling analysis. This further represents an approximate cost calculation due to conversion rates, and differences in CAPEX and OPEX definitions and calculations.

An important aspect in the discussion of LDES costs is the number of cycles per year of charge and discharge. Thus, for example, especially for electrochemical technologies the difference between the costs of 1 cycle and 100 cycles per year is around 100-fold. Storage technologies that have

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[x] See more sources of cost data here: (Cetegen et al. 2024, 2025; Department for Energy and Net Zero, 2023; EsmaeiliShayan, 2025; Friedel et al., 2026; He et al., 2021; IRENA, 2021, 2022; Jackson et al., 2024; McTigue et al., 2025; Mettler & Reinaud, 2025; Tafone et al., 2020; Talukdar et al., 2024; The Royal Society, 2023; UK Government, 2025; U.S. Department of Energy, 2023c, 2024; Viswanathan et al., 2022; WSP, 2020)

longer discharge durations (100+ hours) will not be able to cycle as often, typically fewer than 50 cycles per year in the case of metal-air batteries and even lower for hydrogen salt cavern storage. For these technologies, low system capital/lifetime costs are essential to meet a specific LCOS target, as illustrated in Figure 3: Graphical representation of decreasing system lifetime cost requirement as a function of the cycling frequency (APRA-E, n.d.).

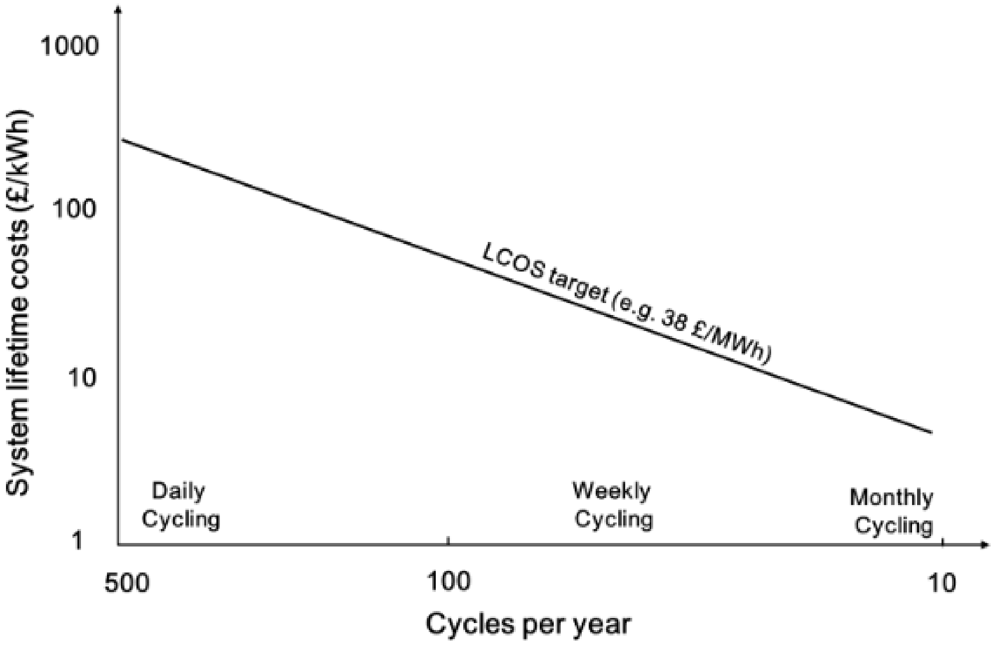

**Figure 3: Graphical representation of decreasing system lifetime cost requirement as a function of the cycling frequency (APRA-E, n.d.)**

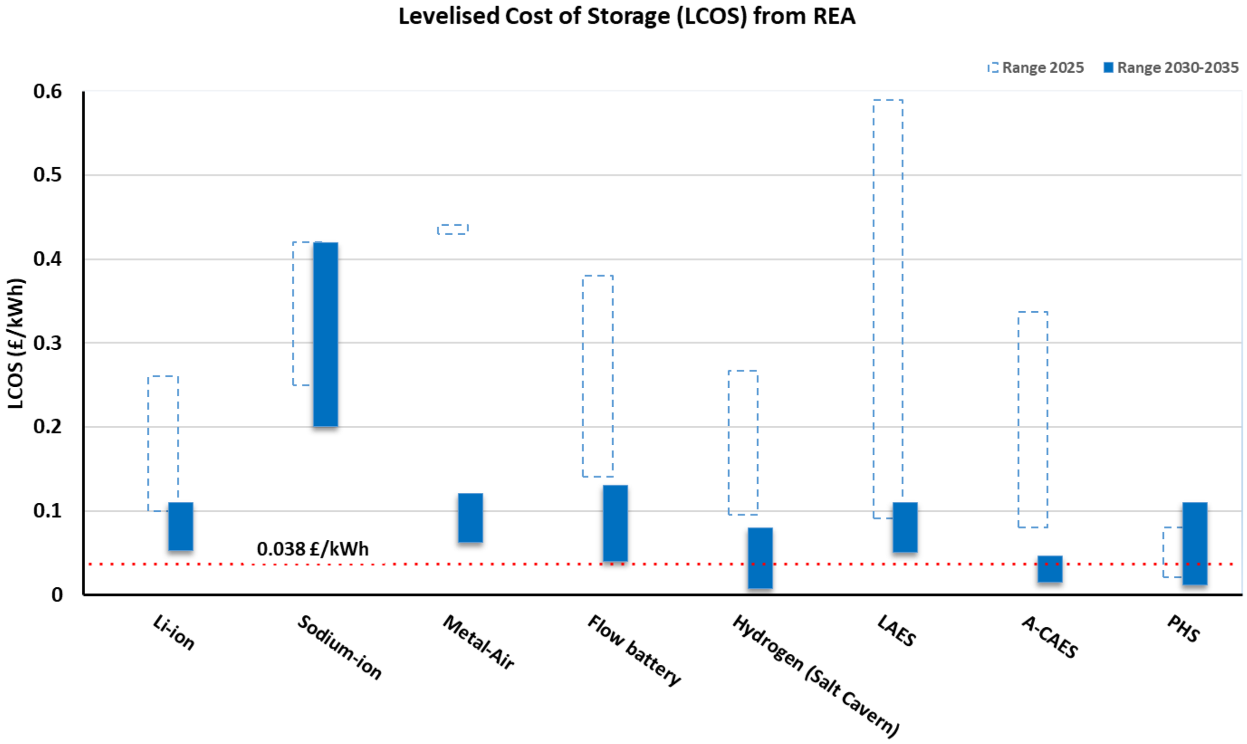

**Figure 4: Levelised (LCOS) cost of storage[xi] for selected LDES technologies[xii] from the REA and modelling**

Figure 4 shows LCOS ranges for LDES technologies considered for inclusion in the shortlist. Since no single, comparable source of UK data was available for all technologies, US DOE Long Duration Storage Shot cost data (U.S. Department of Energy, 2024a) was used to inform the RAG scoring. LDES technologies are rated Low cost or Green where LCOS < £0.038/kWh ($0.05/kWh)[xiii], equivalent to the US DOE's Storage Shot target, and technologies at or above these thresholds are rated Medium-High. The LCOS for amber technologies ranges from £0.038-0.076/kWh ($0.05-$0.1/kWh), with red applying to any technology exceeding £0.076/kWh ($0.1/kWh), above which threshold competing with lithium-ion batteries becomes challenging (BloombergNEF, 2025). Based on these cost thresholds, the RAG score for A-CAES, hydrogen salt caverns, pumped hydro storage is Green, Li-ion, LAES, Flow batteries and Metal (Iron)-Air is Amber and Sodium-ion is Red.

Hydrogen salt cavern storage costs include hydrogen production through electrolysis, compression and storage with power generation (higher costs) and without power generation (lower costs). In our RAG analysis, hydrogen storage costs with reconversion back to power would most likely be Amber. However, since we assess hydrogen LCDP costs separately in the next section, using costs for hydrogen LDES storage, without reconversion to power (but including electrolysis costs) is appropriate and our RAG rating for costs is therefore Green.

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[xi] The red line indicates the threshold for low cost or Green RAG rated technologies where LCOS < £0.038/kWh ($0.05/kWh), equivalent to the US DOE (2024) Long Duration Storage Shot target.

[xii] Hydrogen salt cavern storage costs include conversion, compression and storage with/without power generation.

[xiii] The currency representation throughout this document was converted to GBP using the 2025 HMRC foreign currency exchange average rate of £1=$1.3156. See at: https://www.trade-tariff.service.gov.uk/exchange_rates/view/2025-12?type=average

## 4.3. Low Carbon Dispatchable Power: Priority Technologies and Longlist Matrix

The longlist matrix for LCDP technologies (Table 3) represents all LCDP technologies evaluated against the seven criteria set out in the methodology Section 3, based on collated evidence from the REA, expert elicitation and modelling. To clearly indicate the technologies prioritised for potential innovation funding, we present the matrix split by shortlisted technologies and those on the longer list that were excluded from this prioritisation. All technologies are rated according to the RAG analysis for each criterion, and the key justifications for including or excluding technologies from the shortlist are set out below. Cells are shaded red, amber or green to represent the extent to which a criterion may indicate the suitability of a technology for possible innovation investment and the potential for the technology to be available to the energy system in 2030 to 2035. Grey shading indicates where there was insufficient evidence from the REA, expert elicitation or modelling to inform a RAG rating.

In some cases, the RAG colour for key criteria shown in Table 3 represents an overall or average rating arrived at by assessing several sub-criteria in turn, which includes the use of quantitative metric ranges to inform the RAG analysis.

The TRL rating is a relative rating reflecting the distribution of TRL values across the LCDP longlist (where minimum TRL values are higher than those for LDES), and therefore the thresholds used to determine the colours do not align precisely with those used for the LDES matrix. The TRL values represent our overall assessment for each LCDP technology at the time of collecting all relevant evidence, expressed as a single figure or a range in cases where the TRL varies across component technologies. A red rating applies where the TRL is no greater than 7, amber where the TRL includes but does not exceed 8, and green for a single or maximum value of 9. Where a technology has a TRL of 9 exclusively, it is rated as green even though its technological readiness is mature overall, because there are still niche innovation opportunities for potential R&I investment. In general we prioritise technologies that can deliver at grid scale. They therefore need to be available, commercially and technically viable, either now or by 2035. We further discuss innovation opportunities for shortlisted technologies in Section 5.

The dispatchability RAG rating is an average of individual ratings against quantitative metrics for schedulability (mainly cold start), flexibility (ramp rate, ramp time, deliverable capacity, minimum stable load) and reliability (availability factor, fuel supply / logistics).

Reliable or comparable data on current costs and learning potential of LCDP technologies was difficult to obtain through the REAs, therefore authoritative sources of cost data were combined with data points from the modelling analysis as a basis for this assessment. The process and rationale for the cost RAG rating is explained below.

The remaining indicators are based on qualitative evaluations of the evidence, drawing on detailed assessments for each technology, including the technology summaries presented in the Appendix. Scalability represents an average of individual RAG ratings for the following dimensions: technological, economic, geographical specificity, environmental impact, available critical components / materials. UK competitiveness averages separate ratings relating to whether there are existing / planned projects, an established supply chain, an existing policy / legal framework, available natural resources and world leading R&D capacity / companies in the UK.

## Table 3: Longlist matrix for LCDP ranked by RAG analysis

**Shortlist technologies**

Shortlisted technologies have to be green or amber for deliverability and TRL and focus / Impact of innovation

| Groupings | | LCDP technologies | TRL | Dispatchability | Current cost and learning potential to 2035 | Scalability | UK competitiveness | 2030/2035 potential deliverability including current or planned policies | Potential focus areas and impact of innovation to 2035 |
|---|---|---|---|---|---|---|---|---|---|
| Fuel Based Dispatchable Power Generation | Fossil Fuel | CCGT-CCS | 🟨 8 | 🟨 | 🟨 | 🟨 | 🟩 | 🟨 | 🟩 |
| | Biomass & Waste | BECCS Power | 🟩 8-9 | 🟨 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 |
| | Hydrogen to Power (H2P) | Reciprocating engines | 🟩 9 | 🟩 | 🟨 | 🟨 | 🟥 | 🟨 | 🟩 |
| | | Gas turbines | 🟩 7-9 | 🟨 | 🟨 | 🟨 | 🟥 | 🟨 | 🟩 |
| | Nuclear | Gen III- SMR | 🟨 7-8 | 🟨 | 🟥 | 🟩 | 🟩 | 🟨 | 🟩 |

**Longlist (technologies not shortlisted)**

| Groupings | | LCDP technologies | TRL | Dispatchability | Current cost and learning potential to 2035 | Scalability | UK competitiveness | 2030/2035 potential deliverability including current or planned policies | Potential focus areas and impact of innovation to 2035 |
|---|---|---|---|---|---|---|---|---|---|
| Fuel Based Dispatchable Power Generation | Fossil Fuel | OCGT- CCS | 🟨 8 | 🟨 | 🟥 | 🟨 | 🟨 | 🟥 | 🟨 |
| | Biomass & Waste | Biomethane Power | 🟩 9 | 🟨 | ⬜ | 🟨 | 🟩 | 🟥 | 🟨 |
| | | Biomass Power | 🟩 9 | 🟨 | 🟥 | 🟨 | 🟨 | 🟩 | 🟥 |
| | Hydrogen to Power (H2P) | Fuel cells (SOFC) | 🟩 6-9 | 🟨 | 🟥 | 🟨 | 🟨 | 🟨 | 🟩 |
| | | Fuel cells (PEM) | 🟨 7-8 | 🟩 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 |
| | Nuclear | Conventional Nuclear | 🟩 9 | 🟨 | ⬜ | 🟨 | 🟩 | 🟥 | 🟥 |
| | | Gen IV- AMR | 🟥 4-7 | ⬜ | ⬜ | 🟨 | 🟨 | 🟥 | 🟥 |
| Renewable Dispatchable Power Generation | Hydropower | Conventional Hydropower | 🟩 9 | 🟨 | ⬜ | 🟥 | 🟩 | 🟨 | 🟥 |
| | Geothermal | Conventional Geothermal | 🟩 9 | 🟨 | ⬜ | 🟨 | 🟥 | 🟥 | ⬜ |
| | | Enhanced Geothermal | 🟥 6-7 | 🟨 | ⬜ | 🟨 | 🟨 | 🟥 | 🟨 |
| | Tidal power | Tidal Barrage | 🟩 9 | 🟨 | ⬜ | 🟥 | 🟨 | 🟥 | 🟥 |
| | | Tidal Lagoon | 🟨 6-8 | ⬜ | ⬜ | 🟨 | 🟨 | 🟨 | 🟨 |
| | | Tidal Stream | 🟩 8-9 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 |

## LCDP Technology Shortlisting: Justifications for Inclusion and Exclusion

LCDP technologies were prioritised for their relatively high TRLs (7-9), moderate to high dispatchability and scalability, and potential focus and impact of innovation spend to 2035 (see also Table 4). Shortlisted technologies were required to be green or amber for potential focus areas and impact of innovation, potential deliverability to 2030 and/or 2035 including current or planned policies, and TRL. There were some instances where specific LCDP technologies met these criteria and were otherwise rated quite favourably but were not prioritised. The rationale for decisions relating to marginal cases where technologies were close to making the shortlist, is set out below.

For the purposes of the LCDP assessment, the availability of large-scale hydrogen storage is assumed. This enables temporal separation between hydrogen production and electricity generation and allows hydrogen-based power to be treated as dispatchable. The feasibility and cost of hydrogen LDES technologies have been assessed in Sections 4.1 and 4.2.

Hydrogen fuel cells were not shortlisted because techno-economic assessments show that fuel cells remain capital-cost disadvantaged (£/kW) relative to reciprocating engines and gas turbines in pure distributed generation applications. However, in LDES configurations where hydrogen storage enables the decoupling of power and energy storage capacity, the system-level cost of storage (£/kWh) can become competitive with reciprocating engines and gas turbines despite higher individual component capex for fuel cells (Baringa, 2025; Ishimoto et al., 2024; Li et al., 2024; Mobility Foresights, 2025). Hydrogen fuel cells avoid the emission of $NO_X$ usually associated with hydrogen combustion (either gas turbines or reciprocating engines) but will require higher purity hydrogen fuel to run, especially for proton exchange membrane fuel cells (PEMFC).

Conventional biomass power generation was excluded from the shortlist because it is a mature technology and its innovation potential to 2030/35 is therefore quite limited. Any innovation potential lies in novel processes and/or fuel chains, for example in improving efficiency of combustion through advanced conversion methods, improvements to biomass supply chains and addressing lifecycle emissions to ensure carbon credentials for all biomass sources. In addition, biomass was rated as red for costs based on our assessment of levelised cost of energy (LCOE) using NESO's 2025 Future Energy Scenarios (FES) (see next section). BECCS and SMR are also high-cost options but have been retained in the shortlist. This is because BECCS offers negative emissions potential as well as electricity generation, and SMR costs in alternative sources to the FES are much lower, particularly for nth-of-a-kind (NOAK) plant (National Laboratory of the Rockies, 2024; Rigby, 2025), indicating significant technology cost reduction potential with the caveat that it is unlikely to be achieved before 2035.

## Further Explanation of LCDP Technology Cost Justifications

Because LCDP costs are highly sensitive to assumed load factors, the cost estimates reported in the REA reflect varying underlying assumptions. To ensure consistency and comparability across the shortlisted technologies for the RAG rating matrix, we recalculated their LCOE using harmonised inputs from NESO (2025) Future Energy Scenarios (FES) modelling assumptions, as this represents the latest comprehensive GB dataset available from an official source. Some additional information on load factors was taken from the UK Government's DESNZ (2026) electricity generation cost estimates. These inputs were cross-checked against additional sources and were found to be robust.

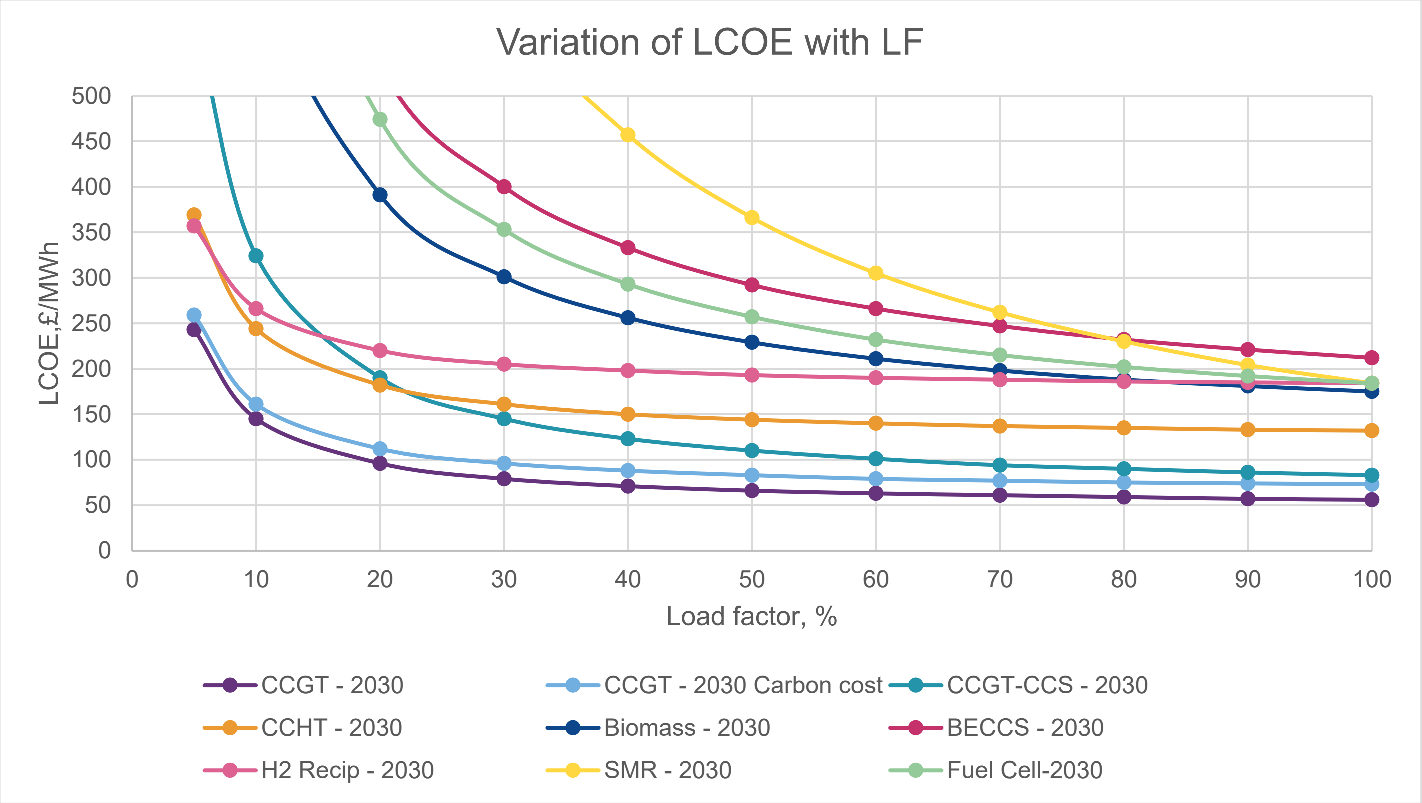
We assess LCDP technologies under two representative operating modes:

1. **Mid-merit operation:** plants that meet moderate daily demand fluctuations for balancing baseload and peak needs with moderate costs and flexibility.
2. **Peaking operation:** plants that can start quickly but are expensive to run, used only for short-duration system needs, and offering high flexibility at a premium.

The load-factor assumptions used across different sources vary significantly. NESO's FES (2025) data defines mid-merit generation at a 50% load factor and peaking generation at 10%, whereas DESNZ's 2026 electricity generation cost data applies load factors of 30% and 5% for the same categories. To avoid depending on any single convention, our approach is based not on the load factors themselves but on the average of the LCOE values calculated *across these ranges of load factors* when estimating LCDP LCOEs for 2030 and 2035 (see Figure 5 and Figure 6).

For mid-merit generation, we take the average of three LCOE estimates corresponding to load factors of 30% (Department for Energy Security & Net Zero, 2026), 40% and 50% (National Energy System Operator, 2025). For peaking generation, we use the average of the LCOE estimates calculated at 5% (DESNZ) and 10% (NESO). This ensures that our results reflect a balanced view across the differing assumptions used in existing datasets.

As a robustness check, we also present a sensitivity chart showing how these LCDP LCOE values vary across load factors from 10% to 100% (in 10-percentage-point increments) for 2030 and 2035 as illustrated in Figure 7 and Figure 8. For the RAG scoring, technologies are rated High cost where LCOE > £500/MWh under peaking operation, and High cost where LCOE > £235/MWh under mid-merit operation; technologies at or below these thresholds are rated Low–Medium (shown in Figure 5 and Figure 6). These thresholds follow directly from the LCOE distributions implied by the averaged load-factor assumptions. Based on these cost thresholds, the RAG score for CCGT-CCS, hydrogen



reciprocating engines, and hydrogen gas turbines is Amber while that for Biomass, BECCS, SOFC, PEM fuel cell and SMR is Red.

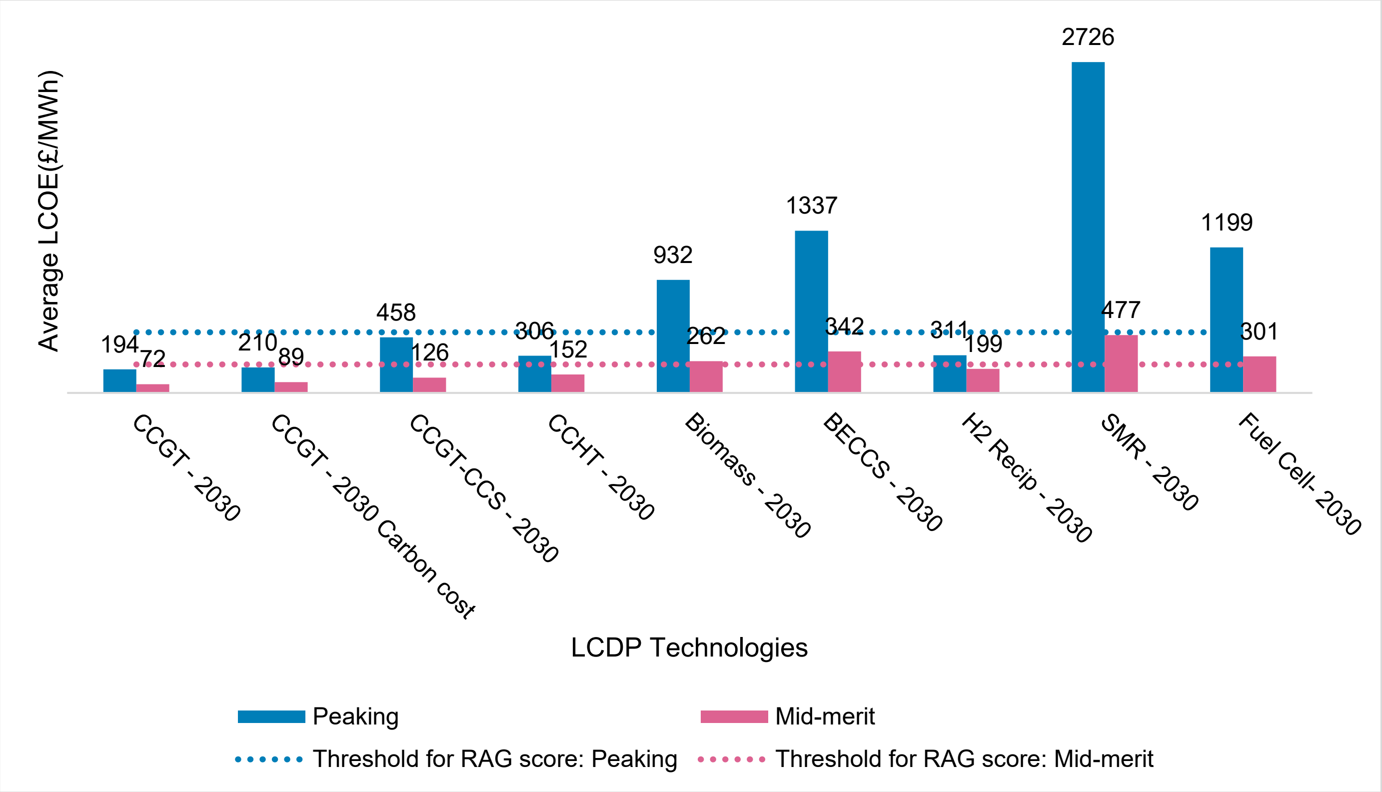


**Figure 5: Average levelised cost of LCDP technologies based on plant operating at average peaking and mid-merit plant load factors for 2030**

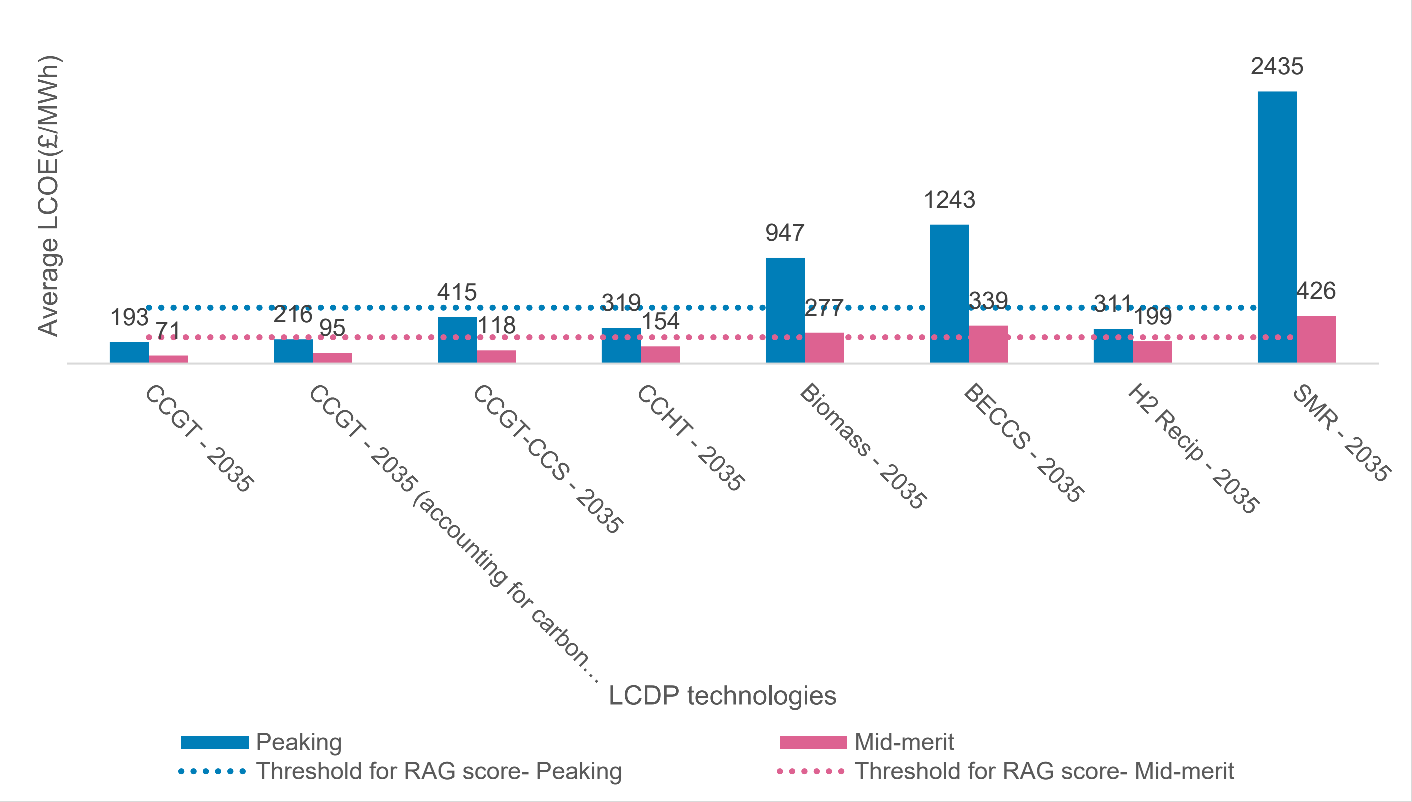


**Figure 6: Average levelised cost of LCDP technologies based on plant operating at average peaking and mid-merit plant load factor for 2035**

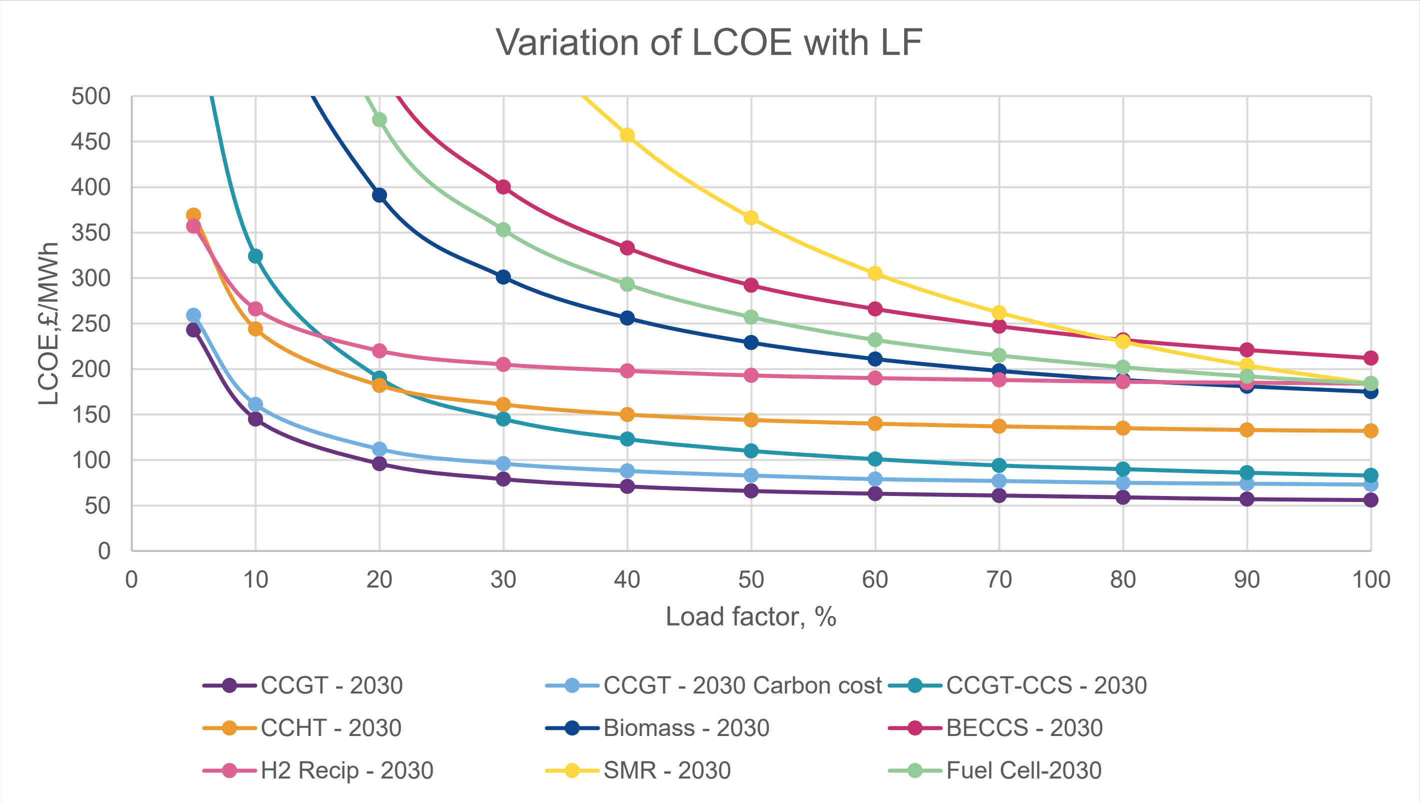


**Figure 7: Variation of levelised cost of LCDP technologies with load factors for 2030**

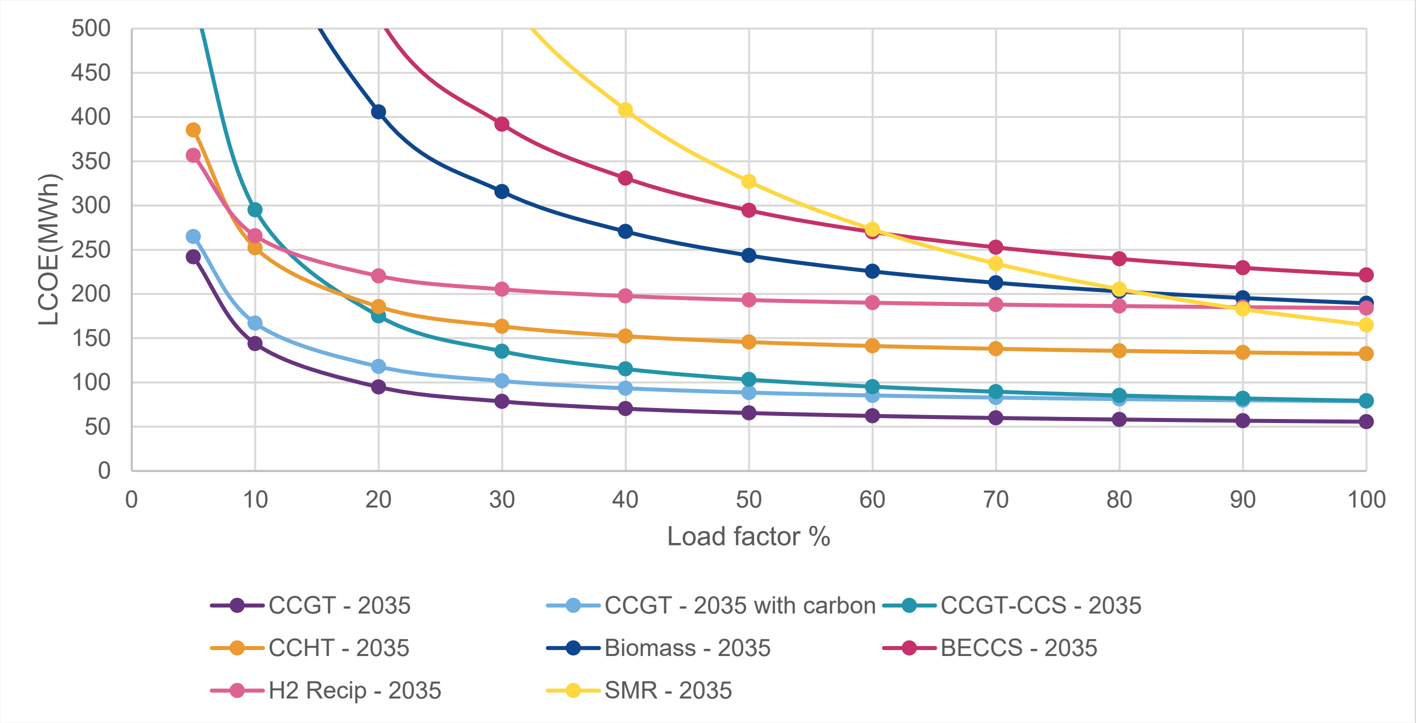


**Figure 8: Variation of levelised cost of LCDP technologies with load factors for 2035**

# 5. Shortlist Technologies

This section evaluates the relative merits and constraints of technologies shortlisted through the RAG analysis approach. These technologies are presented in Table 4 alongside the rationale for shortlisting them. They show highest potential for deployment by 2030-2035 over the other longlist technologies, as explained in the previous section. The text below elaborates on some of the key considerations that informed their shortlisting. More complete summaries describing each of these technologies, along with detailed tables and expert elicitation evidence, are presented in the Appendix in Section 10.

