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Energy Innovation Needs Assessment: Energy Storage

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Authors

The 2025 Energy Innovation Needs Assessment: Energy Storage was commissioned by DESNZ and delivered by a consortium led by the Carbon Trust, including Mott MacDonald, UCL and Pengwern Associates.

Carbon Trust was the lead technical author for the Energy Storage technology theme report.

Views expressed in this report are those of the author and not necessarily those of the UK Government.

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Abbreviations

BESS	Battery energy storage system
BMU	Balancing market unit
CAES	Compressed air energy storage
CAGR	Compound annual growth rate
CAPEX	Capital expenditure
CCGT	Combined cycle gas turbine
CfD	Contract for difference
CM	Capacity market
DC	Dynamic containment
EU	European Union
GVA	Gross Value Added
LAES	Liquid air energy storage
LCOS	Levelised cost of storage
LCCC	Low Carbon Contracts Company
LDES	Long duration energy storage
NESO	National Energy Systems Operator
O&M	Operations and maintenance
R&D	Research and development
TCLC	Transmission Constraint License Condition
TDD	Technical Decision Document
TEC	Transmission Entry Capacity
TNUoS	Transmission Network Use of System
TRL	Technology Readiness Level

Key Findings

The Energy Innovation Needs Assessments (EINAs) have been developed and updated to identify key innovation needs across the UK's energy system, to provide an evidence base for the prioritisation of investment and support for clean energy innovation. This report summarises the analysis and findings from the EINAs across the energy storage sub-theme, focusing on storage durations between 4 – 24-hours, including lithium-ion batteries, sodium-ion batteries, flow batteries, compressed air energy storage (CAES), and liquid air energy storage (LAES). While some of the technologies discussed in this report contribute to meeting longer-duration needs (beyond 24-hours), they are not inclusive of the full range of technologies available across the broader energy storage sector. This report focuses on technologies with the greatest innovation needs and potential for long-duration energy storage, therefore some more established technologies are beyond the scope of this analysis.

Energy system modelling to assess the potential impact of innovation in key net zero technologies was conducted using UK TIMES which was supplemented by HighRES for storage technologies due to the limited time and spatial resolution of UKTIMES. Technologies such as flow batteries, LAES and sodium-ion batteries were not included in the modelling. This is because the 4–8-hour duration range was represented by battery energy storage systems (BESS), and the 8–24-hour range was represented by CAES. Therefore, modelled impacts should be considered based on system function of different storage durations, rather than the specific technology modelled. Technologies were assessed at 3 levels of innovation (low, medium and high) and across three hypothetical scenarios: Minimally Constrained, High Hydrogen and High Diversification.[1] The key results from EINAs system modelling suggests that:

- High levels of innovation in 4-hour batteries can reduce electricity system costs by a relatively moderate amount, with cost savings of up to £191 million a year by 2050 in the Minimally Constrained scenario and £472 million in High Diversification.
- The deployment of 4-hour battery storage ranges from 0 GW to 15 GW in the model runs, almost exclusively higher in 2035 than 2050. This is because it plays a key role as a transition technology, fulfilling the system's need for longer duration energy storage before other technologies, such as CAES and hydrogen storage, are available and cost-effective. Innovation in this technology specifically is key to its deployment, with it only being deployed higher than 3GW when high levels of innovation have occurred.
- Innovation in CAES plays a modest role in reducing systems costs, with annualised cost reductions of between £43 million and £706 million by 2050. Across all model runs in 2035, CAES is deployed at its maximum capacity of 5 GW across, with generation

[1] These scenarios do not represent government policy but were selected due to their differing constraints which provide a diverse set of outputs and insights. More information on the scenarios can be found in Energy system modelling section of this report and in the EINAs Methodology report. High Hydrogen was not run in HighRES due to limitations on the number of model runs that could be completed within the scope of this project.

between 8-11 TWh, implying that 8-24h storage up to this level of generation is a critical way to reduce systems costs.

- In 2050, innovation in CAES has a moderate impact on CAES deployment, but innovation in other technologies significantly impacts the extent to which CAES is needed in the system.
- Hydrogen salt caverns are a key technology for reaching net zero in 2050 with high levels of innovation reducing electricity system costs by between £1.8 and £5.4 billion a year by 2050. Cost reductions are dominated by reductions in storage capex and, in poor weather years, reduction in generation from natural gas and standalone hydrogen generators.
- Deployment of H_2-salt caverns is significantly impacted by innovation in other EINAs technologies – especially innovations which increase the deployment for renewables – which can increase the need for long duration energy storage. Innovation in hydrogen salt caverns allows the UK to increase load factors for nuclear generation, alongside reducing curtailment of renewables.

To enable the deployment and cost savings across the energy system from energy storage technologies, there are a number of potential areas for innovation. These innovation opportunities are outlined in Table 1 and Table 2.

Table 1: Innovation opportunities for 4 - 8-hour duration energy storage technologies

Innovation area	Description
Advancements in cell chemistries	Innovation in this area will be key to increase suitability for longer-duration applications at commercially-viable cost points. Innovation in AI and machine learning to accelerate material discovery and cell design, alongside improvement in in-line monitoring methods, are key enabling technologies. Areas of focus include increasing energy density, maintaining high State of Charge (SoC) conditions, improving cycle life, and reducing material costs.
Advanced monitoring and control systems	Improving control systems could yield improvements in lifetime and efficiency. Improved monitoring and control systems, which can precisely monitor and control the SoC, state of health, and temperature of the battery cells, can ensure optimal performance and prevent overcharging or deep discharging. Advanced control systems can also improve the integration of the battery within the wider energy system by enabling dynamic management of energy flows.

Advanced manufacturing techniques	Innovative processes and technologies can enhance the production of batteries, improving efficiency, precision, scalability, and sustainability. These often involve the integration of automation, robotics, and machine learning to optimise various stages of battery manufacturing, alongside facilitating the use of recycling and waste reduction to improve sustainability. This can also include repurposing existing manufacturing infrastructure for medium-duration batteries, with flexibility to enable adoption of new materials and innovations.
Supply chains and recycling	Innovation in repurposing and recycling lithium and flow batteries is a key opportunity for reducing both cost and risk. For lithium-ion batteries, developing rapid battery health assessments to determine remaining battery life and performance is a focus area. For recycling battery systems, reducing impurities is a key innovation area. For flow batteries, innovations that enhance recycling automation, methods for recycling electrolytes, and recovering byproducts will improve the value proposition for recycling.
Safety	There are inherent safety risks for lithium-ion batteries, which have high flammability. Safety improvements will be necessary to reduce deployment cost and risks to acceptable levels. Innovation should focus on: development of lower flammability electrolytes and stable cathode materials; system architectures that minimise or prevent propagation of failure between cells; controls and monitoring systems that can readily identify the state of safety and trigger mitigation measures. Flow batteries and sodium batteries are inherently lower risk, so reducing the cost and improving performance for these technologies could reduce the need for lithium-ion batteries.

Table 2: Innovation opportunities for 8 - 24-hour duration energy storage technologies

Innovation area	Description
Analytics	Enhancing system modelling and design optimisation through AI and machine learning based techniques could improve compressed air energy storage (CAES) and liquid air energy storage (LAES) performance. Studying digital twins in simulated economic operations can offer valuable insights for refining system design.
Components	Further research into high-efficiency compressors and expanders, turbines that can operate at low temperatures and reciprocating mechanical pistons with heat tolerance are required to improve system efficiency. For isothermal and adiabatic CAES and LAES, high-efficiency thermal stores and multi-stream heat exchangers could reduce lifecycle costs and improve performance.
Advanced manufacturing	Implementation of automation, waste reduction approaches and adaptation of existing infrastructure for CAES and LAES specific use cases can all contribute towards reducing the high upfront cost associated these technologies. A particular area of focus in developing flexible robotic welding in the manufacture of pressure vessels and pipes, which could have wider benefits for related technologies including hydrogen and CCUS.
Deployment and demonstration	With the limited deployment of CAES and LAES technologies, demonstration at scale will be crucial to derisk investment and validate the impacts of innovations in areas such as novel system types (e.g., isothermal, adiabatic CAES), novel air storage vessels and operating strategies on lifecycle costs. These findings should feed into shaping future innovation priorities.

However, there are a number of non-innovation market barriers which should also be considered and addressed to enable effective scale up and deployment of energy storage technologies. These include:

- **Enabling infrastructure:** Some energy storage is constrained by physical or environmental factors, including grid connections. Batteries, unlike other forms of energy storage, can be located almost anywhere, but need access to the electricity grid to charge and discharge. The lack of certainty adds to project risks and costs.
- **Viable business models:** Most markets are accessible for BESS and CAES, but these markets are not fully utilised, and current mechanisms such as the Capacity Market

(CM) do not provide sufficient incentives for optimal longer duration energy storage uptake.[2]

- **Resources and supply chain:** The availability of raw materials, the geographical locations where these materials are processed, and global manufacturing capacity, present significant challenges for battery energy storage in the UK.

The business opportunities calculator suggests the following potential business opportunities for the EINAs energy storage technologies:

- Substantial GVA growth across all scenarios with a CAGR of between 15% and 17% between 2025 and 2050 with GVA reaching approximately £190 million by 2050 in both scenarios with medium innovation.
- Between 2025 and 2040, GVA is approximately 50% higher in the High Diversification scenario. This additional GVA is driven by the higher deployment levels of 4-hour batteries expected in the High Diversification scenario during this period, in turn driven by the greater offshore wind and solar deployment anticipated in this scenario.
- In the Minimally Constrained scenario, GVA is typically much higher for the high innovation scenario relative to the medium or low innovation scenarios throughout most of the period (19-157% higher). This variation is particularly stark in the period between 2030 and 2040 when higher innovation is projected to lead to a significant increase in the deployment of batteries (4-hour), The gap in GVA contribution between the high innovation level and the other innovation levels narrows between 2040 and 2050 as total deployment of energy storage begins to converge across innovation levels. In the High Diversification scenario, by contrast, higher levels of innovation are not projected to unlock additional GVA contribution as, according to the system modelling, higher innovation is not expected to lead to an increase in the total amount of deployment of the two storage technologies in the calculator (batteries (4-hour) + CAES).
- In both scenarios, the cumulative deployment of 4hr batteries is forecast to peak in 2035 and decrease thereafter. This means that the proportion of total GVA associated with 4-hour batteries peaks in 2035 (40-62% of total GVA) but is significantly reduced by 2050 (9-17% of total GVA). This is because the systems modelling results anticipate that, in the latter part of the period, the role of 4-hour batteries will be increasingly displaced by 1hr batteries as the key technology for fulfilling frequency response needs.
- Supported total employment (direct and indirect jobs) within the considered technologies rises to between 3,800 and 3,900 jobs by 2050.
- Across scenarios, 54-56% of supported jobs are direct jobs in 2025, rising to around 63% by 2050.
- The domestic market is expected to support the vast majority of jobs in the sector with 81-88% of jobs supported by domestic deployment in 2035 rising to 93% in 2050. The

[2] In the Capacity Market, existing, new build and refurbishing capacity compete in technology neutral auctions to obtain agreements, under which they commit to making their capacity available (by turning up their generation or turning down their electricity demand) when needed in return for guaranteed payments to support investment. The policy intent of the Capacity Market is to ensure security of electricity supply, but it can also act as an investment route for storage through the incentives it offers.

size of the export market is expected to be relatively constant between 2035 and 2050, contributing approximately 200-300 jobs across the period.

- Batteries (4-hour) represents the more promising export opportunity, contributing 93% of export driven GVA by 2050.
- As the sector matures and the ratio of new capacity to existing capacity falls, a shift from GVA and jobs being driven by construction activity to being driven by operations and maintenance.
- An employment profile that, by 2050, is predominantly supporting high skilled science, research and engineering and technology professional occupations, as well as director/managerial jobs.

Introduction

The Energy Innovation Needs Assessments

Achieving the UK's ambitious Net Zero targets requires the accelerated scaling and deployment of innovative clean energy technologies. The UK government has a central role to play in supporting the research, development and deployment of these innovations to achieve global and national climate objectives. The decisions made now in the prioritisation and investment of crucial clean energy technologies will be pivotal to enable progress in the coming years and decades.

The Energy Innovation Needs Assessments (EINAs) have been developed and updated to identify key innovation needs across the UK's energy system, to provide an evidence base for the prioritisation of investment and support for clean energy innovation. The 2025 publications reflect an update on the 2019 exercise, accounting for the significant changes and progress both in the clean energy sector and the wider economy. To complement and build on the UK's Net Zero Research and Innovation Framework, the updated EINAs will inform key decisions on clean energy innovation funding through a structured evidence base that quantifies and assesses the role and scale of opportunities. The evidence enables comparison across technologies and takes account of wider factors that may impact deployment and scale-up.

The methodology followed is detailed in the EINAs Technical Methodology Report and is summarised below.

The EINAs technologies were decided through a prioritisation exercise, taking into account insights from key sector experts and prioritising against key DESNZ criteria. An initial longlist of technologies for analysis was put together based on:

- Previously published global and national scenarios (including the 2019 EINAs)
- DESNZ priorities
- Insights from DESNZ engagement activities
- Input from technical experts

This longlist was then assessed and prioritised to inform a shortlist of EINAs technologies, which were then taken forward for analysis including:

- An assessment of each technology's innovation needs, costs and barriers to deployment.
- Modelling, using the UKTIMES and HighRES models, to assess the impact of different levels innovation in these technologies on the UK's energy system in hypothetical Net Zero scenarios, including on system cost, capacity and energy security.
- Business opportunities analysis, including Gross Value Added (GVA) and employment, of the deployment of the technologies across scenarios and innovation levels.

This report summarises the findings across the energy storage sub-theme.

The 2025 EINAs publications have been commissioned by DESNZ and produced by a consortium led by Carbon Trust, including Mott MacDonald, UCL and Pengwern Associates. Carbon Trust was the lead technical author for the energy storage sub-theme report.

Scope and Limitations of the EINAs:

The EINAs project is a research exercise to evaluate the potential impact of technological innovations on the UK energy system and Net Zero targets, and help inform decisions on clean energy innovation funding.

A number of technologies were included as part of the prioritization but were not included in the systems modelling due to limitations of the models used for the EINAs, data availability and resource constraints. The three hypothetical scenarios developed to represent potential routes to Net Zero were selected due to their differing constraints which provide a more diverse set of outputs and insights.

The technologies and scenarios selected do not represent UK Government policy.

The energy storage sub-theme

A shortlisting and prioritisation exercise was conducted to determine the energy storage technologies to be modelled and studied in this update of the EINAs. This followed a framework which considered the following factors:

- **Known net zero priority:** Technologies where there is a clear government direction or expert consensus.
- **Energy security:** Technologies necessary for system resilience and to protect against grid and import shocks.
- **UK relevance:** Technologies suitable for UK specific circumstances, and where the UK is likely to have an impact.
- **Technology Readiness Level (TRL) relevance:** Technologies close to commercialisation or likely to be commercially viable by 2040 were prioritised.

This report covers the findings across the energy storage technology theme, encompassing the technology types, categorised by duration of storage, as detailed in Table 3. This categorisation was chosen to align the technologies as defined in the UK TIMES and highRES systems modelling.

Short duration energy storage systems, covering durations under four hours have not been included in this report. This is because storage systems of this duration are being deployed at scale today on a commercial basis. These systems are typically lithium-ion batteries, being deployed to meet the frequency response and short-term balancing needs of the UK electricity system. Whilst further innovation could reduce the costs of this technology class further, this innovation is already occurring in the private sector and further government intervention is less required.

Table 3: EINAs technologies in the energy storage sub-theme

Technology type	Description
4 – 8hour duration	This storage class is used to manage daily energy needs, such as shifting energy from low demand to peak demand periods and supporting renewable energy sources like wind and solar power, which may not generate electricity continuously throughout the day. Currently, much of this system need is met by thermal generators, fuelled by natural gas. However, as we move to a net zero electricity system, alternative solutions will be required. Technologies in this classification include battery storage systems, including lithium-ion, sodium-ion and flow batteries. They can be deployed on a standalone basis or co-located with either generation or demand. Established technologies such as pumped hydro storage (which can also provide storage beyond the 8-hour duration) are also used but further deployment is likely to be restricted due to geographical and environmental constraints. The UK is in a world-leading position in deploying 1-2 hour duration lithium-ion battery systems, with the third highest deployment after China and the USA.[3] However, whilst lithium-ion batteries are a commercially accepted technology at this duration, further innovation is required to reduce costs and improve energy densities to enable longer duration to become commercially viable and derisk supply chains for the development of novel battery chemistries. TRLs for longer duration battery technologies range from 4 (validated in a laboratory environment) to 8 (technology completed and qualified through test and demonstration) depending on chemistry[4][5]. Whilst most R&D activity is occurring in China and Europe, UK companies Faradion and LiNa have both completed demonstrations of their sodium-ion battery solutions and Invinity is scaling up its vanadium flow battery technology to the hundreds of MWh range, operating at 3-100+ MW.

[3] RethinkX (2024) Where in the world is all the battery storage?
[4] UKRI (2022) Eligibility of technology readiness levels (TRL)
[5] DESNZ (2024) Scenario Deployment Analysis for Long-Duration Electricity Storage

Technology type	Description
8 – 24-hour duration	8 – 24-hour duration storage will be required for balancing over the daily cycles of demand and solar PV, alongside resolving prolonged transmission constraints. Currently, as with 4 – 8-hour duration storage, much of this system need is met by thermal generators, fuelled by natural gas. However, as we move to a net zero electricity system, alternative solutions will be required, with GW scale deployment anticipated in the 2030s[6]. The technologies considered in this category are liquid air and compressed air energy storage (LAES, CAES). Flow batteries are covered in the 4 – 8-hour duration section of the report. Current deployment of CAES and LAES in the UK is at demonstration scale, with TRLs of 7 and 8 respectively.[7] UK-based market leaders include HighView Power.
>24-hour duration	Energy storage of longer durations will be required for multi-day events, such as prolonged transmission constraints over low demand weekends and balancing multi-day wind events, caused by weather patterns that drive changes in wind output. It may also be required for rare longer weather patterns that result in longer periods of wind-drought, especially during cold periods. Hydrogen storage is the key technology to meet this need, with liquid air and compressed air storage likely to play a supplementary role. Novel battery chemistries such as iron-air could also meet this need but are at a low TRL and further R&D activity is required. Technological solutions and innovation needs for storing and transporting hydrogen are covered in the Hydrogen report.

[6] National Energy System Operator (2024) Future Energy Scenarios
[7] DESNZ (2024) Scenario Deployment Analysis for Long-Duration Electricity Storage

Energy storage technologies which are out of the scope of this report are detailed in the table below.

Table 4: Energy storage technologies excluded from this report

Technology	Reason for exclusion
Gravitational storage	Gravitational storage methods, such as solid gravitational storage is at an early TRL, so was not considered for the EINAs.
Pumped hydro storage	Pumped hydro storage is already commercially mature and so was not prioritised for the EINAs assessment.
Thermal storage	Thermal storage technologies that fall into the 8 – 24-hour duration classes are included in the Heat and Buildings EINAs report.

Energy storage in the UK energy system

The UK is a global leader in the deployment of energy storage. The UK's leading position on electricity sector decarbonisation through high levels of deployment of intermittent renewable energy technologies such as wind and solar has created the demand for storage faster than in other markets. As Europe's largest utility-scale battery market, batteries are already a key provider of frequency response and reserve in the UK.[8] However, to date, much of this storage capacity is in short duration lithium-ion batteries, targeted at meeting grid frequency response needs and, increasingly, to balance hourly variations in supply and demand.

The UK Government has committed to a clean power system by 2030[9] and has a legally-binding commitment to achieve net zero emissions by 2050.[10] The Government has recognised the role of energy storage in achieving these targets, through replacing flexibility from fossil-fuelled generation, especially required in cold, windless weather conditions, and helping to alleviate constraints on the grid. System modelling estimates savings for the energy system and, ultimately, the energy consumer, could be £24 billion by 2050 from 20GW of energy storage, ranging from durations of 1-hour to up to 100 hours in a central scenario.[11]

A range of technologies can fulfil this requirement, and a combination of them has been shown to result in the optimal deployment through providing a range of storage durations, speeds of response and make use of differing siting requirements. Pumped Hydro Storage (PHS) is the

[8] IEA (2024) Batteries and Secure Energy Transitions
[9] DESNZ (2025) Clean Power 2030 Action Plan
[10] HM Government (2019) The Climate Change Act 2008 (2050 Target Amendment) Order 2019
[11] DESNZ (2024) Long duration electricity storage consultation: Government Response

most mature of these technologies, with 181 GW (up to 9 TWh[12]) deployed globally,[13] 2.7GW (32 GWh) of which is in the UK.[14] However, it is deployment is constrained by geographical and environmental constraints, combined with high upfront capital costs, leading to alternative technologies being required. Technologies likely to reach maturity in the coming decades include Liquid Air Energy Storage (LAES), Compressed Air Energy Storage (CAES), gravitational, high-density pumped hydro, and longer duration batteries using a variety of chemistries, a subset of which are explored in this report. However, global deployment of these technologies is still in its infancy, hindered by a range of technological and non-technological barriers.

To date, support has been provided to longer duration energy storage providers in the UK through the Longer Duration Energy Storage (LoDES) Demonstration Programme[15], and recent decisions to implement a cap and floor support scheme. The floor will be set to allow returns approximately equal to debt cost and the cap will be set to provide a fair return on investment if assets perform well in the market.[16] However, further innovation is required to help technologies to reach the scale required, at commercially viable cost points. The UK will need these technologies earlier than most countries and UK companies are already innovating in this space, meaning the UK is uniquely positioned to capitalise on this emerging market, both to reduce the cost of the energy transition in the UK and as an export opportunity as global demand grows.

Investing in innovation in this area could support the development of domestic supply chains and position the UK for export opportunities, especially through supporting non-lithium solutions. Whilst alternatives do still require some critical minerals, their usage is much reduced. China currently dominates the lithium-ion battery supply chain, with nearly 85% of global battery cell production capacity and substantial shares in cathode and anode active material production.[17] The concentration of the supply chain presents a risk to the UK, as the entire supply chain is vulnerable to policy changes and geopolitical dynamics. This was demonstrated by recent restrictions on the export of graphite from China, a key material in lithium-ion batteries, and the current geopolitical competition to control critical mineral resources in Ukraine. While Europe and the USA both have plans to scale up production[18,19], heavy reliance on lithium-ion storage solutions could still leave the UK vulnerable to supply chain risks, either political or high levels of competition from other countries as global demand increases.

