RAF134/2223
Energy Innovation Needs Assessments

Summary report

June 2025

Acknowledgements:

Research and reports produced by a consortium led by Carbon Trust, including Mott MacDonald, UCL and Pengwern Associates. Commissioned by the Department for Energy Security and Net Zero.

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Acronyms and abbreviations

BECCS	Bioenergy with carbon capture and storage
BESS	Battery energy storage systems
CAES	Compressed air energy storage
CAGR	Compound Annual Growth Rate
CCGT	Closed cycle gas turbine
CCUS	Carbon capture, usage and storage
DACCS	Direct air carbon capture and storage
DESNZ	Department for Energy Security and Net Zero
EINA	Energy Innovation Needs Assessment
GGR	Greenhouse gas removals
GVA	Gross Value Added
LAES	Liquid air energy storage
LCOE	Levelised cost of energy
OCGT	Open cycle gas turbine
PCC	Post combustion capture
TRL	Technology Readiness Level

Key findings

Innovation is critical to delivering Net Zero, bringing down the cost of transition and creating business opportunities. The Energy Innovation Needs Assessments (EINAs) is intended to add to the evidence base for the prioritisation of investment and support for clean energy innovation. To achieve this, it aims to identify key innovation needs in selected clean energy technologies[1] and understand their impact on the UK energy system and potential business opportunities. This work shows that innovation can make technologies that are not yet commercially available ready sooner and make them cheaper so they can be deployed more widely. This has significant potential to accelerate the deployment of key technologies in the UK's transition to Net Zero.

Innovation system impacts

Energy system modelling to assess the potential impact of innovation in selected technologies was conducted using UK TIMES, a cost optimising energy system model of the UK. Technologies were assessed at three levels of innovation (low, medium and high) and across three hypothetical scenarios: Minimally Constrained, High Hydrogen and High Diversification.[2]

If a high level of innovation were achieved in all of the technologies studied by the EINAs (the EINAs technologies) there is the potential to cumulatively save £203bn–£348bn[3] of UK energy system costs between 2025 and 2050 (£2022 basis) compared to low innovation scenarios, while also meeting legal requirements to deliver Net Zero by 2050. Under high innovation in EINA technologies, projected system costs in 2050 are 5–6.5% lower compared to the low innovation scenarios. Additional electricity system analysis from the highRES model indicates that high innovation across EINA technologies could reduce electricity transmission costs by 6–10% by 2050, and innovation in EINA modelled storage technologies could reduce annual electricity system costs by £2bn–£5bn in 2050.

Across individual innovation runs of specific technologies (where all other technologies are held at the baseline low innovation level), innovation in bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), air-source heat pumps and offshore wind lead to the largest reductions in total energy system costs compared to the respective low-innovation cases: potential cost reductions of £41bn by offshore wind, £62bn by DACCS, £75bn by BECCS, and £110bn by air-source heat pumps (cumulative cost savings between 2025 and 2050; £2022 basis). Electricity system analysis from the HighRES model

[1] A full list of the technologies studied by the EINAs can be found in the Introduction of this report.
[2] 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 the System benefits of innovation section of this report and in the EINAs Methodology report.
[3] Real 2022 figures for technologies modelled by UK TIMES (not including Network and Storage technologies, which were modelled differently). Cost savings are undiscounted and over the 2025-2050 period.

suggests that innovation in interseasonal storage provides the largest system cost reduction among storage technologies within the EINA analysis.

Innovation needs and enablers

Within each technology area, the EINAs have identified specific innovation needs that will help bring down the cost of the studied technologies, address key barriers and accelerate their deployment to help unlock the levels of system cost savings identified above. These are summarised by technology in the Mapping Innovation Needs section of this report and provided in more detail in the sector specific reports.

The EINAs have also considered non-technological barriers to the deployment of these clean energy technologies. Common themes included supply chain challenges, a shortage of skills and training, need for enabling infrastructure, improved business models and the need for a stronger regulatory environment. Whilst it is critical to develop and demonstrate new technologies, these other barriers must also be addressed if the technologies investigated are to be deployed at scale and to unlock their potential environmental and economic benefits.