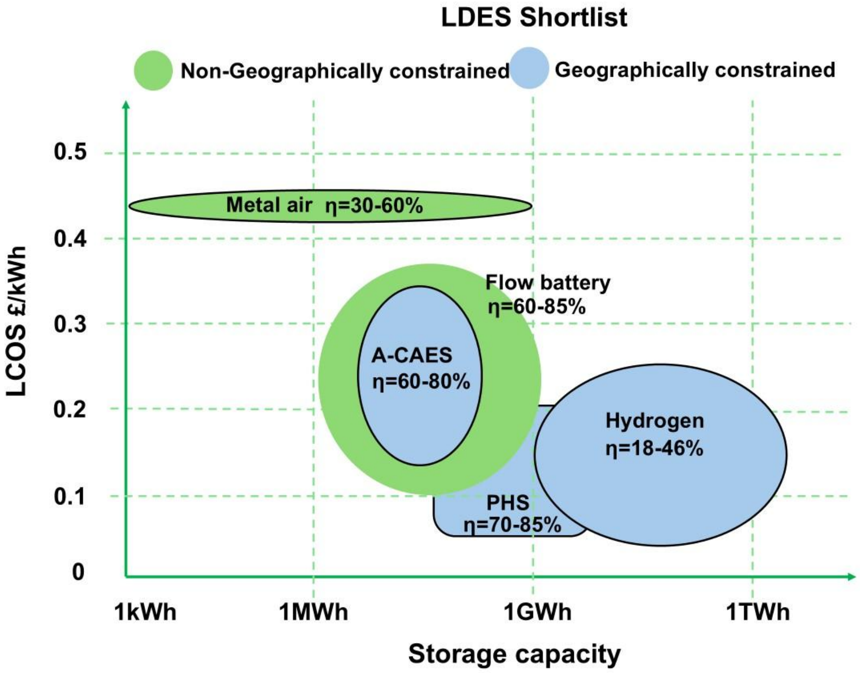
**Table 4: Shortlist technologies rationale**

| LDES Technology | | Rationale |
|---|---|---|
| $H_2$ | Salt cavern storage (Low cycle) | High TRL (9), Long storage/discharge durations, strong UK competitiveness |
| Electrochemical | Metal-air | Low cost, strong scalability potential, strong UK competitiveness |
| | Flow batteries (Vanadium/ Zinc bromine) | Strong scalability potential, relatively high TRL (7-8), relatively low cost |
| Mechanical | A-CAES | High TRL (8), intermediate duration, relatively low cost, strong UK competitiveness |
| | Pumped hydro energy storage | High TRL (9), intermediate duration, relatively low cost, strong UK competitiveness |

| LCDP Technology | | Rationale |
|---|---|---|
| $H_2$ | Reciprocating engines | High TRL (9), high dispatchability |
| | Gas turbines | Relatively high TRL (7-9) (depending on natural gas/hydrogen blend ratio), high scalability |
| CCS | CCGT | High TRL (8), high scalability for core CCGT technology but dependant on available $CO_2$ storage market, strong UK competitiveness especially with vast carbon storage in North Sea |
| | BECCS | High TRL (8-9), strong UK competitiveness especially with vast carbon storage in North Sea |
| Nuclear | SMR Nuclear (Gen III) | Relatively high TRL (7-8), scalability, strong UK competitiveness (Rolls Royce – UK led design) |

## 5.1. Long Duration Electricity Storage Shortlist Technologies

Figure 9 represents the differences between the shortlisted LDES technologies in terms of levelised cost of storage and energy storage capacity. It demonstrates the advantages of hydrogen as an LDES technology due to its higher energy storage capacity and lower costs. Figure 9 assumes that hydrogen salt cavern storage and A-CAES require underground storage, as it's typical for these technologies, and they are therefore geographically constrained. There is, for example, up to 2,150 TWh capacity for hydrogen storage from three 'onshore' basins in the UK (Cheshire, East Yorkshire and Wessex) – see Appendix, Table 21. In contrast, electrochemical storage technologies such as



metal-air and flow batteries are less geographically constrained, but as Figure 9 shows they can be more expensive and metal-air batteries have the lowest median energy storage capacity (although this can extend up to 1 GWh).

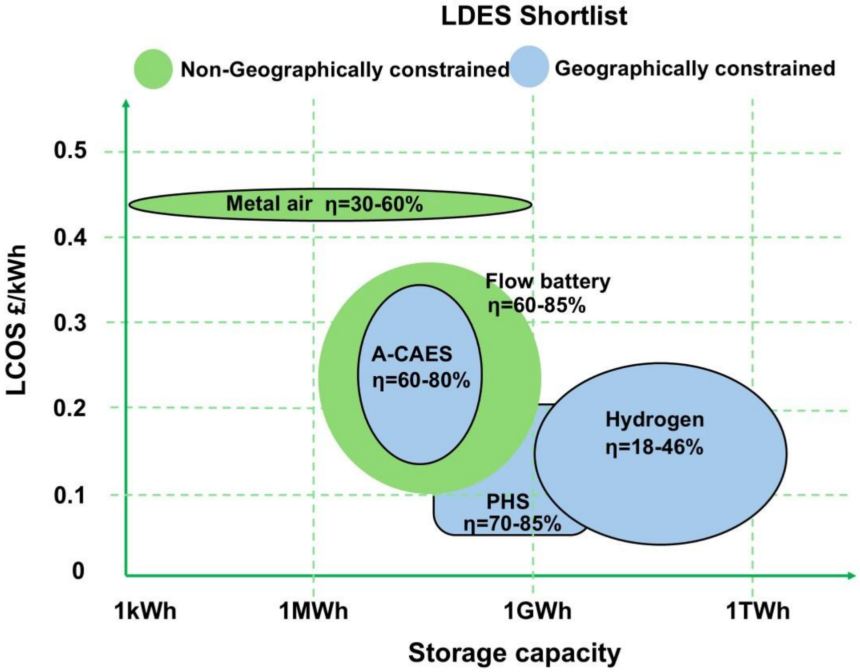


**Figure 9: LDES technologies comparison based on 2025 costs**[xiv]

## Chemical Storage Technology

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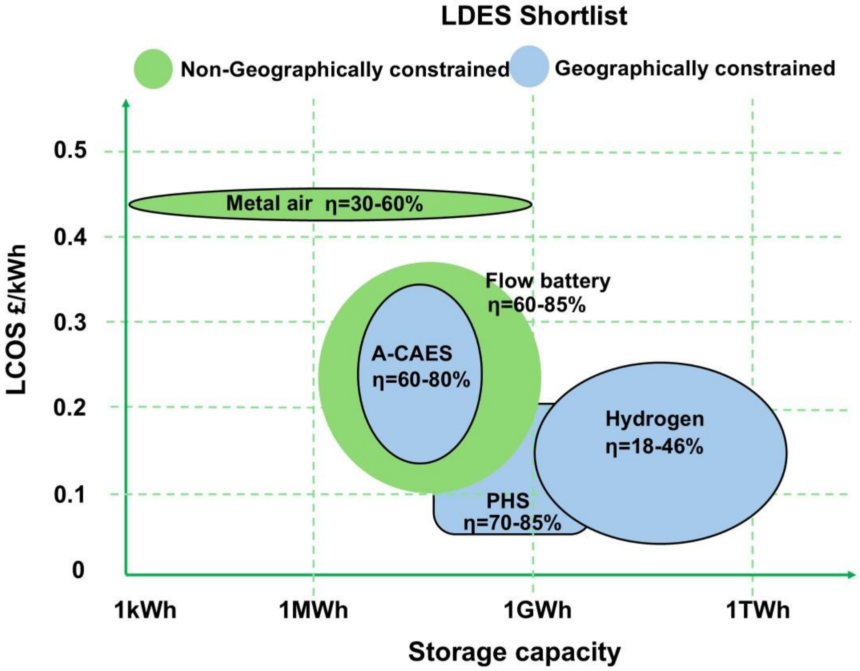
[xiv] η in the Figure 9 represents round trip efficiency.

Hydrogen storage in salt caverns is of interest due to the high state of technology readiness for low cycle storage (TRL 9, cycling up to 10 times a year), low LCOS (Figure 9) and the very long storage durations that technology developers target. Other technology options struggle with such long durations and if very long durations are a priority, then hydrogen storage options should be included in R&I funding strategies. Hydrogen provides other benefits in terms of its use as LCDP, as the availability of external hydrogen supplies can increase its overall usefulness as a dispatchable resource for the power system.



The construction of salt caverns is well established and low-cycle salt caverns are at TRL 9, with individual components such as electrolysers, compressors and fuel cells at a similarly high TRL. Several newer technologies such as Proton Exchange Membrane (PEM) electrolysers and fuel cells are at advanced levels of technological readiness, specifically -TRL 9 and TRLs 8-9 respectively (Cigolotti & Genovese, 2021; IEA, 2025). Other more novel technologies such as reversible electrolysers / fuel cells and fast cycle salt caverns (the latter offering weekly-daily cycling at TRLs 5-6) need funding to progress and to impact upfront installation and operational costs. Producing sufficient volumes of hydrogen for LDES requires substantial additional electrolyser and fuel cell capacity. There will therefore be challenges with procuring electrolysers at scale as there are currently very few UK manufacturers producing large volumes. Alkaline electrolysers are currently the dominant technology internationally, making up ~75% of global manufacturing capacity, and PEM making up the rest. In 2022, China had a manufacturing capacity of 58% of all alkaline electrolysers produced worldwide. ITM Power (focused on PEM technologies) is the biggest manufacturer in the UK by far (~1.5 GW/Y). The UK is targeting 5 GW of green hydrogen production capacity by 2030. This will require a ramp up in electrolyser manufacturing capacity and capabilities in the UK. In Scotland the NZTC (Net Zero Technology Centre) allocated £0.5 million to three innovative projects developing electrolysers to drive investment, supply chains and establish a strong export market.

The UK should continue to drive innovation and help investment in ramping up production capacity. Hydrogen salt cavern storage benefits from UK competitiveness given geological advantages - good quality salt strata at varying depths (Environmental Agency, 2025), existing expertise in subsurface engineering and storage and a range of transferable skills from the natural gas system. Innovation opportunities in hydrogen storage include materials science to understand the replacement frequency for components (embrittlement) and improve material fatigue, integrity and containment. There is also a need for innovation to develop new tools and methods to measure the impact of cycling rates on salt cavern behaviour and the surrounding subsurface environment, as well as to improve the performance, durability and cost of the surface equipment such as compressors. Based on expert views and evidence in the literature it is clear that technology developers see a need for innovation hub type facilities to coordinate development across storage and dispatchable aspects of hydrogen. It may take 5 to 10 years to develop a hydrogen salt cavern (Armitage, 2025; Talukdar et al., 2024), framing the challenge for an innovation programme emerging from R&D MAP with a 5-year funding timeline and aspiration for impact on the grid within 9 years.

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The UK is targeting 5GW of green hydrogen production capacity by 2030. This will require a ramp up in electrolyser manufacturing capacity and capabilities in the UK. In Scotland the NZTC (Net Zero Technology Centre) allocated £0.5 million to three innovative projects developing electrolysers to drive investment, supply chains and establish a strong export market. The UK should continue to drive innovation and help investment in ramping up production capacity. Hydrogen salt cavern storage benefits from UK competitiveness given geological advantages - good quality salt strata at varying depths (Environmental Agency, 2025) (Environmental Agency, 2025), existing expertise in subsurface engineering and storage and a range of transferable skills from the natural gas system. Innovation opportunities in hydrogen storage include materials science to understand the replacement frequency for components (embrittlement) and improve material fatigue, integrity and containment. There is also a need for innovation to develop new tools and methods to measure the impact of cycling rates on salt cavern behaviour and the surrounding subsurface environment, as well as to improve the performance, durability and cost of the surface equipment such as compressors. Based on expert views and evidence in the literature it is clear that technology developers see a need for innovation hub type facilities to coordinate development across storage and dispatchable aspects of hydrogen. It may take 5 to 10 years to develop a hydrogen salt cavern (Armitage, 2025; Talukdar et al., 2024) (Armitage, 2025; Talukdar et al., 2024), framing the challenge for an innovation programme with an aspiration for impact on the grid by 2030 or 2035.

## Mechanical Storage Technologies

Mechanical storage options, such as liquid air and adiabatic compressed air energy storage could be commercial on a 2035 timescale, though experts in our workshops did not all agree that this timescale is possible. Adiabatic CAES (TRL 8) represents the most advanced low carbon CAES variant and is therefore the most plausible candidate for deployment by ~2035. In comparison, isothermal CAES is at TRLs 5-7 (prototype-level deployments); diabatic CAES is mature (TRL 9) but its practical scalability is limited by the policy need to replace fossil fuel combustion with carbon-free fuels. The UK has research leadership in CAES through university expertise and a range of transferable skills given expertise in thermal power plants, oil and gas sector and automotive and manufacturing knowhow. There are also geographic advantages, given appropriate geology close to critical energy infrastructure.

R&I opportunities exist in thermal storage materials and synchronous machine control to ensure reliability of the storage assets. Potential investment requirements gleaned from expert elicitation range from tens of millions of pounds for a system demonstrator, government investment of £1-2m to help leverage private investment for a £50-60m project, and £3m for borehole testing. Incubator type facilities were mentioned as valuable to the CAES innovation mission, with proximity to suitable geology relevant. Synchronous control could be tested at an innovation centre such as the Strathclyde Power Networks Development Centre (PNDC).

High density pumped hydro storage uses high density fluid, instead of water to improve space efficiency, and has the potential to be deployed over elevations 2.5 times smaller than current pumped hydro projects, potentially opening up new sites. The UK possesses both the expertise and the geography to take advantage of high density pumped hydro technologies. The innovation barriers highlighted in expert elicitation focussed on non-technical factors, such as policy or funding gaps and supply chain immaturity. Government backed performance warranties were highlighted as a potential opportunity to derisk investment, and could be an appropriate option in general for the shortlisted LDES technologies. Potential innovation in the novel location of pumped hydro projects is also noted in the literature, such as underground PHS.

## Electrochemical Storage Technologies

Electrochemical options have also been shortlisted, including metal-ion, metal-air and flow battery technologies. Although many electrochemical systems are not yet bankable at 100 hours+ discharge duration on a single-asset basis, they remain in scope because materials advances (electrolytes, electrodes and broader materials science) are extending feasible durations, and system-level deployment strategies can increase the effective duration delivered through modular build-out and coordinated operation. Technology developers working on electrochemical storage technologies are actively targeting such 100 hours+ deployment strategies, but they are currently at lower, pre-commercialisation TRLs, typically around TRL 3–5, reflecting early-stage materials and system-level development (Giacobone, 2026; Maisch, 2026), typically around TRL 3–5, reflecting early-stage materials and system-level development (Giacobone, 2026; Maisch, 2026).

Flow battery chemistries are diverse due to different electrolyte and electrode combinations. Vanadium and zinc–bromine flow batteries have been shortlisted because they are comparatively more mature (TRLs 7-8) and have demonstrated commercial or near-commercial deployment. Other chemistries, such as iron-based (e.g. Fe/Fe or Fe–Cr), organic flow batteries, and polysulfide–bromide systems, are less mature due to challenges including lower stability, electrolyte degradation, limited cycle life, or lack of large-scale demonstration, and were therefore excluded from the shortlist.

Flow batteries store electricity in liquid electrolytes, decoupling energy capacity from power rating; in principle this makes them easier to scale than conventional batteries and enables longer duration and higher capacity deployments (e.g., a 100MW/400MWh flow battery in Dalian, China). However, deliverability at multi-day LDES scale remains constrained as low volumetric energy density (e.g. compared to metal-air batteries or CAES) requires large electrolyte volumes and a more complex balance-of-plant/system design. Together these increase land footprint and upfront CAPEX, while key technical and supply-chain challenges (e.g., materials/components and electrolyte availability) remain. Many flow battery innovators target durations of <24hrs, though experts indicate that longer durations are possible and could be encouraged through appropriate incentives. The UK has a unique skills mix and research leadership in flow battery chemistries, leading to a collaborative R&D environment and at least several UK-based innovators in the space. Invinity Energy Systems is the primary UK-based flow battery manufacturer, with facilities in Scotland producing vanadium redox flow batteries. Invinity is scaling up its UK annual manufacturing capacity to over 500 MWh, with projects including a 20.7 MWh system in South East England and a 5 MWh system at the Energy Superhub Oxford. Other companies include StorTera, who are developing SLiQ (single liquid flow battery - a cutting-edge polysulphide battery technology, designed and engineered in the UK) technology with support from the UK government for longer duration, high-efficiency storage.

Potential innovation opportunities in flow batteries include investment in materials improvement, solvent safety and shared supply chain facilities, helping to drive towards commercial scale. Although flow battery CAPEX is currently higher than, for instance, Li-ion systems, there is a plausible pathway to reduce costs due to the relative simplicity and recyclability of the architecture; the US “Storage Shot” report highlights innovation in novel active electrolytes and scalable manufacturing as key levers that could drive sharp cost reductions by 2030 (U.S. Department of Energy, 2024a)(U.S. Department of Energy, 2024a).

Metal-air batteries, specifically Zinc-air and Iron-air technologies, are also shortlisted. Iron-air is near commercial deployment, while other metal-air batteries may lag slightly behind. The UK has a competitive advantage with established expertise, manufacturing synergies with metal-ion technologies and key support from The Faraday Institution’s Ultrastore programme. Innovation opportunities include novel chemistry development, scalable manufacturing development and pilot funding.

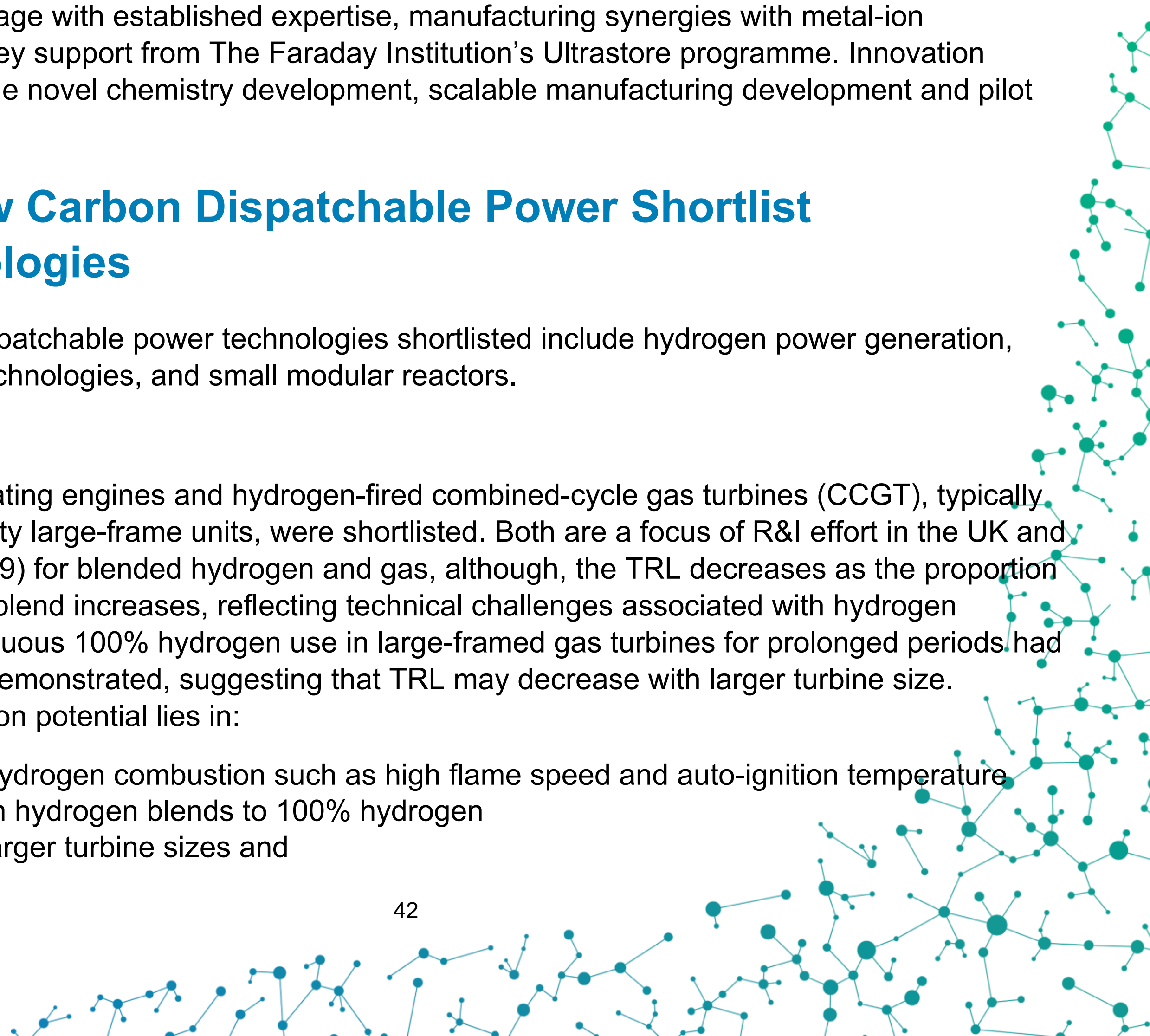
## 5.2. Low Carbon Dispatchable Power Shortlist Technologies

The low carbon dispatchable power technologies shortlisted include hydrogen power generation, CCS associated technologies, and small modular reactors.

### Hydrogen

Hydrogen reciprocating engines and hydrogen-fired combined-cycle gas turbines (CCGT), typically based on heavy-duty large-frame units, were shortlisted. Both are a focus of R&I effort in the UK and have high TRLs (7-9) for blended hydrogen and gas, although, the TRL decreases as the proportion of hydrogen in the blend increases, reflecting technical challenges associated with hydrogen combustion. Continuous 100% hydrogen use in large-framed gas turbines for prolonged periods had also not yet been demonstrated, suggesting that TRL may decrease with larger turbine size. Therefore, innovation potential lies in:

- Managing hydrogen combustion such as high flame speed and auto-ignition temperature
- Moving from hydrogen blends to 100% hydrogen
- Moving to larger turbine sizes and



- Understanding integration into UK electricity networks and hydrogen infrastructure (Onorati et al., 2022)(Onorati et al., 2022).

Hydrogen safety standards, avoiding leakage and managing ventilation is also key (Giacomazzi et al., 2023)(Giacomazzi et al., 2023).

### Carbon Capture and Storage (CCS) enabled technologies

Two CCS associated technologies were shortlisted: CCGT-CCS, and BECCS. The core technologies without CCS are commercial at significant scale. The UK has existing oil and gas expertise and an R&D capability, which has been successfully demonstrated at small scale. The UK also has geological potential through existing storage capacity. Key challenges remain in the integration of CCS and dispatchable operation, which could be a priority for innovation support. Innovation opportunities include improving capture rates, particularly under ramp up/ramp down and CCS solvent development to reduce operational challenges such as high energy requirements, solvent degradation and equipment corrosion (Loachamin et al., 2024)(Loachamin et al., 2024).

### Nuclear

SMRs provide scalable, dispatchable nuclear power with lower scheduling risks and financing costs than conventional reactors. Their modular design, smaller size, and passive safety features enable reduced upfront capital, easier grid integration, and operational flexibility. Challenges remain, including high first-of-a-kind costs, uncertain MWh prices, regulatory and licensing hurdles (initially built for large conventional nuclear reactors and not SMR), long-term operation and maintenance, supply chain resilience, decommissioning strategies, and environmental considerations such as spent fuel, land use, and cooling water. Limited transparency in costs and performance further underscores the need for international collaboration, standardised data, and knowledge-sharing to realise SMRs' full potential.

## 5.3. Limitations

The nature of innovation funding and its impact on technological progress is complex and hard to forecast (see Section 8). Where evidence or expert statements are available on the required investment to reach specific innovation goals, these findings should be treated with caution.

TRLs discussed in this report are often uncertain given that systems of technologies may have differing TRLs across system components. TRLs have been differentiated for systems where possible. Where disagreements on technology or commercial readiness are found in the literature and expert views, ranges are shown and judgement has been used.

Much of the literature utilises some form of levelised cost calculation where costs are reported. These cost estimates are highly dependent on load factor/utilisation.

For LCDP technologies, this study focuses on the technology alone. The availability of fuel to supply that technology is key to its ability to provide dispatchable power. While not covered in the scope of this study, fuel supply chain security including transport and the storage supply chain for hydrogen and the transport and capture component of CCGT-CCS and BECCS will be a key factor in the reliable operation of LCDP technologies.

# 6. Whole System Energy Modelling – Evidence Review and New Modelling

This modelling work is split into two complementary areas, designed to be rapid approaches to deliver valuable insights to support informed decision making:

- **A rapid evidence assessment** of existing, recent, whole systems modelling
- **Bespoke modelling** which leverages the existing investment of the Catapult into their ongoing Innovating to Net Zero 2026 analysis

When making decisions, modelling is not intended to provide answers, but to provide evidence and insights that inform decision making. Every model is both wrong, to differing extents, and insightful if we understand it's purpose, design and assumptions. By combining an understanding of the trends across the published evidence and bespoke modelling to fill in some of the answered questions, this modelling seeks to provide additive evidence to support decision making on the need for, and value of, innovation on a specific range of technologies.

## 6.1. Review of Existing Modelling Evidence

This review was an independent, repeatable assessment of the role and need for LDES and LCDP in the UK energy system between 2030 and 2035. We drew on 22 recent modelling studies, prioritised from over 140 sources using the following criteria:

- Timeframe: published between 2020-2025
- Geography: UK or GB-focused studies only
- Language: English
- Types of literature: peer reviewed academic papers, grey literature and policy documents
- Subject: studies that model the UK (or GB) whole energy system or focus specifically on LDES or LCDP

Our analysis of studies explored how LDES and LCDP technologies are represented, what roles they are expected to play, and why deployment levels vary. The key findings of this exercise are presented below:

- **There is insufficient literature that differentiated enough between technologies in their reporting to support prioritised investment decisions by technology alone**, likely due to simplifications for tractability and ease of reporting. Table 5 summarises both the variability of published technology capacities, as well as the different ways that published documents report on them by, for example, using generic proxy technologies for LDES and LCDP.
- **Deployment ranges for LDES and LCDP technologies in 2030/2035 vary significantly**. LDES is estimated at 1.5-52 GW (0.19-66.4 TWh), while LCDP technologies range from 13–22 GW. Deployment of hydrogen storage, a subset of LDES, is more frequently reported than LDES, with deployment estimates ranging from 2–24 GW in power capacity and 2–55.3TWh in energy capacity.
- **Studies that focus on a subset of technologies tend to show higher deployment levels than whole-system models**. This typically reflects narrower scope, fewer competing technologies, and less constraint from system-wide optimisation. In contrast, whole-system models balance multiple priorities and often apply spatial or policy constraints, which can reduce projected deployment.

- **There is some evidence that including peak events increases LDES needs, particularly for hydrogen storage**, but this is not consistent: Some studies explicitly model extreme events (such as wind lulls or high demand periods). Others rely on historical weather data or apply system-level constraints.
- **More aggressive decarbonisation targets (e.g. clean power by 2030 or 2035) tend to show earlier and more substantial deployment of LDES and LCDP**. In contrast, studies focused on 2050 decarbonisation pathways often delay investment, reflecting assumptions about technology readiness and cost reductions.
- **Modelling studies that include markets, policy and technology readiness levels show limited LDES deployment by 2030**. Most models focus on least-cost system design and do not account for whether technologies can be delivered in practice. However, many studies were published before the UK government's announcement of a cap-and-floor scheme for LDES, which may have provided the policy certainty needed to unlock investment in some longer duration storage technologies.

**Table 5: Summary of technologies deployed in 2030/2035/2050 as reported in prioritised studies (Brackets show how many studies apply to each entry)**

| Technology reported in studies[xv] | Deployment in 2030 | Deployment in 2035 | Deployment in 2050 |
|---|---|---|---|
| **LDES (specific technologies not reported)** | 3-9 GW (2 studies) | 0-12 GW (2 studies) | 2.5-20 GW (2 studies) |
| **LCDP (specific technologies not reported)** | 0-1.4 GW (1 study) | 13-22 GW (1 study) | 48.3-55.2 GW (1 study) |
| **Lithium-ion batteries** | 1.6 GW<br>1.6 GWh (1 study) | 32-34 GW<br>74 GWh (1 study) | 2.4 GW<br>3.2 GWh (1 study) |
| **Iron-air batteries** | 22.8 GW (1 study) | | |
| **PHS** | 13.8 GW<br>193 GWh (1 study) | 6 GW<br>220 GWh (1 study) | 20.7 GW<br>246 GWh (1 study) |
| **CAES** | 1 MWh-11.1 TWh (2 studies) | 13-22 GW<br>135 GWh (1 study) | 19.9 GW<br>1.3 TWh (1 study) |
| **Hydrogen storage** | 5 MW-6 GW<br>150 MWh-55.3 TWh (5 studies) | 4-24 GW<br>2.1-11.5 TWh (3 studies) | 5 MW-90 GW<br>650 MWh-100 TWh (6 studies) |
| **Unabated gas** | | 50 GW (1 study) | 50 GW (1 study) |
| **Gas CCS** | | 4-9 GW<br>30 TWh (2 studies) | 17.5 GW (1 study) |
| **Hydrogen turbines** | | 5-20 GW<br>20 TWh (3 studies) | 9-45 GW (2 studies) |

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[xv] Technologies not listed in this table were not explicitly modelled in any of the reviewed studies.

## 6.2. Peak Gaps

Using the Catapult's whole system-based ESME and ESME Flex models, building on the Catapult's self-funded ITNZ2026 report, this modelling seeks to provide new insights compared to what has been delivered in existing modelling studies to support decision making within the ItAA project.

We defined four 'peak gaps' that drive the value of low carbon dispatchable power and long duration electricity storage.

1. **Peak Power Gap:** The single highest value of Net Excess Demand (NED) across all hours. It answers the question, "Is there enough non-renewables *power* capacity?"
2. **Peak Daily Gap:** The maximum NED averaged over each day to check if there's enough *between-day balancing* capacity.
3. **Peak Energy Gap:** The maximum NED averaged over any 6-hour period. It checks whether there's enough *within-day balancing* capacity.
4. **Peak Duration Gap (Dunkelflaute):** The maximum accumulated NED over long sustained periods (typically multi-week) capturing the total energy deficit during extended spells of low renewables. Within this ItAA project, this gap is the focus for LDES technologies.

We analysed 44 years of historical demand and wind/PV availability factor data alongside the capacities of renewable energy resources and electricity demands from ESME for our base-case scenario to understand how often the different 'peak gaps'[xvi] might be expected to occur in a typical year and how big they could be (Table 6 and Figure 10). Figure 10 shows the frequency at which each gap appears in an average year. Gap size shown as a proportion of the maximum gap in Table 6. This helps us understand how many times a year different technologies might be used and therefore identify how we might support commercial deployment to meet system need.

**Table 6: Characteristics and frequencies of the four 'peak gaps'**

| Gap | # per year | Historical Peak Gap Size | When did it happen? |
|---|---|---|---|
| Power Gap | 365 | 66 GW | 26/01/1991 |
| Energy Gap | 611 | 379 MWh | 26/01/1991 |
| Daily Gap | 365 | 55 GW | 19/01/2001 |
| Duration Gap | 0.12 | 14.7 TWh | 11/12/1989 |

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[xvi] For further definition of the different peak gaps see here: https://es.catapult.org.uk/insight/mind-the-peak-gap/

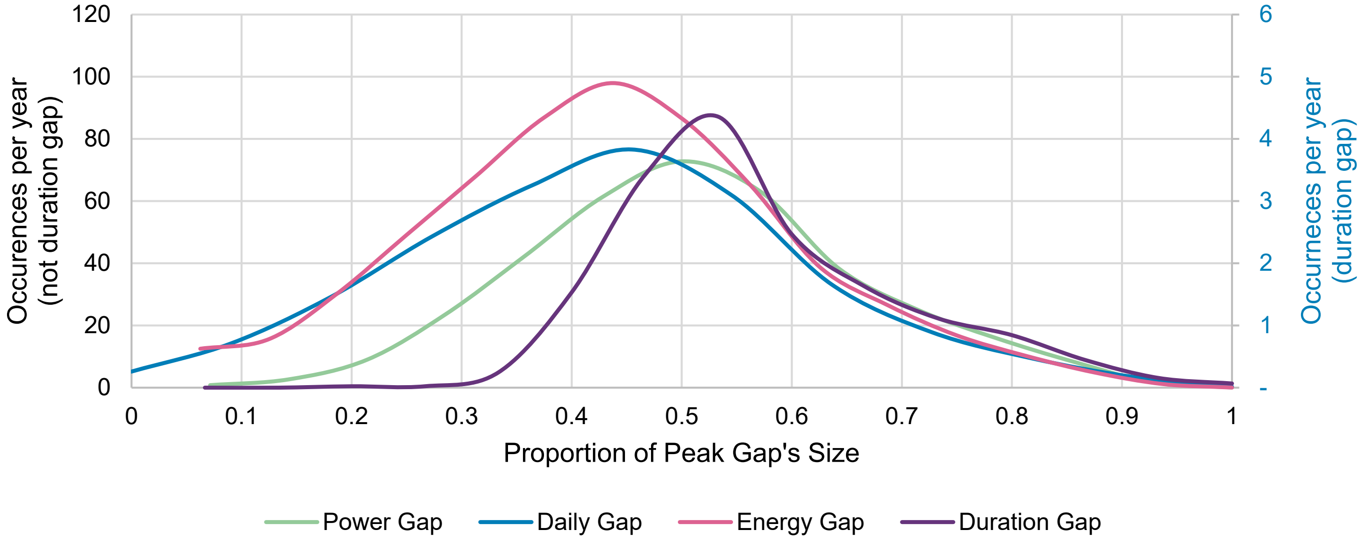

**Figure 10: Frequency and magnitude of all gaps**

In agreement with UKRI, a shortlisted a set of technologies to focus on within this modelling was chosen, based on pre-existing knowledge and judgement of potential suitability for providing over 100-hour duration storage and low carbon dispatchable power[xvii]. Each shortlisted technology was then modelled in the ESME suite in 2035 across four scenarios developed for ITNZ2026 – each meets Net Zero, three meet CP2030, two of which are aligned with NESO CP2030 scenarios:

- **Higher Low Carbon Dispatch** - meets the CP2030 target with high levels of dispatchable power
- **High Renewables** - meets CP2030 with rapid deployment of renewable generation and batteries - based on NESO CP2030 "New Dispatch" scenario
- **Further Offshore Wind** - Similar renewable deployment to the High Renewables scenario but additional offshore wind and batteries - based on NESO CP2030 "Further Flex and Renewables" scenario.
- **Business as Usual** - CP2030 is not met so slower decarbonisation based on the standard ESME optimisation to meet legislated carbon budgets

Least cost systems need a diversity of technologies, for example in a duration gap, batteries contribute to smooth demand within individual days but, due to losses, are net consumer of energy over the whole of the gap. Additional dispatchable power is needed to meet 2-week aggregate demand. This is shown in Table 7 which shows that the storage technologies of interest have consumed up to 179,000 MWh over the whole two weeks of the peak duration gap than they deliver.