[12] International Hydropower Association (Accessed: 2025) Pumped storage hydropower: Water batteries for solar and wind power
[13] IEA (2024) Batteries and Secure Energy Transitions
[14] British Hydropower Association (Accessed: 2025) Pumped Storage Hydro
[15] HM Government (2023) Longer Duration Energy Storage (LoDES) Demonstration Programme: successful projects
[16] DESNZ, Ofgem (2025) Long Duration Electricity Storage: Technical Decision
[17] IEA (2024) Batteries and Secure Energy Transitions
[18] European Parliament (2025) Powering the EU's future: Strengthening the EU battery industry
[19] TechCrunch (2025) Tracking the EV battery factory construction boom across North America

Energy storage innovation opportunities

This section outlines key innovation opportunities to reduce costs, support commercialisation and enable the scale up of 4 – 8-hour and 8 – 24-hour duration storage technologies. Long-duration hydrogen storage is covered in the Hydrogen EINAs report and thermal storage can be found in the disruptive technologies section of the Heat and Buildings report. Key focus areas for innovation are outlined below and mapped along with their likely impact on cost and deployment.

Overview of 4 – 8-hour duration technologies

The shortlisted 4 – 8-hour duration technologies are electrochemical storage technologies, commonly known as batteries. A battery is made up of an anode, cathode, separator, electrolyte, and two current collectors (positive and negative), as illustrated in Figure 1. Different battery chemistries yield different characteristics, such as efficiency, energy density, discharge rates and lifetime. Beyond the batteries themselves, these systems have multiple other components, which are critical for full functionality. These include a battery management system that controls and monitors the state of the battery, a thermal management system, and often fire suppression systems, depending on the battery chemistry.

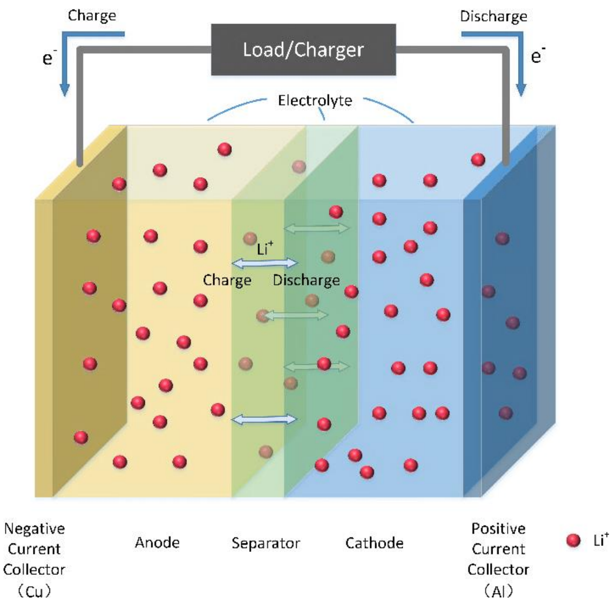

Figure 1: Components of a lithium-ion battery

Lithium-ion batteries

Lithium-ion batteries are a class of electrochemical batteries, widely recognised for their high energy density and efficiency. Lithium-ion batteries have been widely deployed for stationary storage in the past decade, both in behind-the-meter and grid-scale applications, typically at durations of 2 hours or less. However, further innovation is required to reduce costs and improve energy densities to enable longer duration (e.g. 4 – 8-hour) to become commercially viable and derisk supply chains for the development of novel battery chemistries.

For energy storage applications, a range of lithium chemistries with differing properties are used for the cathode, most commonly lithium nickel manganese (NMC) and lithium iron phosphate (LFP). Commonly the anode is made of graphite and current collectors are typically made from copper on the anode side and aluminium or nickel on the cathode side.

The chemistry of lithium-ion batteries allows for a high energy density and discharge rates. They operate efficiently within a temperature range of -20°C to 60°C, with performance degradation occurring outside this range. As lithium-ion batteries are widely used in <2 hour duration use cases, supply chains are already well-established and there is ongoing innovation to reduce cost and improve performance. This provides a robust base to build innovation focused on increasing duration.

However, lithium-ion batteries present certain limitations, such as relatively high costs for longer durations and safety concerns related to thermal runaway, alongside concerns around sustainability in extracting raw materials and reliance on global supply chains as described below in the Market innovation barriers and enablers: deep dives section of this report.

Sodium-ion batteries

Sodium-ion batteries are emerging as a promising longer duration, stationary storage alternative to lithium-ion batteries, primarily due to the abundance and low cost of sodium and the reduced need for critical minerals such as lithium and copper (see Figure 2). Sodium-ion batteries use sodium-iron-phosphate ($NaFePO_4$) or sodium-layered oxide as the cathode material and typically use hard carbon as the anode and current collectors made from aluminium on both anode and cathode sides. While sodium-ion batteries generally exhibit lower energy density and cycle life compared to lithium-ion batteries, recent advancements, especially in the development of new cathode materials, have significantly improved their performance.

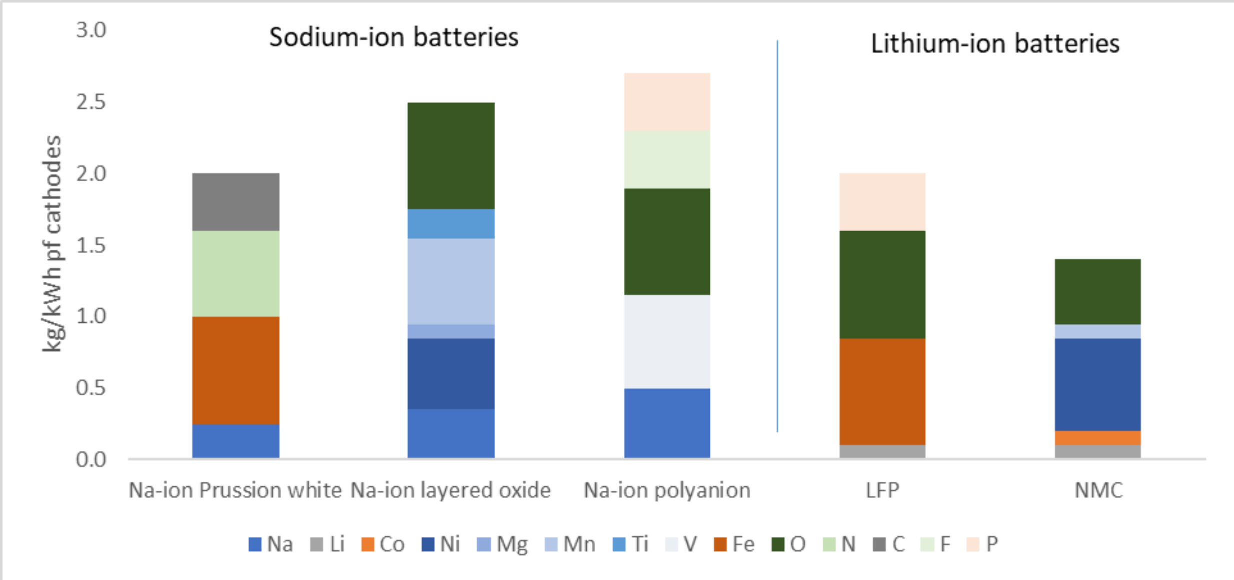

Figure 2: Material intensity of common sodium-ion and lithium-ion battery cathodes

Sodium-ion batteries operate efficiently within a similar temperature range as LIBs but are inherently safer due to the lower risk of thermal runaway. However, sodium-ion batteries are still performing less well on energy density and cycle life relative to lithium-ion batteries.[20]

Unlike lithium-ion batteries, sodium-ion batteries are not a commercially mature technology at TRLs around 7,[21] with supply chains still in their infancy. However, their similarities to lithium-ion batteries may provide opportunities to repurpose existing manufacturing production lines, offering cost savings through amortised equipment costs that would otherwise be incurred with the development of entirely new product lines.

Flow batteries

Flow batteries, also known as redox flow batteries, are a type of rechargeable battery where energy is stored in liquid electrolytes contained in external tanks. The most common types include vanadium redox flow batteries (VRFBs) and zinc-bromine flow batteries. These batteries offer several advantages, such as long cycle life, scalability, a self-discharge rate close to 0% and flexible power to energy capacity ratios. They operate efficiently over a wide temperature range and have a lower risk of thermal runaway compared to lithium-ion alternatives batteries. Flow batteries are also likely to be able to serve durations longer than 8-hours when deployed at scale. However, flow batteries typically have lower energy densities so require large footprints. They can also have higher initial costs due to the complexity of the system and the cost of the vanadium electrolyte can be a barrier where utilised.

However, as noted above, the UK faces challenges in securing a stable supply of vanadium and other critical materials, and further development of chemistries with lower costs of raw materials is required.[22]

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[20] IEA (2024) Batteries and Secure Energy Transitions
[21] US DOE (2023) Technology Strategy Assessment - Sodium Batteries
[22] IEA (2024) Global Critical Minerals Outlook 2024

Innovation opportunities in 4 – 8-hour duration storage

Overview of 4 – 8-hour duration storage innovation areas

Advancements in battery chemistries

Advances in battery chemistries are required for all three technologies considered and are key to improving their capabilities to make them suitable for longer duration applications at commercially viable cost points. Innovation in artificial intelligence and machine learning to accelerate material discovery and cell design, alongside improvements in-line monitoring methods for assessing battery status during test phases, are key enabling technologies in this area.

Key areas of focus include:

Increasing energy density

Enhancing the energy density of storage technologies to store more energy in a smaller footprint is essential for practical and scalable solutions for longer duration batteries. This challenge is currently significantly greater in flow batteries and sodium-ion batteries, which have lower energy density than lithium-ion batteries. Improving energy density in flow batteries has the secondary advantage of reducing the need to transport heavy-liquid electrolytes, further reducing costs.

Maintaining high State of Charge (SoC) conditions

For longer duration applications, there is a greater requirement to maintain a high SoC over an extended period. This is currently a key challenge for lithium-ion batteries, leading to accelerated capacity fade and hence a reduced calendar lifetime.[23] To mitigate this fade, advances for both the positive and negative electrodes of the cell would be beneficial, with a focus on identifying and commercialising materials with lower reactivity.

This is less of a challenge in flow batteries, which maintain SoC well over long timescales due to the separation of the liquid electrolyte from the electrodes until a discharge cycle is required.

SoC is challenging to estimate and model in sodium-ion batteries, as the technologies exhibit distinct characteristics during charging and discharging processes and as they age, due to variations in materials.[24]

Improvements to cycle life

To achieve a significantly long life, it is necessary for electrolytes to have both low chemical and electrochemical degradation rates. There are opportunities for innovation in novel active electrolytes, including those with high chemical stability, innovation of catholytes which couple

[23] US DOE (2023) [Findings from Storage Innovations 2030: Lithium-ion Batteries]
[24] Wang, S. et al (2024) [Accurate state-of-charge estimation for sodium-ion batteries based on a low-complexity model with hierarchical learning]

with sodium metal at lower temperatures, and electrolytes with improved performance at high temperatures, to improve life cycle for flow batteries by up to 40%.[25]

Anode and cathode materials also face degradation over use. For sodium-ion batteries, identifying electrode materials which can reversibly intercalate sodium ions with high capacity and stability is a focus area for innovation to improve cycle lifetime.[26] Innovation in the electrodes for lithium-ion batteries can support improved SoC and longer cycle life, including through reduced reactivity for both the anode and cathode.[27]

Reducing material costs

Reducing the cost of raw materials is crucial to reducing capital costs. This could be achieved through evolving cell chemistries, such as enabling the use of silicon in place of graphite anodes in lithium batteries, which are likely to decrease in cost as the technology develops, Costs can also be lowered through reducing the quantity of high-cost components required. Experts estimate that the cost of active anode materials could be reduced from around US$12/kWh to a potential cost of around US$2-4/kWh.[28]

Improving the performance of sodium-ion batteries could also achieve an overall reduction in materials costs for 4 – 8-hour duration storage. The raw materials in sodium-ion batteries are more abundant and hence less costly than lithium-ion battery or flow battery components. The primary cost advantage is the ability to use aluminium current collector on both the anode and cathode side for sodium-ion batteries. This is not the case for lithium-ion batteries, as lithium forms an alloy with aluminium at low voltages, so one half of the current collectors must use the copper current collector, which is more expensive. Once scaled up, cost modelling suggests that sodium-ion batteries could have up to 30% lower material costs compared to lithium-ion batteries (LFP chemistry),[29] assuming performance can be proved to be equivalent across these technologies. This relative cost advantage is also dependent on lithium prices, which have been volatile over recent years.[30]

For flow batteries, innovation to reduce the quantity and cost of the electrolyte could be a key component of cost reduction, especially for chemistries with high-cost components, such as vanadium. Additionally, improvements in the strength and durability of membranes would allow for thinner, less resistive membranes to be used in stack construction, thereby reducing costs.[31]

Advanced monitoring and control systems

Alongside advances in cell chemistry, improving control systems could also yield improvements in lifetime and efficiency. This can be done through improved monitoring and

[25] US DOE (2023) Technology Strategy Assessment - Flow Batteries
[26] Phogat, P. et al. (2025) Comprehensive review of Sodium-Ion Batteries: Principles, Materials, Performance, Challenges, and future Perspectives
[27] US DOE (2023) Findings from Storage Innovations 2030: Lithium-ion Batteries
[28] US DOE (2023) Findings from Storage Innovations 2030: Lithium-ion Batteries; values quoted are in $2023.
[29] IEA (2023) Batteries and Secure Energy Transitions
[30] IEA (2023) Batteries and Secure Energy Transitions
[31] US DOE (2023) Findings from Storage Innovations 2030: Flow Batteries

control systems, which can precisely monitor and control the SoC, state of health, and temperature of the battery cells, ensuring optimal performance and preventing overcharging or deep discharging. The data from these monitoring systems could also be used to develop predictive maintenance capability, where batteries can be serviced or replaced proactively rather than waiting for outright failures. Advanced control systems can also improve the integration of the battery within the wider energy system, enabling dynamic management of energy flows to maximise revenue opportunities, a key area of ongoing R&D for battery optimisers and aggregators, especially with emerging system operational needs such as reactive power, inertia and voltage management.[32]

Advance manufacturing techniques

Advanced manufacturing techniques refer to innovative processes and technologies used to enhance the production of batteries, aiming to improve efficiency, precision, scalability, and sustainability. These techniques often involve the integration of automation, robotics, and machine learning to optimise the various stages of battery manufacturing, alongside facilitating the use of recycling and waste reduction to improve sustainability. This innovation area also includes repurposing existing manufacturing infrastructure for 8 – 24-hour duration storage technologies, with flexibility in these processes to allow for the adoption of new materials and innovations in battery design.

Supply chains and recycling

Supply chains are a critical area of risk for battery storage in the UK due to several factors:

- Raw Material Dependency: Lithium-ion batteries rely heavily on critical minerals like lithium, cobalt, graphite and nickel, and flow batteries often have vanadium or other rare materials as components. The UK imports most of these materials, making the supply chain vulnerable to geopolitical tensions, trade restrictions, and price volatility. For more detail, refer to the deep dive 3 section. Sodium batteries utilise fewer rare raw materials than the other two technologies, making them less vulnerable to these risks.
- Sustainability of mining and extraction processes: The extraction process of many of the rare earth materials required for these technologies is often water-intensive and can lead to water depletion and contamination, as well as habitat destruction and particulate pollution.[33] Additionally, the mining of critical minerals has been linked with violent incidents and civil unrest in countries with high levels of mineral extraction occurring.[34]
- Limited domestic manufacturing capabilities: whilst the UK has deployed a large number of large-scale, short-duration, stationary lithium-ion batteries, these have been almost universally manufactured overseas. Sodium-ion and flow batteries are also facing challenges in scaling up manufacturing in the UK, particularly since their manufacturing processes are still in development.

Innovation in repurposing and recycling, and standardisation of batteries is a key opportunity for reducing both cost and risk. For lithium batteries, focus is required on developing rapid

[32] ModoEnergy (2025) Podcast: Advanced battery analytics - with Shyam Srinivasan
[33] Institute for Energy Research (2020) The Environmental Impact of Lithium Batteries
[34] Global Witness (2024) Critical mineral mines tied to 111 violent incidents and protests on average a year

battery health assessments to determine the remaining battery life and performance of a system, which would accelerate the process of identifying and repurposing EV batteries for second life applications as stationary storage, alongside increasing buyer confidence. For recycling battery systems, reducing impurities is a key innovation area. Impurities can reduce the efficiency of metal recovery and degrade the quality of the material that is recovered.

For flow batteries, innovations that enhance recycling automation, methods for recycling electrolytes, and recovering byproducts will improve the value proposition for recycling.

Whilst the lower cost and general abundance of the raw materials in sodium-ion batteries is a key strength of this technology, it also reduces the financial case for recycling.

Safety

While DESNZ analysis[35] suggests that there is no greater danger posed by lithium-ion batteries at grid-scale compared to other infrastructure types, it is vital that any risks are appropriately managed to maintain public safety and trust. Lithium-ion batteries carry associated flammability risks and a risk of explosion in severe cases of system failure. While failure incidents at battery storage sites in GB are rare, the safety of battery systems will need to continue to improve in order to reduce deployment cost and risks. This is particularly relevant for anticipated deployment co-located with demand, or for utility scale installations of greater size. Existing and enhanced safety frameworks, as well as innovation can support the continued management of these risks, including:

- development of lower flammability electrolytes and stable cathode materials;
- the design and development of system architectures that minimise or fully prevent propagation of failure between cells;
- controls and monitoring systems that can readily identify the state of safety and trigger mitigation measures.[36]
- In addition, innovation to improve the cost and performance of flow batteries and sodium-ion batteries, which have inherently lower safety risks, can allow them to become competitive with lithium-ion batteries. This should be considered as part of the case for pursuing innovation in these technologies.

Sodium-ion batteries are safer than lithium-ion batteries due to the relative stability of each technology. The higher stability of sodium allows cells to be stored in a fully discharged state, meaning sodium-ion cells can be stored and transported more easily. Furthermore, sodium-ion batteries are less prone to thermal runaway than lithium-ion. All redox flow batteries are inherently safer than lithium-ion because they are less susceptible to failure or short-circuit, which lowers the risk of fire. However, there is a higher risk of leakage of electrolytes and the formation of gases from side reactions within the system, which should be addressed.

[35] Fires at grid-scale battery sites appear to be less likely than those at non-domestic buildings in general from all sources. The latest available 5-year annual average fire incidence rate for GB batteries is 0.7% (2020/21 to 2024 to 2025), lower than that for wider non-domestic building fires in England at 0.8% (2019/20 to 2023/24).
[36] US DOE (2023) Findings from Storage Innovations 2030: Lithium-ion Batteries

Table of innovation needs

This table details key components and areas of technology innovation required to reduce cost and accelerate the deployment of the 4 – 8-hour duration energy storage technologies assessed in this report, lithium-ion, sodium-ion and flow batteries. The table details the direct technology impacts of innovations, as well as the other EINAs priority technologies that could benefit from innovation in these areas. Each innovation is assessed according to its likely impact on cost reduction and deployment for the relevant technology, with a qualitatively assessed 1(very low) – 5 (very high) impact rating. Column descriptors within the table are defined as following:

- Technology: technologies where the innovation is applicable.
- Other impacts: other technology families that are indirectly impacted by this innovation.
- Cost reduction: how the innovation opportunity can reduce the overall costs of the technology, rated from 1 (low) to 5 (high).
- Barrier reduction: how the innovation opportunity can contribute to reducing barriers to deployment, rated from 1 (low) to 5 (high).
- Time frame: period over which the innovation could feasibly start to be adopted and have material implications for the UK energy system and Net Zero

Table 5: Table of innovation needs for lithium-ion, sodium-ion and flow batteries

Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Advancements in cell chemistry: to utilise more abundant materials	Lithium-ion batteries, sodium-ion batteries, flow batteries	EVs	5 – A key cost driver of battery storage is the cost of raw materials such as lithium, nickel, cobalt, copper, graphite and vanadium. Reducing the amount of these materials required will reduce the overall capex of these assets. Incremental improvements to cell chemistries can unlock performance improvements, such as improved energy density and lifetime, improving the viability of these technologies for longer duration applications.	4 - Reducing costs and improving performance is key for these technologies to become cost effective alternatives to building new transmission infrastructure or overbuilding generation capacity. Improvements in energy density can also reduce the site footprint required, aiding in land acquisition, and easing the consenting process.	2030 – 2035

Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Manufacturing techniques	Lithium-ion batteries, sodium-ion batteries, flow batteries	EVs	4 – Improvements in manufacturing process, such as increased automation and precision in component fabrication reduces costs through improvements in productivity and reductions in material usage.	4 - Facilitating the scale-up of promising manufacturing technologies and techniques that have been proven on the laboratory scale ensures that these innovations can be implemented faster on a larger scale, unlocking the cost savings that arise from economies of scale.	2025 – 2030

Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Supply chains, recycling and end of life	Lithium-ion batteries, sodium-ion batteries, flow batteries	EVs	5 - Improving the identification and recycling of defective and degraded cells reduces waste and recovers valuable materials, contributing to cost savings. The lower cost of raw materials in sodium-ion batteries makes this a less critical innovation area for this technology.	3 – Whilst not currently a huge limitation to deployment, supply chains are seen as a significant risk as both demand for rare earth metals and political tensions in regions mining and processing these materials grows. Diversifying to more abundant materials and reducing the cost of repurposing and recycling can mitigate this risk and enable higher levels of deployment during the 2030s. However, increasing the number of battery types deployed could create additional challenges for recycling processes.	2030 - 2035

Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Advanced control systems	Lithium-ion batteries, sodium-ion batteries, flow batteries	>8-hour duration storage; EVs	4 – Advanced controls to extend battery lifetimes through reduced degradation and improve performance has been identified as a critical area to reducing lifecycle costs. This can be achieved through investigation of ageing physics and failure mode analysis.	3 – Advanced control systems can reduce deployment barriers associated with lifetime and operating costs, enabling improved revenue generation and reduced cell degradation.	2025 – 2030
Safety	Lithium-ion batteries	EVs	3 – Lithium-ion batteries require complex thermal management systems to prevent overheating and thermal runaway, which can lead to fires. These systems add cost to the system as well as resulting in higher siting costs due to increasing the site footprint per MWh of capacity. Reducing the need for these systems through improvements in chemistry, cell and stack design and monitoring and control systems can reduce these costs.	2 – Whilst safety considerations can lead to higher costs of deploying lithium-ion batteries, it is not currently impacting deployment rates in most stationary storage use cases as the risks are well-understood and effectively mitigated.	2025 – 2030

Components and costs

This section outlines the primary cost components and opportunities for cost reduction for 8 – 24-hour duration energy storage. Figures included in this section for storage technologies are based on estimates from a range of sources, including studies from the Pacific Northwest National Laboratory, National Renewable Energy Laboratory and ongoing UK based innovation programmes.