Energy networks were identified as a key common enabler across decarbonisation technologies, with a report dedicated to innovation opportunities within this area. Eleven high-priority technology areas were identified within energy networks, as well as the need for an integrated approach to network innovation and improved coordination across the energy system. Successful commercialisation of such innovations would lead to enhanced energy system resilience and accelerate the transition to Net Zero.

Business opportunities

Innovation can support the growth of clean energy industries in the UK. The total business opportunities (real Gross Value Added) that the 26 EINAs technologies could support grows substantially to approximately £19 billion in 2050 (2022 values). This represents a Compound Annual Growth Rate (CAGR) of 7 – 8% over the modelled period. The modelling estimates that the three technology areas that offer the largest business opportunities by 2050 are heating and buildings, offshore renewables and carbon management. This includes the construction, operation and decommissioning of new assets, related to both the domestic deployment in the UK and the potential share of the international markets that UK business may capture.

The 26 EINA technologies assessed for business opportunities could support in the region of 470,000 jobs by 2050. This estimate represents a narrower selection of technologies and sectors compared to the overall clean energy industry, with a focus on areas with highest innovation potential and needs given the scope of the EINAs. The profile of jobs is concentrated in science, research, engineering and technology professionals and skilled trades.

Introduction

Achieving the UK's ambitious Net Zero target 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 contribute to 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 in 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. A shortlist of selected technologies were taken forward for analysis including:

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

The scope of the EINAs project spans the UK energy system. Technologies considered are limited to those that provide clean energy supply, reduce demand for energy or reduce emissions. While transport energy use and requirements were included within modelling, this sector was out of scope for innovation assessments. There are eight separate technology theme reports, detailing the innovation needs, cost saving opportunities, key barriers and enablers and business opportunities of the prioritised EINAs technologies. This summary report provides an overview of the key findings across the selected technologies which have been grouped in the following technology themes: offshore renewables, hydrogen, nuclear energy, heating and buildings, energy networks, energy storage, industry and carbon management.

The 2025 EINAs publications have been commissioned by DESNZ and produced by a consortium led by Carbon Trust, including Mott MacDonald, University College London (UCL) and Pengwern Associates.

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.

A number of technologies were included as part of the prioritisation 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.

Initial technology prioritisation

1. Initial longlist based on published scenarios, DESNZ priorities and engagement activities, and technical expert input.
2. Longlist prioritised according to 4 DESNZ criteria: known Net Zero priority, UK relevance, energy security and TRL.
3. Shortlist further prioritised based on modelling capability and data availability.

Data gathering and updated model

1. Development of three UK energy system scenarios: Minimally Constrained, High Hydrogen and High Diversification.
2. Data gathering across the priority EINAs technologies at three innovation levels.

Energy systems modelling of EINA

1. Modelled scenarios and analysis of innovation opportunities.
2. Innovation values for each EINAs technology area.
3. Cost and deployment for EINAs technologies to 2050.

Economic calculators and analysis

1. Updated economic calculators from the previous EINAs.
2. Updated economic data inputs.
3. Analysis of economic opportunities, including jobs and GVA, for the EINA technologies.

Selected EINAs Sectors

1. Offshore Renewables
2. Nuclear Fission
3. Heating and Buildings
4. Carbon Management
5. Hydrogen
6. Energy storage
7. Networks
8. Industrial Decarbonisation

Final outputs

1. Updated systems models, UK TIMES and highRES, and modelling scenarios
2. Cost savings, deployment and cost modelling outputs across three scenarios
3. Tables of innovation needs
4. Economic opportunity calculators for each EINA
5. Eight sub-theme EINA reports assessing the innovation opportunities
6. An overview EINA report
7. A Technical Methodology EINA report

Figure 1: Overview of the EINAs approach

Clean energy innovation needs

Prioritising innovations to study

To undertake the analysis, the project had to select which technologies to study, including for both the qualitative and quantitative aspects of the research. The EINAs technologies were decided through a prioritisation exercise, taking into account insights from sector experts and prioritising against key DESNZ criteria.