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[xvii] Note that these are not the same as those shortlisted as an outcome of this report because we were running the modelling in parallel and therefore needed to agree a list to focus on prior to findings of the final report being delivered. This is why we are not showing any results here from, for example, pumped hydro storage.

**Table 7: Max/min contributions of technologies to 'peak gaps' within a day across the four scenarios modelled**

| | Peak power gap | | Peak daily gap | | Peak energy gap | | Peak duration gap | |
|---|---|---|---|---|---|---|---|---|
| **Tech** | Max Power (MW) | Min Power (MW) | Max Power (MW) | Min Power (MW) | Max Energy Delivered (MWh) | Min Energy Delivered (MWh) | Max Net Energy Delivered over 2 weeks (MWh) | Min Net Energy Delivered over 2 weeks (MWh) |
| **Li-ion** | 27,400 | 10,000 | 15,000 | 5,700 | 110,000 | 40,000 | -119,000 | -55,000 |
| **CAES** | 1,000 | 0 | 940 | 0 | 250 | 0 | 0 | 0 |
| **Molten Salt** | 8,700 | 0 | 4,100 | 0 | 800 | 0 | -179,000 | 0 |
| **Pumped TES** | 1,600 | 0 | 1,700 | 0 | 6,700 | 0 | 0 | 0 |
| **Biomass CCS** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **CCGT CCS** | 3,700 | 1,000 | 3,700 | 1,000 | 88,000 | 23,000 | 1,235,000 | 483,000 |
| **H2 Turbine** | 5,500 | 0 | 4,100 | 0 | 0 | 0 | 310 | |
| **IGCC CCS*** | 950 | 0 | 55 | 0 | 0 | 0 | 0 | 0 |
| **SNG CCS**** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Waste Gasification CCS** | 120 | 120 | 120 | 120 | 2,900 | 2,900 | 40,000 | 40,000 |

*Integrated gasification biomass with CCS **Biomass gasification with CCS

## 6.3. LDES Use

For the LDES technologies that we had shortlisted to focus on and that were subsequently dispatched in the modelled scenarios in Table 7, we then sought to understand how often different technologies might be deployed at different scales. For each energy gap we combined the frequency of energy gap size with the energy delivered by each technology in the simulations. This gives an indication of how often each technology might be required at different scales.

**Interpretation and notes:**

- The simulations are for the maximum size of each energy gap. These are the most extreme example in terms of energy and are situated at the far-right hand side of the distributions.
- To illustrate the relationship between size of peak and potential utilisation rate of a technology, the analysis assumes that the technologies that are used to meet a gap of the peak size will be used in the same proportion as the gap size decreases. This is unlikely to be reflective of reality, with technologies more likely to operate with some form of merit order for services that also account for their carbon emissions.
- The absolute values of daily delivered energy shown on the Y-axes are dependent on the modelling assumptions and must be considered as an indication of relative magnitude rather than as precise predictions.
- LCDP technologies tend to be run continuously during a peak gap whereas LDES technologies may be charged and discharged within the gap (particularly true for the duration gap). The X-axis on the graphs (

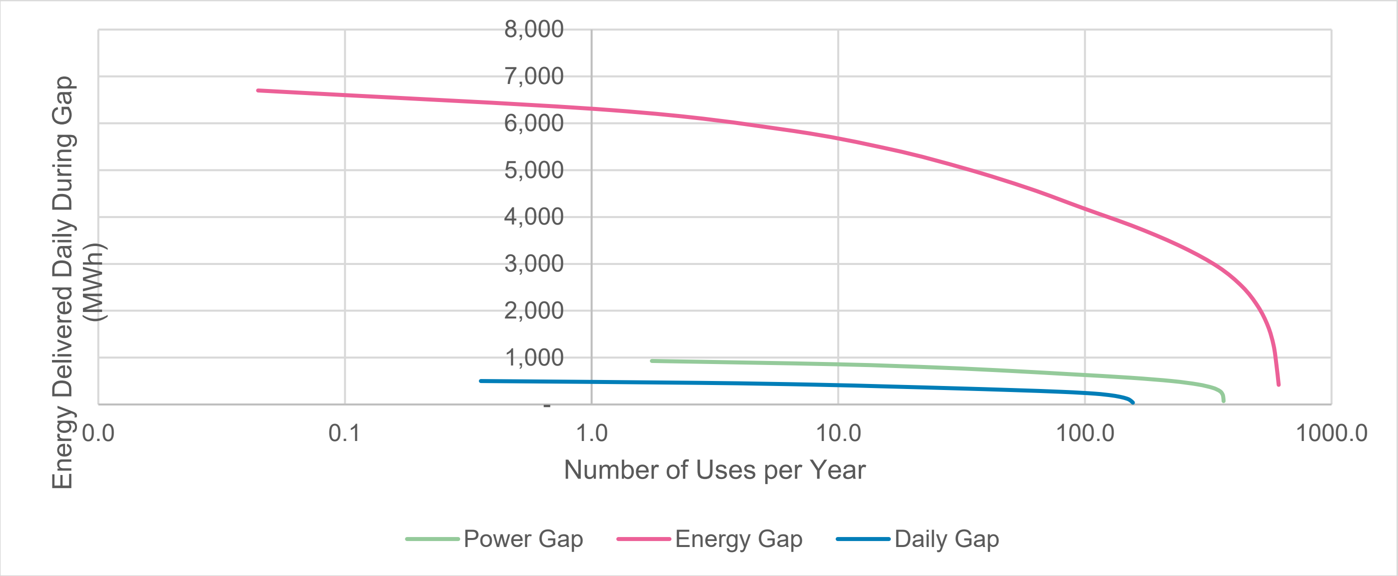


Figure 11 and Figure 12) is therefore subtly different between the two technology groups.

- The following graphs (

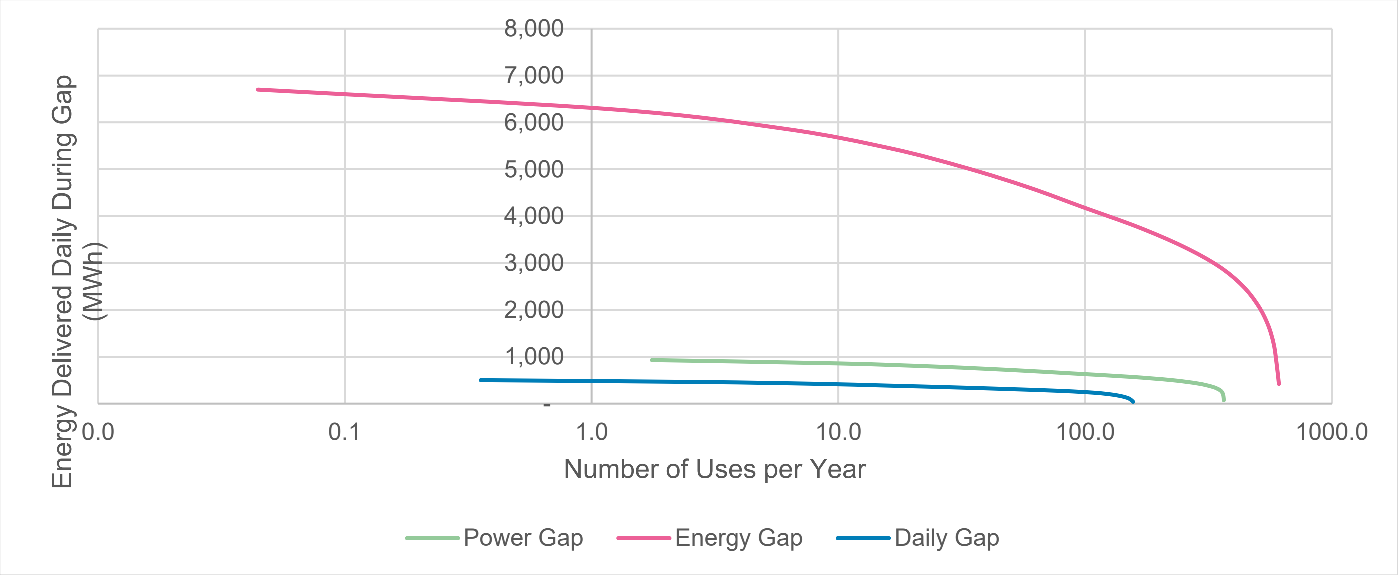
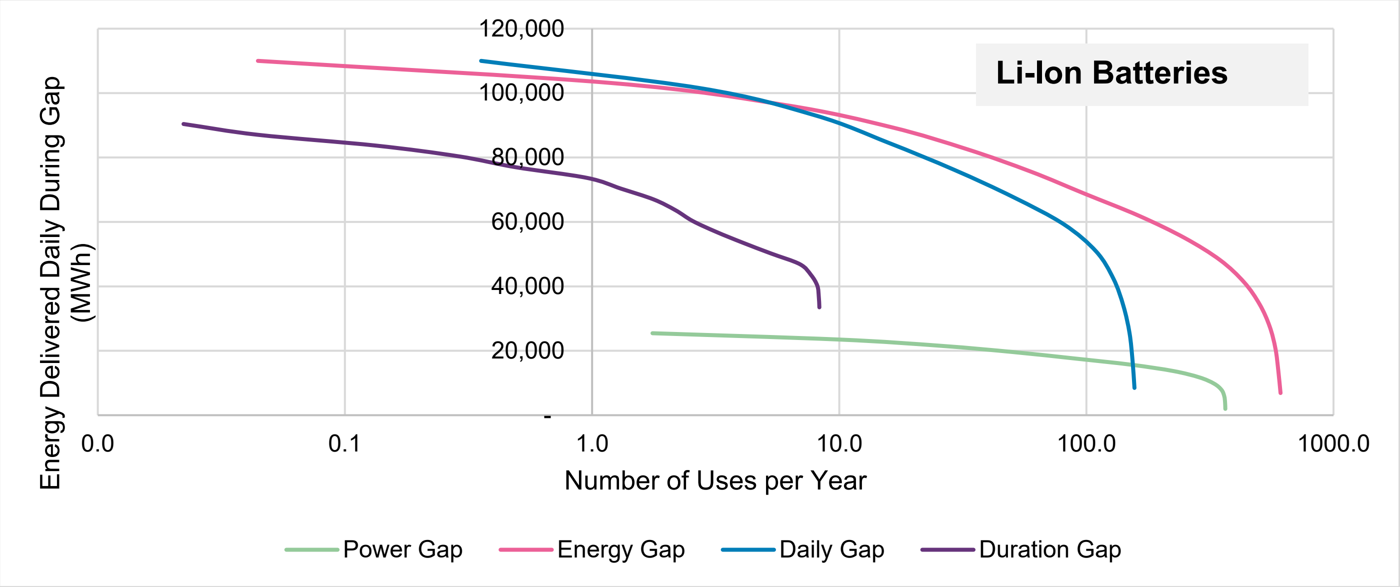
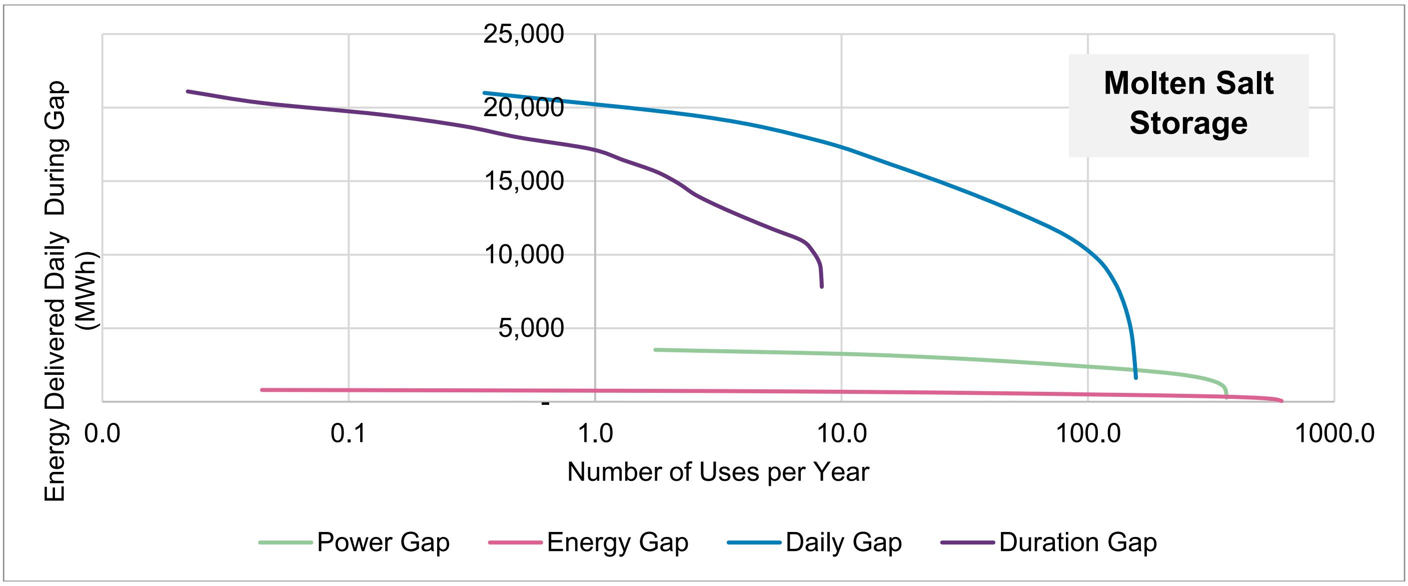


Figure 11 and Figure 12) show the results of this analysis for each technology. Note that the X-axes are on a $\log_{10}$ scale. For each technology the scale of energy delivery required to meet all peak gaps can be considered to be the upper value of all the lines on the graphs.

Li-ion batteries have value across all gaps, illustrating how commercial business models for these relatively high utilisation assets could be relatively easy if they can stack revenues compared to other storage technologies. However, it’s important to recognise that within duration gaps in particular, the storage technologies create a net *additional* demand for energy due to their cycling and efficiency losses. They are not used to *meet* the duration gap, but to *smooth out* the delivery of it. Their system value within the duration gap is their technical ability to ramp up and down, reducing the required capacity of dispatchable power. Other storage technologies (such as molten salt batteries) have similar roles within a duration gap to Li-ion – smoothing demand but adding net additional demand to the size of the gap.

Other storage technologies are unlikely to be used to support all the peak gaps, limiting their opportunities for commercial deployment. Energy delivery requirements for these technologies are likely to be significantly smaller than for Li-ion batteries with molten salt storage showing the greatest commercial opportunity of the technologies modelled.





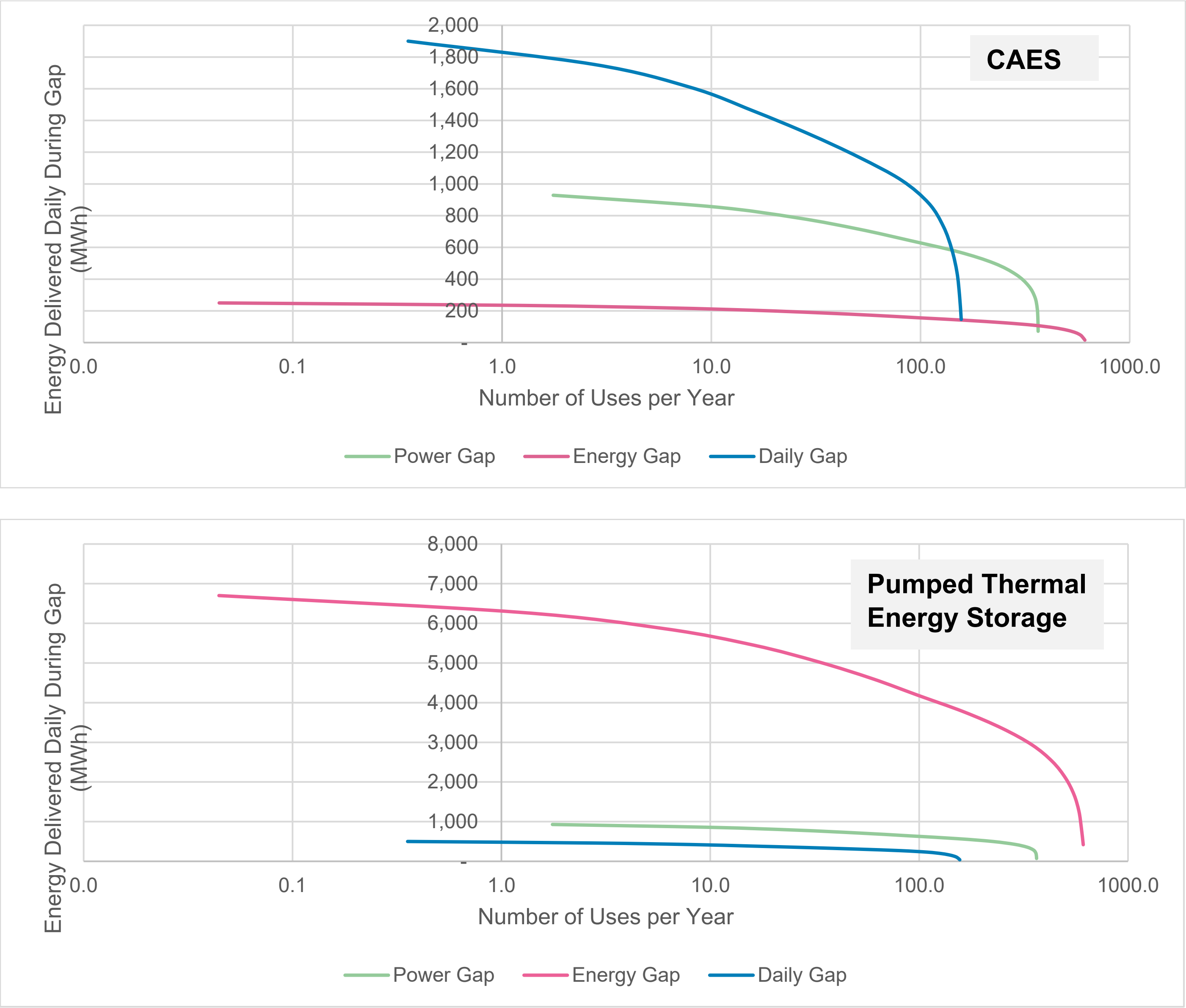


**Figure 11: Annual frequency of energy discharge magnitude for various storage technologies for the 2035 energy system**

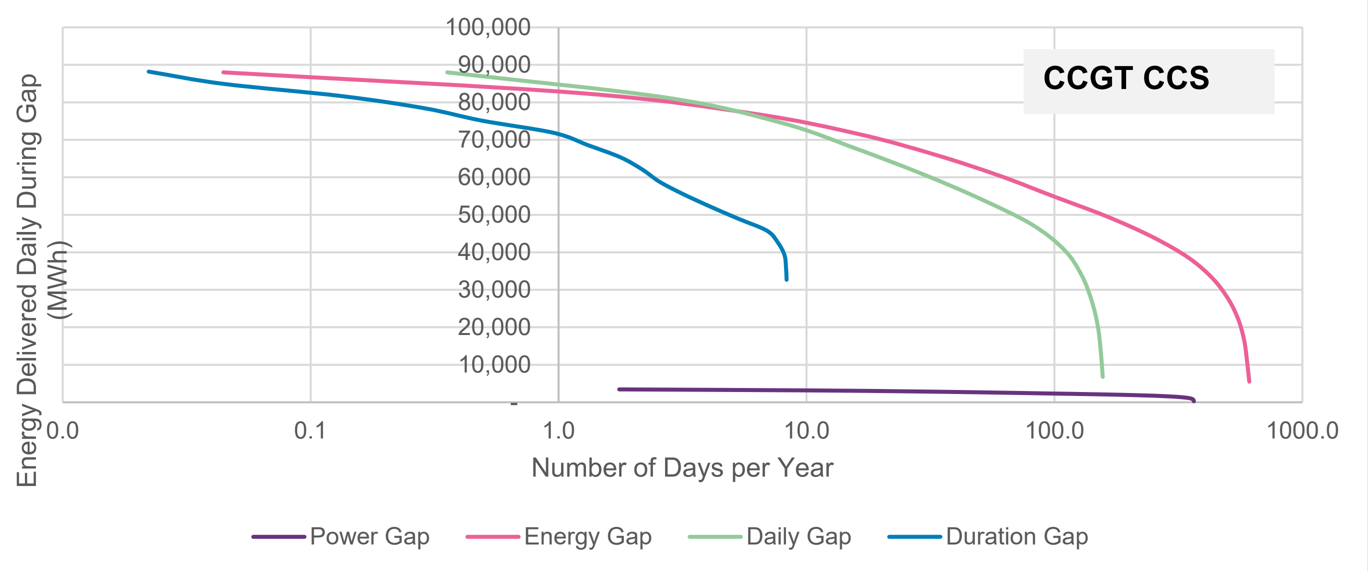
## 6.4. LCDP Use

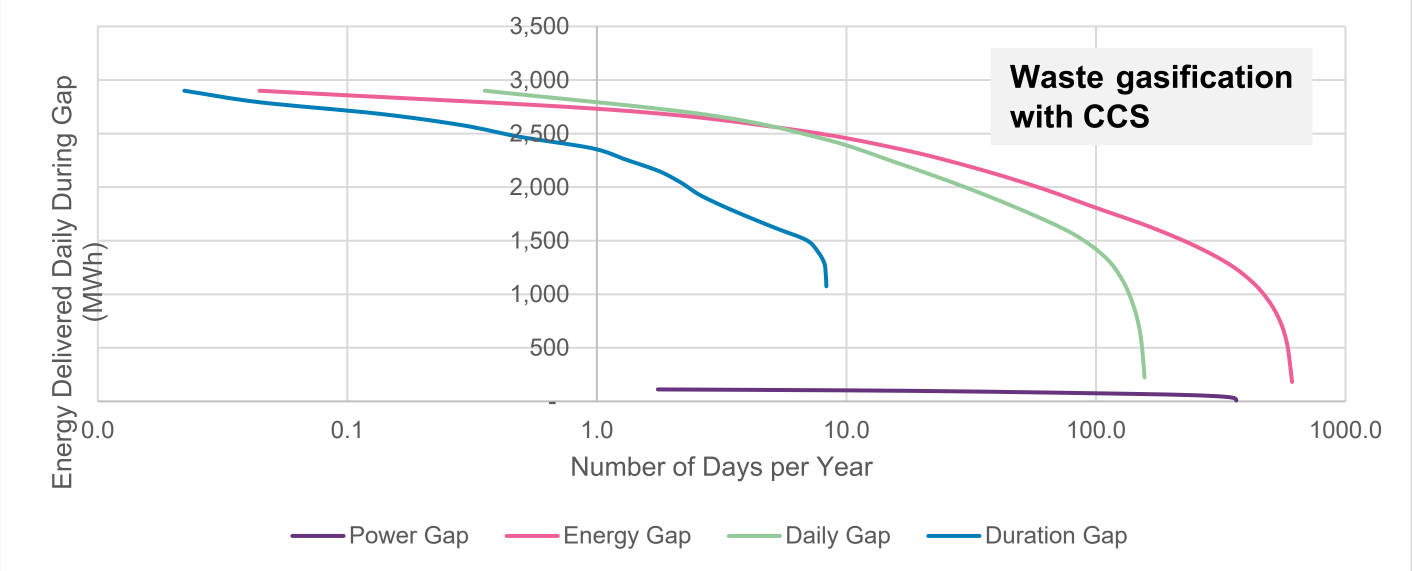
As with the LDES technologies, we sought to understand how often different LCDP technologies might be deployed at different scales by combining the frequency of energy gap size with the energy delivered by each technology in the simulations. As indicated in the LDES Section 6.3, these should be interpreted with the understanding that we have assumed that the split of technologies deployed at the peak gap is proportionally dispatched as the size of the gap is reduced. This is unlikely to be the case, and will vary based upon several factors including carbon constraints and cost-based merit order of technologies.

**By volume of energy delivered, carbon capture and storage (CCS) makes up most LCDP by 2035**, albeit operating in baseload for most of the time. This assumes high CCS efficiencies of 95% can be achieved. Hydrogen turbines also have potential to meet the daily and duration gaps at much lower installed capacity than CCGT with CCS. This is due to the relative costs of operation of the two technologies due to the lower end-to-end efficiency of producing hydrogen for use in electricity generation. This is true whether the hydrogen is made from natural gas with CCS or through electrolysis.

**However, for most LCDP technologies, the energy capacity required to meet the biggest peak duration gaps will only be used less than once every 10 years.** Whilst carbon constraints in the 2030s will allow for cheaper unabated peaking generation, as we move towards net zero, the ratio of peak capacity to utilisation rate of LCDP will likely increase. Given that the expert elicitation indicates that developers of these technologies are finding it challenging to create confidence in the commercial business case for any scale of plant, these results provide an indication of the challenge facing market and policy design to ensure that the technologies that can form least cost systems can be rewarded for lower utilisations and justify building the required capacities.

Waste gasification with CCS is also used to meet all the gaps, but the scale of energy delivered is restricted in our modelling by a build rate capacity constraint. IGCC biomass with CCS is likely to only have a small role to play as it is only used to help meet the daily gap and installations at significant scale are likely to only be used infrequently.





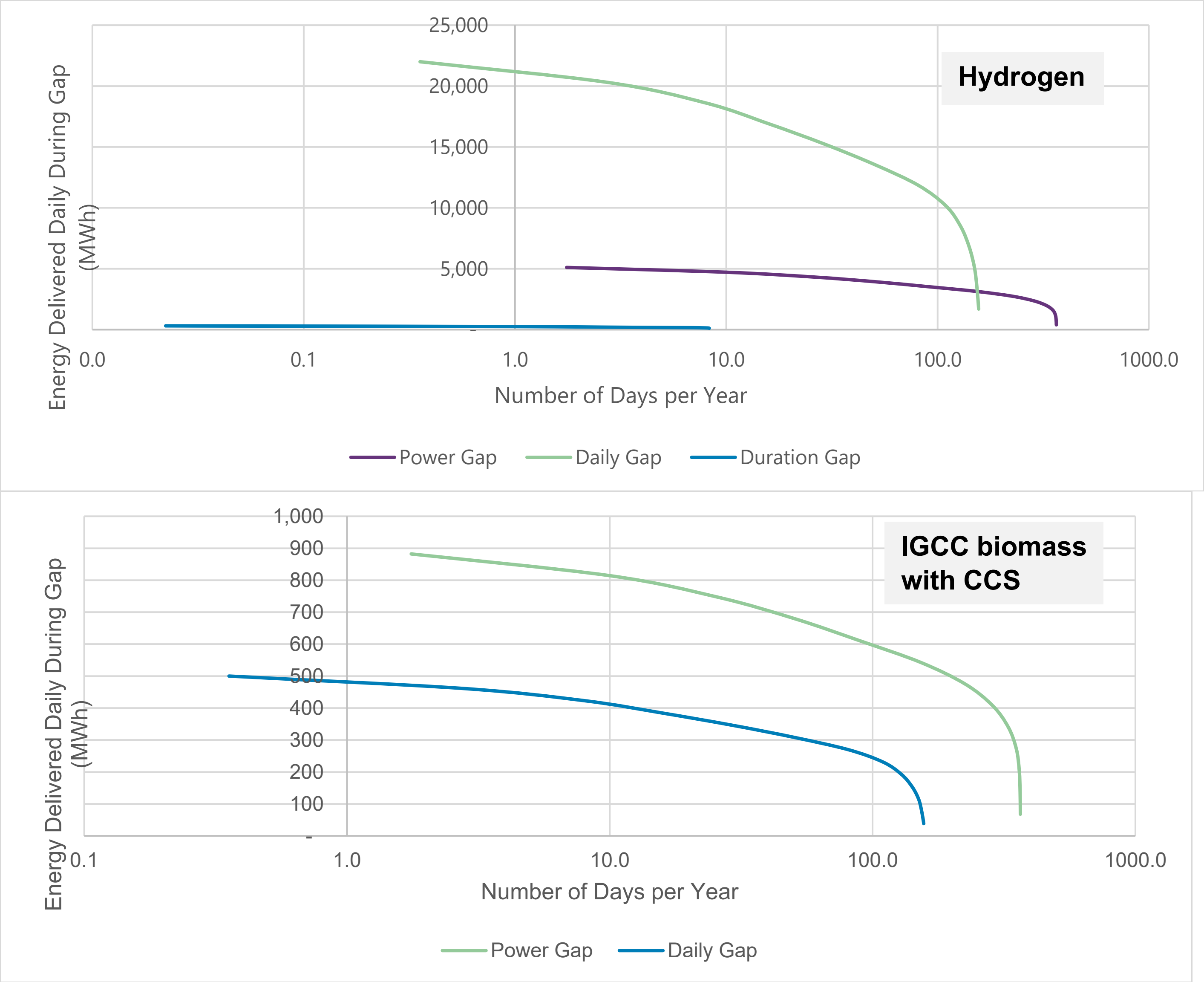


**Figure 12: Annual frequency of energy discharge magnitude for various LCDP technologies for 2035 energy system**

## 6.5. Deployment Value

In least cost modelling, there are two approaches to assessing innovative technology value across a range of technologies:

- Assess the impact of removing each technology in turn – allowing comparable quantification of option value but negating any interactions/dependencies when multiple technologies are or are not available. This allows quantification of value for support in specific technologies.
- Or, exploring cumulative effects of sector development, or the lack of it. This allows interpretation of the potential ‘breadth’ of support required to deliver low-cost systems.

In this analysis we used the latter approach. To understand the impact of technologies not being available in the future, we removed technologies additively in turn, in order of the largest storage capacity (LDES) and power capacity (LCDP) in 2050 within the CP2030 compliant scenario. For example, we removed the largest capacity technology, solved for a net zero system without it, identified the next largest storage capacity, removed that technology, repeating for all the shortlisted technologies being selected in the model. This process gives us an indicative hierarchy of which technologies will have most value in a future net zero energy system, albeit recognising that value could be attributed in other ways. Note that whilst removing a technology will often result in a similar, more expensive technology being deployed, it may also impact upon the wider system. For example, removing a storage technology could lead to more low carbon dispatchable power, interconnectors, larger heat networks, firm low carbon power or unabated generation with increased carbon abatement elsewhere in the energy system.

System cost changes are given as a percentage change in whole system cost to 2050, discounted to 2020 when the technology is removed. **Whilst the changes in system cost as storage technologies are removed are small percentages, these are still significant total costs of around £15bn for a 0.4% change.** Salt caverns have the biggest impact on system cost if they are unavailable.

**When hydrogen salt caverns are removed, we see an eight-times increase in installed capacity of CCGT with CCS and an 82% decrease in installed capacity of hydrogen turbines** in the CP2030 scenarios. Where CP2030 is not achieved, the increase in CCGT with CCS capacity is 3.6 times with a similar reduction in hydrogen turbine capacity to CP2030.

**Removing LCDP technologies leads to an overall reduction of around 60% in salt cavern energy storage capacity**. Combined with the impact on hydrogen turbines above, this shows the importance of evolving hydrogen peaking generation alongside salt caverns as the value of each depends on the other.

**Table 8: Deployment hierarchy for LDES technologies**

| Rank | LDES Technology | Notes | Max Capacity [xviii] | Incrementally additive system cost increase from baseline |
|---|---|---|---|---|
| **1** | Hydrogen Salt Caverns | 100 times larger capacity than any other technology | 18,000 GWh | 0.3% |
| **2** | Battery - Li-ion | 60% capacity increase with no salt caverns | 160 GWh | 0.3% |
| **3** | Flow battery – Redox | Only appears when Li-ion batteries are removed | 95 GWh | 0.4% |
| **4** | Flow battery - Zn-Br | Only appears when Redox flow batteries are removed | 12 GWh | 0.5% |
| **5** | Battery - NaS | Only appears when Zn-Br flow batteries are removed | 35 GWh | 0.5% |
| **6** | Molten Salt Storage | In all scenarios | 18 GWh | 0.6% |
| **7** | Compressed Air Storage of Electricity | In all scenarios. Gradual capacity increase of 400% from base case | 15 GWh | |
| | Liquid Air Energy Storage | In all scenarios. Gradual capacity increase of 300% from base case | 11 GWh | |
| | Pumped Thermal Energy Storage | In all scenarios. Gradual capacity increase of 200% from base case | 8 GWh | |

**Table 9: Deployment hierarchy for LCDP technologies**

| Rank | Technology | Notes | Max Capacity | Incrementally additive system cost increase from baseline |
|---|---|---|---|---|
| **1** | Hydrogen Turbine | Over 10 times larger installed capacity than other LCDP | 37 GW | 0.2% |
| **2** | CCGT with CCS | 10 times capacity increase when H2 turbines are removed | 28 GW | 0.9% |
| **3** | IGCC Biomass with CCS | In all scenarios but only deployed at scale when items higher in the hierarchy are removed | 8 GW | 1% |
| **4** | Biomass Fired Generation with CCS | In all scenarios but only deployed at scale when items higher in the hierarchy are removed | 7 GW | 1.6% |
| **5** | Waste Gasification with CCS | In all scenarios with little capacity change | 2 GW | |

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[xviii] Max capacity is the maximum observed capacity in the simulation across the UK, not necessarily in a single site. It is the maximum capacity observed after all technologies above it in the table have been taken out.

### Why is this analysis important?

Within the expert elicitation, we heard clear challenges associated with building confidence in their investment cases without certainty on the evolving parts of the rest of the system. This modelling, whilst not reflecting real-world markets, quantitatively illustrates these dependencies as part of the low-cost energy systems we are striving to achieve. It helps to show the potential impact of not supporting innovation in one or more of the highest value (by capacity) LDES and LCDP technologies.

This modelling analysis also demonstrates the requirement for markets (or policy-driven incentives) to evolve to reflect the system value of technologies, even when they are not highly utilised.

## 6.6. Innovation Value

Technological innovation and its large-scale deployment can affect a system's cost-effectiveness. We tested sensitivities that intend to represent what innovation could achieve, such as increasing technology efficiency, increasing the rate at which the supply chain can deliver them (represented by increasing ‘build rate’ constraints in the modelling), or reducing the technology cost.[xix]

**Accelerating maximum build rates of all LCDP technologies by five years results in substantial increases in LCDP deployment in 2035**, including an additional 8 GW of gas CCS and 3.2 GW BECCS, reducing total system cost by 1.3%. This implies that **there is system value in innovation in the supply chain for LCDP technologies**. Some of this additional CCS-based generation capacity is at the expense of other LCDP, with H2 turbines reducing by 1.1 GW. For LDES technologies, we do not represent many max build rates, and so this sensitivity does not make much impact.

**Decreasing the costs of technologies does not make much difference to the mix of technologies needed.** We tested what would happen if 2050 projected costs were met in 2030 – in all cases, we saw negligible impacts on the capacity mix across technologies, enforcing the analysis of the various roles that each of these technologies has across each peak gap.

**Increasing efficiency of LDES technologies has marginal impact on required capacities**. We tested increasing efficiencies by up to 33% across LDES technologies. There were very minor changes to deployment of any technology.

**Significant Li-ion cost reduction seems to drive wider system change**. We tested two aspects of battery innovation: cost reduction to £38 ($50) (in 2025) from 2035 and an increase in maximum duration to 100 hours, aiming to simulate daisy-chain operation. We see a 50% power capacity increase, but also wider system changes such as reductions in hot water storage as some heat networks are replaced with electrification, and other LDES technologies such as pumped heat, LAES and CAES are not deployed at all. More analysis is required using ESME Flex to understand the operational behaviour of these batteries across the peak gaps.

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[xix] Note that this is technology cost after reduction through learning, as ESME uses nth of a kind costs, enabling us to focus on strategic innovation value.