LCOS estimates in this section do not include charging costs for the storage system; these have a high level of variability depending on the exact use-case of the asset, ownership model, and collocation with other technologies.

CAPEX costs:

- Storage block, containing battery modules and racks, flow battery stacks, electrolyte, and tanks;
- Balance of system consisting of containers; heating, ventilation, and air conditioning (HVAC); safety disconnects; fire extinguishers; and pumps, valves, and pipes;
- Power equipment and systems integration, including Power Conversion System & DC-DC Converter, controls and energy management systems;
- Grid integration, including costs associated with connecting the ESS to the grid, including transformer cost, metering, and isolation breakers;
- EPC, including engineering, procurement, and construction costs as well as siting, installation, and commissioning of the storage asset;
- Development and project management, including costs associated with permitting, power purchase agreements, interconnection agreements, site control, and financing. These costs can vary significantly depending on whether the asset is being stand-alone or used in combination with other assets, the exact use case it is being deployed for and flexibility to stack revenue streams, and the how established the relationship between the project developer and capital provider is.

CAPEX costs are the largest element of the LCOS in a battery storage system, representing approximately 70% of the cost, although this varies between technologies and the use case of the battery. These costs are typically declining across all three technologies assessed in this category, driven by innovation in the chemistries used and improvements in manufacturing. However, a key area of cost uncertainty is the availability and demand for rare earth metals such as lithium, nickel cobalt and vanadium, leading to volatility in commodity prices for these materials. This volatility could to an extent counteract cost savings made through innovation, or drive a shift to more available, but potentially lower performing battery chemistries.

OPEX costs: this cost covers fixed operation and maintenance costs such as yearly minor maintenance including inspections, filter replacements, alignments, and in some cases software upgrade and replacement of components. O&M costs are assumed to contribute to ~30% of LCOS. Charging costs have not been included in this assessment, due to the dependency of these costs on changes in other parts of the energy sector influencing energy prices combined with the highly use case specific nature impacting the magnitude of exposure to wider energy prices.

Decommissioning costs: The cost components of end-of-life treatment can include disconnection and preparation for removal of the electrical and communications system, removal of the battery modules, rental of equipment including cranes, forklifts, and telehandlers, and removal of battery components from site. In addition, remedial works to the site may be required, depending on the site's characteristics. Recycling lithium-ion batteries is a growing market; EU regulation[37] setting mandatory minimum levels of recycled content for batteries sold within its borders comes into force in 2031 and the UK's ambitions to unlock battery recycling are stated in the UK Battery Strategy.[38] Combined with anticipated cost reductions and efficiency gains in recycling processes, the value recovered from the sale of the high value materials in the battery is expected to result in the decommissioning process being cost neutral by 2030. Decommissioning costs are anticipated to be a more significant part of the cost of sodium and flow batteries, due to their lower value components.

Overview of 8 – 24-hour duration technologies: CAES and LAES

Compressed air energy storage (CAES)

CAES is a form of mechanical energy storage. The process involves using energy to compress air and storing it in large underground caverns or above-ground tanks during periods of low energy demand. This compression phase generates heat as a buy product. When the energy is later required, the stored compressed air is released, heated and expanded through turbines to generate electricity. As the components of CAES are similar to those used in CCGTs, they are widely available and well understood.

Potential underground storage locations include depleted gas wells, salt mines, porous rocks, and caverns. In the UK, the most suitable sites for CAES are salt caverns, primarily located in the North East of England, Cheshire, and Northern Ireland.[39] These sites are also well suited to hydrogen storage solutions, so determining the optimum deployment of both technologies and assigning sites to meet these needs will be required. Suitable rock formations and depleted gas wells are also possible locations, but demonstration of the technology at scale in these locations is still required.

There are fewer than ten CAES plants in operation globally, located in the US, Canada, China and Germany, and none currently operational in the UK. These sites vary in capacity from <10MW and MWhs up to low hundreds of MW and hundreds of MWh. Canda represents the world's first adiabatic CAES plant,[40] while China also hosts an adiabatic CAES plant in

[37] European Union (2023) Regulation - 2023/1542 - EN - EUR-Lex
[38] Department for Business & Trade (2023) UK battery strategy
[39] Mott MacDonald (2018) Storage cost and technical assumptions for BEIS
[40] Energy Storage News (2019) Grid-connected advanced compressed air energy storage plant comes online in Ontario

Shandong Province.[41] Whilst above-ground solutions using tanks as the storage vessel are being investigated, costs are still too high for this approach to be commercially viable.

There are three main types of CAES systems: diabatic, adiabatic, and isothermal. The key differences between them relate to how they treat heat during the compression and expansion process. Diabatic systems dissipate the heat generated during compression, which reduces efficiency, but uses a simpler design and comes at lower capital cost. Diabatic systems represent the simplest and most mature CAES technology. More advanced CAES include adiabatic systems, which store the heat generated during compression and reuse it during expansion, which could improve round trip efficiency from ~50% up to 75%[42, 43]. Isothermal systems aim to maintain a constant temperature during compression and expansion, with the potential to enable round trip efficiencies as high as 80%. However, this is technically more challenging and has not yet been demonstrated at scale.

Strengths of this technology include its ability to scale to very large energy capacities, making it well suited for grid-scale applications. Combined with a long lifetime, this high energy storage capacity makes it a potentially cost-effective solution compared to alternative storage technologies. [44, 45] Once stored, self-discharge rates are low, allowing energy to be stored for extended periods.

Weaknesses are the comparatively low round trip efficiency of diabatic CAES, geographical constraints on siting locations and high upfront capital costs. Compared to battery solutions, response times are slow. CAES also has low energy density, relative to liquid air energy storage, although isothermal CAES can offer improved energy densities relative to adiabatic CAES.[46]

Liquid air energy storage (LAES)

LAES is a subset of CAES and follows similar principes to its parent technology, with energy being stored during a compression stage and electricity generated as the compressed air is released and used to drive a turbine to generate electricity. However, LAES adds the cooling of the compressed air to cryogenic temperatures, turning it into a liquid to be stored in insulated tanks. This allows higher energy densities and removes the requirement for specific geographical formations, thereby enabling greater flexibility in location.

Globally, LAES is still in the early stages of deployment and has been pioneered by UK-based Highview Power. Highview has several large-scale projects in various stages of development.

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[41] World Energy (2024) World's Largest Compressed Air Energy Storage Project Comes Online in China - World-Energy
[42] Urbanao (2025) Compressed Air Energy Storage (CAES): A Comprehensive 2025 Overview
[43] Roos, P., Haselbacher, A. (2022) Analytical modelling of advanced adiabatic compressed air energy storage: Literature review and new models
[44] LCM (2013) Life cycle assessment of compressed air energy storage
[45] Urbanao (2025) Compressed Air Energy Storage (CAES): A Comprehensive 2025 Overview
[46] Roos, P., Haselbacher, A. (2022) Advanced Compressed Air Energy Storage Systems: Fundamentals and Applications

These include a 50MW/400 MWh system in the United States,[47] a 50MW/300 MWh project in Manchester,[48] and seven 50MW/300 MWh facilities in Spain.[49]

As with CAES, LAES has a lower round-trip efficiency (50 – 60%)[50] than alternative storage technologies such as pumped hydropower storage or batteries, alongside high upfront costs.

Innovation opportunities in 8 – 24-hour duration storage: CAES and LAES

Overview of 8 – 24-hour duration storage innovation opportunities

Analytics

Innovation in enhanced system modelling and design optimisation through artificial intelligence and machine learning based techniques presents a significant opportunity to improve CAES and LAES performance.[51] Further innovation in analysis using digital twins in simulated economic operations could offer valuable insights for refining system design, leading to better optimisation and reduced operational costs. This includes analysis into optimal operation when co-located with renewables and integration with the wider electricity system.[52] Innovation in analytics approaches can therefore unlock further insights to inform technological innovation and refinement.

Developing standardised testing and measurement procedures, such as an industry-standard protocol for performance measurement, including component and round-trip efficiencies, will enable consistent evaluation. This will facilitate better comparison and benchmarking, which will drive technological improvements and foster stakeholder confidence.

Component level innovation

While many of the components of CAES and LAES are widely used in other technologies, further research into high-efficiency compressors and expanders, turbines that can operate at low temperatures and reciprocating mechanical pistons with heat tolerance are required to improve system efficiency. For isothermal and adiabatic CAES and LAES, high-efficiency thermal stores and multi-stream heat exchangers could reduce lifecycle costs and improve performance.[53]

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[47] Energy Storage News (2019) Highview Power launches liquid air energy storage into the US with 400MWh Vermont project
[48] Highview Power (Accessed: 2025) Projects | Highview Power
[49] Highview Power (2021) Highview Power Developing 2 GWh of Liquid Air Long Duration Energy Storage Projects in Spain
[50] Roos, P., Haselbacher, A. (2022) Advanced Compressed Air Energy Storage Systems: Fundamentals and Applications
[51] Roos, P., Haselbacher, A. (2022) Analytical modeling of advanced adiabatic compressed air energy storage: Literature review and new models
[52] Ting Liang, et al. (2023) Liquid air energy storage technology: a comprehensive review of research, development and deployment
[53] Roos, P., Haselbacher, A. (2022) Liquid air energy storage technology: a comprehensive review of research, development and deployment

Advanced manufacturing

Implementation of automation, waste reduction approaches, and adaption of existing infrastructure for CAES and LAES specific use cases can all contribute to reducing the high upfront cost associated with these technologies. A particular area of focus is developing flexible robotic welding in the manufacture of pressure vessels and pipes, which could have wider benefits for related technologies such as hydrogen and CCUS.

Deployment and demonstration projects

With the limited deployment of CAES and LAES technologies, demonstration at scale will be crucial to derisk investment and validate the impacts of innovations in areas such as novel system types (e.g., isothermal, adiabatic CAES), novel air storage vessels and operating strategies on lifecycle costs. These findings should feed into shaping future innovation priorities.

Table of innovation needs

This table details key components and areas of technology innovation required to reduce cost and accelerate the deployment of the 8 – 24-hour energy storage technologies assessed in this report, CAES and LAES. The table details the direct technology impacts of innovations, as well as the other EINAs priority technologies that could benefit from innovation in these areas. Each innovation is assessed according to its likely impact on cost reduction and deployment for the relevant technology, with a qualitatively assessed 1 (very low) – 5 (very high) impact rating. The timeframe assessment refers to the time period within which the innovation could be expected to have materials implications for the UK energy system and Net Zero with investment and innovation.

Table 6: Table of innovation needs for CAES and LAES

Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Analytics	CAES, LAES	N/A	3 – Analytics targeting improvements in round trip efficiencies, response times and control systems, using digital twins during the design process of the CAES system.	3 – Improvements in efficiency and operation of the site improve commercial viability and investor interest in the technology.	2025 – 2030

Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Large scale demonstration projects	CAES, LAES	Industrial processes	5 - Field-testing and validation of novel strategies reduce costs by proving viability and efficiency, informing future innovation areas and increasing investor confidence. This includes innovations in isothermal and adiabatic systems. Especially relevant for LAES, these demonstrations could include collocation with either demand sites, which could make use of waste heat or the waste air at the turbine exit, which may be useable in other low-pressure applications.	5 – Alongside reducing costs, demonstration and learning-by-doing can improve investor confidence, market acceptance, and trust. They can also uncover and address challenges in construction, grid integration and reliability that may not be identified in laboratory testing or smaller scale pilots.	2030 – 2035

Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Manufacturing	CAES, LAES	Hydrogen CCUS	4 - Automation of component manufacturing and waste reduction approaches lowers production costs	4 - Facilitating the scale-up of promising manufacturing technologies and techniques that have been proven at laboratory scale ensures that these innovations can be implemented faster on a larger scale, unlocking cost savings from economies of scale.	2035 – 2040
Component level innovation	CAES, LAES	Hydrogen CCUS	4 –Cost reductions through innovation in components will reduce the capital cost of the asset.	3 - The theoretical upper limit of round-trip efficiency is limited by the efficiency of each step in the process. Key to improving efficiency is therefore advances in technology for higher efficiency compressors and expanders, thermal storage and lower temperature turbines, leading to reduced operating costs.	2030 – 2035

Components and costs

This section outlines the primary cost components, and opportunities for cost reduction, for CAES and LAES. Figures included in this section are based on estimates from a range of sources, including studies from the Pacific Northwest National Laboratory, and ongoing UK based innovation programmes.

LCOS estimates given in this section do not include charging costs for the storage system, due to the high level of variability in these costs depending on the exact use case of the asset, ownership model and collocation with other technologies.

CAPEX costs:

- Storage system, covering the upfront costs of the storage vessel, such as the salt cavern on storage tanks;
- Power equipment, including compressors, turbines and generators, controls and communication equipment;
- Grid integration, including costs associated with connecting the storage system to the grid, including transformer cost, metering, and isolation breakers;
- EPC, including engineering, procurement and construction costs as well as siting, installation and commissioning of the storage asset;
- Development and project management, including costs associated with permitting, power purchase agreements, interconnection agreements, site control, and financing. These costs can vary significantly depending on whether the asset is being stand-alone or used in combination with other assets, the exact use case it's being deployed for and flexibility to stack revenue streams, and the how established the relationship between the project developer and capital provider is.

Capital costs are estimated to make up 80% of the LCOS of these technologies, with compressors, turbines and generators accounting for the vast majority of those costs.

OPEX costs:

Fixed O&M for CAES and LAES typically includes labour, safety, site maintenance, communications, training, office costs and administration. Variable O&M costs include chemical treatment and makeup water for the cooling tower and catalyst replacement. Combined, these costs are estimated to contribute to ~20% of the LCOS. Warranty costs have not been included in this assessment, due to the limited number of CAES projects and the approach to constructing them as a civil engineering project rather than as a single manufactured item.

Decommissioning costs:

Limited information exists on the decommissioning costs of CAES and LAES technologies. However, due to the expected long lifetimes (>30 years) of these energy storage methods, they are likely to be a very small proportion of the LCOS and have therefore been excluded from this assessment.

Market innovation barriers and enablers: deep dives

The various types of energy storage in the UK do not face the same limitations or barriers. As such, the approaches to enable deployment of each varies, though there are some overlaps between the storage types.

The primary challenges for each type of storage are outlined below, alongside potential, high-level enabling actions:

Table 7: Overview of barriers for the EINAs energy storage technologies with low/medium/high barrier ratings

	Short Duration Energy Storage (BESS)	**Longer Duration Energy Storage (CAES and LAES)**	**Long Duration Energy Storage (Hydrogen – underground storage)**
Grid queue constraints [0]	High - Ongoing work on queue reform. Particularly more ambitious/positive modelling assumptions and markets to drive this behaviour		Medium - Prioritise based on HND/system plan
Environmental constraints on siting [0]	Low - Limited/no siting constraints	Medium - May require salt/rock caverns	High - Requires salt/rock caverns or disused gas field
Metering / co-location issues [0]	High - CfD metering onerous, but now allowed in principle	Medium - Limited co-location options	Low - No co-location expected
Ability to realise value to system / appropriate markets. [0]	Medium - Most markets accessible but not fully utilised	Medium - Most markets accessible but not fully utilised. CM design only partially rewards Longer Duration Energy Storage	High - Small CM support relative to cost. Cap/floor planned but not yet implemented
Resource and supply chain [0]	High - Location and concentration of critical mineral supply chains	Low - UK well-placed to capitalise on geological storage	Medium - Supply chain constraints on components (e.g. compressors)

Deep dive 1: Siting constraints, including grid connections

Some energy storage is constrained from a physical or environmental perspective. Batteries can be located nearly anywhere, even on offshore platforms. However, forms of storage that rely on geological formations such as salt and rock caverns for gaseous or compressed air storage, valleys to store water for pumped hydro storage, and disused gas fields for natural gas and hydrogen storage are more restricted. The extent to which these are barriers to storage deployment is partly determined by costs and partly by planning permissions and permitting, in addition to the physical geographical constraints.

Furthermore, energy storage, like generators, needs access to the electricity grid to charge and discharge, which has been a growing challenging in recent years. Total GB generation and storage capacity connected to the grid at the end of 2023 was 102.4GW.[54] As of November 2024, there was a total queue of 732GW to connect to the GB transmission and distribution systems,[55] delaying the build-out of key projects to achieve Net Zero targets, including storage projects.

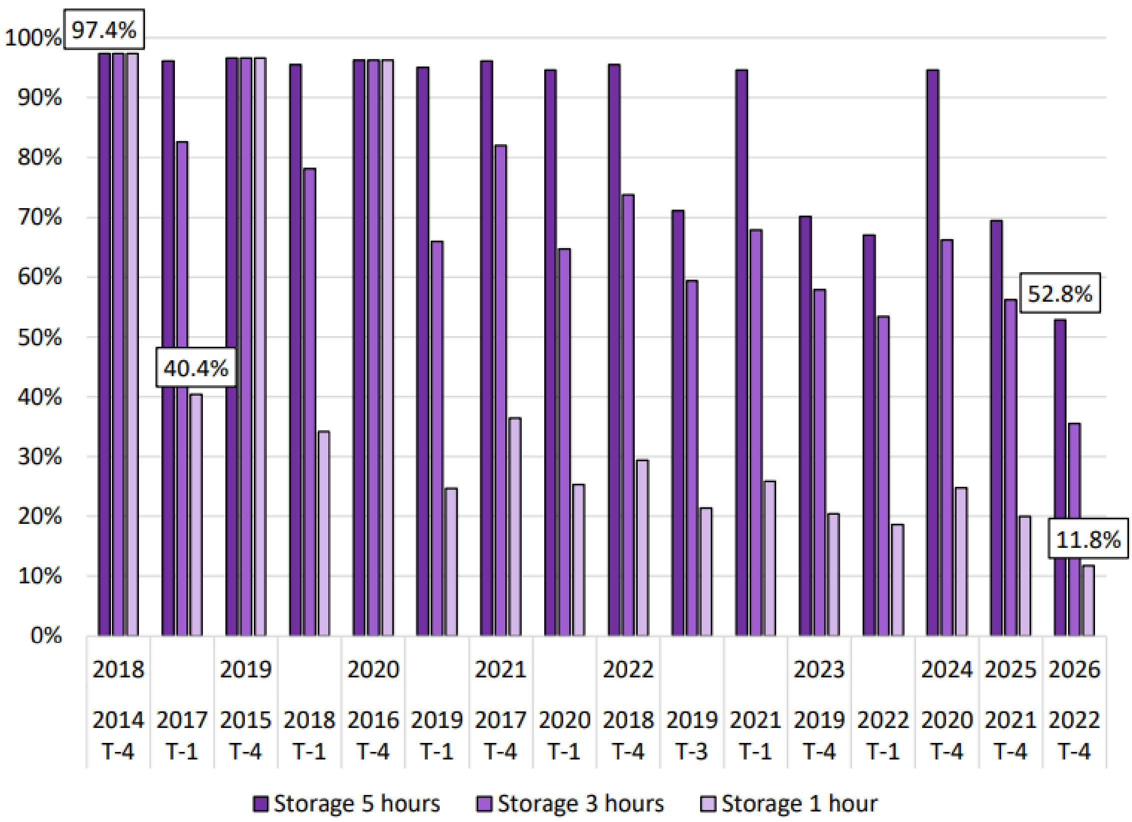
The connection queue is driven by a combination of battery connection applications far in excess of what will be needed, alongside a similar excess of applied-for capacity for renewable energy. The lack of certainty of grid access, and the timing of such access, should it be granted, adds to project risks and costs. This is compounded by the likely presence of speculative projects, which may not have funding or sufficiently robust plans to come to market when needed, crowding out more viable projects. The result is greater investment and delivery risk for the projects that eventually will need to be built and higher cost for end consumers.

Capacity has traditionally been measured in GW, reflecting a system dominated by baseload power. However, the changing energy mix and greater prevalence of variable generation creates a different challenge, where an incentive system focused on GW provision does not fully reflect the system benefits of storage. This is exemplified by the reduction of derated capacity attributed to short-duration storage in the Capacity Market (CM),[56] falling from 40.4% of nominal capacity in T-1 2017 to 11.8% in T-4 2022, see Figure 3,[57] and around 10.5% as of T-4 2025[58] at the time of writing.[59] While the CM is not meant as a support measure for energy storage, rather security of electricity supply, in the absence of other mechanisms the decrease in derating factors over time has meant that providers have limited incentives for deploying sufficient storage, particularly longer duration types which can address low renewable generation periods.

Greater reliance on variable, low carbon generation will lead to greater impact from periods with low wind and sun, known as “Dunkelflaute”. Longer duration energy storage will be

[54] Department of Energy Security and Net Zero (2024) Digest of UK Energy Statistics (DUKES): electricity – Table 5.12
[55] Ofgem (2024) Engaging stakeholders on connections reform
[56] To capture how much storage is expected to contribute to security of electricity supply in modelled stress events, NESO apply a de-rating factor to its nameplate capacity, relative to its duration.
[57] DESNZ (2023) Report on the Role of Ancillary Services to Encourage Low Carbon Operability – Figure 3.
[58]NESO (2025) Electricity Capacity Report (ECR)
[59] The de-rating factor is adjusted annually as per NESO's Electricity Capacity Report

needed to manage these periods and will need to be connected to the electricity grid. Prioritising the queue primarily on the basis of capacity (GW) runs the risk that insufficient energy (GWh) will be brought to market. This will increase the need to use high-carbon, natural gas back-up capacity. Grid connection is particularly challenging for types of energy storage that are geographically limited, e.g. pumped hydro storage, compressed air storage and hydrogen storage.



Actual storage durations range from 0.5 hours to 9+ hours in 0.5 hour increments. Storage for T-4 2018 and 2019 were not separated out in technologies, but according to NGESO communications were pumped storage. However, these are still kept in for completeness.

Figure 3: Capacity market derating factors for selected storage durations. Source: Report on the Role of Ancillary Services to Encourage Low Carbon Operability

The gas network is less constrained than the electricity network. Utilising hydrogen in the existing gas network therefore introduces fewer connection challenges for hydrogen storage, than if it the hydrogen were to be used for localised electricity generation, such as hydrogen-powered OCGT or CCGTs.

The responsibility for managing grid access sits primarily with NESO, National Grid Electricity Transmission (NGET), the electricity distribution network operators (DNOs), Ofgem and, ultimately, the Department for Energy Security and Net Zero (DESNZ).