An initial longlist of priority Net Zero technologies was developed based on the previous EINAs work, published national and global scenarios, input from DESNZ expert engagement, and input from technical experts from across the EINAs consortium.

This longlist was then further prioritised according to the following criteria:

1. **Known Net Zero priority:** Areas where there is clear government direction or expert consensus. Additionally, areas where a technology might not have a high potential for innovation, be necessary for energy security considerations or align with current UK capabilities, but Net Zero cannot be achieved without it and it still requires government intervention were considered for inclusion.
2. **Energy security:** Technologies necessary for system resilience (grid/import shocks). Some technologies may not provide high levels of decarbonisation or economic benefit but are essential in guaranteeing or improving UK energy security and resilience to international disruptions. Where relevant to innovation, such technologies have been considered.
3. **UK relevance:** Areas where the UK is likely to have an impact on the development or deployment of the technology. Some technologies/components may provide high economic and decarbonisation opportunities in principle but may not be adequate for UK specific circumstances (e.g. require scales of production that the UK cannot match relative to larger countries). In such cases narrower component-level opportunities may still be considered as relevant. Additionally, some technologies with high potential are already receiving extensive attention from industry with significant sums dedicated to R&D. In such cases public R&D funding is of lower priority.
4. **Technology Readiness Level (TRL):** Technologies or sub-technologies / components, that are close to commercialisation, approximately TRLs 7-9, and technologies which have limited likelihood of being commercially viable by 2040, even if promising in the longer term, were generally not considered priorities for the EINAs analysis. The definitions for TRL ratings used were aligned with the definitions used by UKRI.[4]

The shortlisted technologies were then taken forward for in-depth qualitative analysis, systems modelling and economic analysis. The qualitative analysis included a barriers and enablers

[4] UKRI (Accessed: 2025) Eligibility of technology readiness levels (TRL)

assessment. The technologies which were prioritised for the EINAs analysis are outlined in **Figure** 2.

28 technologies across 16 technology families were modelled using UK TIMES and HighRES (more detailed information on the models is presented in the EINAs Methodology report). The energy networks report technologies were assessed through stakeholder engagement. Data for the industrial decarbonisation technologies which informed the economic analysis were sourced from recent DESNZ analysis. Some technologies were excluded from the system modelling due to methodological challenges relating to data availability and UK TIMES capabilities, e.g. heat networks, digitisation and industry resource and energy efficiency.

Energy system			
Sector	**Sub-sector**	**Technology family**	**Technology**
Power	Renewables*	Offshore renewables	Fixed offshore wind
			Floating offshore wind
			Tidal stream
	Nuclear*	Nuclear Gen IV	High Temperature Gas Reactor (HTGR)
		Nuclear fission	Small Modular Reactors (SMRs)
	Smart systems	Energy storage*	4 - 8 hour duration energy storage
			8 - 24 hour duration energy storage
Fuel supply and hydrogen	Hydrogen*	Vector coupling	H2 turbine (OCGT and CCGT)
		Production	Electrolysis (PEM, alkaline, solid oxide)
			Autothermal reforming with CCS
		Infrastructure	Hydrogen transmission and distribution pipelines
			Medium duration salt cavern hydrogen storage
			Depleted gas field hydrogen storage
Heating and buildings*	Heating and cooling	Heat pumps	Air source heat pumps (ASHP)
			Ground source heat pumps (GSHP)
			Water source heat pump (WSHP)
		Networks	Heat networks
	Buildings	Building fabric	Insulation - floor
			Insulation - wall
			Insulation - roof
Carbon Management*	CCUS	CO_2 capture	Gas CCS with Post Combustion Capture (PCC)
		CO_2 storage	Geological CO_2 storage
	GGR	BECCs	BECCS - electricity
			BECCS - hydrogen
			BECCS - fuel (Fischer-Tropsch)
		DACCs	DACCS
Networks*	Networks	Networks	Superconducting cables (HTS)
			Dynamic Line Rating (DLR)
			Distributed feeder technologies
Industry*	Industrial decarbonisation	Industrial decarbonisation	CO2 usage
			Electrification
			Other fuel switching (hydrogen and biomass)
			Resource and energy efficiency

Figure 2: Overview of technologies prioritised for EINAs to study the system-wide effects of innovation in these areas. EINAs technology theme reports are identified by an asterisk (*).