### The Faraday Institution very low-cost batteries scenario

We also tested a sensitivity with the more speculative technologies: very low-cost batteries delivered from The Faraday Institution's Ultrastore Challenge. We tested the impact of this technology on the system if they achieve their cost ambitions.

- They are deployed in all scenarios. Starting in 2035 with between 1.2 GW and 2.4 GW, rising to between 22.5 GW and 34.2 GW in 2050.
- In two scenarios, this is additional capacity in 2035 but displaces up to 20 GW of Li-Ion batteries in 2050. In the other scenarios, deployment does not occur until 2045 and is additional capacity.
- Dispatchable generation capacity reduces, mostly through a reduction of CCGT CCS and IGCC Biomass with CCS.
- All scenarios saw a reduction in total system costs to 2050 of up to 0.1%.

They are dispatched differently to other battery technologies, used for inter-day storage, generally charging over a couple of days before discharging. This is shown in Figure 13, contrasting to other batteries which are typically cycled once per day.

In a Dunkelflaute, the low-cost battery capacity deployed is insufficient for it to support the daily peak over the whole period. However, for the first few days they are discharged during the evening peak and not recharged. Once the stored energy has been used the battery is charged opportunistically in short bursts, occasionally partially discharging during the evening. The simulations suggest that, if they can be produced at the cost and performance we modelled, low-cost metal-air batteries could play a useful role in supporting duration gaps, including Dunkelflaute events.

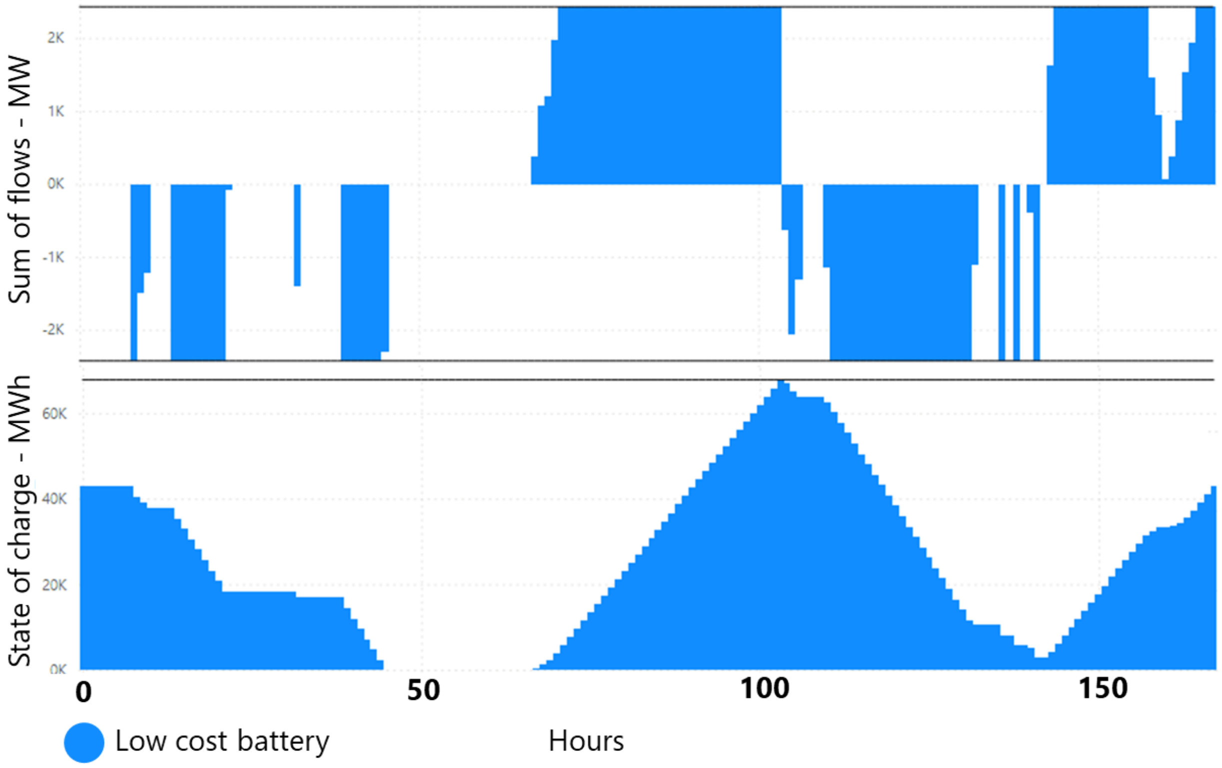

**Figure 13: Low cost battery cycling (top) and state of charge (bottom) for the whole fleet in the Business as Usual scenario (peak daily gap simulation for 2035)**

# 7. R&I: Opportunities and Barriers

This work has gathered evidence from published literature and expert elicitation on innovative LDES and LCDP technologies, as well as the barriers that are inhibiting their deployment at scale within the UK. This section highlights areas of opportunity where R&I can help to address these barriers. First, we present the findings from the expert elicitation. We then combine these with the findings from the evidence review to identify these opportunity areas.

## 7.1. Expert Elicitation: Technology Maturity Across Aspects of Integration

The expert elicitation workshops, structured through the Aspects of Integration, sought to understand the views of experts on key areas of concern for technology innovation in their areas of expertise. This section reports experts' judgment on the state of maturity of technologies across a range of system aspects wider than technology readiness alone.

Table 10 shows a summary of the reported maturities for each technology across each Aspect,[xx] where 0 is broadly "unaware of what may be required", and 5 is "solution ready". This is a summary of all responses, which includes variation in perspectives across stakeholders, as well as variation in maturity within different sub-systems of a particular technology. Therefore, it should be interpreted as illustrative of maturity across aspects, not definitive for an entire technology group. For more information on the context behind each of the scores, see the technology summaries, which include detail on where challenges exist and justify the scoring given by the experts we engaged with.

There were some clear insights from this exercise:

- **Most technology experts across all technologies see barriers across all aspects**, indicating that system wide interventions are needed for deployment.
- **LCDP technologies with high system value in the modelling (e.g. H2 turbines, gas CCS) were assessed by experts to be less mature** than LDES technologies such as electrochemical storage, hydrogen salt cavern storage and compressed air storage.

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[xx] Please note that there are wide ranges in many of these, and some had a low number of experts engaged compared to others. Therefore, should be treated as illustrative only.

**Table 10: Expert elicitation maturity summaries for each technology for each aspect**

| Aspect | H2 caverns & turbines | Flow batteries | LAES | CAES | Gas CCUS | Metal-air | Pumped TES | Aspect average |
|---|---|---|---|---|---|---|---|---|
| Technology | 3.0 | 3.5 | 4.0 | 4.5 | 2.0 | 4.0 | 4.0 | 3.5 |
| Operation and Support | 3.0 | 3.0 | 4.0 | 3.5 | 2.5 | 4.0 | 2.5 | 3.0 |
| People | 3.0 | 3.0 | 3.0 | 3.0 | 2.5 | 3.0 | 3.0 | 3.0 |
| Information | 2.0 | 3.0 | 2.5 | 3.0 | 1.0 | 1.0 | 4.0 | 2.5 |
| Infrastructure & Environment | 3.0 | 4.0 | 5.0 | 4.0 | 2.0 | 2.0 | 3.0 | 3.5 |
| Inter-operability | 3.0 | 3.0 | 5.0 | 3.0 | 3.0 | 2.0 | 4.0 | 3.5 |
| Commercial/organisational | 2.0 | 3.0 | 3.0 | 2.0 | 1.5 | 2.0 | 2.0 | 2.0 |
| Legislation | 3.0 | 3.0 | 5.0 | 3.0 | 1.5 | 3.0 | 2.0 | 3.0 |

## 7.2. Areas of Concern to Experts

Having understood the ‘state of maturity’ of each technology, we identified areas that R&I may have an opportunity to help address. These challenges are a combination of those identified by experts within our workshops, challenges shared within the Ideaonomy platform, and those specified within literature assessed within the rapid evidence assessments. Figure 14 shows that across all of the technologies we focused on in the expert elicitation, 85% of the barriers identified are not technology based, indicating that regardless of technological intervention, wider system changes are required to allow those technologies to succeed.

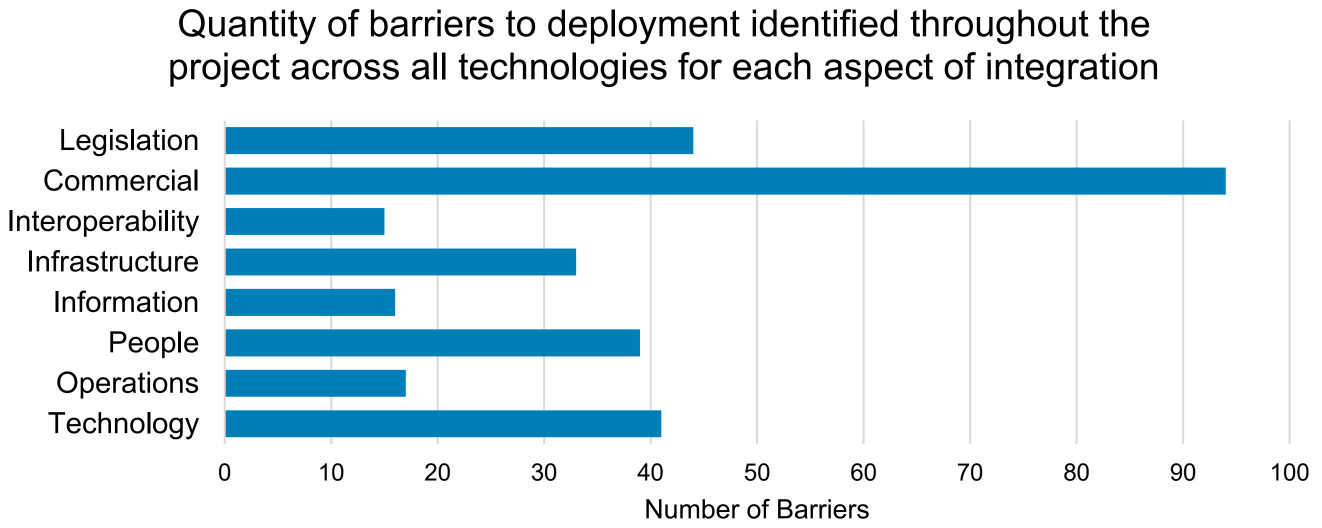

**Figure 14: Distribution of identified barriers by aspect of integration**

We did not engage the same number of experts for each technology due to availability and number of experts within a particular area. Therefore, it’s not useful to compare quantity of barriers per technology. However, we can show how the proportions varied, as shown in Figure 15. Whilst not exhaustive, this data shows us that each technology has its own set of system challenges alongside the development of technology itself, albeit in varying proportions.

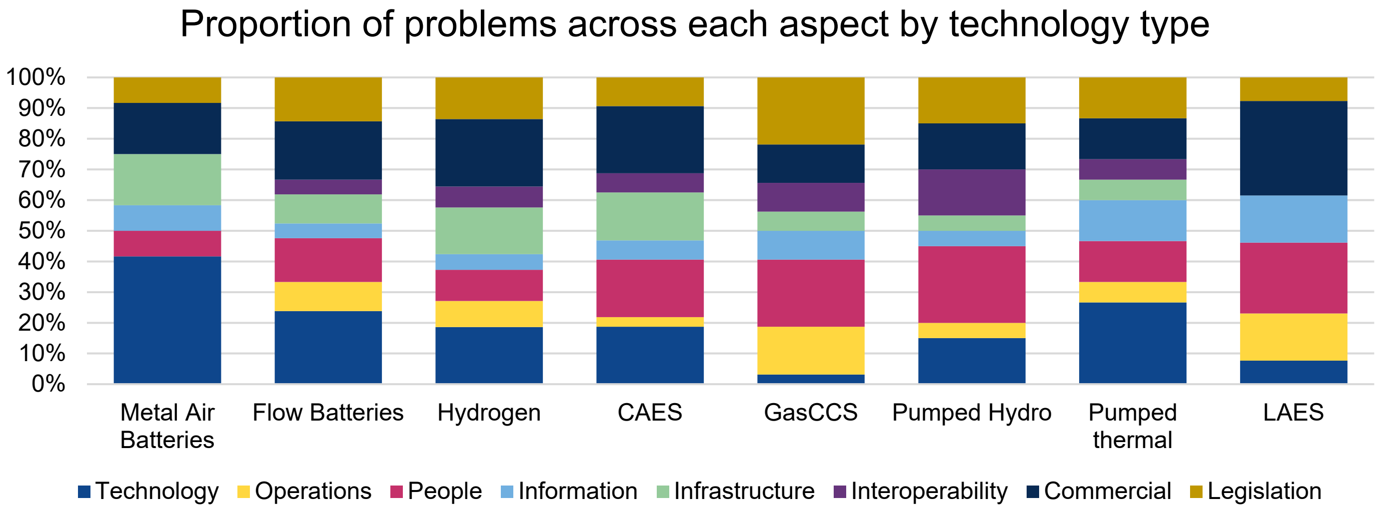

**Figure 15: proportion of types of barriers across each technology focused on within expert elicitation**

## 7.3. Research and Innovation Opportunity Areas

Whilst some barriers identified throughout this project would not lend themselves to R&I (e.g. the adjustment of a specific regulation), many others would. Table 11 highlights thematic areas for R&I that we have identified across both expert elicitation and the rapid evidence assessments. These combine specific ideas raised within expert elicitation, evidence gathered in the literature and the perspectives of the authors. To support interpretation, we have combined our aspects into four categories of R&I intervention.

- **Tech** = Technical innovation – primarily relating to the technical aspect
- **MPR** = Market, Policy and Regulatory Innovation – primarily related to market area of commercial and legislative aspects
- **Syst** = System Innovation – primarily related to people, information, infrastructure and interoperability aspects.
- **Fin** = Financial and business model innovation – primarily related to the non-market areas of the commercial aspect such as investment and business models

**Table 11: Summary of Identified Challenge Areas – not in a prioritised order**

| Opportunity area | Tech | MPR | Syst | Fin |
|---|---|---|---|---|
| **Challenges in accessing investment:** Securing investment for the development and deployment of new technologies remains a significant challenge. Confidence in financial returns is consistently low across the various technologies under consideration, which in turn restricts the flow of capital required for advancement. This lack of assurance around profitability deters both existing and potential investors from committing the resources necessary for progress. Feedback from small and medium-sized original equipment manufacturers (OEMs) indicates that developers are seeking greater certainty regarding their expected returns. The need for enhanced confidence is echoed by developers themselves, who report that third-party financiers demand substantial evidence and assurances before agreeing to provide funding. The emphasis from these financiers is on risk mitigation and clear pathways to recoup their investments. Historically, large utility companies were able to self-fund substantial assets directly from their own balance sheets. However, the landscape has shifted, and most large-scale projects now rely heavily on third-party financing. Many of these external financiers perceive that current arrangements do not sufficiently mitigate risks, further compounding the difficulty of securing the necessary investment to move projects forward. These risks spread across nearly all aspects of the aspects of integration framework, from skills and supply chain to markets and legislation. The forthcoming report from the Transition Finance Council on LDES includes a confirming perspective on the range of risks that investors will need assurance on, from supply chain to operational safety, from regulatory risk to cybersecurity.<br>**How could research and innovation help:** provide the **tools** through which risk can be mitigated and unlock cash flow and stimulate technology development. These could vary from digital tools that aim to provide better projections of revenue robust to policy uncertainty, or tools that enhance transparency and visibility within supply chains or technology cost data. The breadth of scope is wide, but the key is to help de-risk investment decisions outside of ongoing public opex support. However **innovative approaches to policy and market design** are also key ways to de-risk investment that could be explored. |  | ■ | ■ | ■ |
| **Getting to final investment decisions faster and cheaper:** One expert indicated that getting to FID on large LCDP assets could take £50-100m, whilst another stated that it could take towards two years to do the wintering birds analysis required as one part of planning consent. With an aim of delivering |  | ■ | ■ | ■ |

| | | | | |
|---|---|---|---|---|
| large assets at scale, the end-to-end lifecycle needs to be understood and reduced. For LDES assets, securing investment, getting connections and skills shortages have been noted in the evidence gathering as causes of slow progress in deployment. Meaningful scale LDES and LCDP assets are significant infrastructure undertaking.<br>**How could research and innovation help:** provide the **tools** that enable a systematic de-blocking of the end-to-end timeline for delivery in parallel to de-risking condensed timelines for critical stakeholders. These tools could be intervening in the specific, problematic and timely parts of the process, or they could be improving efficiency throughout the whole process. This could be done in parallel to regulatory changes to support efficient pre-FID steps. | | 🟦 | 🟦 | 🟦 |
| **Overcoming technology and operational challenges:** From novel electrolyte development and heat storage to microbial populations and solvent degradation, each technology has its own technical challenges to overcome. Some of these barriers are primarily time and capital dependent, with widely varying cost implications. However, the experts we spoke to also identified that there are not shared facilities available to help testing and provide the operating hours needed to get insurance and investment.<br>**How could research and innovation help:** provide **shared facilities** with connections, access roads and pre-approved planning permission to accelerate demonstration times and **provide investments into specific technology challenges,** potentially in collaboration with future investors. | 🟦 | | 🟦 | |
| **Bridging gaps in both investment and supply chain for mid-scale maturity technologies:** Multiple experts identified challenges with the supply chain available both within the UK and globally for supporting scale up of innovations. Some resort to international supply chains, taking opportunities away from the UK, whilst others resorted to manufacturing some of their own materials due to absence of available supply chain. Multiple stakeholders highlighted that the costs of medium-scale build (e.g. as part of demonstrations) are prohibitive unless ordering at scale. Some have even actively explored opportunities for collaborating with other similar companies to reduce costs, albeit without success due to differences in material needs. A common theme throughout the expert elicitation was the need for grouping together to share cost and accelerate developments. | | | 🟦 | 🟦 |

| | | | | |
|---|---|---|---|---|
| **How could research and innovation help:** Working with the supply chain to reduce risk to them for supporting innovation deployment, either through **locational based grouped demand** (one expert asked for a new Culham Science Centre), or through other routes, potentially similar to the Fit4 programmes delivered by the AMRC and OREC. | | | 🟦 | 🟦 |
| **Collaboration is being shown to work in pioneering cases with large companies, but innovators are finding it hard to make collaboration work to support their scale up:** there are flagship collaborations ongoing in some of these sectors, such as the Aldborough Hydrogen Pathfinder with SSE and Siemens. Some of the challenges are driven by wider regulation and could potentially be overcome through novel business models. For example, one expert explained that hydrogen producers are required to build their own network to connect to consumers, which resulted in two near-identical sets of infrastructure being built to the same consumer.<br>**How could research and innovation help:** Help to **deliver opportunities through which collaboration can yield benefits at lower total costs** for multiple parts of the LDES/LCDP sector, supporting business model innovation and policy makers to unblock key innovation opportunities. | 🟦 | | 🟦 | |
| **Markets in the UK, whilst seen as leading, do not reward the value that LDES and LCDP provide:** both LDES and LCDP sectors see themselves as being under supported financially compared to other sectors (or parts of their own sector) and do not see the markets providing a financially viable route to commercialisation for lower utilisation rates. LDES developers that could technically deliver longer durations are designing systems for shorter durations, whilst other parts of the sector cannot demonstrate return to investors.<br>**How could research and innovation help:** Help to provide **detailed modelling/evidence on the impact of different market designs and incentive schemes** that aim to value energy stored as opposed to capacity delivered. | | 🟦 | | 🟦 |

## 7.4. Barriers and Innovation Opportunities: Hydrogen and Electrochemical LDES

Building on the thematic barriers identified in Section 7.3 and as a first step towards understanding the more specific innovation opportunities and potential for aligned innovation programmes, a more focussed set of barriers and R&I opportunities was extracted from both the expert elicitation exercise and the rapid evidence assessments. For the purpose of this set of barriers and R&I opportunities, we focused strictly on 100 hour+ electrochemical storage technologies and hydrogen salt cavern/turbine systems, as these:

a) Featured in shortlisting as promising technologies – as highlighted in Sections 4 and 5.
b) Have strong potential to meet ultra LDES durations – as discussed in Sections 4 and 5.
c) Have potential innovation interventions that fit within R&D MAP – as shown in the technology summaries from the REA and expert elicitation (see Appendix).

The following sections detail these barriers, and R&I opportunities in turn for each of these two technology groups.

### Hydrogen Salt Cavern and Turbine Barriers

The REAs and expert elicitation exercise generated various specific challenges faced by hydrogen LDES systems. Table 12 presents a consolidated table of challenges for hydrogen salt caverns and hydrogen turbines. These are presented alongside an indicative average maturity rating from the experts workshopped in the expert elicitation – where 0 is no awareness of the challenges, and 5 is a technology which has no challenges to being deployed within the UK energy system. These are indicative only, and should be read as such, as there are wide variations in opinions across different technologies involved in hydrogen to power systems.

Three general findings can be highlighted from this table. First, there are barriers across all aspects of integration, indicating that challenges exist across the whole system relevant to hydrogen LDES innovation. Second, the average maturity level across aspects is 2-3, indicating that these barriers are already some way along their innovation journey, supporting the finding that hydrogen LDES systems have potential to deliver in the near term. Finally, the relatively high number of identified barriers presents challenges for identifying a programme of innovation activities that can address them sufficiently to support commercial deployment over relatively short timescales.

**Table 12: Barriers to hydrogen salt cavern storage and turbines for ultra LDES applications arranged by Aspects of Integration**

| **Aspect of Integration** | **Maturity level (0-5)** | **Barriers**<br>***From expert elicitation**<br>***From REA** |
|---|---|---|
| Technology | 3 | HT1: Certification of some salt cavern components is immature<br>HT2: Salt cavern leaching is extremely slow, it can take multiple years<br>HT3: Salt cavern development takes a long time (5-8 years)<br>HT4: Component lifespan of hydrogen turbines is uncertain |

| | | |
|---|---|---|
| | | HT5: Material compatibility for hydrogen retrofit of existing gas plants is not fully understood, specifically around embrittlement<br>HT6: Challenges with hydrogen combustion instability still needs to be overcome to run a higher ratio of hydrogen to natural gas or even 100% hydrogen fuel in turbines<br>HT7: Hydrogen combustion in turbines generate high NOx emissions requiring advanced dry low NOx (DLN) burners<br>HT8: Retrofitting existing gas plants receives less funding than new hydrogen builds<br>HT9: UK test facilities are insufficient; projects rely on overseas testing (e.g., France)<br>HT10: Existing test facilities have limited hydrogen production volumes and insurance limits on hydrogen<br>HT11: Hydrogen turbines still require a high purity hydrogen (95-97 %) (although not as high as PEM fuel cells – 99.999% ISO 14687) to run to prevent their degradation over time |
| Operation & Support | 3 | HO1: Hydrogen can react with salt minerals or microbial populations, generating H2S that must be managed<br>HO2: Hydrogen has higher safety risks than natural gas, requiring operational maturity before large-scale deployment can be achieved<br>HO3: Tools and processes for maintaining hydrogen salt caverns require further qualification<br>HO4: Durability, inspection and maintenance regimes for hydrogen turbine components are unproven at scale and need qualification<br>HO5: More evidence is needed on end of life, mining brine management (especially where there is no identified market for the brine as a chemical feedstock), long term salt cavern convergence (caverns closing in on themselves) and hydrogen turbine emissions control |
| People | 3 | HP1: Skills shortages will create bottlenecks. Each construction site may require 1,000 skilled staff; multiple parallel projects will amplify the constraint. This shortage is made worse by data centres increasing gas turbine demand<br>HP2: Public concerns and negative perception around hydrogen especially with safety and flammability, air quality because of NOx emissions<br>HP19: Environmental groups argue that hydrogen turbines risk entrenching continued reliance on fossil fuels, particularly with blue hydrogen<br>HP3: Salt cavern supply chains face intense competition from other infrastructure projects, constraining specialist contractors and labour<br>HP4: LCDP require new supply chains across hydrogen production, oil & gas, and transport and shipping<br>HP5: Developers and insurers need specialist risk analysis skills to quantify hydrogen power project risks and the UK consultant base is thin<br>HP6: Manufacturing capacity for turbines, multi-GW electrolyser and fuel cell deployment is limited, few UK suppliers produce at scale, posing procurement and timeline risks |
| Information | 2 | HI1: Data sharing is minimal. Cavern operators withhold data needed to advance fast cycling salt cavern practice, and demand data sits with individual firms, limiting business case development. For permitting, detailed information on $CO_2$ capture solvents is often unavailable from OEMs. |

| | | |
|---|---|---|
| | | HI2: Evidence on largescale hydrogen turbine demonstrations and long-term component life is scarce, which reduces decision confidence<br>HI3: Eligibility requirements for hydrogen turbines and gas CCS plants in the Capacity Market remain unclear |
| Infrastructure | 3 | HF1: The sector needs clarity on local hydrogen production versus a national hydrogen pipeline backbone anchored by fixed storage<br>HF2: Delays are being caused by grid connection difficulties<br>HF3: Hydrogen producers are building private pipelines, creating parallel networks serving the same demand<br>HF4: Current infrastructure designs are not robust to potential future demands<br>HF5: Pipeline routing is difficult<br>HF6: Lack of clarity around how much natural gas storage can be repurposed<br>HF7: Leak detection processes and equipment specifications are unclear and depend on future regulation<br>HF8: Deployment faces siting constraints (suitable underground reservoirs) and aboveground limits: high costs for electrolysers, compressors and fuel cells, and significant space/footprint requirements<br>HF9: Producing GW - TWh of hydrogen will require substantial electrolyser capacity, there is uncertainty around whether there is UK manufacturing capability to meet this potential demand |
| Interoperability | 3 | HX1: Uncertain demand size affects infrastructure and storage design criteria<br>HX2: Decarbonisation choices for existing plants depend on how infrastructure, policy, and wider system uncertainties evolve in the energy system transition<br>HX3: Hydrogen value chain elements are interdependent; progress in one area relies on others<br>HX4: The route to market for hydrogen power is unclear and its role versus alternatives like CCUS at existing plants needs definition |
| Commercial | 2 | HC1: Investment timescales are long, e.g. private investors want to invest into something that will be profitable in months/years<br>HC2: Current government funding is OPEX focused, rather than CAPEX, which could be less cost efficient in the long run<br>HC3: Power prices will have a massive impact on the strike price therefore projects will not be viable initially<br>HC4: Current demonstrators in development are heavily reliant on subsidies (80-85% from HAR, remaining from the Capacity Market and OCGT revenues)<br>HC5: The stop-start nature of funding is a major barrier to progress<br>HC6: Hydrogen supply chain business model interfaces remain uncoordinated<br>HC7: Low carbon hydrogen fuel is expensive<br>HC8: Future hydrogen demand, both in power and other sectors, remains highly uncertain<br>HC9: Banks only willing to support full end-to-end EPC agreements as they are only interested in the lowest risk options, they are not interested in contracts with multiple developers and providers<br>HC10: OEMs are unwilling to develop 100% combustion systems for retrofit without customer contribution or government funding, given demand uncertainties |

| | | |
|---|---|---|
| | 🟧 | HC11: Market interactions between hydrogen and CCS plants are unclear, including merit order priority<br>HC12: Prices for industrial equipment are increasing globally, 15% rise in gas turbine costs in the last 12 months<br>HC13: The first round of the HSBM will support one large-scale project at TRL of 7 and above. The project is expected to be operational from 2031. |
| Legislation | 3 | HL1: UK salt caverns face additional qualification challenges for operating at higher pressures<br>HL2: Funding for hydrogen turbines is delayed by policy and market uncertainty<br>HL3: New standards for hydrogen and regulation for fast-cycling caverns must be developed, like existing gas frameworks<br>HL4: H2 turbines require large volumes of water, increasing EA regulations might make this more challenging to solve<br>HL5: Regulatory and commercial uncertainty are slowing hydrogen development and planning<br>HL5: Current NOx emissions legislation penalises hydrogen turbines.<br>HL6: A lack of regulatory frameworks, alongside limited funding and support, is a major barrier to deploying LCDP technologies in the UK.<br>HL7: Absence of a coherent onshore storage permitting and consenting framework causes delays<br>HL8: HSE seems more stringent on hydrogen power infrastructure than in petrochemical refinery settings |

## R&I Opportunities in Hydrogen Salt Caverns and Turbines

Within the evidence gathering there were several ideas expressed that could advance the maturity of hydrogen to power systems. Table 13 consolidates these and categorises them across the four R&I opportunity areas used in Section 7.3.

Some of these opportunities have multiple potential impacts so these are colour coded to indicate whether they could directly or indirectly benefit the challenges facing the technologies in different facets of deployment. Whilst these ideas are based upon the evidence gathered, they should be interpreted as starting points for development of R&I programmes, stimulating further ideas and discussion on their relative merits. These ideas should be validated and further developed with industry.

**Table 13: R&I opportunities to support advancement in maturity of hydrogen LDES systems.**

| R&I opportunity | Tech | MPR | Syst | Fin |
|---|---|---|---|---|
| Develop accurate models of fast-cycling salt cavern behaviour to ensure cavern stability and safety, especially in areas with multiple adjacent caverns, or in areas where seismicity may be a risk | 🟩 | | | |
| Provide targeted technical support to overcome known technical barriers | 🟩 | | | |
| A long-term demonstrator with continuous H2 supply and 12-18 months of testing to fully understand material durability and replacement intervals | 🟩 | | 🟧 | 🟧 |
| Engage with insurance providers to unlock test scale up in the UK | 🟧 | 🟧 | 🟧 | 🟩 |
| Whole system optimisation of hydrogen salt cavern storage is needed to refine operation, cycling frequency, interactions with other storage technologies, and improve efficiency and cost | 🟩 | | 🟧 | 🟧 |

| | | | | |
|---|---|---|---|---|
| A fast-cycling hydrogen salt cavern storage demonstrator is needed to raise TRL, accelerate learning, and derisk future investment | 🟩 | | 🟧 | |
| Address high costs and footprint constraints for above-ground equipment such as electrolysers, compressors, and fuel cells | 🟩 | | | |
| Innovate construction techniques and explore cushion gas alternatives ($CO_2$, $N_2$) to reduce costs and improve hydrogen recovery | 🟩 | | | |
| Improve round-trip efficiency through advances in compressor, electrolyser, and fuel-cell performance | 🟩 | | | |
| Introduce interventions to accelerate operational maturity ahead of potentially slow commercial deployment | 🟧 | 🟧 | 🟩 | |
| Develop tools to support partnerships and supply chain growth | | | 🟩 | 🟧 |
| Demonstrate hydrogen turbines in collaboration with data centres | 🟩 | | 🟧 | 🟧 |
| Develop advanced construction and manufacturing techniques to ease workforce constraints | 🟧 | | 🟩 | 🟧 |
| Scale up UK manufacturing capacity for electrolysers and fuel cells | 🟧 | | 🟩 | 🟧 |
| A lot of data is commercial in confidence; centralising some as a national resource could support development and reduce duplication | | | 🟩 | |
| Create tools to support clarity of understanding across all participants | | | 🟩 | |
| Develop business model innovations to support development of shared infrastructure | | | 🟩 | 🟧 |
| Provide tools to support the de-risking of projects due to infrastructure uncertainty | | 🟧 | 🟧 | 🟩 |
| Introduce policy and regulatory innovation to build confidence and enable parallel activities | | 🟩 | 🟧 | |
| Develop innovations that reduce dependency risks on future energy systems | 🟧 | 🟧 | 🟩 | |
| Establish a hydrogen-sector equivalent to the Culham Science Centre as a focal point for technical innovation and pooled investment | 🟩 | 🟧 | 🟧 | 🟧 |
| Government co-funding could leverage private R&D (if market confidence exists) | | 🟩 | | 🟧 |
| Develop tools to provide a predictable, clear funding route and reduce stop-start perceptions | | 🟩 | 🟧 | 🟧 |
| Adopt new approaches to valuing energy security to strengthen commercial cases | | 🟩 | | 🟧 |
| Facilitate interfaces between business models across the hydrogen supply chain | | 🟧 | | 🟩 |
| Coordinate development across the hydrogen sector and input into commercial revenue estimates for new hydrogen -system business models | | 🟧 | | 🟩 |
| Prioritise Government funding for FEED | | 🟩 | | 🟧 |
| Explore ways to value system benefits, such as using excess wind to produce hydrogen for low-carbon applications like steel | | 🟧 | 🟩 | |
| Develop innovations to address complexities, dependencies, and conflicts in legislation, regulation, and standards across the hydrogen supply chain | | 🟧 | 🟩 | |

**Key:**

| | |
|---|---|
| **Direct Innovation Benefit** | 🟩 |
| **Indirect Innovation Benefit** | 🟧 |

**From expert elicitation**

**From REA**

## Electrochemical LDES Barriers

This section presents a similar consolidated table of barriers to that seen in Table 12, this time for electrochemical LDES (Highlighted by the barriers below, two observations can be made. First, in comparison to hydrogen LDES, barriers are similarly spread across the full range of aspects of integration. Second, the range of maturities across barriers is wider, with level 1 and level 4 maturities in the table. This suggests that innovation support could be applied across all types of R&I opportunity areas, and that for some aspects of integration (specifically 'Information') the innovation challenge might be in particular need of rapid support.

). Again, these barriers were gathered through the REA and expert elicitation activities. The focus is on technologies that have been shortlisted and can deliver economically viable low utilisation, ultra long duration potential. Metal-air technologies are the focus given they are one of the few electrochemical technologies that could achieve these durations. However, we also include insights from other electrochemical technologies that have been deprioritised (such as flow batteries) which have challenges likely to be shared across electrochemical technologies.

These are presented alongside an indicative average maturity rating from the expert elicitation – where 0 is no awareness of the challenges, and 5 is a technology which has no challenges to being deployed within the UK energy system. These are indicative only, and should be read as such, as there are wide variations in opinions across different technologies involved in electrochemical technologies.

Highlighted by the barriers below, two observations can be made. First, in comparison to hydrogen LDES, barriers are similarly spread across the full range of aspects of integration. Second, the range of maturities across barriers is wider, with level 1 and level 4 maturities in the table. This suggests that innovation support could be applied across all types of R&I opportunity areas, and that for some aspects of integration (specifically 'Information') the innovation challenge might be in particular need of rapid support.

**Table 14: Barriers to electrochemical systems for ultra LDES applications arranged by Aspects of Integration**

| **Aspect** | **Electrochemical storage** | |
|---|---|---|
| | **Maturity level (0-5)**[xxi] | **Barriers**<br>***From expert elicitation**<br>***From REA** |
| Technology | 3 | ET1: [metal air] Fundamental challenges still need to be addressed for novel chemistries to meet cost targets £7.6-£15.2/kWh ($10-$20/kWh)[xxii]<br>ET2: [metal air] Prototypes have challenges such as limited rechargeability and performance (electrolyte/electrode) degradation<br>ET3: [metal air] Need to adapt manufacturing processes for Li/Na batteries to metal-air batteries<br>ET4: [metal air] Commercial scale-up and lack of companies developing these technologies in the UK<br>ET5: [metal air] Advances are needed in separator materials and improved pack- and system-level engineering<br>ET6: [generic] Funding for pilots |
| Operation & Support | 4 | EO1: [generic] High regulatory barriers resulting in additional time before build<br>EO2: [generic] Safety concerns about materials used |
| People | 3 | EP1: [metal air] Potential difficulty in attracting people due to strong competition from other roles within the energy sector<br>EP2: [generic] Supply chain for manufacturing is limited in the UK<br>EP3: [generic] Reluctance from bulk storage developers to take on the risk of new unproven technologies<br>EP4: [generic] Challenges in the UK for identifying cost effective supply chain for mid-scale developments. |
| Information | 1 | EI1: [metal air] A need for transparent modelling that better represents the value of individual technologies |
| Infrastructure | 2 | EF1: [metal air] Large space needed for siting batteries<br>EF2: [metal air & generic] Securing connections<br>EF3: [generic] Identification of suitable sites with right permits and infrastructure for storing hazardous materials |
| Interoperability | 2 | EX1: [generic] Limited time available for smaller innovators to focus on interoperability challenges |
| Commercial | 2 | EC1: [metal air] Current market signals and grid fee structures do not fully reflect the strategic value of long-duration storage<br>EC2: [metal air] No metal air batteries were successful in the first Cap and Floor window (Ofgem), potentially due to eligibility criteria<br>EC3: [generic] Indications of demand from developers/customers but not able to secure investment (hardware-based solutions are currently less attractive to UK investors)<br>EC4: [generic] Challenges with getting insurance and warranties without 5-10 years of battery data<br>EC5: [generic] Installation time and data required to de-risk a technology, especially when none of a technology have been sold |
| Legislation | 3 | EL1: [metal air] Potential new health and safety regulation for novel chemistries<br>EL2: [generic] Current transport regulation related to either bulk chemical transportation or battery transportation is a grey area for new technologies (current legislation does not cover new technologies)<br>EL3: [generic] EU regulation around battery passports is designed for lithium-ion batteries not other types of batteries<br>EL4: [generic] Lack of funding and support to scale up new technologies |

## R&I Opportunities for Electrochemical LDES

Within the evidence gathering there were several ideas expressed that could advance the maturity of electrochemical LDES. The table below consolidates these and categorises them across the four R&I opportunity areas used in Section 7.3.