Addressing the problems with connection queues requires action from both DESNZ and Ofgem. DESNZ set out the Transmission Acceleration Action Plan (TAAP) and published the Connection Action Plan with Ofgem in November 2023.

Based on this guidance, NESO is progressing connection management reform through the Target Model Option 4 (TMO4+).[60] TMO4+ will introduce a two-gate process to filter out the more speculative projects and only award a place in the queue to projects that are likely to progress, reducing those projects' connection risk and costs.

NESO will also focus on Regional Development Programmes (RDP), which look at 'the complex interactions between distribution and transmission in areas with large (or potentially large) volumes of distributed energy resources (DER)'.[61]

With numerous parallel activities in the GB electricity network space, a critical element of success is for the responsible parties – NESO in particular – to efficiently and speedily translate the strong political leadership into practical action on the ground. Delays and uncertainty around implementation will translate into greater connection risk and, ultimately, increased costs to meet Net Zero targets.

The modelling approach that NESO and DNOs take for storage operations will be critical. Storage can be used to manage the capacity on the network area that it is connected to as long as operational signals are clear. A precautionary approach of network operators treating storage like any other form of connection – and therefore limiting total connections to the GW capacity of the cable, whether storage or generation – has been replaced by an assumption that storage will not export at peak (variable) generation and will not import at peak demand. This allows more storage to be connected to a given network as storage is not assumed to exacerbate constraints. However, storage could be assumed (and used) to ameliorate constraints, assuming that storage charges when there is ample generation available and discharges when demand is high. However, for network operators to be able to make this assumption, this activity needs to be seen reliably in real-life operations of the asset. This in turn requires clear, granular market signals, for example in the form of well-designed and coordinated local and national flexibility markets and pricing models.

With sustained political leadership, efficient implementation of policies in the form of well-designed rules and regulations (including improved market signals for storage) and effective national network building plans, it will be possible to achieve Net Zero targets earlier and at a lower cost. Any derisking of investments results in lower required returns and therefore lower costs to consumers; this could be achieved through greater competition or through lower regulated returns required for investment.

With the right amount of lower-cost storage with the necessary combination of durations, GB energy markets (particularly electricity) should see reduced volatility whilst enabling additional build of low cost, variable renewables to power the decarbonisation of heating and transport.

[60] NESO (2024) TMO4+ Presentation
[61] ESO (2024) Regional Development Programme Update 2024

Deep dive 2: Viable business models

Historical View – Learning from seasonal gas storage

Energy storage has long played a significant role in the GB energy market, starting with stockpiling of coal at mines or on coal station premises and, later, natural gas storage. From 1985 to 2017, storage with duration of up to 10 days, all the way to seasonal storage was provided by the Rough natural gas storage facility, a disused natural gas well converted into storage. Shorter-duration (primarily diurnal) electricity storage was largely provided by pumped storage facilities and diesel gensets.

Historically, energy storage enabled and complemented fossil fuel production and consumption. Electrical storage provided peak-shaving (in the form of pumped storage) and for gas, seasonal storage of energy due to the UK being largely self-sufficient in natural gas from the North Sea. Largely stable gas production coupled with very seasonal gas heating demand led to significant summer-winter price differentials, providing a business case for Rough natural gas storage without a need for subsidies. However, Rough also illustrates the potential impact of changing needs. Over time, a number of factors combined to nearly eliminate the GB gas summer-winter spread, undermining Rough's business model and leading to its closure in 2017. These factors included:

- Diminishing North Sea production, leading to less excess gas in summer and a weaker summer-winter spread from seasonal storage.
- Increased interconnection with the rest of Europe, leading to stronger (and less seasonal) price linkages.
- A significant expansion of LNG import terminals, which gave access to a global, more price- stable, gas market.

After a surge in gas prices, due in large part to Russia's invasion of Ukraine in February 2022, Rough re-opened in October 2022. This was in spite of summer-winter spreads remaining low and even negative since the beginning of 2025 (Summer 2025 vs Winter 2026)[62]. This would suggest that the challenges to the fundamental Rough gas storage business model remain significant and unresolved, and that any future reliance on disused gas field storage/seasonal storage will need some form of market support to be brought forward.

Short-duration Electricity Storage

- The structure of the energy market drives the need for energy storage at any given time. In the case of a transmission-constrained electricity grid in Scotland, a battery or pumped storage can absorb some of the otherwise-curtailed electricity in periods of high wind for discharge later, when the transmission constraints are relieved. In the current national price system the day-ahead electricity market price may not reflect the reduced value of excess or curtailed electricity, even though the storage facility can keep space

[62] ICE (2025) UK NBP Natural Gas Futures Pricing

for charging and bid into the balancing market, potentially being paid to charge. A battery storage system could work as follows:

- Assume that day ahead market price minimum is £100/MWh and peak price is £130/MWh with 10% round-trip losses, all ascribed to charging.
- A Scotland-located battery storage facility can charge 1.11MWh (to account for the 10% loss) at a price of £111 and discharge at peak at a price of £130/MWh, earning a short run marginal profit of £19/MWh.
- If, however, the forecast is for more wind generation than the transmission grid is likely to handle, the battery can remain empty until the balancing market.
- NESO asks for bids to turn down / charge. Marginal turn-down is onshore wind supported by ROCs at around -£60/MWh.
- This would also reduce the cost of curtailment for NESO by £30/MWh + £60/MWh (£90/MWh total), reducing costs to end consumers.

In this example, the battery not only earns a higher return from BM than it would get from participation in the wholesale market but also creates value to the system by reducing balancing costs for NESO, though it cannot capture all this value due to constraints around BM bidding as mentioned earlier.

Co-locating batteries with renewable generators where the Transmission Entry Capacity (TEC) for a site is lower than the maximum generation capacity of the site (to save on Transmission Network Use of System (TNUoS) charges) would create a similar set of benefits, though the co-located battery would be able to charge "for free" as the curtailment would happen onsite rather than being paid for by NESO and therefore would not be subject to TCLC.

However, a recent report by Renewable UK outlines the CfD metering complexities to ensure the integrity of the CfD scheme. These include an inability to co-optimise storage and/or electrolysers under the same balancing market unit (BMU) and the (current) inability for co-located energy storage to import electricity from the grid.[63]

In addition to wholesale and BM value, batteries can also capture ancillary services value by providing dynamic containment (DC) and other reserve services. Finally, BESS can also earn Capacity Market (CM) payments by committing to provide its CM committed capacity obligation should a system stress event occur.

4 – 8-hour duration energy storage (BESS)

The build-out of electrical storage in GB has been rapid with a total of ~5GW operational at the end of 2024, ~1GW installed in 2024 alone and ~127GW of capacity in the pipeline. This should indicate that the market for BESS build-out in GB remains attractive. For the UK, efficient deployment of BESS capacity depends on grid access (as discussed above) and clear price signals.

[63] Renewable UK (2025) Offshore wind co-location: integrating offshore wind with flexibility

In the absence of a move to zonal pricing, the value of BM participation in transmission constrained areas is limited by the TCLC, which may lead to a less-than-ideal build-out profile, though with 127GW of capacity in the pipeline, NESO and CP2030 Mission Control may be able to ensure appropriate delivery of storage in the appropriate areas through active management of the grid queue.

8 – 2-hour duration electrical storage (CAES)

While the absolute value of the CM to longer duration projects has been maintained or even increased, the absolute cost of longer duration energy storage is high, so CM is of lower importance to the business case of longer duration electricity storage than it is for shorter duration electricity storage or even open cycle gas generators. As such, mechanisms in addition to the CM are needed for some types of storage, particularly LDES.

As more of BESS are built, these cannibalise the value from certain ancillary services – such as firm frequency response (FFR) – and, to some extent, from BM for both other BESS and longer duration electricity storage. Therefore, there likely exists a market gap between what the optimal longer duration electricity storage on a highly constrained, variable renewables dominated system is and what is being built in GB. A key driver is that the low probability, but high impact, “Kalte Dunkelflaute” circumstances, with low wind and sun and high demand for a period of several days, may not be adequately priced in the CM to bring forward sufficient longer duration electricity storage. This, in turn, leads to the need for a higher utilisation, higher carbon, back-up generation, the usage of which will be increasingly constrained as part of the CP2030 (up to 5% of total generation by 2030).

The responsibility for defining what level of short and long duration energy storage the UK needs sits with the UK government, across DESNZ and NESO. Implementation of rules and markets to enable storage deployment sits with Ofgem, NESO and LCCC, amongst others. Therefore, a key barrier to successful storage deployment is good coordination across these departments and arms-length bodies to ensure alignment and reduce risk of unintended policy clashes.

To ensure that sufficient longer duration energy storage is built and utilised efficiently, the Government announced in its Clean Power 2030 publication a cap-and-floor style support mechanism[64]. Alternatively, additional market signals could be introduced, such as a Storage Level Signal concept proposed by Carbon Trust in 2023 in a DESNZ report on Electricity Network Operability in a low carbon world.[65]

DESNZ has provided leadership through a number of engagements and decisions, e.g. providing LDES with a “cap and floor” support mechanism,[66] similar to what is being used for interconnectors. This is being implemented by Ofgem, which published an open letter in January 2025 laying out the intent to invite applications in Q2 2025 with first LDES under the

[64] DESNZ (2024) Clean Power 2030: Action Plan: A new era of clean electricity
[65] DESNZ (2023) Report on the Role of Ancillary Services to Encourage Low Carbon Operability
[66] DESNZ (2024) Long duration electricity storage consultation: Government Response

scheme planned to come online by 2030.[67] In March 2025, Ofgem and DESNZ published a joint Technical Decision Document (TDD), which provides the details of the scheme.

Challenges to implementation will include making the support scheme sufficiently attractive to serious investors while managing costs to end consumers. This will include accurately assessing the value (or lack thereof) for LDES in ancillary services markets, streamlining planning consents and prioritising LDES for grid connection.

The Low Carbon Contracts Company (LCCC) and DESNZ are working on updating the CfD regulation, consulting on a range of CfD-related issues in Q1 2024.[68] Hybrid metering was specifically consulted on, but DESNZ decided not to allow hybrid metering for the coming Allocation Round 7 “before it is clear how such assets would be treated in the wider system”.[69]

Deep dive 3: Resources and supply chain

The UK supply chain is a major barrier to the development of stationary storage technologies at the scale required to achieve a flexible energy system and deliver Net Zero targets. The stationary storage market is primarily dominated by various lithium-ion chemistries, such as NMC (nickel manganese cobalt-doped lithium oxide) and LFP (lithium iron phosphate). These technologies rely on a range of critical minerals and challenges in their availability has become a major constraint. Key challenges include the availability of raw materials, the geographical locations where these materials are processed, and global manufacturing capacity.

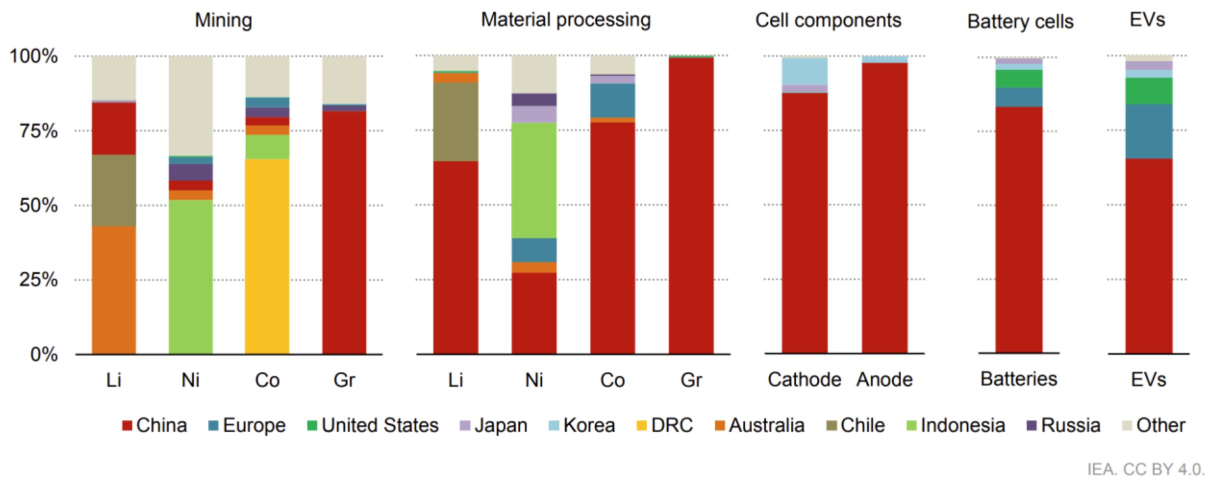
In 2023, global battery demand from EVs and stationary storage reached 865 GWh, a 45% increase from 2022, with batteries representing 56% of global demand for lithium. The extraction and processing of component critical materials has ramped up significantly to meet growing demand and, according to Our World in Data, between 2014 and 2024 production levels of lithium, cobalt, and nickel increased by 540%, 100%, and 69% respectively.[70]

The rapid growth in battery manufacturing is a major factor in global competition to secure access to critical minerals. The production of these critical minerals is dominated by a small number of countries, and geopolitical tensions affecting the security of supply are growing. This impacts the availability and price of battery cells making it onto the global market.

Lithium production is concentrated in just three countries, Australia, Chile and China, which together account for 43%, 28% and 16% of global production respectively[70] Cobalt concentration is even more limited, with the Democratic Republic of the Congo producing 70% of global output in 2023.[71] Indonesia holds the largest proven nickel reserves, with over 55 million metric tons and supplies over 50% of the global mined nickel.[72] Manganese is more

[67] Ofgem (2024) Call for input - LDES Cap and Floor Regime: Our Role, Plan, and response to the DESNZ publication
[68] DESNZ (2024) Contracts for Difference: proposed amendments for Allocation Round 7 and future rounds
[69] DESNZ (2024) Proposed amendments to Contracts for Difference for Allocation Round 7 and future rounds
[70] Our World in Data (2023) Lithium production
[71] Cobalt production
[72] Our World in Data (Accessed: 2025) Minerals Data Explorer

evenly distributed, but South Africa is the largest exporter, controlling 36% of the market share in 2023.[73] Additionally, in the last decade the rights to these reserves have been acquired by foreign powers, through state backed companies acquiring mining rights or buying stakes in mining companies in resource-rich countries.[74]



Notes: Li = lithium; Ni = nickel; Co = cobalt; Gr = graphite; DRC = Democratic Republic of the Congo. Geographical breakdown refers to the country where the production occurs. Mining is based on production data. Material processing is based on refining production data. Cell component production is based on cathode and anode material production capacity data. Battery cells are based on battery cell production capacity data. EVs is based on electric cars production data. For all minerals mining and refining shows total production not only that used in EVs. Graphite refining refers to spherical graphite production only.
Sources: IEA analysis based on EV Volumes; Benchmark Mineral Intelligence; BloombergNEF.

Figure 4: Geographical distribution of the global lithium-ion battery supply chain, 2023, IEA Global Critical Minerals Outlook 2024

The second major supply chain challenge is the downstream manufacturing of battery cells. This is dominated by China, which also dominates battery demand. China has significantly increased its capacity to refine raw materials and produce battery cells in recent years. As of 2023, China has 85% of global battery cell production capacity, 88% of cathode and 98% of anode material production capacity.[75] Furthermore, more than 50% of the materials processing of lithium and cobalt takes place in China.[76]

The location of critical minerals and battery manufacturing presents significant challenges for some energy storage technologies in the UK. China's dominance in the battery cell market and its ability to produce cells at scale and at very competitive prices makes it difficult to compete for market share. Furthermore, relying on lithium-ion technology for 1-hour – 8-hour duration stationary storage concentrates reliance on a small number of countries. This creates a vulnerability in securing the batteries at the necessary scale to meet short-duration demand capacity, as well as creating significant risk of price volatility.

Therefore, due to the geopolitical challenges tied to critical mineral supply chains, innovation should aim to minimise reliance on supply dominated by a single country, and efforts should prioritise innovation to minimise the use of technologies and materials produced from a supplier with a dominant market share.

[73] Our World in Data (Accessed: 2025) Minerals Data Explorer
[74] Georgetown Security Studies Review (2023) China's Monopoly over Critical Minerals
[75] IEA (2024) Status of battery demand and supply – Batteries and Secure Energy Transitions
[76] IEA (2024) Global Critical Minerals Outlook 2024

System benefits from innovation in energy storage

Introduction to systems modelling

System modelling to assess the potential impact of innovation in key net zero technologies was conducted for the EINAs primarily using UKTIMES, an energy system model of the UK that was developed by UCL and the UK Department of Business, Energy and Industrial Strategy (now the Department for Energy Security and Net Zero or DESNZ). For each of the selected technologies,[77] three levels of innovation were developed representing a low, medium and high innovation case for the technology. The low innovation level represents a business-as-usual case where innovation follows recent trends or is generally limited, whilst the high innovation case represents significant innovation in the technology to decrease costs and improve efficiencies.

The low, medium and high innovation cases were each run against three different hypothetical scenarios which were developed by DESNZ to represent potential routes to net zero for the UK, namely Minimally Constrained, High Hydrogen and High Diversification. They do not represent government policy but were selected due to their differing constraints which provide a more diverse set of outputs and insights. A summary of each is presented below, a more in depth description can be found in the EINAs Methodology report.

- **Minimally Constrained:** Designed to show the largest potential impacts from innovation investments by minimising the number of constraints on the energy system. UK Government data assumptions are used across the scenario.
- **High Hydrogen:** Based on the Minimally Constrained scenario, with a range of constraints added to force hydrogen use across the economy. These constraints are based on estimates of H_2 demand ranges in the DESNZ Hydrogen transport and storage networks pathway policy paper published in 2023, and provisional figures from DESNZ sector teams that are set to be refined further for CB7. A maximum hydrogen consumption in each sector and a minimum overall level of consumption is applied in each year from 2035 to 2050.
- **High Diversification:** Based on the Minimally Constrained scenario, this scenario aims to be more energy secure through two means, 1) limiting imports of key commodities to reduce UK reliance on overseas resources, and 2) diversifying resource and technology use across the economy to limit the impacts of any supply interruptions, price rises or technology failures.

For energy storage technologies, UK TIMES alone does not provide robust outputs, due to the limited time and spatial resolution of this model. The UK TIMES analysis was therefore

[77] Technologies such as flow batteries, (LAES), sodium-ion batteries were not included in the modelling. This is because the function of 4–8 hour duration storage was represented by (BESS), and the function of 8–24 hour duration storage was represented by compressed air energy storage (CAES).

augmented with additional model runs with UCL's HighRES model, an electricity system optimisation model with an hourly temporal resolution and a spatial resolution consisting of 9 UK nodes and 9 European nodes, to give insight into the innovation value of these technologies. To ensure consistency with the rest of the EINAs outputs, HighRES uses outputs from UK TIMES EINA runs as inputs, including the following:

- Load curves in HighRES are based on the degree of electrification of energy service demands, modified to account for likely DSR behaviour.
- The total CO2 emission limits in HighRES are set to the UK TIMES grid carbon intensities.
- Capacities of electricity generation technologies from UK TIMES are used as minimum capacities in HighRES.
- Technoeconomic data and innovation assumptions consistent with those used in UK TIMES.[78]

Based on these inputs, HighRES co-optimises capacities and locations of the modelled technologies, alongside the build out of additional storage capacity to minimise the total system cost. The required transmission capacity between zones is then determined, alongside the associated cost of this infrastructure. All Capex costs are annualised based on the respective lifetime of each individual generation, storage and transmission asset.

The years 2035 and 2050 are modelled as standalone snapshots for the Minimally Constrained and High Diversification scenarios. High Hydrogen was not run due to limitations on the number of model runs that could be completed within the scope of this project. Each set of runs is carried out for a typical weather year (2012 data) and an adverse weather year (2010 data), which includes period of low wind coinciding with low temperatures.

The results presented below demonstrate the potential impact of innovation for a specific energy storage technology on achieving net zero within the confines of the scenario. In each model run for a specific technology, all other technologies are held at their low innovation case so that the impact on the UK energy system of that technology can be isolated. Changing the costs and performance of technologies through innovation can have both direct and indirect consequences:

- Direct consequences are a reduction in cost or an improvement in the quality of the energy service supplied by the technology. Only cost reductions are examined in the UK TIMES energy system model.
- Indirect consequences are changes to the wider system caused by a relative change of cost of a technology relative to other technologies. If the deployment of a technology increases due to a lower cost and the deployment of alternative technologies reduces then a cost reduction will be realised. This cost reduction will be lower than the direct cost reduction would have occurred if the new technology had already been used at lower innovation levels. More profound changes could also occur across the energy

[78] Innovation assumptions are assumed to be the same for the UK and European nodes.

system, for example changes in total electricity consumption or in the relative rate of decarbonisation between sectors of the economy.

We have not considered rebound effects where lower costs of energy due to innovation investments lead to higher energy service consumption. All results are presented as annualised cost figures only, in £2022 real values. This differs from UKTIMES results, where cumulative discounted costs can be more easily calculated. LCOE is not calculated for the storage technologies based on HighRES outputs, due to electricity prices not being calculated as part of the model outputs. This limits the ability to quantify the cost of charging storage assets, a key component of the cost stack.

The below analysis refers to only the storage technologies assessed by the EINAs as outlined above. It should be noted that given these results are an output of the system modelling and the three hypothetical scenarios developed for the EINAs that they do not necessarily reflect UK gov deployment targets and ambitions.

Results

Overall role of energy storage innovation in reducing system costs

Innovation in hydrogen storage plays the greatest role in reducing system costs, compared to the baseline all low innovation model run, reducing system costs by between £2.0 billion and £5.4 billion a year in 2050 in the Minimally Constrained scenario and between £1.8 billion and £4.8 billion a year in the High Diversification scenario. This impact is greatest in poor weather years, due to the increased cold, windless periods, where hydrogen storage is key to meeting demand. However, it is important to note that as the modelling provides single-year analysis, it cannot fully represent use cases for hydrogen storage at an inter-seasonal scale. Innovation in CAES and BESS plays a more modest role in system cost reduction.

4 – 8-hour duration storage (4-hourBESS)

Cost reduction potential

High levels of innovation in 4-hour batteries can reduce electricity system costs by a moderate amount by 2050, with cost savings of up to £191 million in the Minimally Constrained scenario and £472 million in High Diversification. Weather conditions have varying impact on these results, with poor weather conditions combined with high innovation levels in batteries resulting in the greatest reduction in system costs in the High Diversification scenario, but a cost increase in Minimally Constrained.