Mapping innovation needs

Each technology was assessed via literature review and by sector experts and DESNZ teams for key areas of innovation required to reduce cost and accelerate deployment. The tables below summarise findings from this innovation mapping exercise across each technology area, outlining high priority innovation areas scoring high on potential for cost reduction and addressing of key barriers. More detailed tables that outline the specific technologies impacted by each innovation, the contribution of innovation opportunities to cost reduction and addressing deployment barriers, estimated time frames for potential deployment, as well as innovation opportunities expected to have relatively smaller impacts are provided in the technology-specific EINAs reports.

Offshore renewable energy

Offshore renewables offer a significant opportunity to accelerate the decarbonisation of the UK's energy system. They play a key role in the provision of clean energy as they replace current fossil fuel based generation technologies. Whilst maturity of these technologies varies by type, there are opportunities for innovation across the offshore renewables value chain to facilitate the scaling of these opportunities.

Technologies covered in the EINAs: Fixed and floating offshore wind and tidal stream.

Table 1: Innovation needs – offshore renewable energy

Innovation area	Description
Component and infrastructure development	Integrated assembly techniques: Design and manufacturing techniques that enable large-scale modular assembly in combination with designs that reduce material requirement. Foundation design and optimisation: Automation of fabrication and material optimisation using advanced mass or batch production techniques. Advanced installation and maintenance techniques such as self-hoisting turbines and cranes and autonomous maintenance systems. Increased size and standardised development of turbines.
Grid integration	Improvements in Direct Current (HVDC) networks and smart grids and holistic network design (HND). Sharing infrastructure generation devices to reduce cost and incentivise network upgrades. HVDC substation development for increasingly distant farms. High Voltage (132kV) array cable development, both HVAC and HVDC. Improved system monitoring: accelerometers, GPS sensors measuring motions, optical fibres measuring cable temperatures.
Advanced design, modelling, controls and monitoring	Advanced monitoring and inspection techniques to manage large scale offshore farm complexity. Advanced turbine control systems: Turbine control systems that optimise individual turbines across a wind farm will aid efficiency and prolong the life of assets. Development of control systems specific to offshore renewables technology.
Testing and industry guidelines	Full-scale testing and consolidation of designs for large-scale floating wind concepts and innovations. Validation of concept and test facilitates. Novel component level development qualifications, e.g. mooring solutions, self-hoisting cranes, and dynamic cables.
Energy storage innovation	Alternatives to network connection or surplus demand, e.g. cost-competitive production of low carbon hydrogen and ammonia onsite to provide fuel for shipping.

Heating and buildings

Decarbonising heat in buildings is achieved by transitioning to systems driven by fuels or energy sources that are or have the potential to be zero carbon, such as electricity produced by renewable energy. This transition benefits from a holistic approach in conjunction with energy efficiency measures, to limit the impact on the consumer operational energy costs and minimise the additional electricity demand required.

Technologies covered in the EINAs: Air-source heat pumps, water-source heat pumps, ground-source heat pumps and building insulation.

Table 2: Innovation needs – heat and buildings

Innovation area	Description
Building insulation	Advancements in modelling and testing to enable increased data collection, analysis and sharing across all stages of building construction; improved design for manufacture and assembly for offsite/prefabricated construction and precision manufacturing for new builds and retrofits; improved and guaranteed performance of insulation materials with focus on improving specification, installation and maintenance processes.
Heat pumps - systems	Low global warming potential refrigerants that can allow high efficiencies at high temperatures (above 60°C); increased component efficiency and temperatures, e.g. new compressors and solid-state technologies
Heat pumps - Installation	Integration of plug-and-play hardware and software alongside easy-to-use modelling tools to design and specify systems; modularised systems, including pre-plumbed or integrated system elements such as hot water cylinders and buffer tanks into heat pump enclosures.
Heat pumps - Manufacturing	Integration of standardised or modular components and systems for mass production; automation and robotics to increase manufacturing capability; streamline supply chains; improving component quality; components to support a circular economy.
Heat networks	Innovate and reduce cost of Heat Interface Unit (HIU); develop tools to increase accuracy of peak demand and heat demand estimates; innovate to minimise household disruptions to enable faster installations. Innovation for Thermal Energy Storage (TES), integrated solutions in buildings to provide flexibility, and support access to balancing and flexibility.