Some of these opportunities have multiple potential impacts so we have applied different colours depending on our perspective of whether they could directly or indirectly benefit the challenges facing the technologies in different facets of deployment. Whilst these ideas are based upon the evidence gathered, they should be interpreted as starting points for our workshop, stimulating further ideas and discussion on their relative merits. All ideas need to be validated once further developed with industry.

**Table 15: R&I opportunities to support advancement in maturity of electrochemical LDES systems.**

| R&I Opportunity | Tech | MPR | Syst | Fin |
|---|---|---|---|---|
| [metal air] Further funding to address fundamental challenges with novel chemistries[xxiii], such as electrolyte degradation and electrolyte issues (bifunctional catalysts, corrosion mitigation, anode hydrogen-evolution tendency and air cathode carbonate deposition) | 🟩 | | | 🟧 |
| [metal air] Further funding to develop low-cost manufacturing methods[xxiv] | 🟩 | | | 🟧 |
| [metal air & generic] Pilot funding to move technologies from concept to demonstration and accelerate TRL progression | 🟩 | | 🟧 | 🟧 |
| [metal air] Encouraging novel engineering and chemistries to reduce cycling degradation and self-discharge issues | 🟩 | | | |
| [metal air & generic] Supply chain support to build up necessary supply chains | | | 🟩 | 🟧 |
| [metal air] Apprenticeships/programs to broaden skills base | | | 🟩 | |
| [metal air] Better awareness of information requirements | | | 🟩 | |
| [metal air] Open modelling platforms with clear, adjustable assumptions that allow for comparison of technology performance | 🟧 | | 🟧 | 🟧 |
| [metal air] Increasing energy density and improved cooling systems[xxv] | 🟩 | | | |
| [metal air] Improve connections processes | | | 🟩 | 🟧 |
| [metal air] Reforming market mechanisms to reward long-duration energy storage | | 🟩 | 🟧 | 🟧 |
| [metal air] Providing mechanisms for securing investment and helping to reduce risk for early-stage technologies | | 🟩 | | 🟧 |
| [metal air] Adjustments to Cap and Floor eligibility criteria, such as TRL level and grid connections, and additions, such as valuing longer term storage | | 🟩 | 🟧 | 🟧 |

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[xxi] For metal-air batteries

[xxii] Details on these fundamental challenges were not provided due to confidentiality reasons

[xxiii] details on these fundamental challenges were not provided due to confidentiality reasons

[xxiv] already covered by The Faraday Institution UltraStore programme

[xxv] to enable vertically stacking, which has lower space requirements than horizontal stacking

| | | | | |
|---|---|---|---|---|
| [metal air] Speeding up implementation of new health and safety regulation | | 🟩 | 🟧 | |
| [generic] Shared supply chain facilities | | | 🟩 | 🟧 |
| [generic] Regulatory innovation to reduce time to build | | 🟧 | | 🟧 |
| [generic] Tools to support risk mitigation | | | | 🟩 |
| [generic] Ensure awareness of information requirements | | | 🟩 | |
| [generic] Database of supply chain capabilities to ease identification | | | 🟩 | 🟧 |
| [generic] Decouple connection securing from TRL/CRL development | | 🟩 | 🟧 | 🟧 |
| [generic] Reduce time required to understand interoperability implications | | | 🟩 | |
| [generic] Support in de-risking investments | | 🟧 | | 🟩 |
| [generic] Identify and overcome key dependencies in technology development journey | 🟩 | | 🟧 | |
| [generic] Identify and address regulatory gaps to pave way for deployment | | 🟩 | | 🟧 |
| [generic] Policy innovation to support technology scale-up | 🟧 | 🟩 | | 🟧 |

# 8. Risks to Technology Choice Conclusions

The technologies shortlisted in this project have the potential for swift deployment on a 2030 to 2035 timeline based on the evidence gathered. However, there are significant uncertainties associated with this technology selection approach to innovation funding, and these should be considered when designing the future funding strategies.

Important information may be learned on the state of innovators in the UK through the responses to calls focussed on innovation challenges rather than technologies, such as market view on innovation costs and the types of technologies and consortia keen to engage in innovation funding in this space. Sandpit consortia building may be utilised as an approach in the near future, to understand some of the gaps in evidence directly from participants where funding is explicitly on offer.

Ultimately, there will be a difficult balance to be struck in innovation funding strategies between focussing on specific technologies, with the risk of incorrect focus, and applying a more technology agnostic approach, with the risk that available funding is spread too thin to have the necessary impact by 2030-2035.

## 8.1. Challenges with Extent of Evidence

There are a number of areas where the available evidence may be lacking. The existing evidence in the literature is likely behind the current knowledge within innovator communities and may not provide coverage across all criteria of interest to UKRI. Where expert views have been sought, willingness of experts to engage, divulge commercially relevant knowledge, and bias driven by commercial incentive may all impact the usefulness of evidence gathered. This is particularly a challenge for evidence on the costs of innovation interventions, or the potential for government funding to leverage private investment, where the literature provides little evidence, and where expert workshops did not uncover extensive evidence from participants.

## 8.2. Technology, Policy and Market Uncertainties

A number of technological, policy and market uncertainties impact LDES and LCDP technologies. Many of these are unpredictable, highly variable and contingent on global factors out of UK control. The cost of supply chain inputs, including fuels and manufacturing inputs, will influence various aspects of future technology costs and will depend in part on global forces. Policy decisions in the UK and in relevant international partners will also have impacts on the future competitiveness of different technology options. These issues will always impact investment decisions, and it will be necessary, but challenging, to design an innovation funding programme that mitigates the issues of a narrow technology choice while allowing for focussed strategic investment that can have an impact on the very tight timescales relevant to this project.

## 8.3. The Innovation Process

Accelerating LDES and LCDP innovation and TRL levels within ten years is a particular challenge since energy technology innovation can take several decades. Only technologies close to commercial readiness and being deployed at scale are likely to be useful to this project. In the UK and France, electricity generation technologies such as CCGT and nuclear took around 40 years to progress from invention to wider commercialisation (Gross et al., 2018)(Gross et al., 2018). Shorter timescales to market penetration of around 25 years have been achieved for end use energy products such as lithium-ion rechargeable batteries (Lund, 2006)(Lund, 2006). In contrast power stations typically have long asset lives, spanning several decades, and require time to achieve up-scaling and wider deployment of large-scale units (Wilson, 2012)(Wilson, 2012). More rapid early commercialisation has been attained where innovations can readily substitute pre-existing technologies, compared to those which take longer to stimulate market demand and integrate with new institutions (Bento & Wilson, 2016)(Bento & Wilson, 2016).

Notwithstanding timescales, there are unpredictable aspects of the innovation process. Technologies might respond in different ways to innovation funding, and innovation barriers may be harder or easier to overcome than predicted. Further, international choices on innovation funding in this space may significantly change the suite of technologies ready for deployment in the 2030s.

There is not a linear relationship between investment and the speed of progress and advancement in technological innovations. In the energy technology literature, standard models of technology evolution (e.g. TRLs or the S-curve plotting technology adoption against time or expenditure) have been critiqued for assuming a linear, successive technology development (Gross et al., 2018)(Gross et al., 2018). Technological innovation does not proceed in a simple one directional journey from basic research to applied research, then technology development and diffusion (Wilson & Grubler, 2013)(Wilson & Grubler, 2013). For example, R&D continues beyond market introduction and can improve performance and reduce costs even in highly mature technologies. Alternative concepts such as ‘technological innovation systems’ and the ‘multi-level perspective’ emphasise complex, systemic feedbacks between supply-push and demand-pull activities, as well as the role of various actors and institutions in developing and deploying technologies within a broader socio-technical landscape (Foxon, 2003). The importance of technological and market niches is also highlighted, through which an innovation can be protected from normal market competition for a period of time.

## 8.4. Whole Systems Challenges

A number of key issues for the innovation in LDES and LCDP are systems challenges. While Aspects of Integration framing and whole systems modelling were designed to understand these issues in more depth, the project is largely oriented more around a technology-by-technology assessment via the available literature and expert evidence. The identified Challenge Areas include common system challenges across multiple technologies but some of these questions may require more attention. Key examples include understanding the system value of LDES vs LCDP technologies, the system value of ultra LDES, and the utilisation rate/load factor that different technologies might operate at in the future system.

# 9. Consolidated Findings

## 9.1. Key Insights

### Shortlisted Technologies

From the LDES technologies shortlisted in this study, **hydrogen salt cavern storage** is the most capable of achieving ultra LDES (100hrs+). **Metal-air and flow battery** technologies have also been shortlisted, and they are currently further from delivering ultra LDES, though there is interest in innovation to support development and cost reduction towards this ultralong duration goal. These technologies offer modular design, and a broader commercial application than storage, which may allow for more rapid innovation relative to larger scale technologies. Two mechanical storage technologies, **adiabatic compressed air energy storage (A-CAES) and pumped hydro storage** are also shortlisted. Pumped hydro storage, A-CAES and flow batteries are currently in the intermediate discharge duration range of 12 to 24 hours, but all have potential to reach 100 hours. Adiabatic compressed air storage has relatively high technology readiness and has cost benefits. There is also significant expertise in the UK. Pumped hydropower energy storage is commercially mature, though innovation in novel types of dense fluid storage may open up wider geographical locations for deployment.

In LCDP, hydrogen power generation technologies have been shortlisted. **Reciprocating engines and gas turbines** are both relevant options for power generation from hydrogen. For all hydrogen to power technologies, optimisation for flexible operation is an important area of technological innovation. Hydrogen technologies on both the LDES and LCDP shortlists presents the possibility that this area could be supported by innovation funding that strategically links these aspects of the whole hydrogen technology system. **CCS** in association with **CCGT or biomass** has also been shortlisted. Key rationale is the high TRL (8-9) for CCGT with CCS and strong UK competitiveness given UK $CO_2$ storage potential. Key technological innovation needs include flexible/dispatchable operation of these technologies, improving high capture rates, particularly under ramp up/ramp down and CCS solvent development. Finally, Gen III **small modular reactors** are shortlisted. Relative to conventional nuclear, their modular design, smaller size, and passive safety features enable reduced upfront capital, easier grid integration, and operational flexibility. There are a host of challenges for SMR, including high first-of-a-kind costs, uncertain MWh costs and regulatory and licensing hurdles.

### R&I Opportunity Areas

Six areas that have opportunities for R&I to accelerate development and deployment of LDES and LCDP technologies have been identified in Section 7. These are:

- **Challenges in accessing investment** driven by confidence in financial returns and other risk assurances to unlock third party investment.
- **Getting to Final Investment Decisions (FID) faster and cheaper**: understanding the process to reach FID and how to reduce both cost and time.
- **Overcoming technology and operational challenges**: technology challenges still need time and investment, though shared facilities may also be key.
- **Bridging gaps in both investment and supply chain for mid-scale maturity technologies**: supply chains and costs are challenging at demonstration stage.

- **Collaboration is being shown to work in pioneering cases with large companies**: but innovators are finding it hard to make collaboration work to support their scale up.
- **Markets in the UK, whilst seen as leading, do not reward the value that LDES and LCDP provide**: what market mechanisms or understandings are missing?

This highlights that, while the funding and investment landscape is a significant concern to experts and technology developers, markets, supply chains and collaborations are also seen as key challenges that need to be overcome. This suggests opportunities to facilitate rapid innovation that lie outside specific technology challenges.

## Insights from Modelling

A number of key insights from modelling suggest options for investment into LDES and LCDP technology research and innovation.

- **Least cost systems need a diversity of technologies, working together to fulfil system requirements – the challenge is then to appropriately reward each technology for the system value that it is providing**. Peak duration gaps such as a Dunkelflaute, and peak daily gaps (across days) are typically used as design cases for LCDP and LDES technologies. However, we have shown least cost systems need a diversity of technologies to meet the variety of system demand cases, from batteries smoothing demand within days to various types of LDES and dispatchable technologies playing a role to meet 2-week aggregate demand. This suggests that investment across both LCDP and LDES would be valuable, potentially focusing on hydrogen, CCS technologies and very low-cost electrochemical storage technologies.
- **LDES technologies such as pumped thermal energy storage, compressed air energy storage and molten salt storage are unlikely to be used to support all the gaps in energy/power that we defined, limiting their opportunities for revenue stacking and thus commercial viability**. Whilst Li-ion batteries are used across all gaps they cannot meet long duration energy gaps. They smooth demand, but by doing so with cyclic efficiency losses they add to the energy deficit in the duration gap. Longer duration energy storage technologies would benefit from additional support to allow scale up and full commercialisation. This may include innovation funding, and policy/market support mechanisms.
- **CCGT with CCS contributes to more peak gaps than other LCDP technologies,** contributing the highest volume of energy. However, it is run primarily in baseload, likely due to the high capital cost of the plant itself. In contrast, **hydrogen turbines have the highest capacity deployed** to support a smaller number of peak gaps, dispatching infrequently to conserve the relatively high-cost hydrogen that is also needed/used across other sectors. These are both LCDP technologies but require different markets to support their operation in a system that minimises total system cost. As unabated dispatchable technologies are squeezed out of the system, these LCDP technologies will likely face further increases in their ratio between their dispatch capacity vs utilisation.
- **Salt caverns and hydrogen turbines are each dependent on each other’s deployment and should be supported as a whole system to deliver electricity system services.** Salt caverns have the biggest impact on system cost if they are unavailable. When hydrogen salt caverns are removed, we see an eight-fold increase in installed capacity of CCGT with CCS and an 82% decrease in installed capacity of hydrogen turbines. The scale of capacity in hydrogen salt cavern storage may therefore be important to the system. Supporting this storage technology may be important, particularly where markets do not easily identify this high system value.

### Challenges with Evidence on Scale of Funding Required

This project has considered two indicative funding scenarios for future R&I investment: £10m or £20m over a five-year funding horizon. Under the lower horizon there is the potential that an R&I programme might be best applied to only one technology group, LDES or LCDP. Under the higher funding scenario, it may be possible to fund R&I programmes across both LDES and LCDP.

The evidence assessment and expert elicitation exercises did not reveal clear evidence on the scale of innovation investment necessary, making it difficult to link quantities of funding to specific innovation outcomes, such as investment required per TRL. Examples of international innovation investment were gathered to provide context on the broad quantities of investment applied in different LDES and LCDP innovation programmes. These relate to public funding for research, development and demonstration projects to bring LDES and LCDP technologies closer to commercialisation. They include examples from Europe, North America and Japan, ranging from the equivalent of several million pounds to programmes which have allocated more than a hundred million pounds, as can be seen in the Appendix. Improving understanding of innovation funding need through engagement with innovators and innovation investors is an important next step for innovation programme development.

## 9.2. Designing R&I Strategies across Dimensions of Relevance

The evidence gathered indicates a number of dimensions that may be considered in designing a funding strategy to avoid the risks of choosing specific technologies and provide the best chance of bringing LDES or LCDP technologies onto the system at scale by 2030 or 2035. In this section we list some key aspects arising from our analysis that may be important to consider in innovation programme design.

### LDES or LCDP

One dimension is decisions on funding across LDES and LCDP. There is the potential that only LDES projects might be funded under the low funding scenario. LDES technologies provide two-way flexibility to the grid. LDES also includes a range of electrochemical technologies that may be more modular, hence amenable to rapid innovation, and have more market opportunities to recover revenue. However, LCDP technologies may have complementary value to the system through dispatchability of an energy source that can be replenished without reliance on electricity surplus. The relative value of these two technology groups is a whole system question. Our modelling work and REA of existing modelling studies indicate that LDES and LCDP are not always in direct competition with each other, often meeting different system needs in different ways and complementing each other. This means that advancing one without the other could either leave an unfilled system need or potentially reduce the viability of the one being advanced. However, more work is needed to fully address this systems question. Ultimately, the ability to fund both technology groups is preferable to explore the innovation potential. One option here may be to frame funding around a hydrogen system challenge, where a complete hydrogen storage system with electricity generation returning power to the grid could provide both LDES and LCDP elements.

### Duration

The problem statement for LDES technologies focuses on ultra long durations of 100hrs+, in line with similar definitions (The Faraday Institution). Durations of 8hrs are already supported to an extent through existing market mechanisms (Cap and Floor). Evidence gathered in this project indicates that a number of technology developers are targeting durations approaching our 100hrs focus, but very few technologies are currently within reach of this 100 hrs target. Optionality in funding approach may be provided by ensuring that funding targets technologies that currently meet ultra long durations and those that have the prospect of meeting these challenging durations by 2035. For the longest durations, hydrogen is likely a key technology, and a hydrogen challenge, as mentioned above, would provide for this aspect of a duration orientated funding strategy. This is supported by modelling evidence, that identifies a high system value for hydrogen salt cavern storage.

## Testbed Approach

There are a number of instances where evidence suggests that challenges in technology innovation, systems integration or supply chain improvements would benefit from some form of shared facility or industrial cooperation to reduce innovation costs, share learning and increase speed of innovation. Testbeds (platforms, facilities or demonstration centres designed to provide for rigorous, transparent and replicable testing of new technologies) would allow for testing of technology integration, demonstration, simulation, validation and derisking of technological solutions in controlled grid test systems at sufficient megawatt scale. This emerges in the challenge statements derived through AI analysis of expert elicitation, where collaboration opportunities are seen as challenging, but important to rapid innovation. In one instance, the Culham Science Centre is cited as an exemplar from the fusion research community. In another instance, existing testbed facilities are highlighted, such as the Strathclyde Power Network Development Centre (PNDC). Shared resources such as these could therefore be a focus of planned innovation investment.

This could be achieved through one of two approaches. First, a new facility could be developed and accelerated through innovation funding. This could focus on key areas where there is alignment across innovation needs, such as shared interest in subsurface research facilities or power network testing to forward the systems integration effort across a range of technologies. The challenge here is that facility development may be counter to the rapid deployment required by challenging 2030 timelines.

An alternative approach could be to map existing test bed facilities and encourage sandpit activity and consortium/proposal development that utilises these existing assets in an efficient and integrated way. PNDC and DNV’s Spadeadam facilities are examples of existing testbeds that might provide value in this approach.

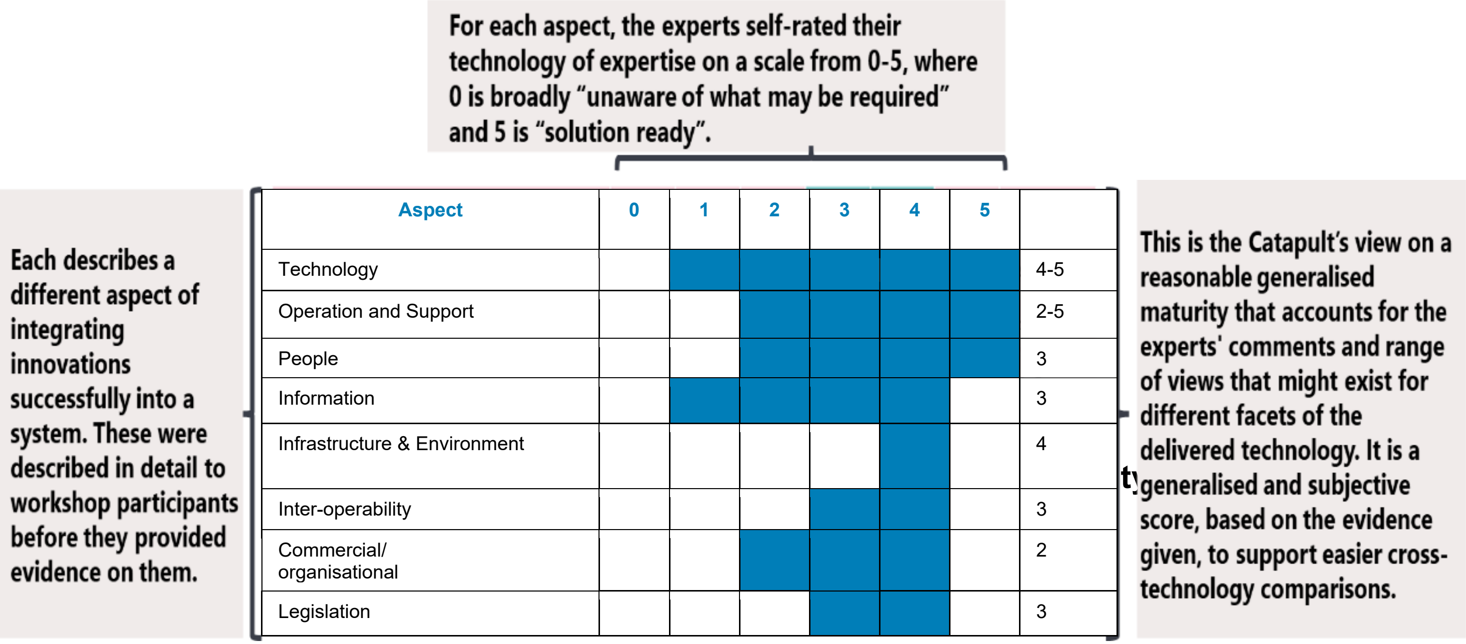
# 10. Appendix - Shortlist Technology Summaries

This appendix includes the summaries of all the shortlisted technologies for LDES and LCDP that were agreed from both the evidence review and the expert elicitation workshops on a range of technologies. Each technology summary features:

**Technology overview** – summarising pertinent information on the technology and its current state in the UK.

**Innovation Challenges** – summarising the key innovation challenges identified in the evidence.

**UK Strengths and Opportunities** – summarising UK strengths that evidence the potential for a sector to rapidly leverage public sector investment to scale towards commercial deployment.



For each aspect, the experts self-rated their technology of expertise on a scale from 0-5, where 0 is broadly "unaware of what may be required" and 5 is "solution ready".

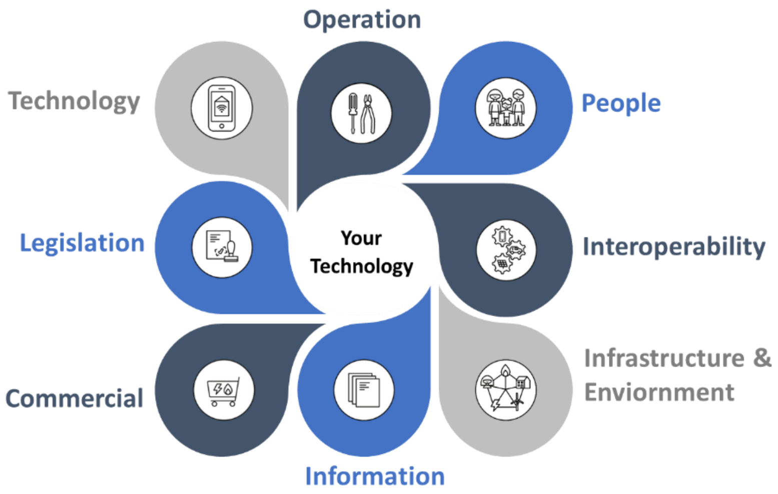
Each describes a different aspect of integrating innovations successfully into a system. These were described in detail to workshop participants before they provided evidence on them.

| Aspect | 0 | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|---|
| Technology | | ■ | ■ | ■ | ■ | ■ | 4-5 |
| Operation and Support | | | ■ | ■ | ■ | ■ | 2-5 |
| People | | | ■ | ■ | ■ | ■ | 3 |
| Information | | ■ | ■ | ■ | ■ | | 3 |
| Infrastructure & Environment | | | | | ■ | | 4 |
| Inter-operability | | | | ■ | ■ | | 3 |
| Commercial/<br>organisational | | | ■ | ■ | ■ | | 2 |
| Legislation | | | | ■ | ■ | | 3 |

This is the Catapult's view on a reasonable generalised maturity that accounts for the experts' comments and range of views that might exist for different facets of the delivered technology. It is a generalised and subjective score, based on the evidence given, to support easier cross-technology comparisons.

## 10.1. Aspects of Integration

### The eight aspects of integration in the current framework



### Technology

Availability and readiness of any new or existing technology required for the solution, and its manufacture, installation and commissioning.

### Operation

Operation, Support and Maintenance of the solution. Disposal and Decommissioning or Withdrawal from service at the end of the planned lifetime. Reliability and Quality (continuous improvement) during the planned lifetime.

### People

Consumer and cultural impact and readiness. Integration of human factors for operation and support of the solution. Training Needs. Job creation. Actors include people, companies, government and communities.

### Information

Availability, accessibility and security of any new or existing information required for the solution, and its management and operation.

### Infrastructure

Availability and readiness of any new or existing infrastructure required for operation or support of the solution.

### Interoperability

Ability of the solution to work in harmony with current or planned parts of the WES and interrelated (sibling) solutions at the ‘system of systems’ level to meet local and national level objectives.

### Commercial

End to end order, manufacturing & logistics process in place. Price & profit sustainability. Resilient to market fluctuations (exchange rates, competitor offerings).

### Legislation

Compliance with existing or planned policy, legislation and regulation. Need for any new or changed policy, legislation and regulation.

## Adjustments to the AoI Framework for ItAA

### Prioritisation of the Aspects

The relevance of the eight aspects within the AoI framework to this ItAA project have been discussed by the project team with the intention to focus the efforts of the team in a rapidly delivered programme of work. Inherently a difficult task as the ambition of the RDMAP programme is to lead to deployment, whilst any underdeveloped aspect could hinder this.

Initially, two aspects were identified for potential deprioritisation: Information and Operation.

**Information** was identified because this is of most relevance to technologies that rely on high quality, real time data flows for successful operation which large, slower-to-respond assets are less likely to be. It was discussed that this could be applied to availability of data on, for example, suitable locations for LDES and LCDP assets though.

**Operation** was identified because it is primarily relating to the point after which deployment has been achieved. However, on discussion it was agreed that there are likely safety and reliability challenges that will need to be addressed prior to investments being made available.

In conclusion, we believe that all aspects are important, and we will take steps in the REAs and Expert Elicitation to ensure that we capture expertise and insight across all aspects where available, whilst ensuring the scope of the work is manageable.

**For the REAs we will:**

- Still include any insights on information and operational aspects that are uncovered in the literature.
- If time constraints are experienced during evidence gathering, we will prioritise evaluation of all but information and operational aspects.

**For the expert elicitation we will:**

- Include all aspects within the workshops, rotating between those we start on to ensure we capture expert views across all areas where available
- Be agile within the workshops and move on from an aspect if those we're speaking to have fewer views on a particular aspect
- Seek to invite a range of experts to engage with us with varying perspectives and experiences on a particular technology

## Adjustments to the Aspects

It was identified during the commissioning of this project that it’s important to include environmental aspects within our framework. We agreed and further refined this into two parts:

- Availability of environmental infrastructure (e.g. Permeatic Basins, access to water or suitable sites for gravitational storage).
- Environmental impact of the technology itself

We considered adding an additional Aspect to the AoI framework but have agreed that the most suitable way to include this factor is through amending the definitions (and associated sub-categories) of the ‘Operation’ and ‘Infrastructure’ Aspects as below:

### Operation

Operation, support and maintenance for the solution. Disposal, decommissioning or withdrawal of service at the end of life. Reliability, *environmental impact*, quality and continuous improvement.

### Infrastructure and Environment

## Technology summaries and tables around seven key criteria highlighted in the methodology Section 3.4

Availability and readiness of any new or existing infrastructure *and environmental* characteristics required for deployment, operation or support of the solutions.

**Adiabatic - Compressed Air Energy Storage (A-CAES)**

Adiabatic CAES (A-CAES) is a near-commercial long-duration storage technology (TRL 8) that captures and re-uses compression heat, giving significantly higher round-trip efficiencies (60–80%) than conventional diabatic CAES. Recent international deployments have taken place in China where three large grid-connected plants (100–300 MW scale) have been operating since 2021–2022— these have accelerated learning on heat-storage integration, system configuration, and cost optimisation. A-CAES enables long lifetimes, high cycling without major degradation, storage durations from hours to weeks (>8 hours), and synchronous-condenser-type grid services. Current costs (LCOS £0.142–£0.337/kWh; capex in power ~£1588/kW; capex in energy ~£3.47/kWh) indicate early-commercial status but strong reduction potential as thermal storage materials, turbomachinery and cavern development reach scale. The technology is heavily dependent on geological suitability - underground caverns or repurposed gas-storage infrastructure are crucial enablers. Above-ground plants remain costlier and are geographically less constrained but require greater footprint (above ground).

**Innovation challenges**

- **R&D and demonstration:** High-temperature TES deployment and whole-system configuration/integration (above-ground and underground salt-cavern) still need optimisation; porous-rock storage remains uncertain around containment, cycling frequency and subsurface response, so further demonstrations and design optimisation are required to improve maturity, efficiency and environmental performance.
- **Infrastructure and supply chain:** Deployment depends on access to suitable underground reservoirs (salt caverns / decommissioned mines), creating geographic siting constraints; above-ground A-CAES faces high costs and space/footprint constraints.
- **Commercial and economics:** Still in a demo-to-early-commercial phase (Ofgem LDES Cap & Floor Stream 2); current LCOS is £0.142–£0.337/kWh, with cost reduction (~60% by 2030) dependent on scale-up and learning from first-of-a-kind projects.

**Policy and regulatory framework:** Reimbursement arrangements and shared/pooled storage models need clarification; regulatory/market frameworks must better support integration with renewable portfolios and participation in energy-market operations.

**UK strengths and opportunities**

- **Resource & Site Endowment:** UK has abundant onshore and offshore salt deposits suitable for underground salt caverns for CAES, with strong potential in areas such as the Cheshire Basin, and good correlation between prospective CAES storage locations and wind-energy resources.
- **Domestic Capability & Project Pipeline:** Presence of domestic CAES developers (e.g., Storelectric) with 40 MW and 500 MW concepts in UK salt-cavern regions indicates an emerging project pipeline and supply chain.
- **Policy & Investment Framework:** A-CAES is categorised as a novel technology under Stream 2 of Ofgem's LDES Cap & Floor scheme, and one project is eligible in track 1 and deliverable by 2030 (TeesCAES, 50 MW).

**Table 16: Readiness level scoring from A-CAES workshop against AoI**

| Aspect | 0 | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|---|
| Technology | | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 4-5 |
| Operation and Support | | | 🟦 | 🟦 | 🟦 | 🟦 | 2-5 |
| People | | | 🟦 | 🟦 | 🟦 | 🟦 | 3 |
| Information | | 🟦 | 🟦 | 🟦 | 🟦 | | 3 |
| Infrastructure & Environment | | | | | 🟦 | | 4 |
| Inter-operability | | | | 🟦 | 🟦 | | 3 |
| Commercial/ organisational | | | 🟦 | 🟦 | 🟦 | | 2 |
| Legislation | | | | 🟦 | 🟦 | | 3 |

**Table 17: Adiabatic -Compressed Air Energy Storage technology summary**

| Criteria | Adiabatic - Compressed Air Energy Storage (A-CAES) [xxvi] |
|---|---|
| TRL (e.g. including for technology as a whole and separate aspects) | TRL: 8 |
| Technical aspects (e.g. capacity / potential output, energy density, storage / discharge duration, dispatchability, ramp rates) | • RTE: 60-80%<br>• Capacity / potential output: 10-100 MW / 100-400 MWh<br>• Energy density: 2-25 kWh/m$^3$<br>• Storage / discharge duration: hours-weeks / >8 hours<br>• Lifetime cycles: 10000 |
| Current cost and learning (cost reduction) potential | • LCOS: £0.142–£0.337/kWh (2030: reduce by 60%)<br>• Capex in power: £1588/kW; Capex in energy: £3.47/kWh; Fixed Opex: £15.88/kW/yr |
| Scalability e.g. technological, economic, geographical specificity and environmental impact / availability of critical components or materials | • Scalability tied to geology or vessel build-out<br>• Optimal geological siting can significantly reduce costs<br>• Stands ready for widespread implementation (Three grid-connected ACAES plants are now in operation in China. The first is a 10 MWe/100 MWhe plant, which has been in operation since September 2021, with air stored in a salt cavern and heat in supercritical water. The second is a 50 MWe/300 MWhe plant, which has been in operation since May 2022, with air storage in a salt cavern, and heat stored in thermal oil. The third is a 100 MWe/400 MWhe plant, which started operation in September 2022, with air storage in an artificial mined rock cavern and heat stored in supercritical water.) |
| UK competitive advantage | • Presence of domestic CAES developers (e.g. Storelectric) with concepts for 40 MW and 500 MW CAES in UK salt-cavern regions and EU PCI status, indicating an emerging project pipeline and supply chain.<br>• UK has geological sites suitable for A-CAES. In practice, 20 TWhe (which would require some 3000 caverns) should be regarded as a strong upper bound on the onshore capacity. |
| Potential deliverability to 2030 and/or 2035 including current or planned policies | • TeesCAES (A-CAES) (50 MW, track 1 in LDES C&F scheme, deliverable by 2030) |
| Potential focus areas and impact of additional innovation spend by 2030 and/or 2035 | • Using thermal energy storage (TES) systems that can operate at high temperatures for better efficiency<br>• System configuration and integration (above and underground systems) optimisation<br>• The potential for storage in porous rocks remains poorly understood in terms of containment, frequency of cycling and response of the subsurface to the storage of large volumes of air<br>• Policy measures are needed to clarify reimbursement arrangements and to enable shared or pooled energy-storage models<br>• Regulatory framework improvement is required to support the effective integration of CAES with renewable energy portfolios and its involvement in energy-market operations |

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[xxvi] (ERM, 2024; Friedel et al., 2026; Storelectric, n.d.; The Royal Society, 2023; U.S. Department of Energy, 2024a)

## Pumped Hydro Storage (PHS)

Pumped hydro storage is a proven mature technology that currently provides the majority (2.9 GW / 27 GWh) of medium-duration (6–24-hour - days) storage in the UK. Pump hydro storage projects have high capital costs (Capex in power: £1526-£2289/kW) and long lead times (takes about five –ten years to build) and are geographically limited. The cap and floor scheme has encouraged PHS developers to put forward projects that would otherwise be difficult to fund. While deployment is shaped by geographical constraints and the civil-works footprint, several innovation pathways—such as hybrid PHS configurations, new materials and structural durability solutions, and large-scale 3D-printing techniques—are emerging to expand feasible sites and support future cost reduction.

### Innovation challenges

- **R&D and optimisation:** PHS could utilise advanced control and optimisation techniques to ensure better integration (co-locate) with variable renewable energy and other storage sources.
- **R&D:** Novel technologies at medium TRLs (6-7) such as the use of high-density fluids & low-head PHS (e.g., RheEnergise) that enable new viable sites and reduce civil-works footprint could be incentivised through trials and demonstrator funding.
- **Long lead times and approval processes:** Construction of PHS is complex and is a large civil engineering endeavour. Development can take 5-10 years, leading to potential cost escalations. Innovations that reduce complexity especially on permitting, environmental impact and approval processes would be welcomed.

**Connectivity:** PHS are often located in remote sites and connection to the wider grid is a significant challenge due to the cost and environmental hurdles of building new, high-capacity transmission lines.

### UK strengths and opportunities

- **Support energy system security:** PHS systems can provide frequency response and black start capability.
- **Market participation:** PHS systems can participate in day-ahead, intra-day and balancing markets; primary/secondary/tertiary reserve provision. PHS systems can access many revenue streams.