Under average weather conditions, cost reductions primarily arise as a result of reduced nuclear and natural gas OPEX and a very small reduction in transmission costs. In Minimally Constrained specifically, this is also complemented by a reduction in natural gas capex costs.

Under poor weather conditions, significant differences are observed between Minimally Constrained and High Diversification runs. In Minimally Constrained, cost reductions are low in the medium innovation scenario, largely arising from lower storage capex costs. In this model run, it is most cost effective to increase imports from Europe instead of deploying 4-hour batteries in the UK. When high innovation levels are achieved, an additional deployment of 3.84GW of 4-hour batteries occurs in the UK. However, across Europe, this technology is deployed at a much greater scale as a result of the high innovation levels, with 124GW deployed. In turn, this unlocks an additional 100GW of solar capacity and fundamentally changes the economics of the European power system, including the use of interconnectors with the UK. The system now choses to build more CAES storage capacity in the UK, to be used in place of natural gas and grid imports from Europe. An overall cost increase is seen for the UK system as a result of innovation in this technology.

In contrast, in High Diversification poor weather conditions a large decrease in system costs is observed because of innovation in 4-hour batteries. This is as a result of a reduction in CAES and H_2-salt cavern storage capex and opex and trade costs. Instead, an increase in generation opex is observed, from biomass and standalone H_2 generators. This model run has the highest deployment of 4-hour batteries in the UK out of all conditions tested.

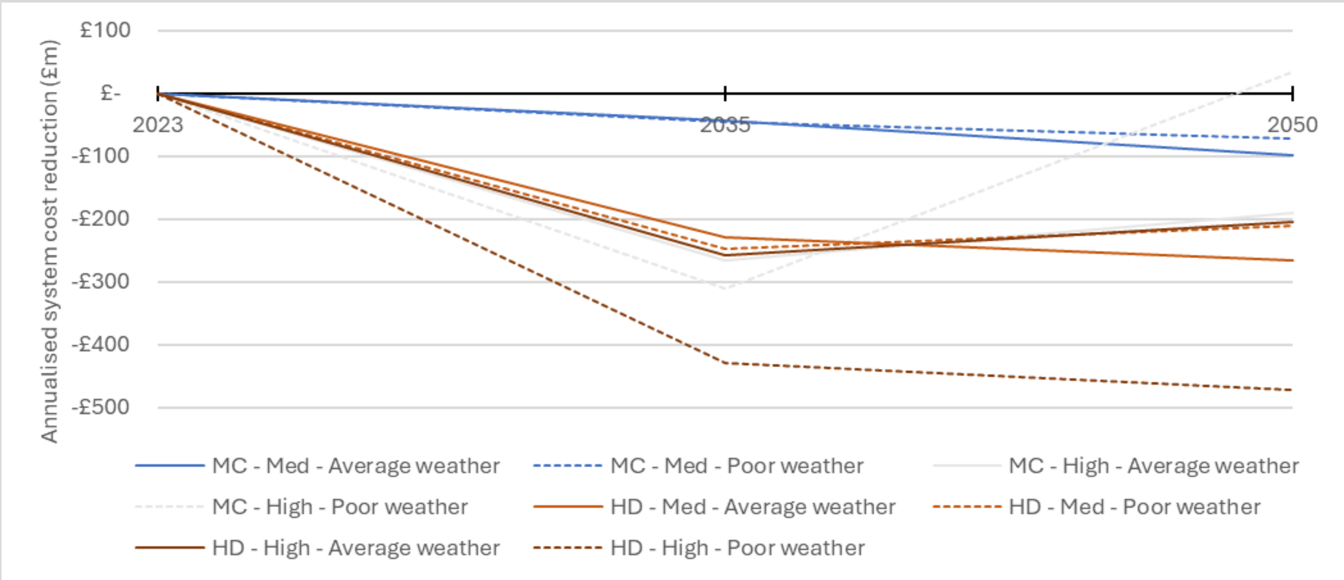


Figure 5: Annualised reduction in system costs from BESS innovation, compared to the base All Low innovation case

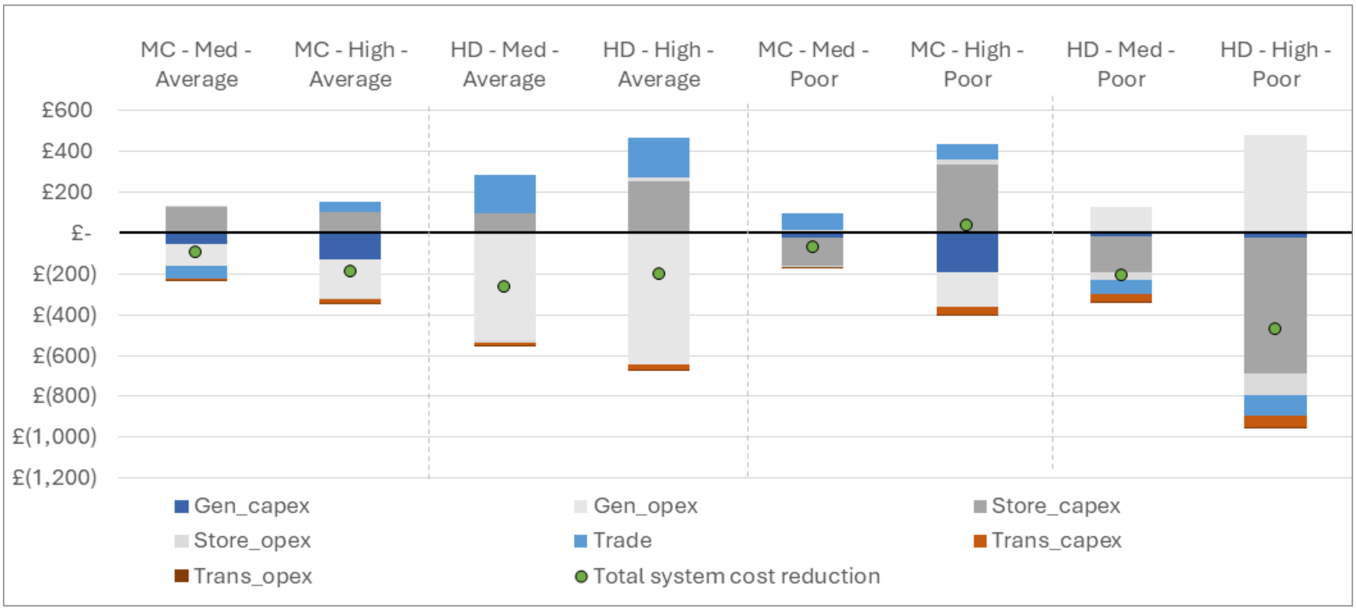


Figure 6: Change in costs due to innovation in 4-hourBESS, 2050

Impact of innovation on deployment of BESS

The deployment of 4-hour batteries ranges from an installed capacity of 0 GW to 15GW (0 – 60 GWh), with deployment being almost exclusively higher in 2035 than 2050 in all model runs. This highlights this technology's role as a transition technology, fulfilling the system's need for longer duration storage before other technologies such as CAES and hydrogen storage to become available at cost effective levels. In 2050, the system deploys greater levels of 1-hour batteries to ensure frequency response needs are still met.

Capacity factors range from between 5 and 11% across model runs, reflecting the importance of this technology in provision of system services and managing the balance of supply and demand, rather than as a core generation technology.

Innovation in this technology specifically is key to its deployment, with it only being deployed higher than 3GW when high levels of innovation have occurred (either as a standalone technology or in the All High model run). In Minimally Constrained, no deployment occurs without at least medium levels of innovation. In High Diversification, deployment remains between 1 and 3GW in 2035 across runs where technology innovation has occurred in non-battery technologies, dropping to 0GW in 2050.

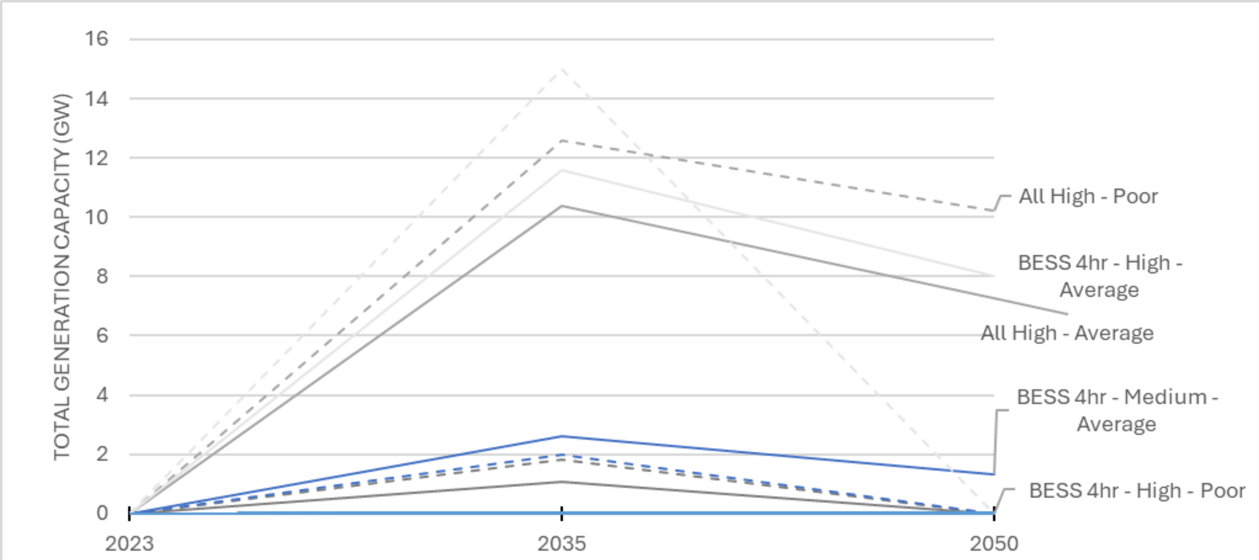


Figure 7: Installed capacity of 4-hour BESS in the Minimally Constrained scenario. Average weather runs are shown with solid lines, poor weather runs with dashed lines.

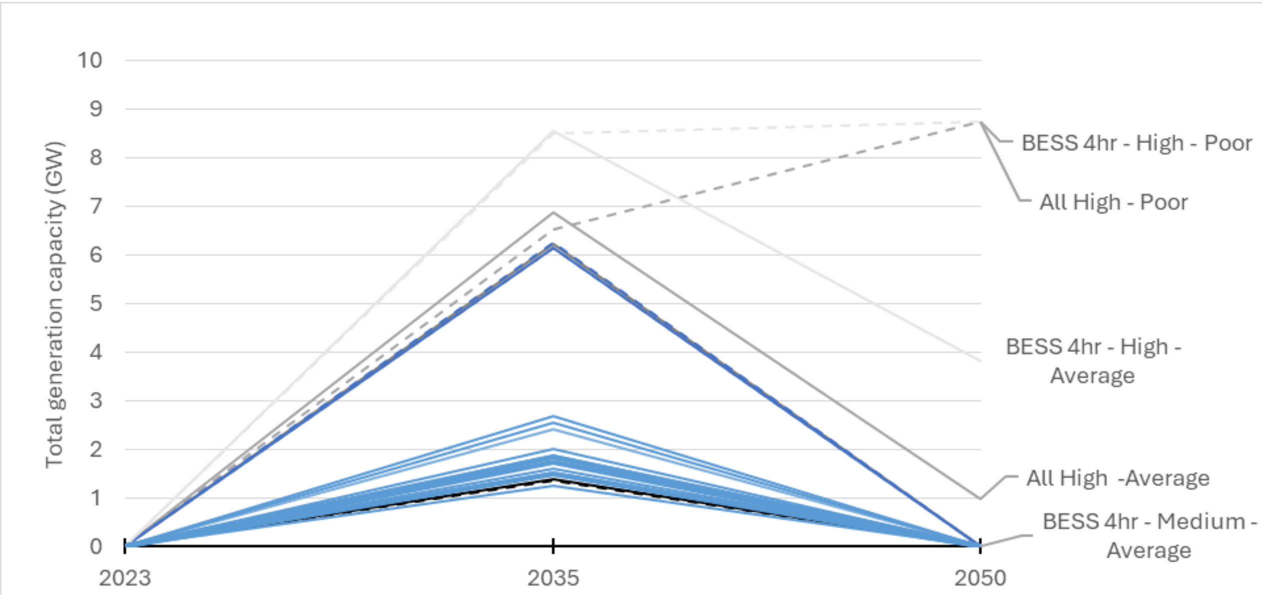


Figure 8: Installed capacity of 4-hour BESS in the Minimally Constrained scenario. Average weather runs are shown with solid lines, poor weather runs with dashed lines.

Wider impact on other technologies

Innovation in 4-hour batteries has relatively minor impacts on generation of a range of other EINAs technologies compared to the All Low innovation case in Minimally Constrained (at most around a 15% change for all technologies). Higher levels of deployment from 4-hour batteries reduces the system need for generation from nuclear, natural gas and typically CAES technologies, alongside typically reducing overall levels of curtailment. These trends are observed in both Minimally Constrained and High Diversification scenarios.

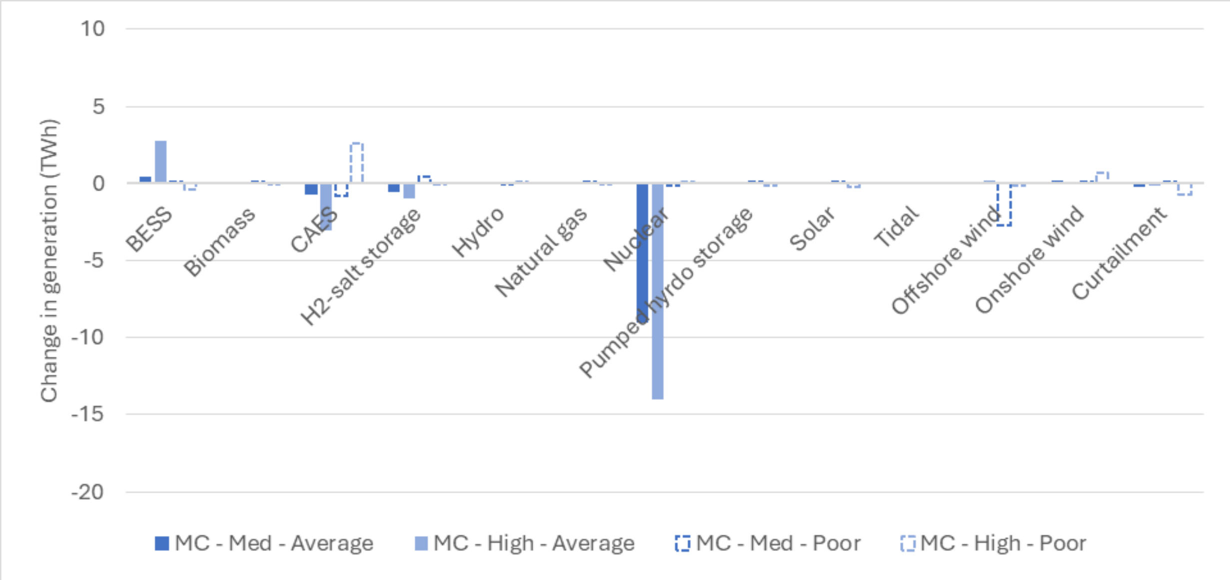


Figure 9: Impact of innovation in BESS on generation of other technologies in 2050 compared to low innovation level run in the Minimally Constrained scenario

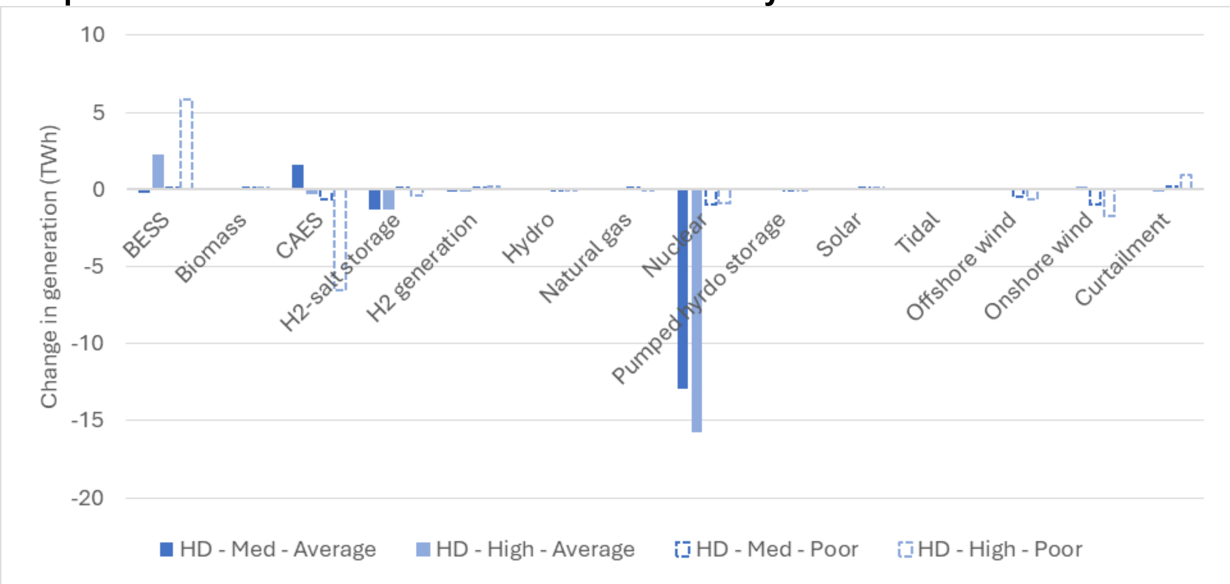


Figure 10: Impact of innovation in BESS on generation of other technologies in 2050 compared to low innovation level run in the High Diversification scenario.

Role in system services

In all scenarios and runs, batteries are the main technologies providing frequency response to the system, followed by pumped-hydro storage, on average providing ~70% of the frequency response capacity into the system in 2035 in both weather conditions and scenarios. The mix of 1-hour to 4-hour systems providing this capacity is highly dependent on high levels of cost reduction in the high innovation scenarios allowing 4-hour systems to become cost effective for other, non-frequency purposes. BESS also plays a role in providing reserve capacity to the system, especially at peak times, where it is providing ~20% of total reserve.

In 2050, BESS continues to be a key technology in frequency response in the Minimally Constrained scenario. However, in High Diversification, average frequency response provision drops to 30% in an average weather year 54% in a poor weather year in high innovation scenarios and as low as 5% in the medium innovation scenario and pumped hydro picking up the dominant role, covering 92% of average frequency response needs. This is partially due to a lower overall frequency response requirement. At peak periods of frequency response need, CAES, hydrogen and natural gas play a greater role in this scenario. Across all scenarios, BESS plays a very minimal role in reserve and inertia provision.

8-hour – 24-hour duration storage (CAES)

Cost reduction potential

Innovation in CAES plays a modest role in reducing system costs, with annualised cost reductions of £50 million up to £102 million in 2035, increasing to reductions of £43 million to £706 million in 2050. Cost reductions are greatest when tested under average weather conditions, for both time periods. In 2035, this cost reduction is driven by reduced natural gas capex in Minimally Constrained and reduced natural gas opex in HD. In 2050, this cost reduction is driven by a reduction in storage capex and opex, alongside a reduction in nuclear opex and transmission costs. In the HD scenario, this is offset by higher interconnector costs.

In a poor weather year, cost reductions are much lower across all scenarios, and in the case of the HD High CAES innovation scenario, there is an increase in system costs of £50m a year. This is because HighRES optimises the total system cost, including European nodes. Europe would see the same innovation levels as the UK, and thus the whole system would adapt, leading to a higher cost of imported energy, or alternatively, as in 2035 poor weather year results, higher storage capex or generation opex costs, as the system choses to store or generate more electricity within the UK to avoid this higher import cost.

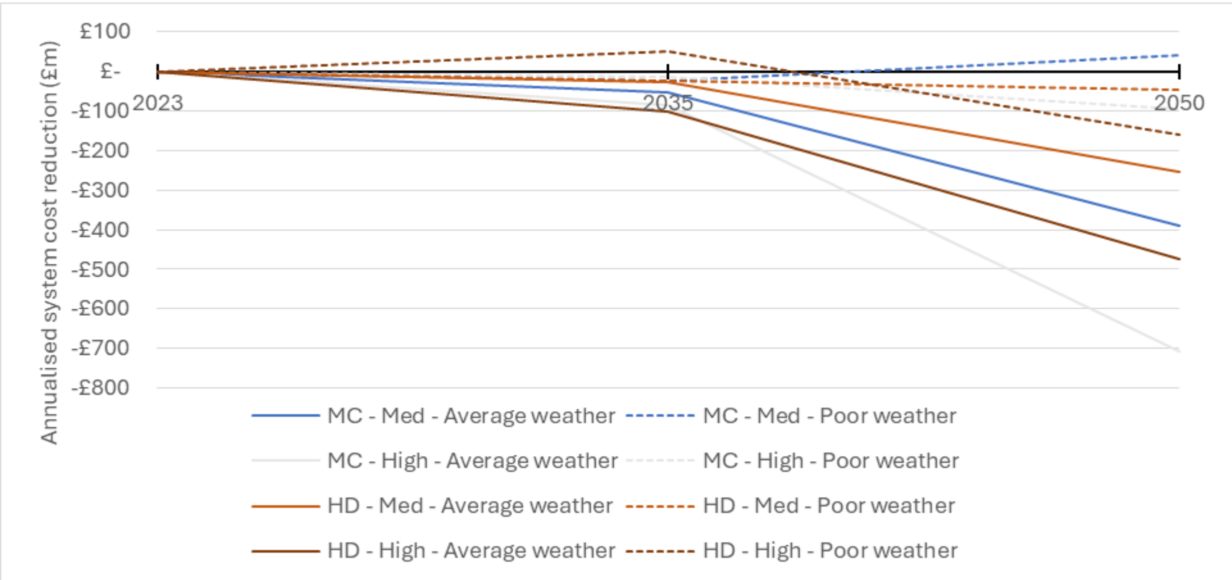


Figure 11: Annualised reduction in system costs from innovation in CAES, compared to base All Low Innovation cases

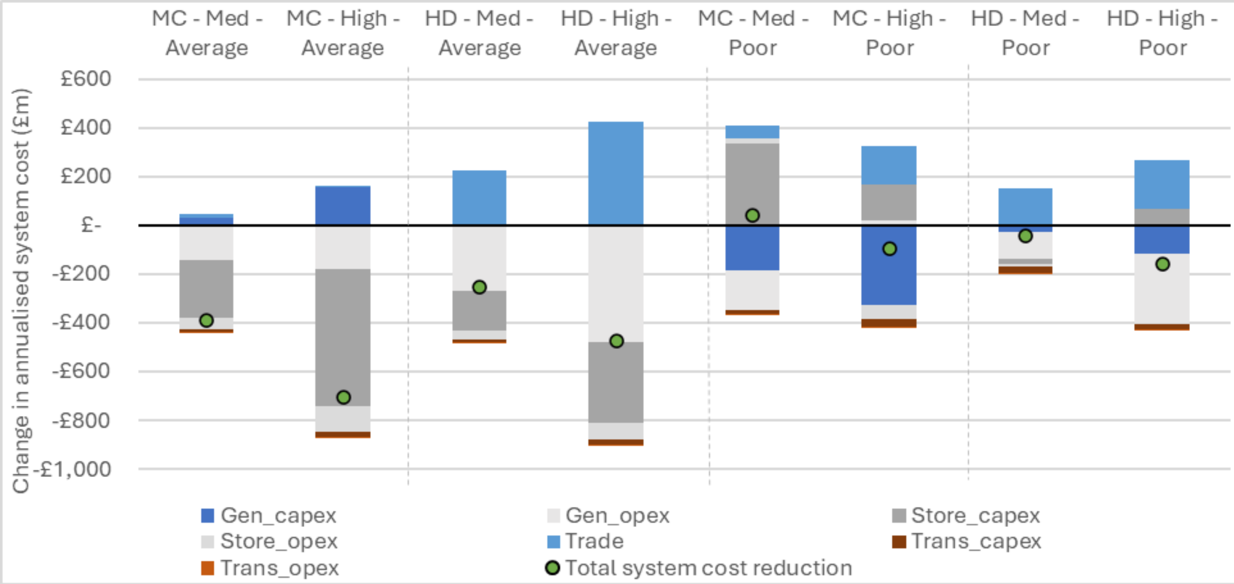


Figure 12: Change in costs due to innovation in CAES, 2050

Impact of innovation on deployment of CAES

A 5 GW feasibility cap is imposed for CAES in 2035, across all scenarios and innovation levels. In all runs, CAES is deployed at its maximum level, with virtually the same generation for all innovation runs for each scenario – around 8 TWh in the MC scenario, and around 11 TWh in the High Diversification scenario. This implies that CAES, at least up to this level, is a critical way of reducing system costs.