Hydrogen

Hydrogen is expected to play an important part in the UK's clean energy transition due to its versatility across a range of low carbon applications. Low carbon hydrogen is produced using methods including steam methane reformation with Carbon Capture and Storage (CCS), and electrolysis. Low carbon hydrogen can be used to decarbonise hard-to-abate sectors including industry through direct use as a fuel and a feedstock, or through providing industrial-grade heat, fuel for hard to electrify transport sectors (e.g. ammonia production for shipping), flexible low carbon power generation and seasonal energy storage. There are opportunities for innovation across the hydrogen value chain to facilitate the scaling of these opportunities.

Technologies covered in the EINAs: Electrolysis (proton exchange membranes, alkaline and solid oxide), autothermal reforming with Carbon Capture and Storage (CCS), hydrogen transmission and distribution pipelines, medium duration salt cavern hydrogen storage, depleted gas field hydrogen storage, and hydrogen gas open cycle gas turbines (OCGT) and closed cycle gas turbines (CCGT).

Table 3: Innovation needs – hydrogen

Innovation area	Description
Autothermal reforming with CCS	Small-Scale Modular Reformers combining combustion, heat recovery and reaction and could be advantageous for offshore, remote or small-scale methanol plant applications. For both ATR and SMR, innovation is needed to integrate with CCS at scale. New Water-Gas Shift Technologies, particularly reverse WGS (RWGS), are emerging for a range of applications including the production of sustainable aviation fuel.
Electrolysis	Effective integration with renewable electricity sources. Improved electrode design and materials for low temperature electrolysers to reduce dependence on precious metals. Modularising components to adapt for various power requirements. High Temperature Electrolysers– Enhancing durability of materials to achieve mechanical, thermal and chemical stability while reducing costs. Increasing the density of stacks to reduce need for mechanical compression.
Hydrogen storage and transport	Improved efficiency in ammonia production, improving transport viability and use for shipping. Improved efficiency, cost, scalability and operational flexibility in gas separation technologies to enable de-blending hydrogen into existing infrastructure. New network design for re-purposing key gas network sections to high pressure transmission pipelines.
Hydrogen OCGTs and CCGTs	Improved safety measures for flammable hydrogen gas, including the gas turbine enclosure and ventilation system design. Demonstration of 100% hydrogen gas turbines use over long periods of time.

Nuclear energy

Nuclear energy can support the move to Net Zero by 2050 as a source of reliable and low carbon electricity, providing additional system resilience by diversifying generation sources. The EINAs focus on recent technological developments and innovation opportunities within the sector. Despite long-term potential, fusion is not considered as part of EINAs due to uncertainty on scale of deployment viable by 2040, which is one of the criteria used for the technology prioritisation within this analysis.

Technologies covered in the EINAs: High Temperature Gas Reactors (HTGRs) and Small Modular Reactors (SMRs).

Table 4: Innovation needs – nuclear energy

Innovation area	Description
Mining, processing, enriching and fabricating	Opportunities in fuels which remain in SMR and HTGR reactors for longer, increasing operational periods; fuels that can achieve higher burn-ups, producing less high-level waste and are compatible with earlier disposal in a geological disposal facility.
Components and systems	Adoption of standardised, modularised and productised design to maximise factory fabrication and minimise on-site installation; design simplification using safe and passive features and reduction in the quantity of nuclear-grade components; development and adoption of advanced machining, assembly, metrology, joining (e.g. local vacuum electron beam welding) and additive manufacturing to reduce cost, increase speed and reliability of components; use of robotics for in-service inspection, autonomous processes, remote handling in harmful environments, and size reduction..
Construction, installation and commissioning	Maximise use of Commercial Off the Shelf (COTS) components to reduce bespoke construction, installation and commissioning; develop a supply chain that can provide suitable COTS components for nuclear (through life availability, ability to maintain etc.).
Energy systems integration	Improve use of SMR energy generation with more flexibility and wider contribution to decarbonisation, such as: advanced power conversion cycles, district heating, hydrogen production, heat storage, and direct air capture of CO_2.
Operations and maintenance	Increased digitalisation, e.g. in instrumentation and control systems, enabling greater operational modes for SMRs. Equipment optimised for reduced maintenance (e.g. improved material, lubrication, electronics etc.)
Decommissioning	Use of robotics for in-service inspection, autonomous processes, remote handling in harmful environments and size reduction, which reduces reactor down time and allows in service component removal and inspection,