**Policy & Investment Framework: The Cap and Floor scheme has shortlisted five potential PHS projects. The largest project is the Earba PHS scheme (Loch Earba, Scotland: 1.8 GW/40 GWh). This highlights the potential support given by the scheme to large-ticket and complex LDES schemes, which ordinarily might be difficult.**

**Table 18: Readiness level scoring from PHS workshop against AoI**

| Aspect | 0 | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|---|
| Technology | | | ■ | ■ | | | 2-3 |
| Operation and Support | | | ■ | ■ | ■ | | 2-4 |
| People | | | ■ | ■ | | | 2-3 |
| Information | | | | | ■ | | 4 |
| Infrastructure & Environment | | ■ | ■ | ■ | | | 3 |
| Inter-operability | | | | | | ■ | 5 |
| Commercial/organisational | | | ■ | ■ | | | 2-3 |
| Legislation | | | ■ | ■ | | | 2-3 |

**Table 19: Pumped Hydro Storage technology summary**

| Criteria | Pumped Hydro Storage (PHS)[xxvii] |
|---|---|
| TRL (e.g. including for technology as a whole and separate aspects) | TRL: 9 |
| Technical aspects (e.g. capacity / potential output, energy density, storage / discharge duration, dispatchability, ramp rates) | • RTE: 70-85%<br>• Capacity / potential output: 100-1000 MW / 1-3 GWh<br>• Energy density: 0.5-2kWh/m$^3$<br>• Storage / discharge duration: hours-days-week / 6-20 hours<br>• Lifetime cycles: 40000-60000 |
| Current cost and learning (cost reduction) potential | • LCOS: £0.09-£0.124/kWh (2030 baseline: £0.02-£0.026/kWh; top10% best innovation portfolios: £0.014-£0.019/kWh)<br>• Capex in power: £1526-£2289/kW<br>Note: the cost can vary strongly, mainly depending on whether a storage reservoir already exists or needs to be built. |
| Scalability e.g. technological, economic, geographical specificity and environmental impact / availability of critical components or materials | • Scalability tied to geographical constraints<br>• Innovation solutions like high density PHS make it more adaptable to various geographical and topographical conditions |
| UK competitive advantage | • UK has existing PHS fleet (2.9 GW)<br>• Policy mechanisms noted with defined Cap & Floor, explicit 8+ h eligibility, and focus on bankability for large-ticket LDES, which many markets lack<br>• |
| Potential deliverability to 2030 and/or 2035 including current or planned policies | • Glenmuckloch PHS (200 MW, track 1 in LDES C&F scheme, deliverable by 2030)<br>• Loch Kemp Storage PHS (660 MW, track 1 in LDES C&F scheme, deliverable by 2030)<br>• Loch na Cathrach PHS (500 MW, track 1 in LDES C&F scheme, deliverable by 2030)<br>• Earba PHS (1.8 GW, track 2 LDES C&F scheme, deliverable by 2033)<br>• Coire Glas PHS (1.45 GW, track 2 LDES C&F scheme, deliverable by 2033) |
| Potential focus areas and impact of additional innovation spend by 2030 and/or 2035 | • Supply chain & modularisation - Standardised design in modular projects / Design & implementation of modular PSH<br>• New configurations & siting options - Underground PSH (e.g. mines, caverns) / Underwater PSH<br>• Civil works, tunnelling & geotech - Tunnel boring / drilling technologies<br>• High-density fluids & low-head PHES – Enabling new viable sites and reducing civil-works footprint (e.g., RheEnergise demonstrator) |

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[xxvii] (Cleantech for Europe, 2025; EsmaeiliShayan, 2025; IEA, 2024; OFGEM, 2025; U.S. Department of Energy, 2023b; White, 2024)

**Hydrogen: Salt cavern storage**

Hydrogen stored in salt caverns can provide large scale (GWh-TWh) multi-week to seasonal storage. Construction of salt caverns is well established and low-cycle salt caverns are at TRL 9, with. individual components such as electrolysis, compressor and fuel cell systems at a similarly high TRL. Several newer technologies such as Proton Exchange Membrane (PEM) electrolysers and fuel cells are at advanced levels of technological readiness, specifically -TRL 9 and TRLs 8-9 respectively. Other more novel technologies such as reversible electrolysers / fuel cells and fast cycle salt caverns (the latter offering weekly-daily cycling at TRLs 5-6) need funding to progress and to impact on upfront installation and operational costs (multi cycling- even daily cycling increases the potential markets that hydrogen could participate in). Salt caverns could take 5-8 years to develop; therefore, an approach to encourage development and construction of multiple salt cavern systems in parallel may be prudent to meet long duration storage capacity targets for 2035.

**Innovation challenges**

- **R&D and optimisation:** Whole-system configuration/integration of hydrogen salt cavern (normal and fast cycle) storage needs optimisation to determine optimal operation, cycling frequency, interaction with other storage technologies and to improve efficiency and operational cost performance.
- **R&D and demonstration:** Optimisation may show the value of fast cycle salt caverns. A fast-cycling salt cavern demonstrator could help push the technology to higher TRL levels and help learning and "de-risk" future investments.
- **Infrastructure costs and constraints:** Deployment depends on access to suitable underground reservoirs (salt caverns / decommissioned mines), creating geographic siting constraints; Above ground, equipment costs relating to electrolysers, compressors and fuel cells are high along with space/footprint constraints.
- **Commercial and economics:** Upfront construction costs for new salt caverns and above ground infrastructure are in the £0.22-£0.61/kWh range, lower for repurposed salt caverns (£0.12/kWh). Potential learnings through improved construction techniques (vertical vs horizontal caverns), optimised above ground equipment selection/sizing (efficiency of PEM electrolysers/fuel cells or even novel reversible fuel cells) and layout. LCOS is £0.008/kWh. - 0.05/kWh and is dependent on several variables such as cycling.
- **Resource & Site Endowment:** UK has potential 100s TWh underground capacity for hydrogen salt cavern storage from three 'onshore' basins (Cheshire, East Yorkshire Wessex).
- **Infrastructure:** Potential repurposing of gas pipeline for hydrogen use. This may help to bypass electricity network constraints and connection delays. Conversion of gas CCGTs to burn 100% hydrogen could lead to substantial savings.
- developments.

  Development of fast-cycle salt caverns have the potential to drive LCOS reduction through greater cycling capability. Alterative arrangements for cushion gas ($CO_2$, $N_2$) could have positive impacts on costs and hydrogen recovery rates.
- **Manufacturing & supply chain readiness:** Producing GWs of hydrogen requires substantial additional electrolyser and fuel cell capacity. There are concerns on procuring electrolysers at scale as there are very few UK manufacturers producing large volumes (e.g. ITM Power).

**Deployment acceleration: It potentially takes 5-8 years to develop a salt cavern storage system. Multiple projects will need to be commissioned in parallel to meet ambitious hydrogen storage targets by 2035.**

**Table 20: Readiness level scoring from Hydrogen salt cavern workshop against AoI**

| Aspect | 0 | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|---|
| Technology | | ■ | ■ | ■ | ■ | ■ | 3 |
| Operation and Support | | | ■ | ■ | ■ | ■ | 3 |
| People | | | ■ | ■ | ■ | | 3 |
| Information | | ■ | ■ | ■ | | | 2 |
| Infrastructure & Environment | | | ■ | ■ | | | 3 |
| Inter-operability | | ■ | ■ | ■ | ■ | | 3 |
| Commercial/ organisational | ■ | ■ | ■ | ■ | | | 2 |
| Legislation | ■ | ■ | ■ | ■ | ■ | ■ | 3 |

**UK strengths and opportunities**

- **Workforce capability & project pipeline:** UK is a world leader in oil and gas technologies with a skilled workforce and well-developed supply chain. Salt Cavern construction is a UK strength. The UK has two hydrogen projects under development (HyKeuper and Aldborough). The technical learnings (underground storage and above ground equipment) will benefit future

- **Legislation:** UK has a fully developed gas regulatory and health & safety framework which should in theory allow for a straightforward transfer to hydrogen systems (experience of ‘Town Gas’).
- **Policy & Investment Framework:** The Hydrogen Storage Business Model (HSBM) is a UK government policy framework designed to incentivise and support the development of large- scale, long-duration hydrogen storage facilities, primarily in geological formations like salt caverns. The first round of the HSBM will support one large-scale project at a TRL of ≥7. The project is expected to be operational from 2031.

**Table 21: Hydrogen Salt cavern storage**

| Criteria | Hydrogen: Salt cavern storage[xxviii] |
|---|---|
| TRL (e.g. including for technology as a whole and separate aspects) | • Low-cycle salt cavern: TRL 9 (~cycling up to 10 times a year)<br>• Fast-cycling salt cavern: TRL 5 – 6 (cycling weekly-daily) |
| Technical aspects (e.g. capacity / potential output, energy density, storage / discharge duration, dispatchability, ramp rates) | • RTE: 18-46%<br>• Capacity / potential output: GWh per cavern (clusters can contain ~ 10-20 caverns - TWh)<br>• Energy density: ~280 kWh/$m^3$ @100 bars and $20^{oc}$ (storage pressure in cavern ~ 40 – 250 bars)<br>• Storage duration: Multi-week - months<br>• Discharge rate / duration: ~1.2 GWh/day |
| Current cost and learning (cost reduction) potential | • Capital cost: £0.22-£0.61/kWh for large, 'new' solution mined salt caverns<br>• Capital cost: £0.12/kWh repurposed existing salt caverns<br>• LCOS: £0.008-£0.05/kWh (LHV conversion; 9 cycles per year; pressure - 250 bars) |
| Scalability e.g. technological, economic, geographical specificity and environmental impact / availability of critical components or materials | • Geographic limitations: Potential 2151 TWh capacity for hydrogen storage from three 'onshore' basins in the UK (Cheshire Basin: 129 TWh East Yorkshire: 1,465 TWh Wessex Basin 557 TWh) - There are studies that reduce this capacity by ~70-90% (due land constraints and differing geological calculations).<br>• Salt is chemically inert, minimal contamination risk.<br>• Integrated siting could be key, if hydrogen power plant or fuel cells are for instance 100 miles away from storage sites this would add to cost of transport.<br>• Risks associated with construction and utilisation of salt caverns are broadly associated with two types of hazards. The first is geological, which may result in ground movement (subsidence), and some seismic activity. The second is the release of gas from either the borehole or the cavern.<br>• Impact assessment on availability of water resource for large-scale electrolysis is vital.<br>• The brine solution (that results from the construction of a salt cavern) needs to be safely disposed.<br>• Cushion gas requirements: 25-30% of total cavern volume. Possible alternatives include $CO_2$ and $N_2$. |
| UK competitive advantage | • UK advantage through gas-production and storage regulatory /safety expertise.<br>• Repurposed gas pipe network could be used to bypass electricity network constraints.<br>• Conversion of gas CCGTs to burn 100% hydrogen could lead to substantial savings (time and money)<br>• UK is a leader in cavern gas storage; one of few countries with operational $H_2$ geological stores (there are 3 caverns in Teesside, primarily used as a feedstock for chemical processes)<br>• High potential to leverage offshore wind resources for hydrogen production and storage (the "North Sea hydrogen project")<br>• Strong subsurface mapping & geoscience capability (British Geological Survey long-running programme on underground energy storage, incl. CAES and hydrogen) |

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[xxviii] (Arup, 2024; Department for Energy and Net Zero, 2023; Hough et al., 2023; Jenkins & Sepulveda, 2021; Liu et al., 2025; The Royal Society, 2023; Williams et al., 2022)

| | |
|---|---|
| Potential deliverability to 2030 and/or 2035 including current or planned policies | • Current projects in development (salt cavern), are HyKeuper (Cheshire, 19 caverns, construction started in 2022 – it will take 10 years to develop) and Aldborough (aiming to complete construction by early 2030s - 8 years development time) this will add 1.2TWh and 0.5TWh storage capacity.<br>• Multiple projects will need to be commissioned in parallel to meet ambitious hydrogen storage targets by 2035. |
| Potential focus areas and impact of additional innovation spend by 2030 and/or 2035 | • Improvement in RTE: focus on equipment such as hydrogen compressors, electrolyser and fuel cell efficiencies.<br>• Fast-cycling storage of hydrogen in caverns is not yet deployed, with questions remaining regarding response of caverns to higher frequency/larger changes in ranges of pressure. |

### Metal-air battery (MAB)

A Metal-air battery (MAB) is an electrochemical cell that uses a metal as the anode and oxygen from the air as the cathode. The metal is oxidised while the oxygen is reduced, generating electricity and forming metal oxides. MAB's have attracted attention as next-generation energy storage systems due to their high theoretical energy densities, lightweight designs, and potential cost-effectiveness. There are many different chemistries such as lithium-air, sodium-air, aluminium-air and magnesium-air. The two chemistries that are further on the technology readiness scale are zinc-air and iron-air. These two chemistries have slightly lower theoretical energy densities than other MABs. Iron-air is the most advanced chemistry and two companies, Form Energy, which was backed by the Department of Energy (USA) and Ore Energy a spin-out from Delft University of Technology (Netherlands) are both at advanced trial stages and pre-commercialisation of their respective systems. Materials like iron and zinc are abundant, safer (lower volatility) and far cheaper than lithium. MABs and in particular, iron air batteries are aiming for costs (~£12-£23/kWh) of one-tenth of comparable lithium-ion batteries.  MABs offer long-duration electricity storage (months), discharged over long periods (100+ hours). A major challenge for all MABs is that prototypes have shown limited rechargeability, performance (electrolyte/electrode) degradation and are therefore currently suited a low number of battery cycle scenarios. Continued cost reduction and commercial progress will depend heavily on targeted innovation across the value chain, including advances in separator materials, improved pack- and system-level engineering, and the development of robust demonstration projects to validate performance at scale.

### Innovation challenges

- **R&D:** A focus on improving RTEs, that are currently far lower than lithium-ion batteries, encouraging novel engineering and chemistries to reduce cycling degradation issues self-discharge issues.
- **Demonstrators:** Competitors in the USA and Netherlands (Form Energy, Ore Energy) are in advanced trial/pre-commercialisation stages for iron-air batteries. The learning accrued will advance their competitive edge (technology, operational and design/costs). The UK must follow this path to ensure UK laboratory success is followed up with demonstrators. No UK companies in this space are at trial/pre-commercialisation stage. Additionally, USA based competitors can tap into large investor capital/funds.
- **Policy and investment:** No MAB's were successful in the first window of the Cap and Floor scheme. This is potentially a great scheme but adjustments on eligibility criteria such as TRLs, grid connections and additions such as valuing longer term storage, could benefit novel battery technologies such as MABs.

### UK strengths and opportunities

- **Strong research base:** The UK has strong expertise in innovation and R&D in general in electrochemical energy storage, and in metal-air batteries (universities).
- **Policy & Funding opportunities**: The UKRI funded The Faraday Institution launched the 'UltraStore Challenge' in 2025. This is a research initiative that seeks radical, early-stage concepts beyond incremental improvements to store energy for months and discharge it for over 100 hours at a target capital cost of under £7.6/kWh ($10/kWh). The eventual aim is commercialisation of the technology with a goal of maximising the economic impact for the UK. MABs are a front runner technology for this challenge.

**Table 22: Metal-air battery technologies summary**

| Criteria | Zinc-air battery [xxix] | Iron-air battery [xxx] |
|---|---|---|
| TRL | TRL: 6-8 | |
| Technical aspects | • RTE: 50-60%<br>• Capacity / potential output: 20kW-50 MW / 0.1-400 MWh<br>• Energy density: >300 Wh/L<br>• Storage / discharge duration: days-weeks / 8-24 hours<br>• Lifetime cycles: 1000-2000 cycles | • RTE: 30-50%<br>• Capacity / potential output: 5-10 MW / 500-1000 MWh<br>• Energy density: >200 Wh/L<br>• Storage / discharge duration: days-weeks / 100 hours<br>• Lifetime cycles: degrading 20-30% after just 300-500 cycles |
| Current cost and learning (cost reduction) potential | • Capex in energy: £46-£191/kWh (2030: £34-160 /kWh)<br>• LCOS: £0.11–£0.17/kWh (2030 with Top 10% innovation portfolios for Zn batteries: £0.06–£0.07/kWh) | • Capex in energy: £12-£23 /kWh (target: £15.3/kWh; general claim "< one-tenth Li-ion" cost)<br>• LCOS: £0.04–£0.06/kWh (2030+ at commercial scale: <£0.04/kWh) |
| Scalability e.g. technological, economic, geographical specificity and environmental impact / availability of critical components or materials | • Same-type and cross-chemistry aggregation<br>• Abundant and cheap raw materials (iron, zinc)<br>• High theoretical energy density and potential cost-effectiveness<br>• Designed for multi-day grid support – low self-discharge | |
| UK competitive advantage | • The UK has strong expertise in innovation and R&D (universities).<br>• MABs are front runner technologies for The Faraday Institution's 'UltraStore Challenge'.<br>• | |
| Potential deliverability to 2030 and/or 2035 including current or planned policies | • Form Energy (USA) is deploying an iron-air battery system by 2026 (1.5 MW/150 MWh) – initially support from US government support and latest funding round raised £307.8m ($405m) (total £0.91bn ($1.2bn) from venture capital).<br>• Ore Energy (Netherlands) connected a FOAK fully operational iron-air battery system ( ~1 MWh) to the electric grid in the city of Delft - July 2025 (first in the world). All materials were sourced from the EU.<br>• Zinc8 Energy Solutions (Canada/USA) is developing a zinc–air energy storage system, with a 100 kW / 1 MWh pilot project in New York – supported by the New York State Energy Research and Development Authority (NYSERDA) as part of state-level long-duration energy storage programmes.<br>• NantEnergy (USA) is deploying rechargeable zinc–air battery systems for telecom and off-grid applications (kW–100 kW scale), with over 3,000 installations across Asia and Africa – supported by private investment and development finance initiatives for energy access.<br>• No UK-based company is yet at the same "near commercial grid-scale LDES" stage<br>• FuturEnergy (Ireland) is facing strong local opposition and an appeal of the granted planning permission for an iron air battery system. Community groups have raised concerns about the project's location, environmental impact, and the novelty of the technology. | |

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[xxix] (Bielewski, 2023; Nazir et al., 2024; U.S. Department of Energy, 2023d)

[xxx] (Agatie, 2023; Form Energy, 2023; Jackson et al., 2024; Sun et al., 2024; Woodford et al., 2022)

| | |
|---|---|
| Potential focus areas and impact of additional innovation spend by 2030 and/or 2035 | • Low RTE is potential area for improvement<br>• Limited cycle life and electrode/electrolyte degradation highlighted<br>• R&D needs on electrode degradation and electrolyte issues (bifunctional catalysts, corrosion mitigation, anode hydrogen-evolution tendency and air cathode carbonate deposition) |

### Flow battery

Flow batteries in this assessment focus on two leading chemistries: vanadium flow batteries (VFB) and zinc–bromine flow batteries (ZBFB). They are positioned as longer-duration electrochemical storage (typically hours to days) with a distinctive architecture in which power and energy are decoupled—power is set by the stack, while total energy capacity is set by the electrolyte tank volume. Current innovation priorities focus on advancing novel active electrolytes, strengthening manufacturing capabilities for scale, and accelerating the discovery of new metrics and materials, all of which underpin efforts to enhance performance and reduce system costs. Flow batteries can support a range of grid-services applications (including backup, ramping, load-following, black-start and voltage regulation) and are described as inherently safer in terms of fire risk, because energy is stored in large tanks of electrolyte fluids and they typically do not contain flammable electrolytes. At the same time, their response is characterised as slower (seconds to minutes) than some alternatives, and energy density is noted as comparatively lower than other battery technologies (particularly for VFB).

### Innovation challenges

- **R&D and performance improvement:** Both chemistries face core technical trade-offs around low energy efficiency and/or low energy density (noted explicitly), and further materials and component innovation is needed to reduce system cost (e.g., via separators / electrodes / manufacturing). For ZBFB specifically, R&D needs include hydrogen evolution suppression and zinc dendrite mitigation.
- **Manufacturing & supply chain readiness:** Critical-material dependence is a constraint—vanadium is a UK critical material (with toxicity concerns, and China dominating a large share of global production) and zinc is also deemed critical by the UK (with China leading global zinc production); in addition, UK supply chain capacity for some electrolyte manufacture is limited.
- **Commercialisation, investment case & market conditions:** VFBs face higher upfront costs and lower energy density, while ZBFBs have lower material costs but more complex hybrid designs with safety concerns. Across flow batteries, revenue-stack components remain uncertain, with financing barriers and a need for mechanism support. There is also concern that the Capacity Market does not reward the LDES capability required to scale.
- **Policy & regulatory framework:** The assessment highlights financing barriers and the need for revenue-stacking / mechanism support to make flow-battery projects investable. It also notes that the Capacity Market does not currently reward the long-duration capability needed for LDES, weakening the business case for scaling beyond short charge/discharge services and increasing the importance of FOAK de-risking support.

**Table 23: Readiness level scoring from flow batteries workshop against AoI**

| Aspect | 0 | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|---|
| Technology | | | | 🟦 | 🟦 | | 3-4 |
| Operation and Support | | | 🟦 | 🟦 | | | 3 |
| People | | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 3 |
| Information | | 🟦 | 🟦 | 🟦 | 🟦 | | 3 |
| Infrastructure & Environment | | | | | 🟦 | 🟦 | 4 |
| Inter-operability | | 🟦 | 🟦 | 🟦 | 🟦 | | 3 |
| Commercial/organisational | | | 🟦 | 🟦 | 🟦 | 🟦 | 3 |
| Legislation | | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 3 |

### UK strengths and opportunities

- **Innovation leadership & R&D ecosystem:** The UK has innovation leadership in next-generation flow-battery chemistries, supported by a strong R&D ecosystem (e.g., The Faraday Institution and the LODES competition), including the Faraday Institution funding for novel flow chemistries (incl. Zn–Br).
- **Domestic capability & demonstrator pipeline:** The UK has recognised capability via Invinity Energy Systems (VRFB), including a planned 20.7 MWh VFB commercial UK site (2026) and £11M DESNZ funding for a 30 MWh system (noted as the largest grid-scale battery manufactured in the UK).
- **Policy & investable deployment pipeline (LDES Cap & Floor)**: Flow batteries classified as Stream 2 “novel tech” under Ofgem’s LDES Cap & Floor scheme, with VFB and VFB/Zinc projects eligible in Track 1 and targeted for 2030 delivery.

**Table 24: Flow battery technologies summary**

| Criteria | Vanadium flow battery[xxxi] | Zinc-bromine flow battery [xxxii] |
|---|---|---|
| TRL | TRL: 8 | TRL: 7-8 |
| Technical aspects | • RTE: 65–85%<br>• Capacity / potential output: hundreds MW/up to GWh<br>• Energy density: 15-35Wh/L<br>• Storage / discharge duration: hours-days/>8 hours<br>• Life cycles: 7000 (20 years) | • RTE: 60-70%<br>• Capacity / potential output: 5-30 MW / 20-100 MWh<br>• Energy density: 40-85 Wh/L<br>• Storage / discharge duration: hours-days / 4-12 hours<br>• Life cycles: >5000 (10 years) |
| Current cost and learning (cost reduction) potential | • Capex in energy: £229–£534/kWh (2030: £153–£382/kWh)<br>• LCOS: £0.12-£0.23/kWh (2030: £0.06-£0.15/kWh) | • Capex in energy: £190–£382/kWh (2030: £115–£268/kWh)<br>• LCOS: £0.12-£0.23/kWh (2030: £0.06-£0.15/kWh) |
| Scalability e.g. technological, economic, geographical specificity and environmental impact / availability of critical components or materials | • Safety – typically do not contain any flammable electrolytes<br>• Low self-charge rate - the segregation of electrolyte in distinct tanks<br>• Same-type and cross-chemistry aggregation<br>• Invinity Energy Systems plans to deliver a 20.7 MWh vanadium flow battery system at its first commercial site in the UK in 2026 | • Scalable to 100 MWh; early-commercial deployment (Redflow 3kW/10kWh; Primus Power 25kW/125kWh; India Energy (California) 3.5 MW/35 MWh)<br>• Zn–Br identified as one of the most mature flow chemistries |
| UK competitive advantage | • Innovation Leadership: Next-Gen Chemistries<br>• Commercial "First-Mover" Advantage<br>• Strong R&D Ecosystem – The Faraday Institution, LODES competition | • Strong general flow-battery capability (incl. Zn–Br), but not a big manufacturing base<br>• The Faraday Institution funding for novel flow chemistries, including zinc-bromide<br>• Evidence of an emerging UK market for Zn–Br |
| Potential deliverability to 2030 and/or 2035 including current or planned policies | • 5 Vanadium Flow Battery projects (0.9 GW in total) are eligible in track 1 in LDES C&F scheme, deliverable by 2030<br>• 15 Vanadium Flow Battery/Zinc Battery projects (2.515 GW in total) are eligible in track 1 in LDES C&F scheme, deliverable by 2030 | • The UK Zn–Br market value is projected to rise roughly 7× between 2024 and 2033 (£13.4m→£97.7m), including a grid-scale segment, indicating that commercial Zn–Br deployments in the UK should exist and expand during the 2030–2035 period, albeit from a small base |
| Potential focus areas and impact of additional innovation spend by 2030 and/or 2035 | • Vanadium material cost risk; supply price volatility for vanadium - "promising cost declines" with advancements and sulfur-based chemistries<br>• Longevity concerns; system failures possible from corrosive electrolytes and plumbing/pumping issue<br>• Develop cost-effective redox couples such as non-aqueous solvents to improve cost and increase voltage window for enhanced energy density<br>• Low energy efficiency and density | • Scope to improve energy efficiency and density<br>• Hydrogen evolution suppression<br>• Zinc dendrite formation mitigation<br>• Further studies needed for scalable, practical implementation<br>• System cost reduction via separators/cathodes/manufacturing<br>• Support schemes needed to de-risk FOAK projects |

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[xxxi] (Jafari et al., 2022; Liu et al., 2023; Supergen, 2025; The Faraday Institution, 2024; U.S. Department of Energy, 2023a)

[xxxii] (Aunedi et al., 2023; California Energy Commission, 2021; Koripella, 2024; Market Strides, 2025)

## 10.2. LCDP Shortlist Technology Summaries

### Definition of Terms for LCDP Technologies

1. **Ramp rate:** This is the operational speed at which power output changes over time, expressed in MW/min or a percentage of nominal power output per unit time (% of MW/min)

2. **Ramp up time:** This is the total time that a power generator takes to reach a certain output from its *minimum stable load* and vice versa while in operation measured in hours or minutes (mins or hrs).

3. **Hot, warm and cold start up time**: Start up time is the time taken from the moment a generator is turned on to the moment it starts supplying power to the grid at its low operating level normally expressed in hours (h). The classification of hot, warm, and cold start-up times depends on the duration for which the power generating unit has been offline. And this duration may be same across similar class of LCDP technologies such as turbines but may differ across different LCPDs such as between turbines and nuclear due to difference in their physical operating principles, thermal constraints, and system roles.

    a. A **hot start** typically refers to restarting the unit after a downtime of approximately ***8 hours or less***, when most residual heat is still retained.
    b. A **warm start** occurs after a shutdown period of ***roughly 8 to 48 hours***, during which partial cooling has taken place.
    c. A **cold start** is required when the unit has been offline for ***more than 48 hours***, by which time the plant has cooled to near ambient conditions and most of its stored heat has been lost.

4. **Minimum stable load**: This is the lowest level of power output at which a generating unit can operate safely and reliably, without causing damage or violating emissions standard expressed in percentage of rated power (%).

5. **Availability factor:** This is the percentage of time a power generation technology is ready to operate and produce electricity during a specific period. It is calculated by dividing the time the plant is available to generate power by the total time in that period, and it is not the same as the capacity factor, which measures how much energy is actually produced compared to the maximum possible.

**Natural gas -fired Combined Cycle Gas Turbine with CCS (CCGT-CCS)**
Both CCGT and CCS are mature technologies, each at TRL 9. The combination of technologies is at TRL 8-9, with no commercial plant operating so far anywhere in the world. However, there are plans in the UK for an 860 MW CCGT with CCS to be built on Teesside (Planning Inspectorate, 2024)(Planning Inspectorate, 2024)(Planning Inspectorate, 2024)(Planning Inspectorate, 2024)(Planning Inspectorate, 2024)(Planning Inspectorate, 2024)(Planning Inspectorate, 2024)(Planning Inspectorate, 2024). CCGT with CCS is relatively low carbon with operational emissions around 31 to 35 $gCO_2e$/kWh. The technology is also dispatchable with full schedulability, combined with moderate flexibility and reliability. Capital costs are estimated at around 1508/kW (CCGT+CCS), with levelised cost of electricity in 2025 of £75-£110/MWh for FOAK (baseload), but costs are highly dependent on load factor. CCGT has higher technical and economic scalability than OCGTs, due to efficiency and large-scale design, with plant sizes between 200 MW – 1+GW. CCS can scale with strong storage infrastructure, carbon pricing, and regulatory support. Retrofitting existing plants could aid near-term growth, but resource intensity and environmental trade-offs require innovation. Overall, CCGT-CCS is deliverable in limited volumes by 2030, constrained by early CCS infrastructure. By 2035, deliverability improves substantially, with several GW possible as $CO_2$ transport and storage expand.

**Innovation challenges**

- **Flexible $CO_2$ capture operation:** Develop downsized capture facilities and optimise compressor/solvent management to maintain ≥70% capture efficiency at low load and during rapid ramping.
- **Advanced control strategies:** Create integrated plant-wide control systems for coordinated operation of CCS, gas turbine, and heat recovery steam generator to minimize energy penalties and enable dynamic response to grid variability.

**Utilising solvent storage:** Design and validate rich and lean solvent storage systems to decouple carbon capture from instantaneous plant output, supporting rapid load changes and improved operational flexibility.

**UK Strengths and Opportunities**

- Strong existing gas pipeline network
- Skilled labour, oil & gas expertise, strong R&D, and cluster opportunities.
- Innovation in solvents, energy efficiency, and flexible CCS operation will drive competitiveness.
- Lower levelized cost of electricity (LCOE) compared to OCGT-CCS
- UK has a global leading geological advantage – having one of the greatest $CO_2$ storage potentials of any country in the world - reaching up to 78 billion tonnes

**Table 25: Readiness level scoring from CCGT-CCS/Hydrogen turbine workshop against AoI**

| Aspect | 0 | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|---|
| Technology | | ■ | ■ | ■ | ■ | ■ | 1-3 |
| Operation and Support | | ■ | ■ | ■ | ■ | ■ | 2-3 |
| People | | | ■ | ■ | ■ | ■ | 2-3 |
| Information | | ■ | | | | | 1 |
| Infrastructure & Environment | | ■ | ■ | ■ | ■ | ■ | 2 |
| Inter-operability | | ■ | ■ | ■ | ■ | ■ | 2-4 |
| Commercial/organisational | ■ | ■ | ■ | ■ | ■ | ■ | 1-2 |
| Legislation | | ■ | ■ | ■ | ■ | ■ | 1-2 |

**Table 26: Natural gas-fired Combined Cycle Gas turbine with CCS technology summary**

| Criteria | Combined Cycle Gas Turbine with CCS (CCGT-CCS) (Solvent Based Post Combustion)[xxxiii] |
|---|---|
| TRL | • CCGT – Mature – TRL 9<br>• CCS (post-combustion with storage, amine absorption with storage) – TRL 9<br>• Overall – Precommercial stage- TRL 8 |
| Technical Aspects | • Carbon intensity of CCGT - CCS : 90 % capture rate – 31 to 35 $gCO_2e/kWh$ (operational)<br>• Dispatchability: Schedulable, moderately flexible (but higher flexibility than OCGT-CCS) and moderately reliable4<br>• Ramp rate – 2- 4 % of maximum load per minute (max ramp: 35-50 MW/min)<br>• Hot start (CCGT with CCS)– 45- 55 mins<br>• Warm start (CCGT with CCS) – 120 mins<br>• Cold start (CCGT with CCS) – 180 mins<br>• Regenerator preheating – Hot: 1-2 hr / Warm: 3-4 hr<br>• Minimum stable load - ~30% of rated power<br>• Ramp up time – hours<br>• Availability factor – 85 - 90% for CCGT without CCS<br>• Technical capacity:<br>CCGT – Operational in the UK (2025): Tens to hundreds of MW<br>CCS – Operational in the UK (2025): No large-scale CCS operation<br>Operational in the world (2025): 50 Mt $CO_2$<br>CCGT-CCS – Operational in the UK & World: None |
| Current cost and learning (cost reduction) potential | **CAPEX:** ~£1508/kW (CCGT + CCS)[5]<br>~£570/kW (CCS) (based on Zero Emissions Platform (ZEP), together with the Global CCS Institute (GCSSI) reports)<br>**OPEX**: Fixed OPEX : £10,250/MW per year,<br>Variable OPEX: £0.93/MWh (2018)<br>**LCOE:** ~£75-£110/MWh FOAK (Plant commissioned in 2025) based on 2012 prices<br>~£76/MWh FOAK (Plant commissioned in 2030) (baseload operation)<br>Lower levelized cost of electricity (LCOE) compared to OCGT-CCS (for baseload operation). As peaking, it could be costlier. |
| Scalability e.g. technological, economic, geographical specificity and environmental impact / availability of critical components | • High technical scalability due to mature, efficient CCGT design (>60% for H-class). Integration of CCS adds complexity but is feasible for large plants.<br>• Economies of scale favour 200 MW–1+ GW plants. CCS increases capital and operating costs, making larger units more cost-effective.<br>• Geographically dependent on proximity to suitable $CO_2$ storage sites and natural gas supply. Grid access also influences siting. |
| UK competitive advantage | • Strong existing gas pipeline network |

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[xxxiii] (Bates & Read, 2018; Bukar & Asif, 2024; Department for Business, 2019; Domenichini et al., 2013; Gridwatch, n.d.; IEAGHG, 2022; Schnellmann et al., 2023; UK Government, n.d., 2018; UK Parliament, 2015)(Bates & Read, 2018; Bukar & Asif, 2024; Department for Business, 2019; Domenichini et al., 2013; Gridwatch, n.d.; IEAGHG, 2022; Schnellmann et al., 2023; UK Government, n.d., 2018; UK Parliament, 2015)

| | |
|---|---|
| | - Manufacture and assemble key gas turbine and CCS components—like pumps, heat exchangers, and modular assemblies—through companies such as Centrax, Tranter International, Whessoe Engineering.<br>- UK has a global leading geological advantage – having one of the greatest $CO_2$ storage potentials of any country in the world – reaching up to 78 billion tonnes<br>- Dedication to developing regional CCS clusters fostering coordinated infrastructure, shared service that accelerates deployment. |
| Potential deliverability to 2030 and/or 2035 including current or planned policies | CCGT is highly scalable, however it is constrained by carbon capture and storage (CCS) lead times and flexibility.<br>CCGT-CCS is deliverable in limited volumes, constrained by early CCS storage and transport infrastructure<br>By 2035, Scalability improves substantially, with several GW possible as $CO_2$ transport and storage expand. |
| Potential focus areas and impact of additional innovation spend by 2030 and/or 2035 | - **Flexible $CO_2$ capture operation:** Develop downsized capture facilities and optimise compressor/solvent management to maintain ≥70% capture efficiency at low load and during rapid ramping.<br>- **Advanced control strategies:** Create integrated plant-wide control systems for coordinated operation of CCS, gas turbine, and heat recovery steam generator to minimize energy penalties and enable dynamic response to grid variability.<br>- **Utilising solvent storage:** Design and validate rich and lean solvent storage systems to decouple carbon capture from instantaneous plant output, supporting rapid load changes and improved operational flexibility.<br>- **Low-energy CCS solvents:** Develop next-generation post-combustion capture solvents to lower energy penalties, solvent degradation, equipment corrosion and reduce costs. |

[4] CCGT with CCS is ***schedulable*** (can be planned ahead of time), ***moderately flexible*** technology, it offers superior flexibility to OCGT with CCS. The OCGT configuration is hampered by the need for an external boiler and a capture plant that cannot match the turbine's fast start times. The integration of carbon capture introduces new complexity, resulting in a moderate reduction in ***reliability***.

Further notes on Dispatchability: Ramping capability is **largely unaffected by CCS** — the primary constraints remain the gas turbine and heat recovery steam generator (HRSG) thermal stresses. CCS mainly affects operation **below ~30% load** or during start-up, not ramp rate.