In 2050, innovation in CAES directly causes a moderate impact in CAES deployment, with an installed capacity of 23.5 GW, 24.2 GW, and 24.8 GW for the low, medium, and high CAES innovation levels in the Minimally Constrained scenarios, and 20.8 GW, 21.9 GW, and 22.9 GW in the respective HD scenarios. Across all the runs carried out, deployment of CAES varies much more widely, from 10GW to 27GW in Minimally Constrained and 6GW to 23GW in High Diversification, indicating that innovation in other technologies can significantly impact the need for CAES in the system. In MC, highest deployment is seen with High levels of CAES innovation and poor weather conditions.

Lowest deployment is seen in both the MC and the HD scenarios in the All High innovation model run, and when innovation in H_2-salt caverns is high only, showing that H_2-salt caverns can displace the need for CAES if the relative cost of this technology is reduced. This is particularly apparent in poor weather conditions.

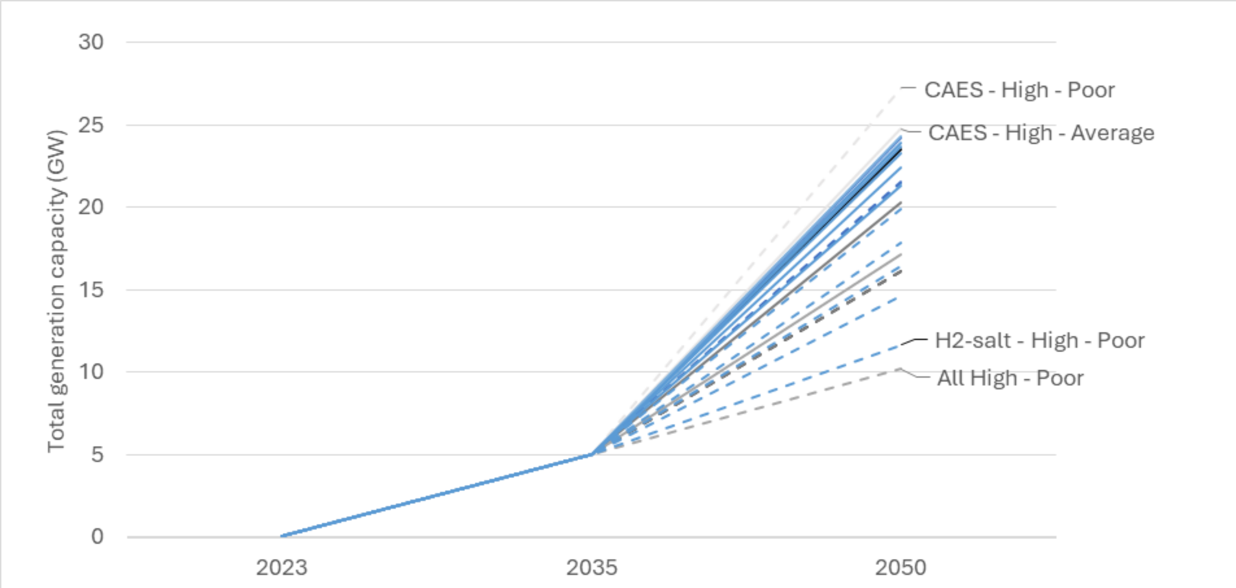


Figure 13: CAES Installed capacity for each innovation run in the Minimally Constrained Scenario. Dotted lines represent model runs conducted for poor weather conditions. Blue lines show runs where innovation in CAES only has occurred at medium (dark) and high (l

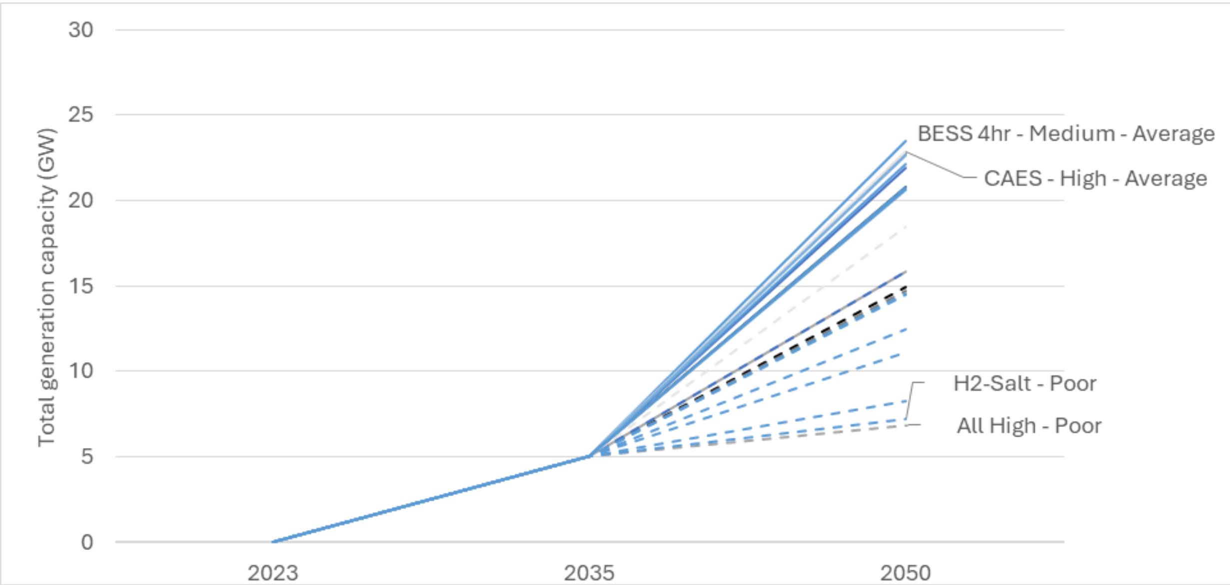


Figure 14: CAES Installed capacity for each innovation run in the High Diversification Scenario. Dotted lines represent model runs conducted for poor weather conditions. Blue lines show runs where innovation in CAES only has occurred at medium (dark) and high (light) levels.

System services

CAES provision of system services varies widely between model runs, showing its flexible nature, but it is consistently most active in providing reserve capacity and system inertia. In MC 2035, CAES provides 10-12% of the average reserve capacity in the system and ~8-12% of system inertia provision, under both weather conditions. In HD 2035, this proportion is lower, with CAES providing 2-4% of average reserve capacity but up to 18-20% of average system inertia.

In 2050, this reaches as high as 50-60% of average reserve capacity being provided by CAES. In HD, this is much reduced due to the higher deployment of natural gas and hydrogen turbines, due to the constraints in this scenario to diversify energy sources.

CAES plays a more limited role in frequency response, providing less than 3% of this service across all years and innovation runs.

Wider impacts on other technologies

Innovation in CAES has moderate impact on generation of a range of other EINAs technologies compared to the All Low innovation case in Minimally Constrained. Higher levels of generation from CAES in an average weather year reduces the systems need for generation from H_2-salt storage and nuclear. In a poor weather year, the largest impacts on a GWh basis are enabling an increase in onshore wind and a reduction in curtailment of renewables. As with an average weather year, increased CAES deployment leads to a reduction in generation from H_2-salt-storage.

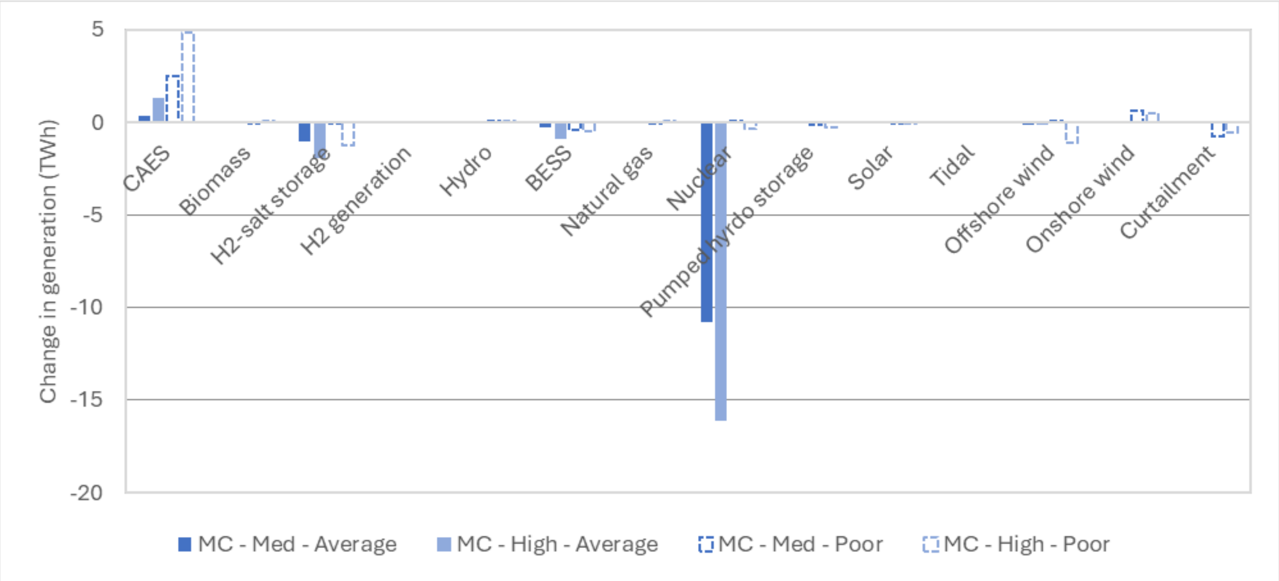


Figure 15: Impact of innovation in CAES on generation of other technologies in 2050 compared to low innovation level run for the Minimally Constrained scenario

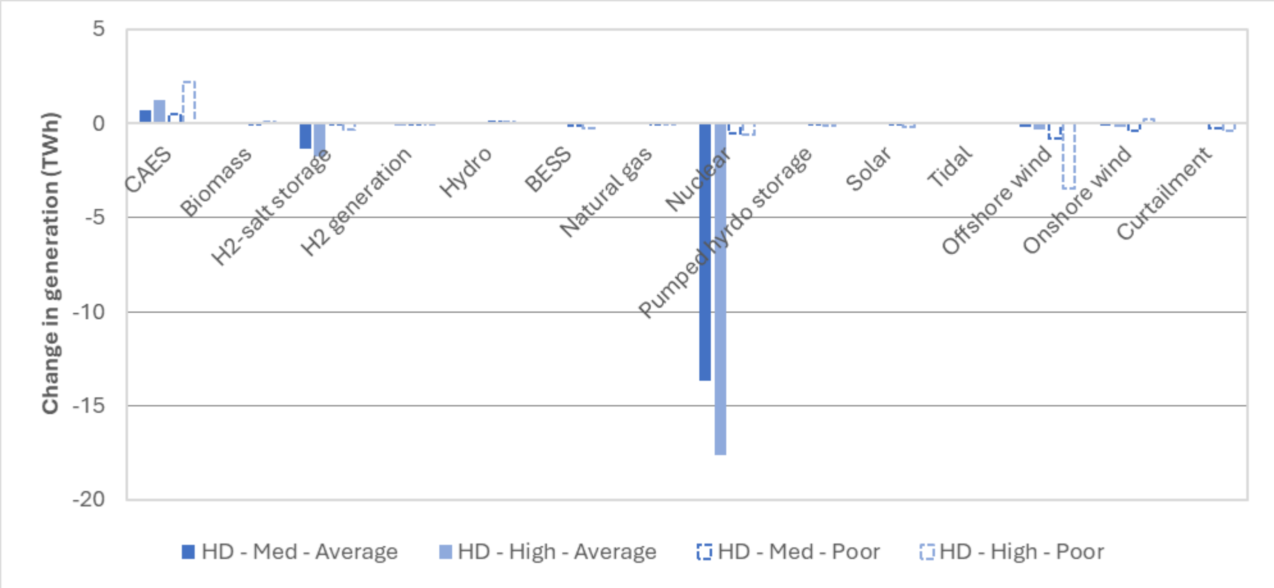


Figure 16: Impact of innovation in CAES on generation of other technologies in 2050 compared to low innovation level run for the High Diversification scenario

Long duration energy storage (hydrogen-salt caverns)

Cost reduction potential

Innovation in hydrogen salt cavern storage can reduce electricity system costs by between £1.8 and £5.4 billion a year by 2050, with savings greatest in poor weather conditions. Across both scenarios, H_2-salt cavern storage is a key technology for reaching net zero and innovation in this technology could enable significant cost savings. In the Minimally Constrained scenario, cost reductions are largely a result of reductions in storage capex costs and, in poor weather years, a reduction in generation capex and opex, from natural gas generators. In the High Diversification scenario, cost savings are again dominated by reductions in storage capex in the average weather conditions, enhanced by a reduction in interconnector costs. In poor weather conditions, a reduction in generation opex from standalone hydrogen generators also plays a significant role.

In 2035, impact of innovation on system costs is more varied. In average weather years and HD poor weather year, system cost reductions largely come from a reduction in generation and storage capex costs, which are offset by an increase in the cost of imported electricity from Europe. In poor weather years for Minimally Constrained, this trend reverses, with reduced cost of imported electricity, as it becomes more economical to build out higher levels of generation capacity in the UK, increasing generation capex costs.

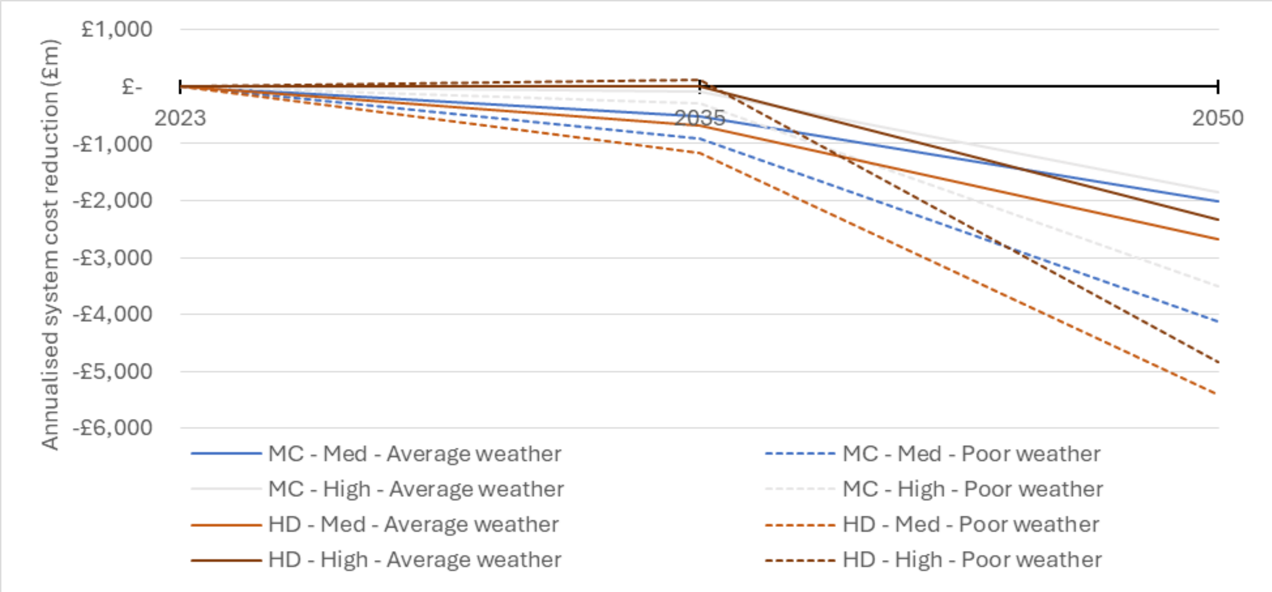


Figure 17: Annualised reduction in system costs from H_2-salt cavern innovation, compared to base All Low Innovation case

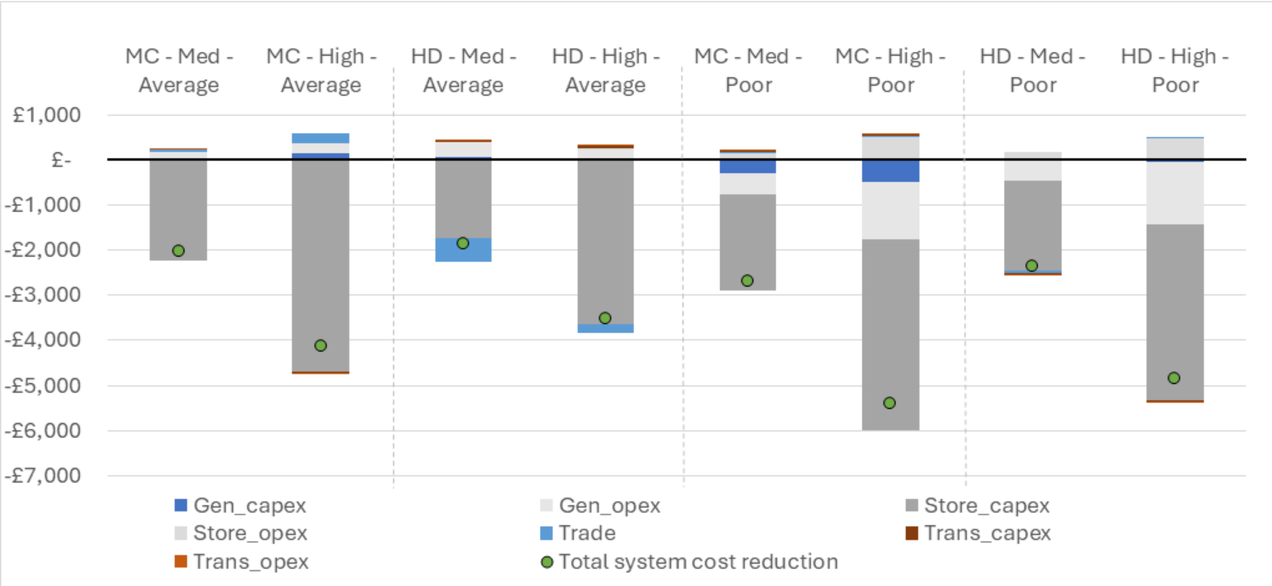


Figure 18: Change in costs due to innovation in H_2-salt cavern storage, 2050

Deployment

In 2035, the feasibility cap of 7.5 GW over the sum of all hydrogen turbine power capacity, including standalone hydrogen turbines and H_2-Salt-OCGT/CCGT (representing a PEM electrolyser, salt cavern storage, and a hydrogen OCGT/CCGT), is met in all scenarios and innovation levels. However, the energy component of the storage caverns are unconstrained, with energy storage capacity varying between ~8 TWh in average weather years and ~18 TWh in poor weather years for the Minimally Constrained scenario and 2 TWh to 18 TWh in High Diversification. However, it is important to note that that as the modelling provides single-year analysis, it cannot fully represented use cases for hydrogen storage between years. In 2035, capacity factors are between 14-15% for average weather years, increasing to 17-18% for poor weather years. In 2050, hydrogen storage is utilised less, and the difference between weather years is more significant, with capacity factors of 7-8% in average weather years increasing to 13% in poor weather years.

In 2050 Minimally Constrained, the power capacity of H_2-Salt-CCGT has only a minor increase from 61.1 GW in the low innovation run, to 61.5 GW in the high innovation run. However, the energy component has a more slightly more significant increase from 72.1 TWh to 73.9 TWh, reducing the need for CAES and batteries. Greatest deployment of H_2-salt caverns in average weather conditions occurs in the All High innovation run, demonstrating that innovation in other sectors can positively increase the need for long duration energy storage in the energy system. This is primarily due to the higher deployment of renewables as a result of innovation reducing the cost of these technologies. In the poor weather year, greatest H_2-salt cavern deployment occurs alongside high levels of innovation in CAES.

Similar trends in deployment are observed in the HD scenarios in 2050. The exception to this is in the average weather year, where innovation in all technology families does not lead to a higher need for H_2-salt caverns. This is due to greater levels of biomass and natural gas generators in the HD scenario, which can ramp up and down as required, reducing the need for long duration storage capacity.