Carbon Management - Carbon capture, usage and storage (CCUS) and Greenhouse gas removals (GGR)

Carbon management technologies are essential in addressing hard-to-abate sectors. Carbon Capture and Storage (CCS) involves the capture of CO2 from large point sources such as power plants and industrial facilities. Greenhouse Gas Removal (GGR) is the capture of CO2 directly or indirectly from the atmosphere. In both cases, the captured CO2 is compressed and transported to be stored deep underground, or for use as a feedstock in a variety of applications.

Table 5: Innovation needs – carbon management – post combustion capture (PCC): Gas CCS and bioenergy with carbon capture and storage (BECCS)

Innovation area	Description
CO_2 Capture	Next generation solvents such as hot potassium carbonate solvents, other non-amine-based solvents and non-aqueous solvents; reduction of regeneration energy consumption in solvents; emerging technologies such as solid sorbent (e.g. MOFs), pressure swing, rotating packed beds, fuel cell and membrane-based capture technologies (e.g. polymeric membranes).
Process	R&D and demonstration of process improvements including optimisation of flue gas pre-treatment, Exhaust Gas Recirculation (EGR), Selective Exhaust Gas Recirculation (S-EGR) and heat integration, Specific to power BECCS: Optimisation of flue gas pre-treatment, flue gas recycling, integration of biomass and capture plant, and re-use of waste heat to dry biomass; techniques to mitigate risks in capture plant associated with impurities in flue gases from biomass burning.
Scale demonstration	Construction of mid-scale demonstration facilities for emerging technologies; sustained reliable operation to remove uncertainties, Reduces financing risks once technology considered proven, with transferable benefits to BECCS and industry.

Table 6: Innovation needs – carbon management – hydrogen BECCS

Innovation area	Description
Feedstock	Utilising cheaper waste fuels (with biogenic content for BECCS). There will be a need to overcome negative impacts on plant reliability due varied feedstocks and produce consistent quality syngas; improved feedstock pre-processing approaches to reduce costs and improve gasification performance.
Gasification	Improvements to gasifier designs to allow improved feedstock flexibility, reduced maintenance requirements and improved syngas quality; R&D and demonstration of alternative gasification methods such as entrained flow gasification; replacement of Air Separation Unit (ASU) to provide oxygen with a membrane unit or similar next generation technology. Improved syngas treatment technologies.
CO_2 capture	See table 5.
Process	Process improvements including recovery of waste heat to dry biomass; recovery of waste heat to generate some or all of the electricity requirements for the plant, or to generate oxygen; other measures to improve hydrogen yield; reduction of parasitic power losses.
Other	Improve reliability across the entire process chain allowing reduced downtime, e.g. by improving integration, adding redundancy and pre-processing feedstock to improve compatibility with installed equipment; modularisation of entire systems or individual components;

Table 7: Innovation needs – carbon management – direct air carbon capture and storage (DACCS)

Innovation area	Description
CO_2 Capture	R&D and demonstration of emerging DAC technologies such as electrochemical regeneration methods which could require less energy, mineral carbonation and membrane-based technologies. Novel liquid solvents and solid sorbents with improved capture performance, reducing energy required to release CO_2, degradation rates and harmful degradation products.