[5] This costs do not reflect current or future cost increase or reductions for CCS systems.

**Hydrogen Fuelled Gas Turbines**

A hydrogen gas turbine is essentially a modified version of a conventional natural gas turbine, designed to burn hydrogen instead of—or blended with—natural gas. It can provide grid-scale electricity generation in combined-cycle power plant, replacing natural gas to achieve near-zero carbon emissions. There are a significant number of (mostly small-scale) commercial plant in the world running on hydrogen blends (TRL 9), whereas turbines using 100% hydrogen fuel are at best in the demonstration phase (TRL 6-8). The technology has zero operational carbon emissions and is dispatchable, being schedulable, moderate flexible (relative to $H_2$ reciprocating engine) and highly reliable. Electricity costs range from £117/MWh (load following turbines) to £346/MWh (peaking plants) using renewably produced hydrogen at £1.9-£3.4/kg ($2.5- 4.5/kg). The technology can be deployed at various power scales (MWs to 10s of MW for 100% hydrogen). However, Hydrogen gas turbine deployment could be limited by the need for advanced combustion technology to handle hydrogen safely, the higher costs of hydrogen fuel and turbine retrofits, the availability of regional hydrogen production and infrastructure, environmental considerations such as $NO_x$ emissions, and the limited global supply of critical hydrogen-compatible turbine components. If these challenges are overcome then the deployment of hydrogen-capable gas turbines in the UK by 2030 is highly plausible and by 2035 deployment is likely at commercial scale, given both technological progress and supportive policy frameworks.

**Innovation challenges**

- Advanced hydrogen combustion technologies: Developing combustors that can burn pure or higher volume ratios of H2 safely and efficiently with low NOx emissions (dry low- NOx (DLN) burners (currently at TRL 2).
- Hydrogen -Turbine integration: Explore seamless coupling of gas-fuelled turbines with hydrogen supply, storage, and blending infrastructure, including on-site electrolysis and dynamic fuel switching.
- Materials and Thermal Management: Hydrogen flames are hotter and more reactive than natural gas, so advanced alloys, coatings, and cooling strategies are essential to ensure turbine durability, efficiency, and safety.

**UK Strengths and Opportunities**

- Leveraging world-class gas turbine engineering expertise (Rolls-Royce/aerospace) to develop hydrogen technology
- Leading global position in hydrogen turbine research and strategic creation of domestic market demand via industrial clusters and robust hydrogen supply infrastructure (CCUS/offshore wind)

**Table 27: Hydrogen-fuelled Gas Turbine summary**

| Criteria | Hydrogen-fuelled Gas Turbines[xxxiv] |
|---|---|
| TRL | • **Gas Turbine** – Mature TRL 9<br>• **Gas turbines with low $H_2$ blends (up to 30%) with natural gas** – TRL 8-9 {Diffusion Combustion Technology}<br>• **Pure Hydrogen adapted Gas turbines** – TRL 6-7 |
| Technical capacity | • **Carbon intensity -** 0 $gCO_2e/kWh$ (operational for pure adapted gas turbine). Life-cycle emissions highly variable and dependent on the technologies (and fuels) used to produce the hydrogen.<br>• **Efficiency:** 42% for natural gas fuelled OCGT but slightly higher hydrogen fuelled OCGT<br>▪ 62-65% for natural gas fuelled CCGT but slightly higher hydrogen fuelled CCGT<br>o (based on the effects of hydrogen co-firing with natural gas on thermal efficiency)<br>• **Dispatchability:** Schedulable, moderate flexible (relative to $H_2$ reciprocating engine) and highly reliable[8,9]<br>• **Ramp rate:** Hydrogen gas turbines are expected to maintain ramp rates comparable to natural gas units (e.g., OCGT: 5–33%/min; aero-derivatives: 87–120%/min). Hydrogen's faster flame speed may enable slightly quicker transient response in the turbine itself, though overall plant ramping is limited by control systems and safety constraints.<br>• **Hot start-up times** – (e.g., 5–30 minutes for OCGT; 30–70 minutes for CCGT) are generally similar or marginally faster than natural gas turbines due to hydrogen's high reactivity.<br>• **Warm start** – no data available<br>• **Cold start** – slower for hydrogen turbines—up to ~180 minutes for CCGT—because the fuel system must undergo a time-consuming inert gas purge to prevent flashback and ensure safe fuel admission.<br>• **Minimum stable load –** Modern natural gas fuelled turbines can operate reliably down to 10–15% of rated power, $H_2$ turbines may need to maintain 40–60% load unless advanced combustor designs are used. Hydrogen turbines face higher minimum stable loads (MSL) than natural gas units due to increased risk of flashback and combustion instability at low output<br>• **Ramp up time** – minutes to hours<br>• **Availability factor** – no specific data available, but gas turbines running on natural gas typically have availability factors > 85%.<br>• **Technical capacity:**<br>o Hydrogen and Natural gas blends – Hundreds of MW<br>o Pure Hydrogen fuelled gas turbines- Tens of MW<br>• Gas turbines have advantages of lower emission capability, less down-time per machine, simple design, compact equipment and better suitability for continuous operation compared to gas reciprocating engines |
| Current cost and learning (cost reduction) potential | £117 (load following turbines) – £346(peaking plants)/MWh (LCOE) with renewable hydrogen between £1.9-£3.4/kg<br>£710,000/MW (CAPEX)<br>The cost of capacity and not generation cost according to government report for 100% Hydrogen CCGT: £101-£121/kW at 1000MW at 500hrs/year (2025 commissioning dates) |

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[xxxiv] (Aerospace Technology Institute, 2022; Burgess, 2025; Dennis et al., 2013; Department for Business, 2021a; ETN Global, 2024; GE Vernova, n.d.; Hanwa, 2023; Mitsubishi Power Americas, n.d.; Sintef, n.d.; SSE, 2025; UK Government, 2021)

| | |
|---|---|
| Scalability e.g. technological, economic, geographical specificity and environmental impact / availability of critical components | High Unit Scalability and can be deployed at various power scales (tens of MW to MW) - from small decentralized to large centralised systems to meet local or expanded large grid scale plants<br>However, Hydrogen gas turbine scalability is influenced by the need for advanced combustion technology to handle hydrogen safely, the higher costs of hydrogen fuel and turbine retrofits, the availability of regional hydrogen production and infrastructure, environmental considerations such as NO$_x$ emissions, and the limited global supply of critical hydrogen-compatible turbine components |
| UK competitive advantage | The UK's advantage lies in its dual strategy:<br>Leveraging world-class gas turbine engineering expertise (Rolls-Royce/aerospace) to develop hydrogen technology<br>Leading global position in hydrogen turbine research and strategic creation of domestic market demand via industrial clusters and robust hydrogen supply infrastructure (CCUS/offshore wind) |
| Potential deliverability to 2030 and/or 2035 including current or planned policies | • The delivery of hydrogen-capable gas turbines in the UK by **2030 is highly plausible** and by **2035 is likely at commercial scale**, supported by both technological progress and active policy frameworks<br>• Most new and existing gas turbines can already operate efficiently on natural gas and hydrogen blends up to 50% or more by volume with minimal retrofitting.<br>• The delivery of 100% hydrogen-fuelled industrial-scale gas turbines is progressing from demonstration to pre-commercial phase with projects such as HYFLEXPOWER and SSE's "Mission H2 Power" collaboration for the SGT5-9000HL turbine, indicating probable commercialisation by 2030. This is supported by the UK's target of 10 GW of low carbon hydrogen production |
| Potential focus areas and impact of additional innovation spend by 2030 and/or 2035 | • **Advanced hydrogen combustion technologies**: Developing combustors that can burn pure or higher volume ratios of H2 safely and efficiently with low NOx emissions (dry low- NOx (DLN) burners (currently at TRL 2).<br>• **Hydrogen -Turbine integration:** Explore seamless coupling of gas-fuelled turbines with hydrogen supply, storage, and blending infrastructure, including on-site electrolysis and dynamic fuel switching.<br>• **Materials and Thermal Management:** Hydrogen flames are hotter and more reactive than natural gas, so advanced alloys, coatings, and cooling strategies are essential to ensure turbine durability, efficiency, and safety. |

[8] Reciprocating Engines offer superior Flexibility and Schedulability due to their modular design, low thermal inertia, and minimal start/stop time constraints, allowing for extremely fast ramp rates (100% per minute) and operation at very low minimum loads. Gas Turbines provide slightly higher Reliability and are better suited for sustained, high-power baseload operation because their large, high-temperature components have better longevity in continuous use, though they are slower to ramp up (20-50% per minute) due to strict thermal stress limitations.

[9] Hydrogen turbines are equally schedulable as natural gas turbines but depend on fuel availability and start-up procedures. Natural gas fuelled turbines are proven and highly flexible, while hydrogen fuelled turbines could respond faster but face flame stability and combustor design challenges. In terms of reliability, Natural gas fuelled turbines are well-established with decades of experience, whereas hydrogen fuelled turbines are emerging with unproven long-term performance and fuel-handling issues.

**Hydrogen Fuelled Reciprocating engines (H2-ICE)**

A hydrogen-fuelled reciprocating engine is an internal combustion engine that uses hydrogen gas as its primary fuel, igniting it within cylinders to produce mechanical power. It can be used for power generation as a flexible and clean alternative to traditional fossil-fuel engines, providing backup or peak-load power. The technology is currently at TRL 7-9, with projects worldwide moving from demonstration to commercial deployment for small plant sizes and hydrogen/gas blends. The technology is zero carbon in operation and dispatchable, as it is fully schedulable, highly flexible (relative to gas turbines) and moderately reliable. It is also moderately scalable. Individual engine units are typically limited to around 10–15 MW due to mechanical stress, combustion instability, and thermal constraints associated with hydrogen combustion. However, overall capacity can be effectively increased by deploying multiple standardised engines in parallel, enabling flexible system-level scaling especially if not operating in a firm mode. Slow coordination and unclear allocation processes for hydrogen types create investment uncertainty. Current subsidies do not support intermittent hydrogen production. While specific policies to support deployment of hydrogen reciprocating engines remain limited, the UK's 10 GW hydrogen production target by 2030, ongoing allocation rounds, and government funding, combined with recent technical advances in hydrogen internal combustion engines, make it realistic that the technology could be deployed at commercial or near commercial scale by 2035

**Innovation challenges**

- **Advanced combustion systems:** Controlling hydrogen's high flame speed and temperature to prevent pre-ignition, knocking, and limit $NO_x$ emissions.
- **Blending flexibility:** Maintaining stable operation with variable hydrogen-natural gas blends during transition periods.
- **Materials and durability:** Mitigating hydrogen embrittlement, thermal stress, and component wear for long-term reliability.

**UK Strengths and Opportunities**

The UK's advantage lies in its engineering expertise and R&D capability and investment, which supports the development of hydrogen reciprocating engine technology, alongside domestic hydrogen supply and industrial clusters that create early market demand.

**Table 28: Hydrogen fuelled Reciprocating Engines technology summary**

| Criteria | Hydrogen fuelled Reciprocating Engines (H2-ICE)[xxxv] |
|---|---|
| TRL | Engines capable of operating at low to moderate natural gas blend, TRL 7-9<br>Higher blend or 100% hydrogen, 8-9 |
| Technical capacity | **Carbon intensity -** 0g$CO_2$e/kWh (operational, with pure hydrogen engines). Life-cycle emissions highly variable and dependent on the technologies (and fuels) used to produce the hydrogen.<br>**Efficiency**: 48-50% {typical engines between 2.5- 20 MW)<br>**Dispatchability:** Schedulable, highly flexible (relative to gas turbines) and moderately reliable[8]<br>**Ramp rate:** 5 MW/min<br>**Hot start** – 3 -10 mins<br>**Warm start** – *no data available*<br>**Cold start –** 10 – 15 mins<br>**Minimum stable load –**<br>**Ramp up time** – seconds to minutes<br>**Availability factor** – *no data available*<br>**Technical capacity:** Hundreds of kW – Tens of MW (23 MW- Wärtsilä systems) (Commercially available)<br>Higher power capacity (MW) in demonstration/precommercial stage.<br>Gas engines compared to gas turbines include higher thermal efficiency in simple cycle mode, lower capital costs for small schemes (<10 MWe), better suitability for variable load applications, greater robustness to fuel impurities, greater tolerance to high ambient temperatures and lower fuel pressure requirements and fast start up time. |
| Current cost and learning (cost reduction) potential | LCOE: £342-£456 () (INNIO, 2023); no cost of hydrogen fuel provided for these value |
| Scalability e.g. technological, economic, geographical specificity and environmental impact / availability of critical components | • Hydrogen-fuelled reciprocating engines are **moderately scalable**. Individual engines are typically limited to **10–15 MW** due to mechanical stress, combustion instability, and thermal constraints of hydrogen combustion. Overall capacity can be scaled by deploying multiple standardized engines in parallel, enabling flexible system-level expansion (e.g., Wärtsilä systems).<br>• Scalability is further influenced by **economic and infrastructural factors**, including the high cost of hydrogen-compatible components, fuel storage systems, and safety requirements.<br>• **Geographical scalability: H2-ICE** Can be deployed modularly across distribution sites, but large-scale plants require stacking multiple engines, increasing footprint and relying on proximity to reliable hydrogen supply or on-site production |
| UK competitive advantage | The UK's advantage lies in its engineering expertise and R&D capability and investment, which supports the development of H2-ICE, alongside domestic hydrogen supply and industrial clusters that create early market demand |

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[xxxv] (Brainport Eindhoven, n.d.; Department for Energy Security & Net Zero, 2024; DEUTZ, n.d.; Wartsila, n.d.)

| | |
|---|---|
| Potential deliverability to 2030 and/or 2035 including current or planned policies | While specific policies for hydrogen reciprocating engines remain limited, the UK’s 10 GW hydrogen production target by 2030, ongoing allocation rounds, government funding, and recent advances in hydrogen internal combustion engines make it plausible that $H_2$ICE could reach commercial or near-commercial scale by 2035. Deployment will likely centre on flexible, modular, or distributed power generation, with feasibility hinging on hydrogen supply growth, site infrastructure, engine/demonstration investment, and supportive regulation. |
| Potential focus areas and impact of additional innovation spend by 2030 and/or 2035 | • **Advanced combustion systems:** Controlling hydrogen’s high flame speed and temperature to prevent pre-ignition, knocking, and limit $NO_x$ emissions.<br>• **Blending flexibility:** Maintaining stable operation with variable hydrogen-natural gas blends during transition periods.<br>• **Materials and durability:** Mitigating hydrogen embrittlement, thermal stress, and component wear for long-term reliability. |

### BECCS Power

BECCS integrates biomass combustion/gasification with $CO_2$ capture and storage. It is a technically feasible and deployable option for dispatchable low-carbon power and large-scale carbon dioxide removal and is generally considered to be at a pre-commercial stage (TRL 7-8). It is a negative emissions technology, but with highly uncertain and variable life-cycle emissions ranging from -1137 to -647 $gCO_2e$ /kWh according to one study for the UK. It also dispatchable, being schedulable, moderately flexible (less flexible than biomass power due to constraints imposed by the CCS plant) and moderately reliable. Electricity generation costs are higher than for biomass power (without CCS) and are in the range £114/MWh to £251/MWh (NOAK) depending on the technology. FOAK costs could be 15% higher. BECCS power is technologically scalable at the plant level and can integrate with standard CCS systems, but overall deployment is highly constrained by sustainable biomass availability and supply-chain limits. The CCS integration challenges are at least as significant as for gas-CCS, which is a more mature and standardised technology. The social legitimacy of BECCS projects needs to be shaped by engaging national government and regional/local authorities, relevant industry actors including energy producers, regulators, NGOs, local communities and landowners. Overall, BECCS power has low practical deliverability by 2030, as no UK project has yet reached Final Investment Decision (FID) and the Drax conversion timeline has slipped to the early 2030s due to uncertainty over government contracts and $CO_2$ transport and storage (T&S) infrastructure. Larger-scale deployment by 2035 is possible, but remains highly contingent on policy commitment, sustainable biomass supply, and timely cluster infrastructure development**.**

### Innovation challenges

- **Advanced biomass conversion:** Increase efficiency and performance through high-efficiency gasification, CHP integration, and innovative thermochemical or biological methods.
- **Sustainable feedstock supply:** Secure reliable, high-quality biomass to enable scalable, long-term deployment.
- **Lifecycle emissions optimisation:** Assess and reduce carbon impacts across domestic and imported biomass supply chains.
- **Low-energy CCS solvents:** Develop next-generation post-combustion capture solvents to lower energy penalties and reduce costs.
- **$CO_2$ capture integration:** Design retrofit solutions for existing biomass plants without disrupting operations.

### UK Strengths and Opportunities

- Existing large, dedicated biomass power plants (such as Drax and Lynemouth) which significantly lowers first-mover operational risk
- Global leadership in BECCS power deployment
- Proximity to extensive offshore geological storage in the North Sea enables co-location of capture, shipping and storage infrastructure
- Dedication to developing regional CCS clusters fostering coordinated infrastructure, shared service that accelerates deployment.

**Table 29: BECCS power technology summary**

| Criteria | BECCS Power[xxxvi] |
|---|---|
| TRL | Precommercial Stage - TRL 7-8 |
| Technical Aspects | • **Carbon intensity of BECCS Power -** 0 g$CO_2$e/kWh (operational). Life-cycle emissions are highly variable and uncertain but could be significantly negative e.g. in the range -1137 to -647 g$CO_2$e /kWh<br>• **Dispatchability:** Schedulable, moderately flexible (less flexible than biomass power) and moderately reliable[6]<br>• **Ramp rate:** 1- 5% of power capacity per minute<br>• **Hot start** - *data unavailable*<br>• **Warm start** – *data unavailable*<br>• **Cold start –** *data unavailable*<br>• **Minimum stable load – slightly higher than** 30 – 40% of rated power for biomass<br>• **Ramp up time** – *data unavailable*<br>• **Availability factor** – likely 80 - 85%<br>• **Technical capacity**: Operational in the UK: None<br>Projected capacity: Hundreds of MW. (Drax Power Plant: 2 × 460 MW) |
| Current cost and learning (cost reduction) potential | CAPEX and LCOE of Bioenergy with different CCS options (Ricardo, 2020)<br>• £36/MWh CAPEX, LCOE: £114-£175/MWh (Chemical looping) – NOAK[7]<br>• £45/MWh CAPEX, LCOE: £130-£191/MWh (Carbonate looping) – NOAK<br>• £47/MWh CAPEX, LCOE: £149-£230/MWh (Post Combustion capture) - NOAK<br>• £53/MWh CAPEX, LCOE: £157-£237/MWh (Oxy fuel combustion) - NOAK<br>• £64/MWh CAPEX, LCOE: £173-£251/MWh (IGCC plant) – NOAK<br>The range of LCOE prices is based on prices of fuel (low fuel price- £15/MWh, central fuel price; £25/MWh and high fuel price ; £30.4/MWh)<br>Overall, this means that the LCOE for FOAK plant are likely to be about 15% higher than those for NOAK plan (FOAK starting in 2029; NOAK starting in 2031) |
| Scalability e.g. technological, economic, geographical specificity and environmental impact / availability of critical components | • BECCS power is technologically scalable at the plant level and can integrate with standard CCS systems, but overall deployment is tightly constrained by sustainable biomass availability and supply-chain limits.<br>• Integration challenges are at least as significant as for gas-CCS, which is a more mature and standardised technology. |
| UK competitive advantage | • Existing large, dedicated biomass power plants (such as Drax and Lynemouth) which significantly lowers first-mover operational risk<br>• Global leadership in Power BECCS Deployment<br>• Proximity to extensive offshore geological storage in the North Sea enables co-location of capture, shipping and storage infrastructure<br>• Dedication to developing regional CCS clusters fostering coordinated infrastructure, shared service that accelerates deployment. |

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[xxxvi] (Department for Energy Security & Net Zero, 2023; Department of Energy Security and Net Zero, 2025b; García-Freites et al., 2021; Odeh, 2020)

| | |
|---|---|
| Potential deliverability to 2030 and/or 2035 including current or planned policies | • BECCS power has low practical deliverability by 2030, as no UK project has yet reached Final Investment Decision (FID).<br>• Drax is the only advanced proposal, but its original timeline has slipped due to uncertainty over government contracts and $CO_2$ transport and storage (T&S) infrastructure.<br>• Development consent (planning approval) exists, yet construction cannot begin until long-term support and transport and storage (T&S) access are secured.<br>• The first BECCS unit could feasibly enter service in the early 2030s if these conditions are met.<br>• Larger-scale deployment by 2035 is possible, but remains highly contingent on policy commitment, sustainable biomass supply, and timely cluster infrastructure development. |
| Potential focus areas and impact of additional innovation spend by 2030 and/or 2035 | • **Advanced biomass conversion:** Increase efficiency and performance through high-efficiency gasification, CHP integration, and innovative thermochemical or biological methods.<br>• **Sustainable feedstock supply:** Secure reliable, high-quality biomass to enable scalable, long-term deployment.<br>• **Lifecycle emissions optimisation:** Assess and reduce carbon impacts across domestic and imported biomass supply chains.<br>• **Low-energy CCS solvents:** Develop next-generation post-combustion capture solvents to lower energy penalties and reduce costs.<br>• **$CO_2$ capture integration:** Design retrofit solutions for existing biomass plants without disrupting operations. |

## Nuclear Power (SMRs)

SMRs are compact nuclear fission reactors (10– ~500 MWe) with components that are factory-built and shipped to site, reducing construction time and cost. Designs incorporate passive safety systems and simplified architecture. There are a few demonstration reactors around the world and plans for the UK’s first SMR to be built at Wylfa. The TRL is assessed at 7 to 8. SMRs are zero carbon in operation and fully dispatchable, being schedulable and highly flexible and reliable. Costs are expected to be cheaper than conventional nuclear with one estimate of electricity costs at £60-£75/MWh (FOAK), but FOAK projects face high capital and financing risks. Long-term economic viability depends on serial production, export markets, and blended financing models (e.g., public-private partnerships) and appropriate regulatory structures. The technology is modular and has scalability multiple modules can be combined for higher output. SMRs have a smaller footprint, lower water needs and can be placed on existing industrial sites or remote locations where conventional plants would not be suitable. However, public acceptance could be a major barrier. There is a strong institutional, financial and technical momentum supporting a credible path for the deployment of at least one SMR in the UK by 2035 with a modestly sized first fleet a few years later.

### Innovation challenges

- **Advanced manufacturing**: These include advanced manufacturing & materials and next-generation nuclear fuels to improve efficiency and safety.
- **Factory manufacturing and design standardisation:** Establish full-scale, automated nuclear component factories capable of serial production of reactor modules, steam generators, and vessels. This would reduce CAPEX costs and enables competitive unit economics and rapid capacity deployment.

### UK Strengths and Opportunities

- Small modular reactor (SMR) benefit from strong government support and funding match with private investment (Rolls Royce) to drive their rapid deployment
- Rolls Royce is building SMR of 470 MWe and its technology gives the UK control over the design, IP and manufacturing

**Table 30: Conventional nuclear power**

| Criteria | Gen III- Small Modular Reactor (SMR)[xxxvii] |
|---|---|
| TRL | 7-8 |
| Technical capacity | **Carbon intensity -** 0 $gCO_2e$/kWh (operational). Life-cycle emissions are very low; around 6 to 13$gCO_2e$/kWh<br>**Dispatchability:** Schedulable, highly flexible and highly reliable[12]<br>**Ramp rate:** 5 – 10% per minute<br>**Hot start** – 1- 2 hours<br>**Warm start** – *no data available*<br>**Cold start –** 3-4 days<br>**Minimum stable load –** 10 – 20% of rated power<br>**Availability factor** – 85-95% (projected)<br>**Technical capacity:** Operational in the UK: None (2025)<br>Projected (UK): 1.4 GW total (3 × 470 MWe) [Rolls Royce] |
| Current cost and learning (cost reduction) potential | LCOE: £60 - £75/MWh (FOAK)<br>CAPEX: £1.8m-£6.5m /MW(FOAK)<br>(estimated made for 2025) |
| Scalability e.g. technological, economic, geographical specificity and environmental impact / availability of critical components | • High and flexible modular scalability.<br>• Smaller footprint, lower water needs and can be placed on existing industrial sites or remote locations where conventional plants are impossible. |
| UK competitive advantage | • Small modular reactor (SMR) benefit from strong government support and funding match with private investment (Rolls Royce) to drive their speedy deployment<br>• Rolls Royce is building SMR of 470 MWe also its technology gives the UK control over the design, IP and manufacturing |
| Potential deliverability to 2030 and/or 2035 including current or planned policies | There is a strong institutional, financial and technical momentum supporting a credible path for SMRS in the UK by 2030-2035 with modestly sized first fleet by mid 2030s. |
| Potential focus areas and impact of additional innovation spend by 2030 and/or 2035 | • **Advanced manufacturing and supply chain**: These include advanced manufacturing & materials and next-generation nuclear fuels to improve efficiency and safety. Also, strengthen supply chains for critical components, localise manufacturing of non-safety parts, and develop flexible logistics for remote sites<br>• **Factory manufacturing and design standardisation:** Establish full-scale, automated nuclear component factories capable of serial production of reactor modules, steam generators, and vessels. This would reduce CAPEX costs and enables competitive unit economics and rapid capacity deployment.<br>• **Regulatory and Licensing Innovation:** Develop fit-for-purpose licensing frameworks, streamlined approval processes, and international harmonisation of safety, siting, and waste regulations to reduce time and cost to market and FOAK risks |

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[xxxvii] (Department for Business, 2021b; Department of Energy Security and Net Zero, 2025a; Lewis et al., 2016; Rolls Royce, 2025)

[12] Small Modular Reactors (SMRs) offer higher flexibility and better operational Schedulability than large reactors due to their smaller cores, lower thermal inertia, and modular multi-unit layouts. This modularity also reduces outage risk by allowing staggered maintenance. Large nuclear plants remain the most proven in reliability, but SMRs are engineered to match or exceed their performance through simplified systems and passive safety, with actual reliability verified as fleets scale.

## 10.3. International Examples of Public Funding Initiatives to Advance LDES and LCDP

As an additional activity to the REAs, we carried out desk research to identify illustrative examples of international funding interventions to stimulate the development of LDES and LCDP technologies, helping us to anchor the scale of costs associated with different types of initiatives that could be supported by innovation funding. These examples are set out for LDES and LCDP in the tables below.

**LDES: international examples of investment in demonstration projects**

| Geographical location, timescale | Technology information (durations if applicable) | Public funding invested (current GBP equivalent[xxxviii], original currency, year, type) | Purpose of funding | Potential or actual outcomes | Source / reference(s) |
|---|---|---|---|---|---|
| EU (Horizon project launched in 2025/2026) | LDES (next generation batteries at low TRL levels with 10+ hours storage durations) | **£13 million**<br>EUR (2025), 15 million | Covers cost-effective next-generation batteries for long-duration stationary storage at low TRL levels. | Potential outcome: Energy storage system cost (CAPEX) lower than 50 €/kWh; | (European Commission, 2025c)European |

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[xxxviii] USD to GBP currency conversions based on: https://www.oecd.org/en/data/indicators/exchange-rates.html ; EUR to GBP currency conversions based on: https://ec.europa.eu/eurostat/databrowser/product/page/TEC00033 ; Japanese YEN to GBP currency conversion based on: https://www.ons.gov.uk/economy/nationalaccounts/balanceofpayments/timeseries/ajfo ; Danish DKK and Canadian CAD to GBP currency conversions based on https://www.exchangerates.org.uk/DKK-GBP-spot-exchange-rates-history-2021.html and https://www.exchangerates.org.uk/CAD-GBP-spot-exchange-rates-history-2025.html respectively. Once converted to GBP, pre-2025 values were adjusted for inflation to November 2025 GBP using an inflation calculator: https://www.bankofengland.co.uk/monetary-policy/inflation/inflation-calculator

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| | | | | Projected lifetime of 20 years with minimised self-discharge in operating and ambient conditions typical of the selected application;<br>Minimum round-trip efficiency of 50% at energy storage system (AC) level and 75% at cell level;<br>Large-scale deployment in the long term of reliable materials supply and manufacturing of cell or reaction stack. | Commission (2025c) (2025c) |
| EU (Horizon project launched in 2025/2026) | LDES general (>12 hours discharge) | **£12 million**<br>EUR (2025), 14 million | To develop advanced integrated models and tools for optimising LDES within cross-regional energy networks. | Potential outcome: To deliver operational guidance on cross-regional strategies to combine diverse clean LDES and cross-sector integration, optimising co-location/hybridisation with renewable sites, industrial hubs, and districts to support the grid. | European Commission (2025a) |
| EU (Horizon project launched in 2023) | LDES (targets innovative chemical, mechanical, and thermal storage solutions) | **£12.6 million**<br>EUR (2023), 14 million | To foster European leadership in sustainable energy solutions by developing novel long-term electricity storage technologies. | To enhance pioneering long-term electricity storage projects. | European Commission (2023) |
| Netherlands (project launched in 2025) | Battery systems that can store renewable energy for 8 to 100 hours. | **£18 million**<br>USD (2025) 23 million grant | To foster building of a coherent, national programme where innovative battery materials and components, production technology, and recycling approaches are assessed. | Potential to build the knowledge, technology and demonstrators needed for commercialisation of long duration battery systems and position the Netherlands as an international leader in sustainable energy storage. | SLDBatt.(2025) |
| Spain (launched in 2023, online by 2026) | Standalone energy storage projects, thermal energy storage and reversible pumped hydro. | **£242 million**<br>USD (2025): 310 million in grants | Grants for developers to test and deploytechnologies ahead of grid scale deployment. | Aimed at bringing forward the time over which the technologies can be deployed without subsidy. | LDES Council (2025) |
| UK (2021-2025) | Innovative LDES projects (including electric, thermal and power-to-x; lithium ion and pumped hydro out of scope). | **£69 million**<br>Capital funding available across 2 competition streams. | Stream 1 aimed to accelerate commercialisation of projects through to actual demonstrations in operational environments. Stream 2 aimed to accelerate commercialisation through to first-of-a-kind (FOAK) full-system prototypes in relevant or operational environments. | Stream 1: 6 projects were funded, covering power-to-X energy storage and electrical energy storage.<br>Stream 2: 26 projects were funded, covering thermal energy storage, power-to-X energy storage and electrical energy storage. | Department for Energy Security and Net Zero (2023) |
| US (launched in 2020) | LDES technology (general): electrochemical, mechanical, thermal, chemical carriers, or any combination that has the potential to meet the necessary duration and cost targets for grid flexibility (focus on 10+ hours duration). | **£1.1 billion**<br>USD (2022): 1.16 billion | To achieve target storage costs at £0.05/kWh or lower by 2030. | Following this, the DOE launched the USD 75 million Grid Storage Launchpad at Pacific Northwest National Laboratory, supporting energy storage technologies from materials screening to prototype testing and long-term system validation. | U.S. Department of Energy (2021) |

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| US (2023/24) | LDES general (US DOE includes technologies that provide 10 or more hours of energy storage discharge at full power). | **£253 million**<br>USD (2025): 325 million grant | To advance pre-commercial technologies and scale up commercial technologies. | Nine projects received a total of USD 286 million. Another six projects secured USD 39 million under the “LDES Demonstrations Lab Call” for deployment at national labs. | LDES Council (2025)Error! Bookmark not defined. |
| US (2024) | Non-lithium ion LDES (10+ hours discharge and stationary storage)- electrochemical, mechanical and thermal. | **£81 million**<br>USD (2024) 100 million | To support pilot-scale energy storage demonstration projects.<br>The Office of Clean Energy Demonstrations planned to fund 5-15 projects, offering USD 5-20 million each with a 50% minimum non-federal cost share per project. | Potential outcome: to use this funding to move energy storage technologies closer to commercial viability and utility-scale deployment. | U.S. Department of Energy (2024c) |
| US (California, launched in 2020) | LDES (focused on non-lithium ion) | **£211 million**<br>USD (2025): 270 million in grants | To advance demonstration and deployment of non-lithium-ion LDES across California. | Eight projects received USD 270 million. One USD 5 million Electric Program Investment Charge (EPIC) project established the Rapid Integration and Commercialization Unit (RICU) at MCAS Miramar, San Diego. The California Energy Commission awarded an additional USD 4.85 million in June 2024 for Phase 2 demonstrations, including iron flow, zinc-bromine flow, and zinc-air batteries. | California Energy Commission (2025) |
| Japan (2025) | Grid-based battery energy storage | **£180 million**<br>JPY (2025) 36.3 billion | To advance installation of lithium and non-lithium battery storage technologies. | Overall, 11 projects were awarded more than 1 billion yen, seven were awarded between 200 million yen and 1 billion yen, and 19 were awarded less than 200 million yen. | Japan Energy Hub (2025) |

**LCDP: international examples of investment in demonstration projects**

| Geographical location, timescale | Technology type and technical information | Public funding invested (current GBP equivalent[i], original currency, year, type) | Purpose of funding | Potential or actual outcomes | Source / reference(s) |
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| Denmark (2023-2032) | BECCS | **£375 million**<br>The NECCS fund (Fund for negative emissions via CCS) made up to DKK 2.5 billion (2021) available in subsidies. | The NECCS fund supported negative emissions from $CO_2$ capture of biogenic sources and geological storage, aiming to achieve negative emissions of an additional 0.5 Mt per year from 2025 onwards. | The Danish Energy Agency awarded contracts to three companies for BECCS projects in April 2024, although the NECCS Fund was not fully used up. Companies receive support on a per tonne of $C0_2$ basis once they have documented that the $CO_2$ has been captured and stored permanently in underground geological storage. | Danish Energy Agency (2024); IEA (2023) |
| US (2022-2026) | Fossil fuel power plants and industrial facilities integrated with CCUS. | **£2.3 billion**<br>The Infrastructure Investment and Jobs Act allocated USD 2.5 billion (2022) to develop six demonstration projects including fossil fuel power plants with CCUS. | To accelerate the deployment of CCUS technologies. This formed part of an overall USD 12 billion support package for carbon management technologies including direct air capture. | By February 2024, around 45% of the USD 12 billion had been allocated to CCUS projects. | U.S. Department of Energy (2022) (2022); Fajardy & Greenfield (2024) |
| France (2020-2024) | Hydrogen gas turbine | **£11.9 million**<br>EUR 10.4 million (2020), Horizon 2020, EU funding | First fully integrated power-to-$H_2$-to-power industrial scale power plant, including an advanced dry-low emissions hydrogen gas turbine. | The project achieved all its technical objectives, including: the development, construction, and demonstration of a power-to-$H_2$-to-power solution for an existing SGT-400 CHP plant; and the development and demonstration of a dry low emissions (DLE) $H_2$ combustion technology operating an DLE SGT-400 gas turbine with 100% green $H_2$. | CORDIS (2025); HYFLEXPOWER (2024) |
| Germany (2024-2026) | Hydrogen combustion engine | **£4.4 million**<br>EUR 5 million (2024), German Federal Ministry for Economic Affairs and Climate Protection | To develop the necessary technologies for a highly efficient first-of-a-kind hydrogen combustion engine to drive combined heat and power (CHP) systems, with potential to be carbon neutral when fuelled by green hydrogen. | The project is expected over its three-year duration to develop a sufficiently mature technology concept that can be applied in a complete prototype engine. | Rolls-Royce (2024) |
| Germany (2024-2027) | Hydrogen gas turbine | **£3.85 million**<br>EUR 4.4 million (2024), EU funding | The EU-funded HyCoFlex project aims to develop retrofittable, decarbonised, cogeneration of power and industrial heat using 100% H2-fired gas turbines. | Includes demonstration at an industrial site in Saillat-sur-Vienne in France, advancing the infrastructure of a previously developed and | CORDIS (2026) |