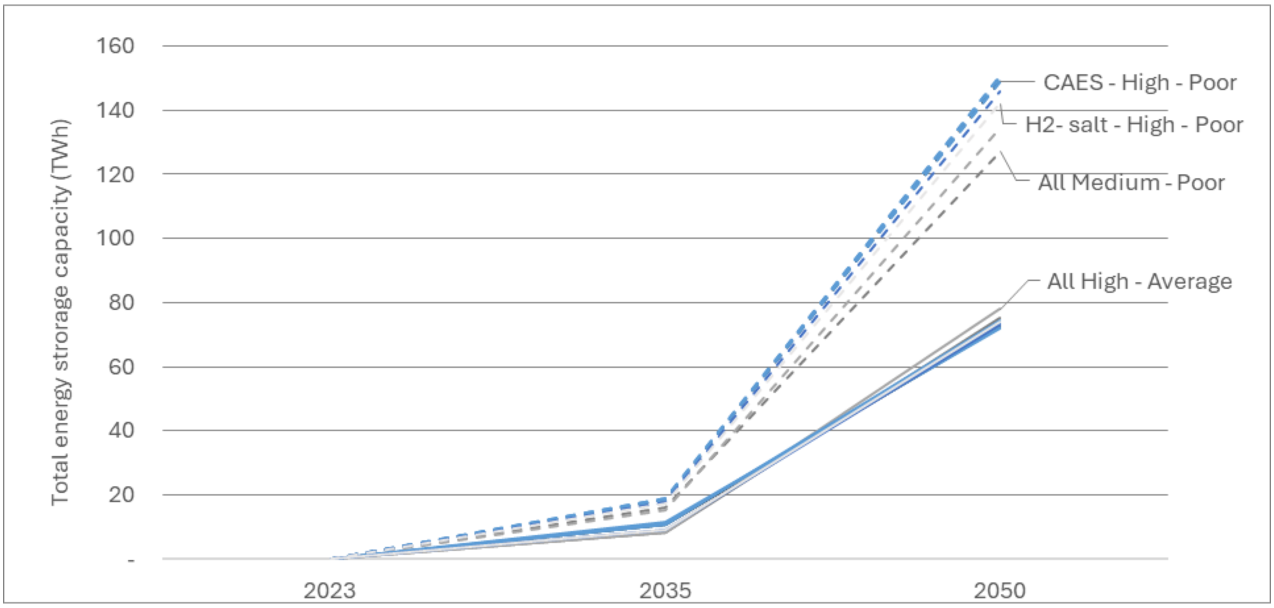


Figure 19: H_2-salt cavern storage installed capacity for each innovation run in the Minimally Constrained Scenario. Dotted lines represent model runs conducted for poor weather conditions. Blue lines show runs where innovation in H_2-salt cavern storage only has occurred at medium (dark) and high (light) levels.

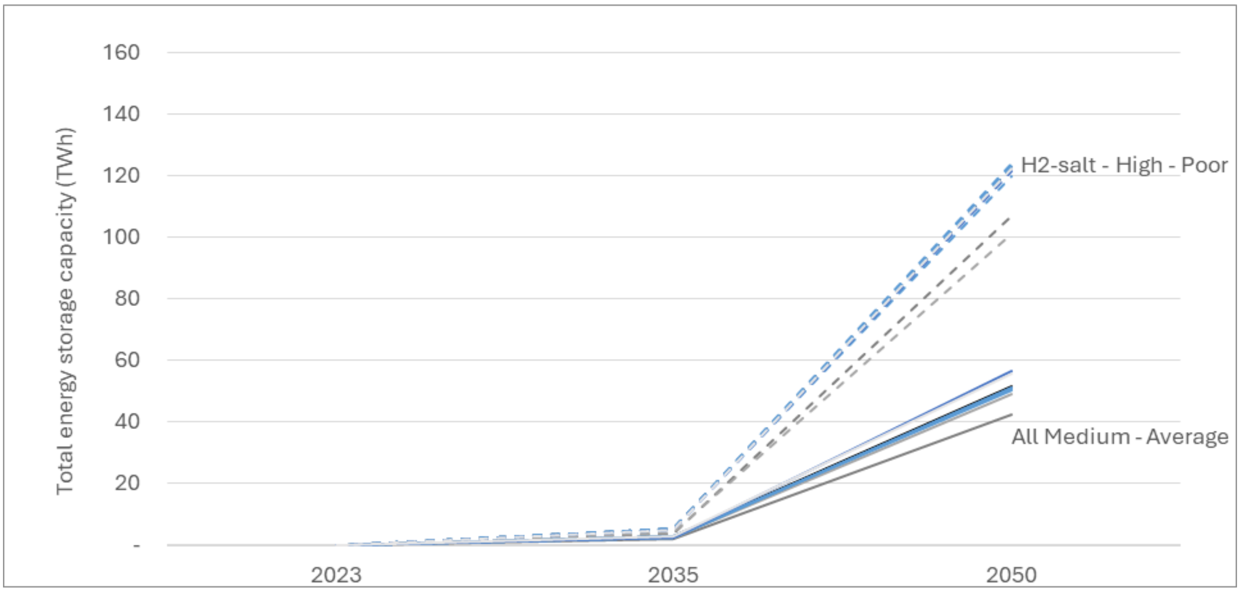


Figure 20: H_2-salt cavern storage installed capacity for each innovation run in the High Diversification scenario. Dotted lines represent model runs conducted for poor weather conditions. Blue lines show runs where innovation in H_2-salt cavern storage only has occurred at medium (dark) and high (light) levels.

Impact on other technologies

Innovation in hydrogen salt caverns allows the UK to increase load factors for nuclear generation, alongside reducing curtailment of renewables. In poor weather conditions, H_2-salt cavern innovation also results in higher deployment of solar. When combined with CCGTs, CAES deployment decreases across all scenarios and innovation levels, leading to an increase in the deployment of natural gas OCGT turbines to fulfil this need. When combined with OCGTs, the reverse is true, with CAES deployment increasing and natural gas capacity reducing.

Additionally, increased innovation in H_2-salt caverns results in high levels of electricity exports from the UK. Net exports account for 13.2 TWh in the H_2-Salt medium innovation level, and 14 TWh in the high innovation level, compared to the base case at low innovation where net exports are 1.6 TWh.

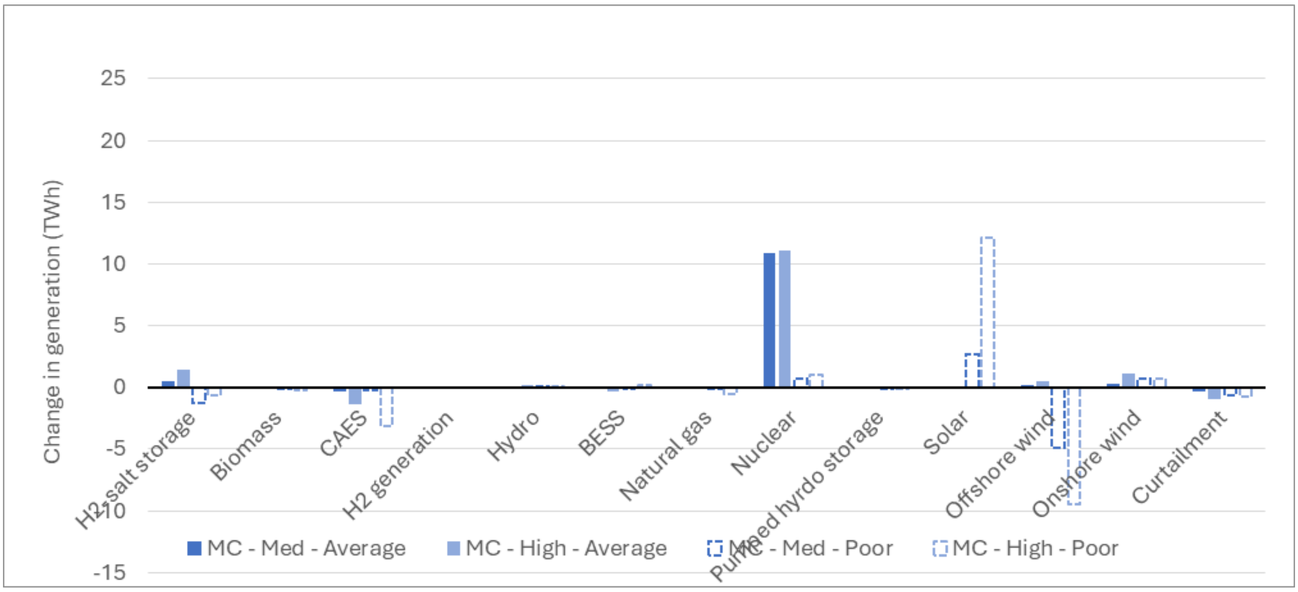


Figure 21: Impact of innovation in H_2-salt cavern storage on generation of other technologies in 2050 compared to low innovation level for the Minimally Constrained scenario

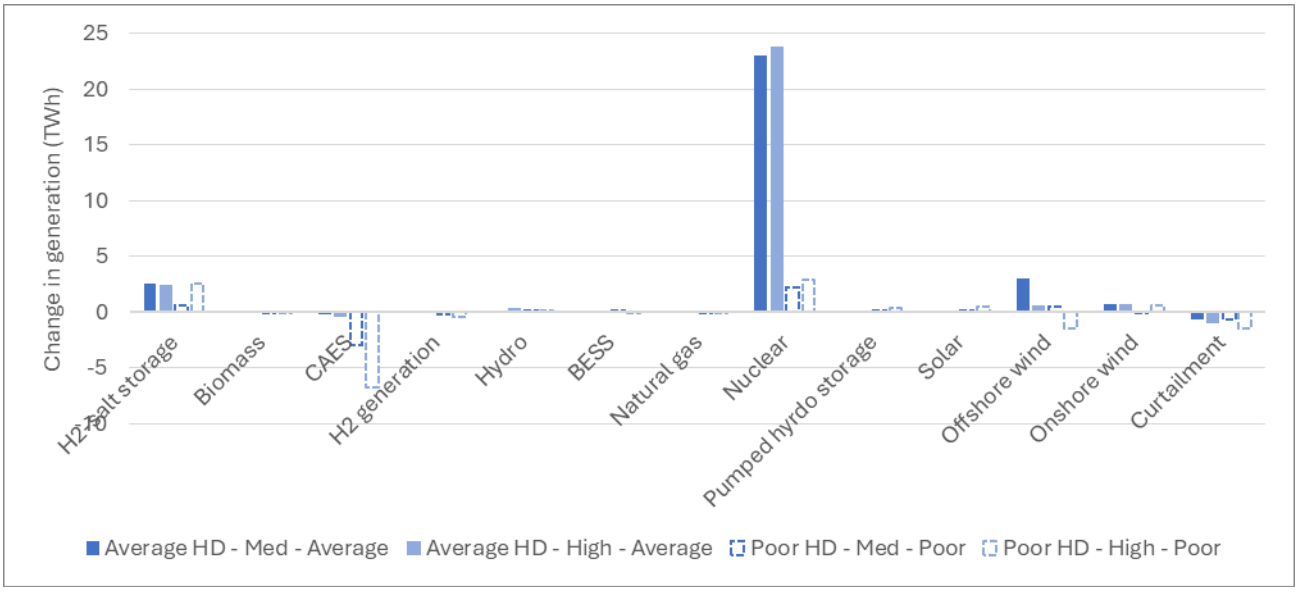


Figure 22: Impact of innovation in H_2-salt cavern storage on generation of other technologies in 2050 compared to low innovation level run for the Minimally Constrained scenario

Role in system services

When paired with a CCGT, H_2-salt cavern storage plays a critical role in provision of system services, providing ~50% of peak system inertia needs in the Minimally Constrained scenario in 2050 average weather conditions. This increases to 60% in the poor weather year, with innovation in H_2-salt caverns. In High Diversification, higher capacities of nuclear and biomass fulfil a greater proportion of this system need, with the share provided by H_2-salt dropping to between 33% and 43%.

Additionally, H_2-salt caverns paired with OCGTs can play a material role in provision of reserve capacity with innovation in this technology. In 2050 in the Minimally Constrained scenario, salt cavern linked hydrogen turbines provide 41% of the average reserve capacity in the system in the medium innovation run average weather run, increasing to 65% with high innovation levels. This almost entirely replaces the need for natural gas turbines. These values are reduce to ~10% and ~20% respectively in the HD scenario, where the diversification constraints in the scenario lead to higher levels of standalone hydrogen and natural gas turbines, which fulfil this need.

H_2-salt caverns play a less critical role in provision of frequency response, typically providing <5% of the system need on average across the weather conditions and innovation levels in the Minimally Constrained scenario. In High Diversification in 2050, this can increase to ~10% of average frequency response needs and up to 41% of peak frequency response needs. This is due to this scenario having a lower overall need for frequency response, reducing the deployment of batteries as it is more cost effective to use pumped hydro to cover the bulk of this everyday need, supplemented with other sources as required in peak times.

Business opportunities of energy storage technologies

Introduction

The purpose of this section is to explore the potential scale of the business opportunities for the UK associated with the national and global development in the energy storage technologies covered in this report (4-hour battery storage and CAES).[79] Innovation will be a key driver in supporting the growth of this sector in the UK and realising these business opportunities, and therefore an important element to capture as part of this innovation assessment.

The section summarises the key findings from the development of a series of 'business opportunities calculators'. These calculators integrate projections of domestic deployment of the two technologies, derived from scenario-based systems modelling (*see System benefits from innovation in energy storage*) with assessments of the UK's potential market share in overseas markets, informed by global modelling and literature reviews. They combine this understanding of potential deployment with assumptions around the cost structure and employment intensity of the different activities required for the manufacturing, deployment, operation and decommissioning of each technology to generate an understanding of the potential business opportunities in terms of:

- Gross Value Added (GVA) – a measure of the value generated by the production of goods and services. GVA can be thought of as broadly equivalent to the contribution of that sector/activity to Gross Domestic Product.
- Employment – Employment is measured in terms of jobs and includes both direct employment – the jobs associated with the construction and operation of the assets – and indirect employment – the jobs associated with the production of the goods and services needed by the workers with direct jobs i.e. jobs associated with the supply chain needed to construct, operate and, as necessary, decommission the assets.

All results are illustrative of potential business opportunities of technological innovation. They are generated using a particular set of technologies, hypothetical deployment scenarios, modelling outputs and other assumptions to help inform UK Government decision making.

The modelling outputs on which the results are based include modelled expectations for deployment in both 2020 and 2025. While efforts have been taken to calibrate these modelled outcomes with existing deployment data, some inconsistencies will remain. Looking forward,

[79] Long term hydrogen storage (in salt caverns and depleted gas fields) is also included in EINAs 2.0 but business opportunities calculator outputs associated with this technology are reported alongside those for other hydrogen technologies.

results do not reflect UK government targets/ambitions regarding neither deployment of these technologies nor the business opportunities that might be realised.

It is also important to stress that the results are specific to the particular technologies of focus for the report and that could be modelled, rather than the GVA and employment for the wider energy storage sector within which these technologies may often be categorised. As such, care should be taken when comparing the figures presented below with estimations which cover the entire sector, and use different scenarios and models.

The methodologies for the calculators, along with key caveats and assumptions, is available in the EINAs Technical Methodology report. All monetary values in this section refer to 2022 GBP.

In contrast to the business opportunities calculators for other technology families considered as part of EINAs work, results are only provided for the Minimally Constrained and High Diversification scenarios, as these are the only scenarios for which systems modelling results are available, as detailed in the section above, and in the EINAs Technical Methodology report.[80]

Energy storage market landscape

UK market position

As set out in the *Energy storage in the UK energy system* section, the UK is a global leader in the deployment of energy storage. It has been recognised by the UK Government that longer duration energy storage will be key to achieving its goals for a clean power system by 2030 and achieving Net Zero 2050.

By the end of 2024, the UK had 4.7 GW of installed utility-scale battery storage capacity.[81] Data from Renewable UK shows that there has been rapid growth in the installation of battery storage capacity since the turn of the decade, with average capacity also rising.[82] The majority of deployment to date has been shorter duration 1-2 hour lithium-ion batteries, although 4-hour batteries are expected to become increasingly prevalent.[83] More generally, as of December 2024, Renewable UK was reporting a strong pipeline of battery storage projects, in excess of 125 GW.[84] Consistent with this growth trend, the ONS Low Carbon and Renewable Energy Economy survey reports that direct full time employment in the 'fuel cells and energy storage'

[80] The highRES modelling outputs for deployment and cost of batteries and CAES in the UK used in the business opportunities calculator pertain to a scenario where levels of deployment are resilient to adverse weather conditions.
[81] Modo Energy (2025) GB battery energy storage markets: 2024 year in review
[82] Renewable UK (2024) Battery storage capacity in the UK: the state of the pipeline
[83] AMP Clean Energy (Accessed: 2025) AMP announces market leading four-hour battery storage projects to support clean energy transition.
14% of the battery storage capacity awarded in the 2024 One Year Ahead Capacity Auction (T-1) was 4-hour capacity, up from 0% the year before. NESO (2025) Auction results
[84] Renewable UK (2024) Battery storage capacity in the UK: the state of the pipeline

sector (a more expansive category of technologies than considered in this report)[85] has increased from 800 people in 2019 to 5,600 people in 2022.

For CAES, there are no large-scale CAES plants in operation in the UK as of 2025. Despite this, the research taking place at the UK's world-class universities and the engineering expertise available in relevant industries – such as combustion engines, aero-derivative engines and turbomachinery – mean that some commentators have placed the UK just behind China as a potential global leader in the technology.[86] The government's recent decision to implement a cap and floor support scheme for energy storage technologies that have a duration of at least 8-hours is expected to further accelerate investment in the area.[87]

Global energy storage market

This positioning means the UK could capture a modest share of what is expected to be a rapidly growing global market short to medium term energy storage technologies.

- 4-hour Battery storage – IEA (2024) forecasts that the global deployment of battery storage capacity could grow to 4,900 GW by 2050 in a Net Zero 2050 scenario.[88] To estimate the share of that total battery storage which is 'medium term' battery storage (4-hour), the National Energy System Operator's (NESO's) Future Energy Scenario (FES) 2023 estimate for the proportion of total short and medium term storage (liquid air, compressed air and battery storage, and pumped hydropower) which is expected to be medium term in the 'leading the way' scenario is used as a proxy. Using this approach, it is estimated that 23% of battery storage capacity might be medium term in 2050 which equates to 1,108 GW.[89]
- CAES – IEA (2024) forecasts that the global deployment of 'other storage' capacity could grow to 6 GW by 2030 in a Net Zero 2050 scenario.[90] It is assumed that this is representative of the level of CAES deployment by 2030. It is assumed that global deployment grows to 50GW by 2050. In absence of published forecasts for deployment post-2030, the 2050 estimate relies on the judgement of sectoral experts.

Building on this discussion, the quantitative analysis below assumes that the UK can capture a modest share of its domestic market in these technologies, while also accessing a modest share of the global market. Specifically, the analysis is based on previous modelling conducted by Ricardo for DESNZ using GEM-E3 modelling.[91] Based on an economic modelling assessment, Ricardo estimate that the UK consistently captures only approximately 4% of the

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[85] This is defined by the ONS as 'The design, development, manufacture, specialised consultancy services and installation of energy storage systems, referring to the conversion of energy into a form which can be stored, the storing of that energy and subsequent use of that energy' and includes activities such as flywheel energy storage, fuel cells, thermal energy storage as well as batteries and any other form of energy storage system.
[86] Barbour, E. (2023) Sustainable, Affordable and Viable Compressed Air Energy Storage – Written evidence
[87] DESNZ (2025) Long Duration Electricity Storage: Technical Decision Document
[88] It is assumed that the IEA (2024) forecast for battery storage does not include any battery storage with a duration of over 24-hours. Source: IEA (2024) Batteries and secure energy transitions
[89] NESO (2024) Future Energy Scenario documents
[90] IEA (2024) Batteries and secure energy transitions
[91] The 2024 Ricardo report is title *"Research to quantify the economic opportunities for the UK as a result of the global energy transition"*.

domestic market associated with 'smart systems' (which includes a range of storage technologies) between 2025 and 2050. This is significantly lower than in most of the other EINA's technologies and implies a heavy reliance on imports. They also estimate a current global market share for UK-based firms in the same sector of 0.1% which is forecast to remain stable until 2050. All operations and maintenance activities are assumed to be undertaken by domestic firms.

Energy storage business opportunity analysis

Gross Value Added (GVA)

The business opportunities calculators suggest that, assuming a 'medium' level of innovation, GVA in the energy storage sector will grow strongly across both modelled scenarios. Figure 23 shows that GVA in real terms grows from approximately £5m in 2025 to approximately £190m in 2050. Depending on the scenario, this represents a CAGR of 15-17%. The total amount of GVA produced in 2050 is very similar between scenarios but the paths taken to reach that point are distinct. In the High Diversification scenario, GVA grows more quickly between 2025 and 2040 on the back of a more rapid deployment of batteries (4-hour) whereas, in the Minimally Constrained scenario, growth is quickest between 2040 and 2050 due to an increased level of CAES deployment over that period. The greater total GVA over the period in the High Diversification scenario is driven by the more substantial deployment of offshore wind and solar in this scenario, necessitating a greater role for these technologies to provide both frequency response and storage.

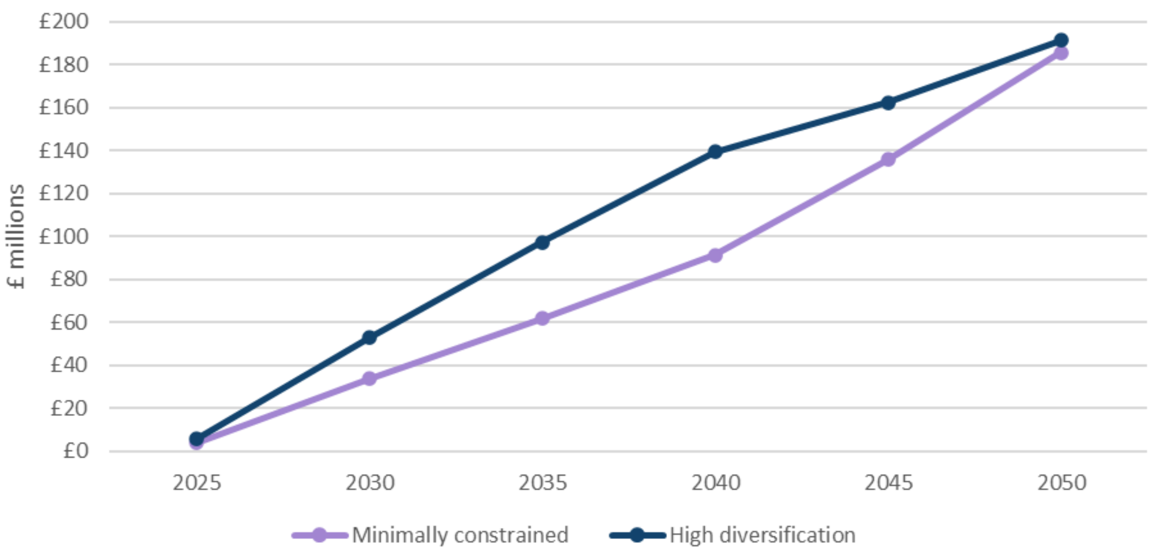

Figure 23: GVA by scenario
Note: The figure reports outputs associated with a medium level of innovation.