Resources	Demonstration of integration of large heat sources, e.g. from nuclear generation Energy from Waste (EfW) plants or emerging heat sources such as geothermal or low-grade waste heat from heat networks. Approaches replacing natural gas with hydrogen or renewable electricity to provide high temperature heat for regeneration, to eliminate the need to capture CO_2 from the combustion of gas;; research on optimal location of DACCS projects with access to low-carbon energy (renewables, waste heat), CO2 transport and storage, land and water.
Other	Demonstration of a range of DACCS approaches at scale to provide real world data to verify performance and remove uncertainties; modularisation of entire systems or individual components, e.g. solid sorbent filters.

Table 8: Innovation needs – carbon management – geological CO_2 storage

Innovation area	Description
Exploration, appraisal and characterisation and MMV	Technologies and methods that can model, simulate, and appraise stores faster with a high degree of confidence without the need for wells; CO_2 monitoring techniques outside of the storage formation into either the surrounding geology or atmosphere.
Infrastructure	Development and demonstration of pressure management technologies to increase injectivity; deploying sub-sea installations instead of platforms; advanced materials including nanomaterials (e.g. to increase reservoir capacity through subsurface wetting) and composites (e.g. reduce pipeline capex through ease of installation and pipeline maintenance through reduced corrosion).

Energy storage

The UK holds a leading position in electricity sector decarbonisation, with significant existing storage capacity in short duration lithium-ion batteries meeting grid frequency response needs. However, innovation in longer duration storage technologies, from 1 hour to over 24 hours, will be essential to provide flexibility with increasing renewable energy generation. The categorisation of storage duration was chosen to align the technologies as defined in the UK TIMES and highRES systems modelling.

Table 9: Innovation needs – energy storage – 4 hour – 8 hour duration (battery energy storage systems - BESS)

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 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. For molten salt sodium batteries, end of life disposal is still challenging and needs to be addressed.

Table 10: Innovation needs – energy storage – 8 hour – 24 hour duration (CAES/LEAS)

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.

Networks

The UK's energy networks need to adapt to address future challenges, especially in the context of achieving Net Zero targets. Strategic innovation is essential to meet these goals at the required pace and scale. The growing demand for electricity, coupled with the need to decarbonise gas networks and ensure energy security, requires an integrated approach to innovation

Technologies covered in the EINAs: Superconducting cables, Dynamic Line Rating and distributed feeder technologies.

Table 11: Innovation needs – networks

Innovation area	Description
Enhanced network capacity	There is a strong focus on reducing costs, improving fault mitigation and recovery, and enhancing the commercial case for high temperature superconducting cables (HTS). HVDC converter hubs require advancements in testing and simulations to stay ahead of technical specifications and planning for the upcoming offshore boom. Distributed feeder technologies need optimal system topologies to meet project reinforcement demands, while Dynamic Line Rating (DLR) involves wider system integration with real-time line sensing. Subsea cables require innovation to increase power, decrease losses, and increase their maximum subsea depth while retaining commercial viability.
Digitalised control systems and 'smart' networks	Key innovation in digitalised control systems and smart networks requires advanced next-generation dispatch algorithms to process vast amounts of data from various sources to optimise energy dispatch in real-time. Critical AI tools for networks can significantly improve network planning, system coordination, and asset optimisation.
Cybersecure networks	Cybersecure networks need innovation in quantum encryption and cryptography to develop quantum-resistant cryptographic algorithms ensuring network data security. Islanded architecture of critical infrastructure requires technologies for isolating and securing critical assets both in communications and grid infrastructure.
Resilient and climate-ready networks	Resilient and climate-ready networks require grid-forming technologies to determine the optimal penetration of grid-forming inverter-based resources, along with live system trials to understand wider system impacts. Gas network repurposing involves operational and business models needed for a coordinated and integrated system approach to decarbonisation of gas assets by 2050.

Industrial decarbonisation

In 2023, industry was the third highest-emitting sector in the UK, accounting for 17% of GHG emissions, totalling 64.1 MtCO2e. The largest contributors to UK industrial emissions are the chemicals, refineries and iron and steel sub-sectors. Emissions arise from the combustion of fossil fuels, where innovation will be required in low-carbon technologies, particularly in heat production, or from reactions that are intrinsic to the manufacturing process, requiring process-specific decarbonisation innovations that may not be easily transferrable between sub-sectors. Industrial CCS is covered qualitatively within the carbon management report.