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| | | | | demonstrated power-to-$H_2$-to-power industrial plant. | |
| Netherlands (2025-2027) | Hydrogen production plant | **£139 million**<br>EUR 162 million (2025) Innovation Fund financed by the EU Emissions Trading System. | To establish a first-of-a-kind, 1000MW low-carbon hydrogen production facility using a single-train Autothermal Reforming (ATR) process. An integrated point-source system will capture most of the emitted $CO_2$ and transport it for permanent storage under the Norwegian continental shelf. | Due to enter into operation from 2031. Expected to avoid 13 million tonnes of $CO_2$ equivalent emissions, during its first decade of operation. Estimated that the project could create 400 new jobs in Groningen and 650 in the Netherlands. | European Commission (2025b) |
| US (since 2021) | Hydrogen-fuelled turbines | **£134 million**<br>USD 147 million (2021), US Department of Energy, Office of Fossil Energy and Carbon Management. | To explore new, clean methods of producing hydrogen and to improve the performance of hydrogen-fuelled turbines. Supports US DOE's Hydrogen Shot initiative aimed at clean hydrogen cost reduction, to USD 1 per 1 kilogram in 10 years. | Expected to develop advanced materials and components which can better cope with the extreme environment produced during hydrogen combustion, helping to facilitate the use of up to 100% low-carbon hydrogen in gas turbines. | U.S. Department of Energy (2024b) |
| US (2025) | Generation III + SMR | **£684 million**<br>USD 900 million (2025) from US Department of Energy under two-tier programme. | USD 800 million to support two first mover teams and additional USD 100 million committed to deploying a first Gen III+ SMR plant while facilitating a multi-reactor, Gen III+ SMR to close domestic nuclear industry gaps in the US. | Expected impact is to bridge the gap between the nation's current fleet of reactors and more advanced reactor designs that will be demonstrated through the Advanced Reactor Demonstrations Program. | U.S. Department of Energy (2025) |
| Canada (2023-2027) | SMR technologies in general | **£2.4 million**<br>CAD 4.5 million (2025), Canadian Government | R&D programme on radioactive waste, manufacturing and fuel supply chain for SMR. | Potentially expected to contribute to SMR development and deployment, knowledge transfer activities, capacity building and training, and standards development activities. | Government of Canada (2025) |
| EU (2024) | SMR in general | **£264 million**<br>EUR 300 million, EU State aid rules (2024) | Aims to develop processes for the design and construction of SMRs based on a simple and modular design and with a power output equivalent to or less than 300 MWe. | Expected to contribute to the achievement of the strategic objectives of the European Industrial Strategy and the European Green Deal. | European Commission (2024) |

# 11. References

Aerospace Technology Institute. (2022). *Hydrogen Gas Turbines & Thrust Generation UK Capability and Overseas Landscape*. https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-PPN-CAP-0068-Hydrogen-Gas-Turbines-and-Thrust-Generation-Capabilities.pdf

Agatie, C. (2023, January 16). *Iron-Air Batteries 10 Times Cheaper Than Li-Ion Will Start Mass Production in 2024*. Autoevolution. https://www.autoevolution.com/news/iron-air-batteries-10-times-cheaper-than-li-ion-will-start-mass-production-in-2024-208539.html

APRA-E. (n.d.). *Duration Addition to electricitY Storage (DAYS) Overview*. Retrieved February 13, 2026, from https://arpa-e.energy.gov/sites/default/files/migrated/documents/files/DAYS_ProgramOverview_FINAL.pdf

Armitage, T. (2025, April 3). *Making the case for underground hydrogen storage in the UK*. https://www.bgs.ac.uk/news/making-the-case-for-underground-hydrogen-storage-in-the-uk/

Arup. (2024). *Assessing the Regional Demand for Geological Hydrogen Storage Building a Strategic Case for Investment in the East Coast Cluster*. https://www.arup.com/globalassets/downloads/insights/a/assessing-the-regional-demand-for-geological-hydrogen-storage.pdf

Aunedi, M., Al Kindi, A. A., Pantaleo, A. M., Markides, C. N., & Strbac, G. (2023). System-driven design of flexible nuclear power plant configurations with thermal energy storage. *Energy Conversion and Management*, *291*. https://doi.org/10.1016/j.enconman.2023.117257

Baringa. (2025). *Hydrogen to Power Costs and Barriers*. https://assets.publishing.service.gov.uk/media/69663541e8b93f59c3aecd76/hydrogen-to-power-cost-barriers.pdf

Bates, C., & Read, A. (2018). *CCUS technical advisory: report on assumptions*. https://www.gov.uk/government/publications/power-carbon-capture-usage-and-storage-ccus-technologies-technical-and-cost-assumptions/ccus-technical-advisory-report-on-assumptions

Bento, N., & Wilson, C. (2016). Measuring the duration of formative phases for energy technologies. *Environmental Innovation and Societal Transitions*, *21*, 95–112. https://doi.org/10.1016/j.eist.2016.04.004

Bielewski, M. (2023). *Battery technology in the European Union*. https://setis.ec.europa.eu/battery-technology-european-union_en

BloombergNEF. (2025, December 9). *Lithium-Ion Battery Pack Prices Fall to $108 Per Kilowatt-Hour, Despite Rising Metal Prices*. BloombergNEF. https://about.bnef.com/insights/clean-transport/lithium-ion-battery-pack-prices-fall-to-108-per-kilowatt-hour-despite-rising-metal-prices-bloombergnef/

Brainport Eindhoven. (n.d.). *NPS Driven launches hydrogen combustion engine*. Retrieved January 27, 2026, from https://brainporteindhoven.com/en/news/nps-driven-launches-hydrogen-combustion-engine

Bukar, A. M., & Asif, M. (2024). Technology readiness level assessment of carbon capture and storage technologies. *Renewable and Sustainable Energy Reviews*, *200*. https://doi.org/10.1016/j.rser.2024.114578

Burgess, J. (2025, April 14). *All new Mitsubishi Power gas turbine projects in Europe are hydrogen ready, CEO says*. SP Global. https://www.spglobal.com/energy/en/news-research/latest-news/energy-transition/041425-interview-all-new-mitsubishi-power-gas-turbine-projects-in-europe-are-hydrogen-ready-ceo-says

California Energy Commission. (2021). *Life Cycle Assessment of Environmental and Human Health Impacts of Flow Battery Energy Storage Production and Use*. https://www.energy.ca.gov/sites/default/files/2021-12/CEC-500-2021-051.pdf

California Energy Commission. (2025). *Long Duration Energy Storage Program*. https://www.energy.ca.gov/programs-and-topics/programs/long-duration-energy-storage-program

Cetegen, S. A., Gundersen, T., & Barton, P. I. (2024). Evaluating economic feasibility of liquid air energy storage systems in US and European markets. *Energy*, *300*. https://doi.org/10.1016/j.energy.2024.131524

Cetegen, S. A., Gundersen, T., & Barton, P. I. (2025). Evaluating economic feasibility of liquid air energy storage systems in future US electricity markets. *Energy*, *321*. https://doi.org/10.1016/j.energy.2025.135447

Cigolotti, V., & Genovese, M. (2021). *Stationary Fuel Cell Applications: Current and Future Technologies - Costs, Performances, and Potential*. https://ieafuelcell.com/wp-content/uploads/2024/11/2021-stationary-application-performance.pdf#:~:text=For%20building%20applications%20and%20micro%2Dcogeneration%2C%20PEM%20systems,installed%2C%20being%20more%20mature%20than%20other%20technologies%2C

Cleantech for Europe. (2025). *Cleantech Reality Check - Long Duration Energy Storage*. https://www.cleantechforeurope.com/publications/cleantech-reality-check/crc-2-series2-electrification

CORDIS. (2025). *HYdrogen as a FLEXible energy storage for a fully renewable European POWER system*. https://cordis.europa.eu/project/id/884229

CORDIS. (2026). *Hydrogen for Cogeneration in Flexible operation*. https://cordis.europa.eu/project/id/101138002

Danish Energy Agency. (2024). *Three new CCS projects have been pledged support to capture and store biogenic CO2*. https://ens.dk/en/press/three-new-ccs-projects-have-been-pledged-support-capture-and-store-biogenic-co2

Dennis, R. A., White, B., & Sampath, S. (2013). *Advanced Thermal Barrier Coatings for Operation in High Hydrogen Content Fueled Gas Turbines-Stony Brook University Background*. https://www.netl.doe.gov/sites/default/files/2017-12/FE0004771.pdf

Department for Business, E. & I. S. (2019). *Re-use of oil and gas assets for carbon capture usage and storage projects consultation*. https://assets.publishing.service.gov.uk/media/5d36e613ed915d0d083f29cf/reuse-oil-gas-assets-ccus-projects.pdf

Department for Business, E. & I. S. (2021a). *Combined Heat and Power-Technologies A detailed guide for CHP developers-Part 2*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/961492/Part_2_CHP_Technologies_BEIS_v03.pdf

Department for Business, E. & I. S. (2021b, November 9). *UK backs new small nuclear technology with £210 million*. https://www.gov.uk/government/news/uk-backs-new-small-nuclear-technology-with-210-million

Department for Energy and Net Zero. (2023). *Hydrogen Transport and Storage Cost Report*. https://assets.publishing.service.gov.uk/media/659e600b915e0b00135838a6/hydrogen-transport-and-storage-cost-report.pdf

Department for Energy Security & Net Zero. (2023). *Biomass Strategy 2023*. https://www.gov.uk/government/publications/biomass-strategy

Department for Energy Security & Net Zero. (2024). *Hydrogen net zero investment roadmap: leading the way to net zero*. https://www.gov.uk/government/publications/hydrogen-net-zero-investment-roadmap/hydrogen-investment-roadmap-leading-the-way-to-net-zero

Department for Energy Security & Net Zero. (2026). *Electricity Generation Costs 2025*. https://assets.publishing.service.gov.uk/media/696697d19d9b9da37c04c2e4/electricity-generation-costs-report-2025.pdf

Department for Energy Security and Net Zero. (2023). *Longer Duration Energy Storage (LoDES) Demonstration Programme: successful projects*. https://www.gov.uk/government/publications/longer-duration-energy-storage-demonstration-programme-successful-projects

Department of Energy and Climate Change. (2012). *Electricity market reform: policy overview*. https://assets.publishing.service.gov.uk/media/5a74bd75ed915d502d6ca9b2/5349-electricity-market-reform-policy-overview.pdf

Department of Energy Security and Net Zero. (2025a, June 10). *Rolls-Royce SMR selected to build small modular nuclear reactors*. https://www.gov.uk/government/news/rolls-royce-smr-selected-to-build-small-modular-nuclear-reactors

Department of Energy Security and Net Zero. (2025b, October 6). *Clean Energy Superpower Mission areas of research interest - GOV.UK*. https://www.gov.uk/government/publications/clean-energy-superpower-mission-areas-of-research-interest/clean-energy-superpower-mission-areas-of-research-interest

DEUTZ. (n.d.). *Hydrogen Engine - technology of tomorrow in production today*. Retrieved February 9, 2026, from https://www.deutz.com/en/products/hydrogen-engines/

Domenichini, R., Mancuso, L., Ferrari, N., & Davison, J. (2013). Operating flexibility of power plants with carbon capture and storage (CCS). *Energy Procedia*, *37*, 2727–2737. https://doi.org/10.1016/j.egypro.2013.06.157

ECOS. (2021). *7 key points about the EU Taxonomy's 100g emissions threshold*. https://ecostandard.org/wp-content/uploads/2021/12/EUTaxonomy_100g_7points.pdf

Environmental Agency. (2025, September 2). *The geomechanics of hydrogen storage in salt caverns: environmental considerations*. https://www.gov.uk/government/publications/the-geomechanics-of-hydrogen-storage-in-salt-caverns-environmental-considerations

ERM. (2024). *LDES NODE WP2-Techno-economic Analysis*. https://www.enwl.co.uk/globalassets/innovation/strategic-innovation-fund/ldes-node/discovery/ldes-node-wp2-techno-economic-analysis.pdf

EsmaeiliShayan, M. (2025). Solar energy storage systems: A comprehensive study for techno-economic aspects and sustainable grid integration. *Journal of Cleaner Production*, *529*. https://doi.org/10.1016/j.jclepro.2025.146811

ETN Global. (2024). *Hydrogen Gas Turbines*. https://etn.global/wp-content/uploads/2024/11/ETN-Global-Hydrogen-Gas-Turbines-Report-10-2024.pdf

European Commission. (2023). *HORIZON-CL5-2023-D3-01-13: Development of novel long-term electricity storage technologies. Funding & Tenders Portal*. https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/HORIZON-CL5-2023-D3-01-13

European Commission. (2024). *Commission approves €300 million French State aid measure to support Nuward in researching and developing small modular nuclear reactors*. https://ec.europa.eu/commission/presscorner/detail/es/ip_24_2228

European Commission. (2025a). *Cross-regional network and market model for optimisation of long duration storage (HORIZON-CL5-2025-02-D3-21). CORDIS*. https://cordis.europa.eu/programme/id/HORIZON_HORIZON-CL5-2025-02-D3-21

European Commission. (2025b). *H2M Eemshaven: Kick starting the EU hydrogen value chain by realizing a 1,000 MW low-carbon hydrogen production plant in the Eemshaven (NL) industrial area*. https://ec.europa.eu/assets/cinea/project_fiches/innovation_fund/101191122.pdf

European Commission. (2025c). *HORIZON-CL5-2025-01-Two-Stage-D2-02: Cost-effective next-generation batteries for long-duration stationary storage [Funding & Tenders Portal]*. https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/HORIZON-CL5-2025-01-Two-Stage-D2-02

Fajardy, M., & Greenfield, C. (2024). *It is time for CCUS to deliver* (IEA Commentary). https://www.iea.org/commentaries/it-is-time-for-ccus-to-deliver

Form Energy. (2023, August 17). *Form Energy awarded grant to deploy first multi-day battery system in New York*. https://formenergy.com/form-energy-awarded-grant-to-deploy-first-multi-day-battery-system-in-new-york/

Foxon, T. J. (2003). *Inducing innovation for a low-carbon future: Drivers, barriers and policies - A report for The Carbon Trust*.

Friedel, L., Grenz, J., & Hagist, C. (2026). A Comparison of Long Duration Energy Storage Technologies Based on Levelized Cost of Storage. *Journal of Energy Storage*, *153*. https://doi.org/https://doi.org/10.1016/j.est.2026.120679

García-Freites, S., Gough, C., & Röder, M. (2021). The greenhouse gas removal potential of bioenergy with carbon capture and storage (BECCS) to support the UK's net-zero emission target. *Biomass and Bioenergy*, *151*. https://doi.org/10.1016/j.biombioe.2021.106164

GE Vernova. (n.d.). *Hydrogen fueled gas turbines*. GE Vernova. Retrieved January 27, 2026, from https://www.gevernova.com/gas-power/future-of-energy/hydrogen-fueled-gas-turbines

Giacobone, B. (2026, February 18). *The race for the 100-hour battery has new entrants*. Latitude Media. https://www.latitudemedia.com/news/the-race-for-the-100-hour-battery-has-new-entrants/

Giacomazzi, E., Troiani, G., Di Nardo, A., Calchetti, G., Cecere, D., Messina, G., & Carpenella, S. (2023). Hydrogen Combustion: Features and Barriers to Its Exploitation in the Energy Transition. In *Energies* (Vol. 16, Number 20). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/en16207174

Government of Canada. (2025). *Enabling small modular reactors program: funded projects*. https://natural-resources.canada.ca/energy-sources/nuclear-energy-uranium/enabling-small-modular-reactors-program-funded-projects

Gridwatch. (n.d.). *Operating Power Stations*. Gridwatch. Retrieved January 27, 2026, from https://gridwatch.co.uk/stations

Gross, R., Hanna, R., Gambhir, A., Heptonstall, P., & Speirs, J. (2018). How long does innovation and commercialisation in the energy sectors take? Historical case studies of the timescale from invention to widespread commercialisation in energy supply and end use technology. *Energy Policy*, *123*, 682–699. https://doi.org/10.1016/j.enpol.2018.08.061

Hanwa. (2023, June 29). *Successfully Demonstrate a 59.5% Hydrogen Co-firing Rate in 80-megawatt-class Gas Turbines*. https://www.hanwha.com/newsroom/news/press-releases/hanwha-becomes-worlds-first-to-successfully-demonstrate-a-59-5-hydrogen-co-firing-rate-in-80-megawatt-class-gas-turbines.do

He, W., Dooner, M., King, M., Li, D., Guo, S., & Wang, J. (2021). Techno-economic analysis of bulk-scale compressed air energy storage in power system decarbonisation. *Applied Energy*, *282*. https://doi.org/10.1016/j.apenergy.2020.116097

Hough, E., Monaghan, A., & Boon, D. (2023). *British Geological Survey-Written evidence (LES0016)*. https://committees.parliament.uk/writtenevidence/124509/pdf/

House of Lords. (2024, March 13). *House of Lords - Long-duration energy storage: get on with it - Science and Technology Committee*. https://publications.parliament.uk/pa/ld5804/ldselect/ldsctech/68/6802.htm

HYFLEXPOWER. (2024). *From concept to clean energy reality: Green hydrogen, power generation & the HYFLEXPOWER project*. https://www.hyflexpower.eu/wp-content/uploads/2024/06/HYFLEXPOWER-final-workshop-summary_R1.2.pdf

IEA. (2023). *Danish NECCS Fund*. https://www.iea.org/policies/17547-danish-neccs-fund

IEA. (2024). *Technology: Pumped Hydroelectric Energy Storage*. https://iea-es.org/wp-content/uploads/public/FactSheet_Mechanical_Pumped_Hydroelectric.pdf

IEA. (2025). *Electrolysers - Energy System*. https://www.iea.org/energy-system/low-emission-fuels/electrolysers

IEAGHG. (2022). *Start-up and Shutdown Protocol for Natural Gas-fired Power Stations with CO2 Capture*. https://ieaghg.org/publications/start-up-and-shutdown-protocol-for-natural-gas-fired-power-stations-with-co2-capture/

IRENA. (2021). *Innovation outlook Renewable Methanol*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf

IRENA. (2022). *Innovation Outlook Renewable Ammonia*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf

Ishimoto, Y., Wulf, C., Schonhoff, A., & Kuckshinrichs, W. (2024). Life cycle costing approaches of fuel cell and hydrogen systems: A literature review. *International Journal of Hydrogen Energy*, *54*, 361–374. https://doi.org/10.1016/j.ijhydene.2023.04.035

Jackson, S., Wilson, R., & Adamson, J. (2024). *Breakthrough low-cost, multi-day energy storage*. https://www.iso-ne.com/static-assets/documents/100017/2024-10-29_etwg_a05_iron-air_battery_technology_and_applications_overview_final_2.pdf

Jafari, M., Botterud, A., & Sakti, A. (2022). Decarbonizing power systems: A critical review of the role of energy storage. In *Renewable and Sustainable Energy Reviews* (Vol. 158). Elsevier Ltd. https://doi.org/10.1016/j.rser.2022.112077

Japan Energy Hub. (2025, December 30). *37 grid-scale BESS projects secure 36.3B yen through METI's FY2025 storage subsidy program*. https://japanenergyhub.com/news/meti-fy2025-grid-scale-bess-subsidy/

Jenkins, J. D., & Sepulveda, N. A. (2021). Long-duration energy storage: A blueprint for research and innovation. *Joule*, 2241–2246. https://doi.org/10.1016/j.joule.2021.08.002

Koripella, R. (2024, September 20). *Introduction to Long Duration Energy Storage, Part 2. Non electrochemical Technologies*. https://www.sandia.gov/app/uploads/sites/273/2024/09/CEC-webinar1-Koripella-2.pdf

LDES Council. (2025). Deploying LDES: Implementation best practices. In *2025*. https://ldescouncil.com/wp-content/uploads/2025/05/FINALDeployingLDESImplementationBestPracticesShortUpdated220125-1.pdf

Lewis, C., MacSweeney, R., Kirschel, M., Josten, W., Roulstone, T., & Locatelli, G. (2016). *Small modular reactors: Can building nuclear power become more cost-effective?* https://www.researchgate.net/profile/Giorgio-Locatelli/publication/321715136_Small_modular_reactors_Can_building_nuclear_power_become_more_cost-effective/links/5c16150ea6fdcc494ff829d9/Small-modular-reactors-Can-building-nuclear-power-become-more-cost-effective.pdf?_tp=eyJjb250ZXh0Ijp7ImZpcnN0UGFnZSI6InB1YmxpY2F0aW9uIiwicGFnZSI6InB1YmxpY2F0aW9uIn19

Li, J., Wang, C., Zhai, G., Li, Q., Lim, S. H., Abdoli, S., Kook, S., Yeoh, G. H., & Chan, Q. N. (2024). Evaluating the techno-economic feasibility of hydrogen-fuelled reciprocating engines for renewable base-load power generation. *Energy Conversion and Management*, *311*. https://doi.org/10.1016/j.enconman.2024.118515

Liu, J., Pei, J., Wei, J., Yang, J., & Xu, H. (2025). Development status and prospect of salt cavern energy storage technology. *Earth Energy Science*, *1*(2), 159–179. https://doi.org/10.1016/j.ees.2025.01.001

Liu, J., Xiao, J., Yang, J., Wang, W., Shao, Y., Liu, P., & Whittingham, M. S. (2023). The TWh challenge: Next generation batteries for energy storage and electric vehicles. *Next Energy*, *1*(1), 100015. https://doi.org/10.1016/j.nxener.2023.100015

Loachamin, D., Casierra, J., Calva, V., Palma-Cando, A., Ávila, E. E., & Ricaurte, M. (2024). Amine-Based Solvents and Additives to Improve the CO2 Capture Processes: A Review. In *ChemEngineering* (Vol. 8, Number 6). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/chemengineering8060129

Lund, P. (2006). Market penetration rates of new energy technologies. *Energy Policy*, *34*(17), 3317–3326. https://doi.org/10.1016/j.enpol.2005.07.002

Mahmoudi Larimi, Y. (2024). *Isothermal Compressed Air Energy Storage for Decentralised Energy Grid*. https://www.era.ac.uk/wp-content/uploads/2024/01/1-Yasser_IMechE_Jan_2024.pdf

Maisch, M. (2026, January 21). *Noon Energy demonstrates 100+ hour ultra-long-duration energy storage system*. Energy Storage. https://www.ess-news.com/2026/01/21/noon-energy-demonstrates-100-hour-ultra-long-duration-energy-storage-system/

Market Strides. (2025, November). *United Kingdom Zinc Bromine Battery Market Size & Outlook, 2025-2033*. https://marketstrides.com/omega/insights/zinc-bromine-battery-market/united-kingdom

McIlroy, T. (2025, October 3). *Snowy Hydro 2.0 flags another cost blowout with $12bn price tag now considered unachievable*. The Guardian. https://www.theguardian.com/environment/2025/oct/03/snowy-hydro-20-flags-another-cost-blowout-with-12bn-price-tag-now-considered-unachievable

McTigue, J., Hirschey, J., & Ma, Z. (2025). Advancing pumped thermal energy storage performance and cost using silica storage media. *Applied Energy*, *387*. https://doi.org/10.1016/j.apenergy.2025.125567

Mettler, A., & Reinaud, J. (2025). *Cleantech Reality Check - Electrification*. https://www.systemiq.earth/wp-content/uploads/2025/02/CRC-electrification.pdf

Mitsubishi Power Americas. (n.d.). *Hydrogen-Capable Gas Turbines*. Mitsubishi Power Americas. Retrieved January 27, 2026, from https://power.mhi.com/regions/amer/products/hydrogen-gas-turbine

Mobility Foresights. (2025, May 27). *UK Fuel Cell Technology Market Size and Forecasts 2030*. Mobility Foresights. https://mobilityforesights.com/product/uk-fuel-cell-technology-market

National Energy System Operator. (2025). *Future Energy Scenarios: Pathways to Net Zero*. https://www.neso.energy/document/364541/download

Nazir, G., Rehman, A., Lee, J. H., Kim, C. H., Gautam, J., Heo, K., Hussain, S., Ikram, M., AlObaid, A. A., Lee, S. Y., & Park, S. J. (2024). A Review of Rechargeable Zinc–Air Batteries: Recent Progress and Future Perspectives. In *Nano-Micro Letters* (Vol. 16, Number 1). Springer Science and Business Media B.V. https://doi.org/10.1007/s40820-024-01328-1

Odeh, N. (2020). *Analysing the potential of bioenergy with carbon capture in the UK to 2050*. https://assets.publishing.service.gov.uk/media/5f3fe1f28fa8f55df267bc17/potential-of-bioenergy-with-carbon-capture.pdf

OFGEM. (2025). *LDES Eligibility Assessment Outcome*. https://www.ofgem.gov.uk/sites/default/files/2025-09/LDES%20Eligibility%20Assessment%20Outcome.pdf

Onorati, A., Payri, R., Vaglieco, B. M., Agarwal, A. K., Bae, C., Bruneaux, G., Canakci, M., Gavaises, M., Günthner, M., Hasse, C., Kokjohn, S., Kong, S. C., Moriyoshi, Y., Novella, R., Pesyridis, A., Reitz, R., Ryan, T., Wagner, R., & Zhao, H. (2022). The role of hydrogen for future internal combustion engines. In *International Journal of Engine Research* (Vol. 23, Number 4, pp. 529–540). SAGE Publications Ltd. https://doi.org/10.1177/14680874221081947

Planning Inspectorate. (2024, February 16). *The Net Zero Teesside Project development consent decision announced*. https://www.gov.uk/government/news/the-net-zero-teesside-project-development-consent-decision-announced

Rabi, A. M., Radulovic, J., & Buick, J. M. (2023). Comprehensive Review of Liquid Air Energy Storage (LAES) Technologies. In *Energies* (Vol. 16, Number 17). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/en16176216

Rolls Royce. (2025, January 31). *Rolls-Royce SMR welcomes growing strategic cooperation with the UK on nuclear energy*. https://www.rolls-royce-smr.com/press/rolls-royce-smr-welcomes-growing-strategic-cooperation-with-the-uk-on-nuclear-energy

Rolls-Royce. (2024). *Rolls-Royce collaborates with technology partners on highly efficient hydrogen engine for stationary power generation*. https://www.rolls-royce.com/media/press-releases/2024/24-06-2024-rr-collaborates-with-technology-partners-on-highly-efficient-hydrogen-engine.aspx

Schnellmann, M. A., Chyong, C. K., Reiner, D. M., & Scott, S. A. (2023). *Deploying gas power with CCS: The role of operational flexibility, merit order and the future energy system* (1836; Cambridge Working Paper in Economics). https://www.jbs.cam.ac.uk/wp-content/uploads/2023/12/eprg-wp1836.pdf

She, X., Wang, H., Zhang, T., Li, Y., Zhao, X., Ding, Y., & Wang, C. (2025). Liquid air energy storage – A critical review. In *Renewable and Sustainable Energy Reviews* (Vol. 208). Elsevier Ltd. https://doi.org/10.1016/j.rser.2024.114986

Sintef. (n.d.). *HyPowerGT - Demonstrating a hydrogen-powered gas-turbine engine fuelled with up to 100% H2*. Sintef. Retrieved January 27, 2026, from https://www.sintef.no/en/projects/2024/hypowergt/

SLDBatt. (2025, November 13). *Dutch Consortium Secures Major Funding to Advance Sustainable Long-Duration Battery Technology*. https://www.sldbatt.nl/news/2025/11/682121/dutch-consortium-secures-major-funding-to-advance-sustainable-long-duration-battery-technology

Sorrell, S. (2007). Improving the evidence base for energy policy: The role of systematic reviews. *Energy Policy*, *35*, 1858–1871. https://doi.org/https://doi.org/10.1016/j.enpol.2006.06.008

Speirs, J., Gross, R., & Heptonstall, P. (2015). *Developing a rapid evidence assessment (REA) methodology A UKERC TPA technical document*. https://d2e1qxpsswcpgz.cloudfront.net/uploads/2020/03/developing-a-rapid-evidence-assessment-v3.pdf

SSE. (2025, October 3). *Ground broken on test site for cutting edge 100% hydrogen fired turbines*. SSE. https://www.sse.com/news-and-views/2025/10/ground-broken-on-test-site-for-cutting-edge-100-hydrogen-fired-turbines/

Storelectric. (n.d.). *Large-scale, long-duration electricity storage*. Retrieved January 27, 2026, from https://storelectric.com/electricity-storage/

Sun, B., Wang, H., & Peng, C. (2024). Harnessing solid-state technology for next-generation iron-air batteries. In *Sustainable Energy and Fuels* (Vol. 8, Number 24, pp. 5711–5730). Royal Society of Chemistry. https://doi.org/10.1039/d4se01224k

Supergen. (2025). *Energy Storage Gaps and Opportunities Analysis*. https://supergenstorage.org/assets/Energy-Storage-Gaps-and-Opportunities-Analysis-July-2025.pdf

Tafone, A., Ding, Y., Li, Y., Xie, C., & Romagnoli, A. (2020). Levelised Cost of Storage (LCOS) analysis of liquid air energy storage system integrated with Organic Rankine Cycle. *Energy*, *198*. https://doi.org/10.1016/j.energy.2020.117275

Talukdar, M., Blum, P., Heinemann, N., & Miocic, J. (2024). Techno-economic analysis of underground hydrogen storage in Europe. *IScience*, *27*(1). https://doi.org/10.1016/j.isci.2023.108771

The Faraday Institution. (2024). *Market and Technology Assessment of Redox Flow, Hybrid and Other Aqueous and Non-Aqueous “Flow” Battery Technologies That Could Provide Low Cost, Sustainable Energy Storage for Developing Economies Request for Proposal*. https://www.faraday.ac.uk/opportunities/flow-batteries-rfp/

The Faraday Institution. (2025, March). *Ultra Low Cost Long Duration Energy Storage Transformational Challenge: UltraStore*. https://www.faraday.ac.uk/wp-content/uploads/2025/03/UltraStore_Challenge_Co-creation_EOI_March2025.pdf

The Royal Society. (2023). *Large-scale electricity storage*. The Royal Society. https://royalsociety.org/-/media/policy/projects/large-scale-electricity-storage/large-scale-electricity-storage-report.pdf

UK Government. (n.d.). *Carbon capture, usage and storage*. Business.Gov.Uk. Retrieved January 27, 2026, from https://www.business.gov.uk/invest-in-uk/investment/sectors/carbon-capture-usage-and-storage/

UK Government. (2018). *Clean Growth*. https://assets.publishing.service.gov.uk/media/655e35b83e1c2e0011693715/uk-ccus-deployment-pathway-action-plan.pdf

UK Government. (2021). *UK Hydrogen Strategy*. [Dandy Booksellers Ltd]. https://assets.publishing.service.gov.uk/media/64c7e8bad8b1a70011b05e38/UK-Hydrogen-Strategy_web.pdf

UK Government. (2024). *Clean Power 2030 Action Plan: A new era of clean electricity*. https://assets.publishing.service.gov.uk/media/677bc80399c93b7286a396d6/clean-power-2030-action-plan-main-report.pdf

UK Government. (2025). *ANNEX 5: Long Duration Electricity Storage*. https://assets.publishing.service.gov.uk/media/6819db12fb59a222d4f172f3/Annex_5_Planning_and_Infrastructure_Bill_Impact_Assessment_-_Long_Duration_Electricity_Storage.pdf

UK Parliament. (2015, November 26). *Fossil Fuelled Power Stations: Carbon Emissions and Nitrogen Oxides*. UK Parliament. https://questions-statements.parliament.uk/written-questions/detail/2015-11-26/17799

U.S. Department of Energy. (2021). *Long Duration Storage Shot: An introduction (DOE/EE-2384)*. https://www.energy.gov/sites/default/files/2021-07/Storage%20shot%20fact%20sheet_071321_%20final.pdf

U.S. Department of Energy. (2022). *The Infrastructure Investment and Jobs Act: Opportunities to accelerate deployment in fossil energy and carbon management activities*. https://www.energy.gov/sites/default/files/2022-09/FECM%20IIJA%20BIL%20Factsheet_revised%20September%202022.pdf

U.S. Department of Energy. (2023a). *Technology Strategy Assessment Findings from Storage Innovations 2030 Flow Batteries*. https://www.energy.gov/oe/storage-innovations-2030

U.S. Department of Energy. (2023b). *Technology Strategy Assessment Findings from Storage Innovations 2030 Pumped Storage Hydropower*. https://www.energy.gov/sites/default/files/2023-07/Technology%20Strategy%20Assessment%20-%20Pumped%20Storage%20Hydropower_0.pdf

U.S. Department of Energy. (2023c). *Technology Strategy Assessment Findings from Storage Innovations 2030 Sodium Batteries*. https://www.energy.gov/oe/storage-innovations-2030

U.S. Department of Energy. (2023d). *Technology Strategy Assessment. Findings from Storage Innovations 2030: Zinc Batteries*. https://www.energy.gov/sites/default/files/2023-07/Technology%20Strategy%20Assessment%20-%20Zinc%20Batteries.pdf

U.S. Department of Energy. (2024a). *Achieving the Promise of Low-Cost Long Duration Energy Storage An Overview of 10 R&D Pathways from the Long Duration Storage Shot Technology Strategy Assessments*. https://www.energy.gov/oe/storage-innovations-2030

U.S. Department of Energy. (2024b). *U.S. Department of Energy Invests $8.8 Million to Improve Hydrogen Turbine Performance*. https://www.energy.gov/hgeo/articles/us-department-energy-invests-88-million-improve-hydrogen-turbine-performance#:~:text=WASHINGTON%2C%20D.C%20%E2%80%94%20The%20U.S.%20Department,Fossil%20Energy%20and%20Carbon%20Management

U.S. Department of Energy. (2025). *Generation III+ Small Modular Reactor Program*. https://www.energy.gov/ne/generation-iii-small-modular-reactor-program

U.S. Department of Energy, O. of C. E. D. (2024c, September 5). *OCED announces $100 million for non-lithium long-duration energy storage pilot projects*. https://www.energy.gov/oced/articles/oced-announces-100-million-non-lithium-long-duration-energy-storage-pilot-projects

Vattenfall. (2025, February 27). *HYBRIT: Large-scale storage of fossil-free hydrogen gas successfully proven*. https://group.vattenfall.com/press-and-media/pressreleases/2025/hybrit-large-scale-storage-of-fossil-free-hydrogen-gas-successfully-proven/

Viswanathan, V., Mongird, K., Franks, R., Li, X., Sprenkle, V., & Baxter, R. (2022). *2022 Grid Energy Storage Technology Cost and Performance Assessment*. https://www.pnnl.gov/sites/default/files/media/file/ESGC%20Cost%20Performance%20Report%202022%20PNNL-33283.pdf

Warren, P. (2020). Evidence reviews in energy and climate policy. In *Evidence and Policy* (Vol. 16, Number 1, pp. 83–98). Policy Press. https://doi.org/10.1332/174426418X15193815413516

Wartsila. (n.d.). *Flexible baseload power plants*. Retrieved January 27, 2026, from https://www.wartsila.com/energy/engine-power-plant-solutions/flexible-baseload-power-plants

White, A. (2024, October). *Energy storage and support schemes: "the new normal"? UK Long-Duration Energy Storage regime*.

Williams, J. D. O., Williamson, J. P., Parkes, D., Evans, D. J., Kirk, K. L., Sunny, N., Hough, E., Vosper, H., & Akhurst, M. C. (2022). Does the United Kingdom have sufficient geological storage capacity to support a hydrogen economy? Estimating the salt cavern storage potential of bedded halite formations. *Journal of Energy Storage*, *53*. https://doi.org/10.1016/j.est.2022.105109

Wilson, C. (2012). Up-scaling, formative phases, and learning in the historical diffusion of energy technologies. *Energy Policy*, *50*, 81–94. https://doi.org/10.1016/j.enpol.2012.04.077

Wilson, C., & Grubler, A. (2013). Energy Technology Innovation. In A. Grubler & C. Wilson (Eds.), *Energy Technology Innovation. Lessons from Historical Successes and Failures* (pp. 3–10). Cambridge University Press. https://doi.org/https://doi.org/10.1017/CBO9781139150880

Woodford, W. H., Burger, S., Ferrara, M., & Chiang, Y. M. (2022). The iron-energy nexus: A new paradigm for long-duration energy storage at scale and clean steelmaking. In *One Earth* (Vol. 5, Number 3, pp. 212–215). Cell Press. https://doi.org/10.1016/j.oneear.2022.03.003

WSP. (2020). *Making Batteries Work*. https://www.wsp.com/-/media/insights/uk/documents/making-batteries-work290920.pdf

Yang, D., Wang, Y., Wang, J., Rui, Z., & He, W. (2025). Cost-reducing adiabatic compressed air energy storage for long duration energy-storage applications. *IScience*, *28*, 113967. https://doi.org/https://doi.org/10.1016/j.isci.2025.113967