As is shown in Figure 24, GVA in the sector is projected to become almost exclusively dependent on the domestic market, as a result of the assumed challenges that UK-based firms will have in accessing export markets. As discussed in deep dive 3 on resources and supply chains, this reflects some of the challenges surrounding accessing the raw materials needed for battery technologies, the geographical locations where these materials are processed, and the current distribution of global manufacturing capacity. The domestic market could generate between £51 and £87 million in GVA in 2035 (83-89% of the total, depending on the scenario), potentially rising to between £174 and £180 million (94% of the total) by 2050. Exports are relatively stable between 2035 and 2050, generating around £10 million in GVA per year as the rate of global deployment stabilises and, assuming as per the Ricardo analysis that, the UK's share of export markets is steady. Despite some of the supply chain challenges they face, batteries (4-hour) represent the somewhat more promising export opportunity relative to CAES, contributing 93% of export driven GVA by 2050 on account of the larger global market expected for this technology.

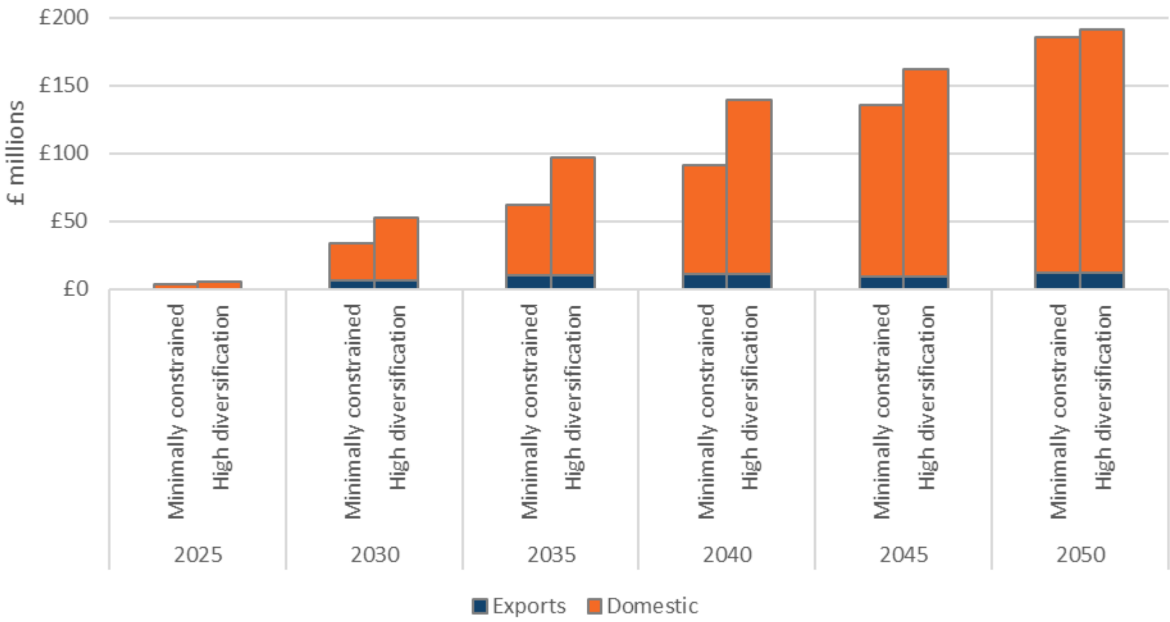

Figure 24: GVA by scenario by market
Note: The figure reports outputs associated with a medium level of innovation.

Figure 25 shows that in the Minimally Constrained scenario, the variation in GVA according to the extent of innovation in the sector is high between 2030 and 2040, before reducing markedly by 2050. In this scenario, higher levels of innovation facilitate a significantly greater deployment of these energy storage technologies between 2030 and 2040, such that GVA in the high innovation scenario is 142-157% higher than in the low innovation scenario during this period. This is driven primarily by greater 4-hour battery deployment in the high innovation scenario which becomes relatively more attractive at providing frequency response. Beyond 2040, the deployment of the two energy storage technologies begins to converge across innovation levels meaning that the variation in GVA between the highest and lowest innovation levels narrows to 19% by 2050.

While there is an intuitive relationship between innovation and GVA in the Minimally Constrained scenario, the results are more complicated in the High Diversification scenario. In certain instances, within this scenario, lower levels of innovation are associated with higher levels of GVA. The reason for this counterintuitive result is due to the relationship between costs and economic activity. All else being equal, goods and services that have higher costs, provided they continue to be purchased, are associated with the ascribed value of those goods and services being higher i.e. that the activity leading to those goods and services makes a higher GVA contribution. Because the High Diversification scenario already requires a greater deployment of storage technologies than the Minimally Constrained scenario, deployment is less responsive to the lower costs associated with greater innovation.

The potential impact that higher or lower costs may have on the output, and hence GVA contribution, of other sectors in the economy is not captured in this analysis.

Figure 25: GVA by scenario for low, medium and high innovation levels

Figure 26 shows the distribution of GVA between the two storage technologies over time in the two scenarios modelled (and with the ‘medium’ innovation level). It shows a number of patterns:

The majority of the variation in GVA between scenarios is driven by the differing deployment patterns for 4-hour batteries. In the High Diversification scenario, driven by the additional solar and offshore wind deployment in this scenario, battery (4-hour) domestic deployment is forecast to reach a peak deployment of 6.1 GW in 2035, whereas in the Minimally Constrained scenario the 2035 peak deployment is just 1.8 GW. These deployment forecast patterns are directly reflected in the GVA estimates, with the GVA contribution associated with 4-hour batteries being roughly 2-2.5 times greater in the High Diversification scenario than in the Minimally Constrained scenario across the period.

- For both scenarios, the cumulative deployment of 4-hour batteries, and the GVA associated with that deployment, is forecast to peak in 2035 and decrease thereafter. This reflects the systems modelling results which anticipate the role of 4-hour batteries as one of a transition technology that, by 2050, are displaced by 1-hour batteries as the key technology for fulfilling frequency response needs.
- As a corollary, CAES grows in relative importance across the modelled period, especially beyond 2035. The amount of GVA supported by CAES is very similar between scenarios, growing from £3 million in 2025 to £159-168 million (a CAGR of 17-18%, depending on the scenario) in 2050.

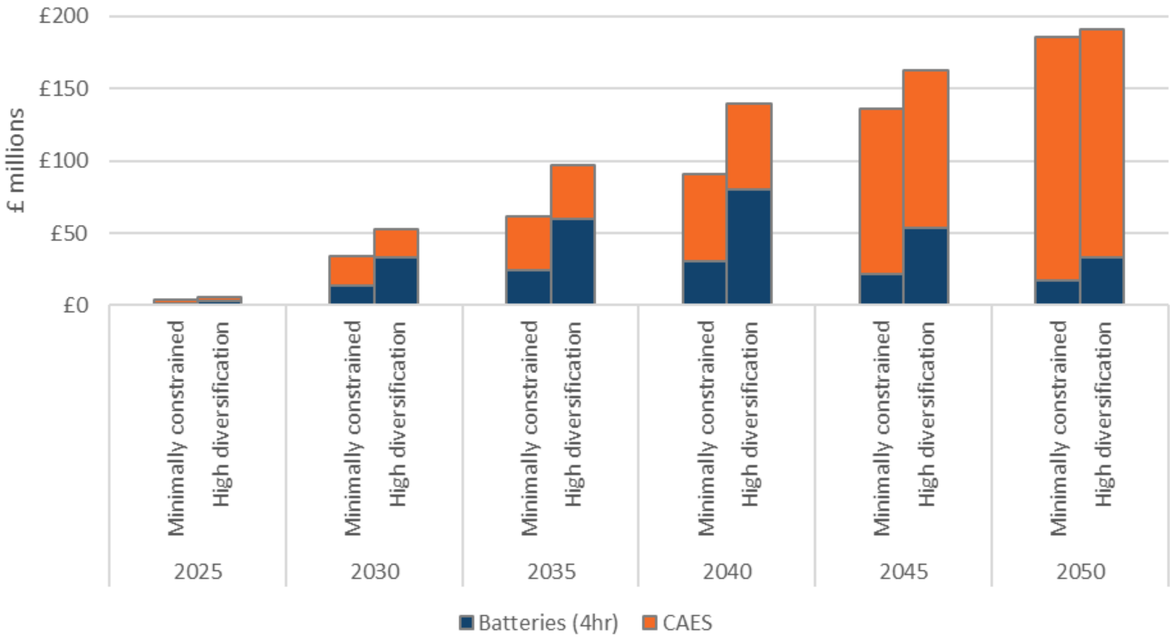

Figure 26: GVA by scenario by technology

Note: The figure reports outputs associated with a medium level of innovation.

Direct and indirect jobs

Supported employment (direct and indirect jobs[92]) follows the rapid growth in GVA. Across the scenarios, supported employment reaches approximately between 3,800 and 3,900 jobs in 2050. 54-56% of these jobs are direct jobs in 2025 (depending on the scenario), rising to approximately 63% by 2050, as industry activity shifts from construction to operation and maintenance (see also Figure 30 below), the latter having supply chain activities which are less employment intensive. In line with the GVA results, by 2050, there is very little variation – around 100 jobs – in the expected number of supported jobs between scenarios. Over the period as a whole, however, there is a marked difference in jobs supported between the two

[92] A direct job is employment associated with the stated activity. An indirect job is a job that exists to produce the goods and services needed by the workers with direct jobs i.e. those jobs associated with supply chain activities. The estimate of indirect jobs is based on the application of Type 1 multipliers to the different cost categories (activities) within the sector.

scenarios: the greater deployment of 4-hour batteries in the High Diversification scenario leads to, on average, an additional 500 jobs per year.[93] The difference peaks (in absolute terms) in 2040, where there are an extra 1,000 jobs supported in the High Diversification scenario compared to the Minimally Constrained scenario (52% extra).

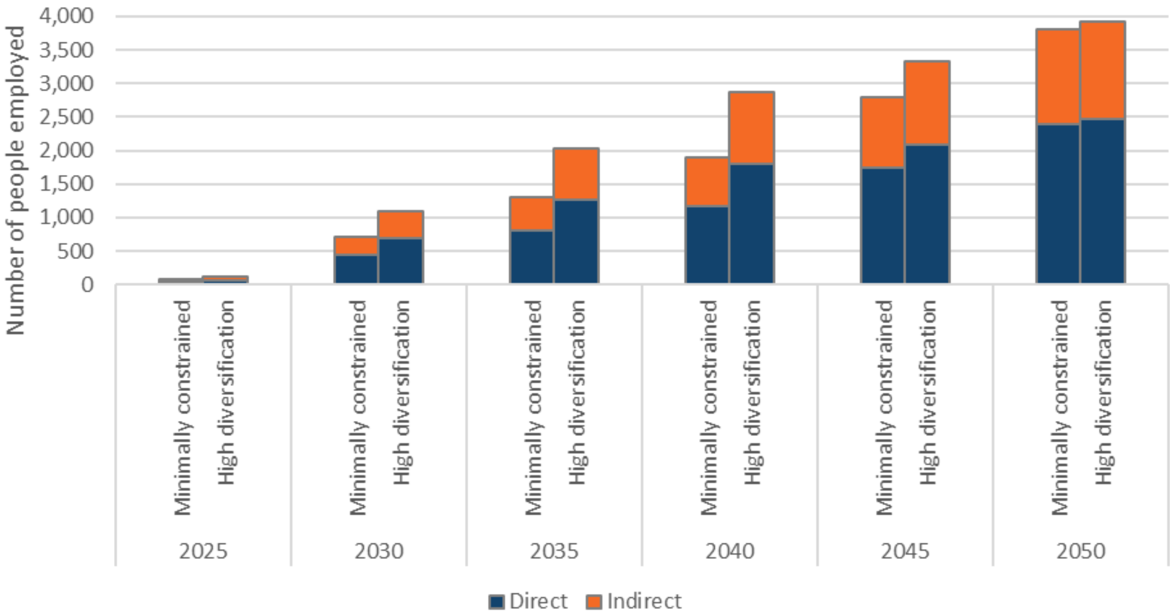

Figure 27: Total jobs supported by scenario by direct vs indirect
Note: The figure reports outputs associated with a medium level of innovation.

Figure 28 and Figure 29 show the breakdown of employment by domestic/export market and across different cost categories i.e. construction, operation & maintenance and decommissioning, respectively, focusing specifically on 2035 and 2050.

As is the case for GVA, employment in the sector is projected to be heavily reliant on the domestic market. The domestic market might support between approximately 1,000 and 1,800 jobs in 2040 (81-88% of the total, depending on the scenario), potentially rising to between 3,500 and 3,600 by 2050 (93% of the total). The drivers of these trends are the same as those for GVA, a stable global market of which the UK is assumed to capture a consistent share and a rapidly growing domestic market of which UK firms are also expected to capture a consistent share (See Figure 28).[94]

Estimates of the number of jobs supported by cost category follow the expected trend with jobs supported by construction activity reducing in importance between 2035 and 2050 as the stock of assets increases and the operations and maintenance jobs associated with that stock increases. CAPEX-related jobs make up between 18% and 25% of employment (depending on the scenario) in 2035 falling to 11-12% of employment (depending on the scenario) by 2050.

[93] Average taken over the 6 specific years for which the modelling results provide employment estimates (2025, 2030, 2035, 2040, 2045, 2050).
[94] The rapid growth in the domestic market is primarily driven by growth in the OPEX segment of the market (See Figure 28)

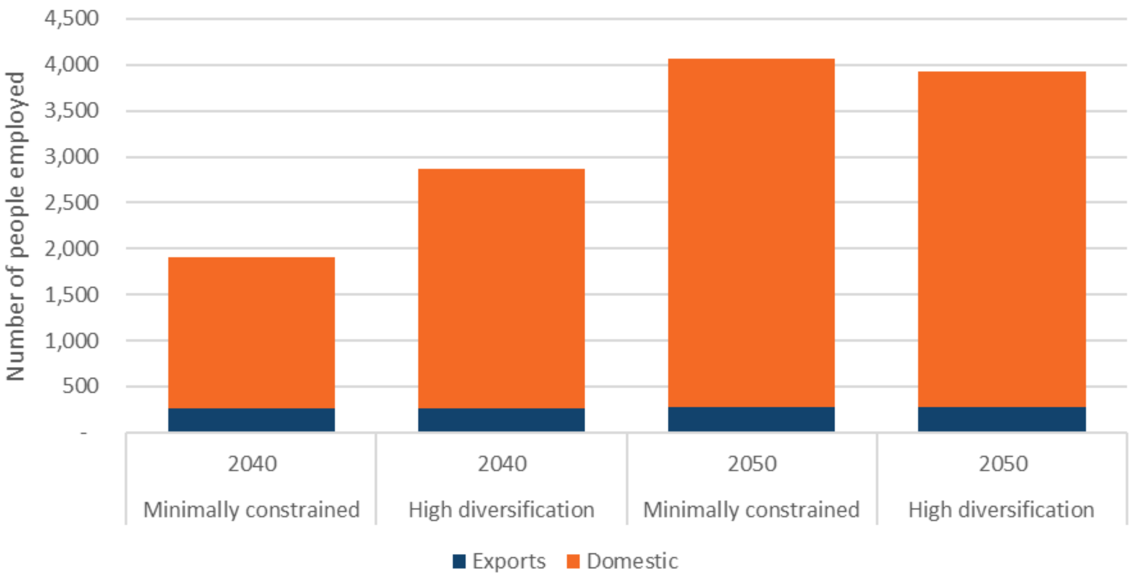

Figure 28: Total jobs supported (direct + indirect) by scenario by market

Note: The figure reports outputs associated with a medium level of innovation.

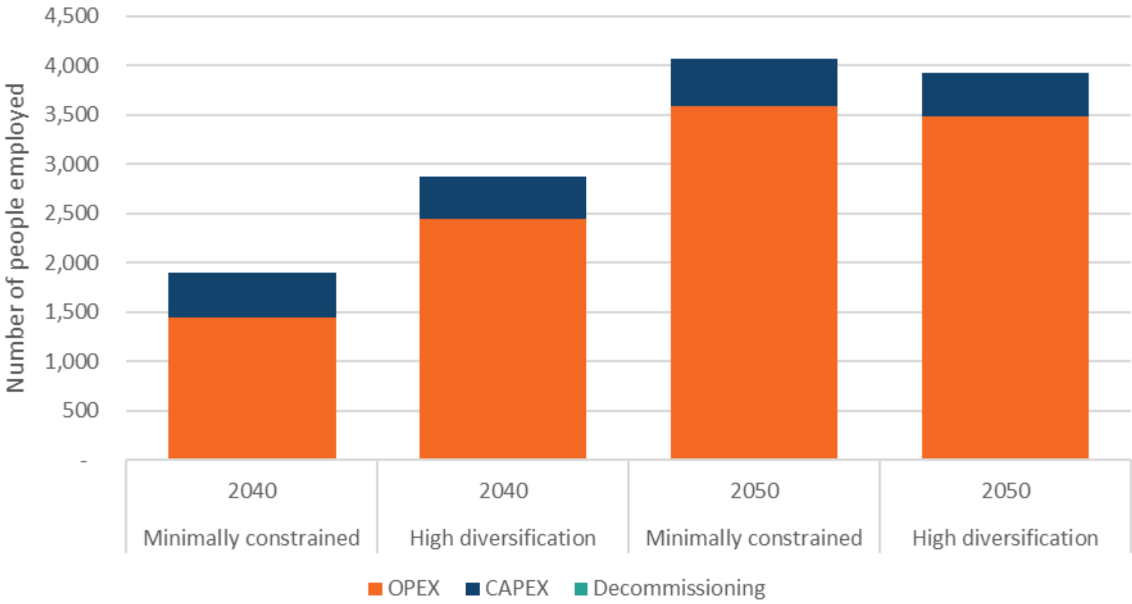

Figure 29: Total jobs supported (direct + indirect) by scenario by cost category

Note: The figure reports outputs associated with a medium level of innovation.

Finally, Figure 30 shows that, in all modelled scenarios, most of the direct jobs supported by the sector in 2050 are expected to be in high-skilled professional occupations. The occupations that account for the largest number of jobs supported are professionals in science, research, engineering and technology (between 900 and 1,000 direct jobs, 39% of the total), followed by other professional occupations (approximately 400 direct jobs, 15% of the total) and managers, directors and senior officials (approximately 300 direct jobs, 13% of the total). The sector is also expected to support around 300 jobs in skilled trade jobs by this date.

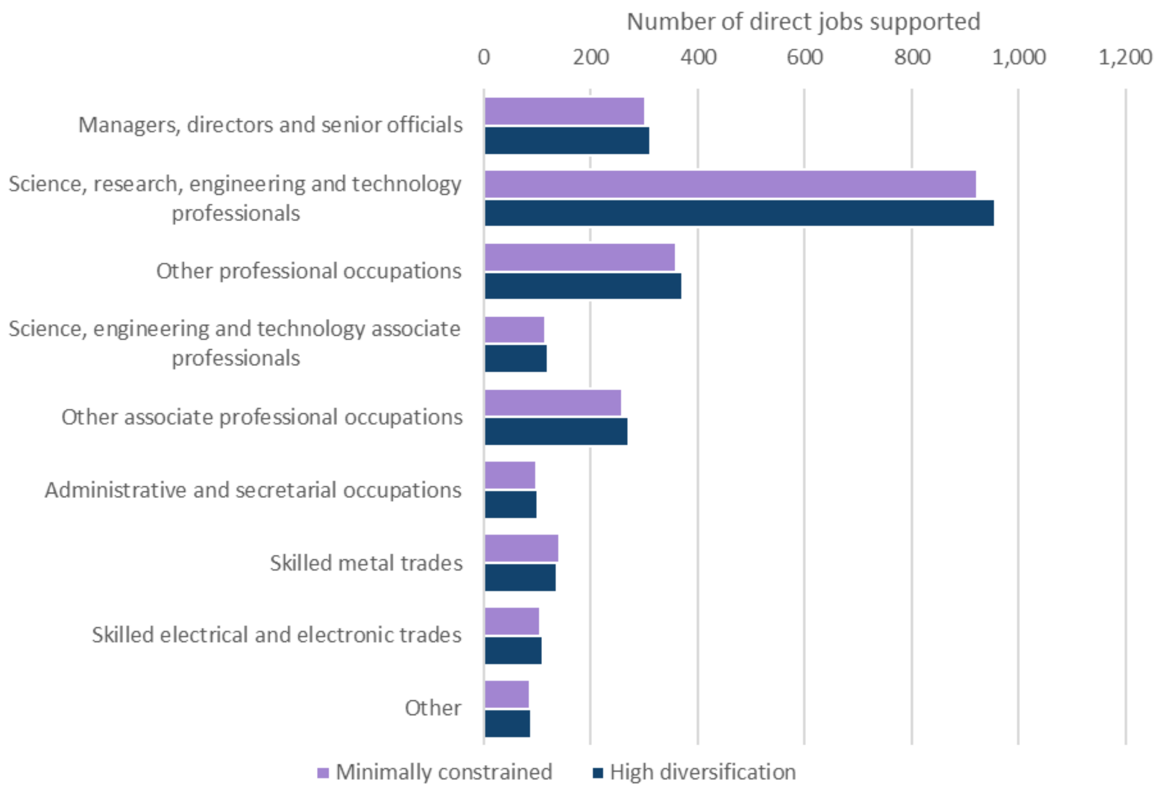

Figure 30: Direct jobs supported by scenario by occupation type in 2050

Note: The figure reports outputs associated with a medium level of innovation. For the purposes of this analysis, the 412 4-digit SOC codes have been aggregated to 15 SOC groupings. See the EINAs Technical Methodology Report for more details on this aggregation. In Figure 32 the heading 'other' covers the following 7 SOC groupings: Skilled construction and building trades; other skilled trade occupations; process, plant and machine operatives; transport and mobile machine drivers and operatives; elementary occupations; sales and customer service occupations; and caring, leisure and other service occupations.

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