Technologies covered in the EINAs: CO_2 usage, electrification, other fuel switching (hydrogen and biomass), resource and energy efficiency (REE).

Table 12: Innovation needs – industrial decarbonisation

Innovation area	Description
CO_2 usage	Reducing energy requirements during the conversion of CO_2 to fuels and chemicals (e.g. reverse water gas shift); advanced CO_2 conversion routes (e.g. high temperature electrolysis and plasmolysis); demonstration of reliability of CO_2-based construction materials.
Electrification	R&D of higher temperature industrial heat pumps, and integration of heat pumps and MVR to elevate temperatures provided by heat pumps; electric cracker for pyrolysis steam cracking including testing of product yield and quality; R&D and scale up of electric arc calciners.
Fuel switching	technologies for high temperature direct firing using hydrogen in specific industrial applications, e.g. hydrogen flame stability, Nox emissions, impact on existing equipment, impact on product quality.
Resource and energy efficiency	Advanced manufacturing technologies, such as near net shaped and additive manufacturing (or 3D printing) to create lighter, cheaper and less resource intensive materials and reduce lead times; Digital Twin technology to identify potential issues and inefficiencies and improve the cost effectiveness, efficiency and flexibility of production; light weighting through material substitution or lead design to reduce the weight of material inputs into a product;

Market barriers and enablers

Whilst technological innovations are important to accelerate their deployment, addressing these innovations alone is not sufficient. It is important to understand and address the wider market barriers to deployment. As part of the EINAs, a barriers and enablers assessment was undertaken across the prioritised technologies to understand the factors which should be considered alongside technology innovation. This included qualitative analysis across eight variables and includes low/medium/high ratings for each element to indicate the risk of each barrier to the deployment and scale-up of the technology. The details of these assessments, alongside qualitative 'deep-dives' into the 3-5 top barriers and enablers for each technology, are included in the technology-specific EINAs reports. The framework used to assess barriers and enablers across each technology is included in Table 13.

Table 13: Barriers and enablers assessment framework

Theme	Indicator	Description of indicator
Market enabler	Enabling infrastructure	The extent to which infrastructure, which itself is a prerequisite for the technology to be able to be deployed effectively, exists.
	Regulatory environment	The extent to which there exists a well-functioning, coherent regulatory environment that sends clear signals to the market regarding the regulations around technology.
	Stakeholder acceptance	An assessment of the extent to which relevant stakeholders (including end consumers and the public where relevant) accept the deployment and use of the technology, do not perceive there to be considerable risks to its adoption and are willing to pay to adopt the technology.
Business model	Availability of funding and investment	The availability of private finance to invest in the technology at a low cost, commercial rate or for research and development (R&D), and to support financial access for consumers and businesses.
	Business model viability	The strength of the financial proposition to investors/consumers, based on viability of the business model and revenue generation through providing the low carbon technology relative to incumbent high carbon technologies.

Capability to deliver	Resource availability	The extent to which there are adequate resources/raw materials available to deliver the required deployment of the technology.
	Supply chain	The extent to which the necessary supply chain is in place to deliver the technology at the required scale and pace.
	Skills and training	The extent to which the necessary skills and training are in place to deliver the technology at the required scale and pace.

Table 14: Overview of key barriers across the EINAs priority areas

Technology area	Barrier 1	Barrier 2	Barrier 3
Offshore renewables	**Supply chain:** There is a need to expand UK manufacturing capacity. Globally, support vessels for installation, maintenance and decommissioning will be required to enable larger turbine installation. Floating wind and tidal stream will both require specialist components.	**Skills and training:** Highly skilled workers including scientists, engineers and technicians will be required to meet targets. Currently, the rate of growth of the workforce is slower than the rate required. Workers will be needed in coastal and remote locations where the infrastructure is situated.	**Regulatory environment:** Consenting time is a major bottleneck to implementing large-scale offshore renewables, due to the lengthy and complicated permitting processes. These processes vary across administrations and technologies and depend on the location and capacity of the proposal. For commercial wind farms, the process from pre-application to final determination of the necessary consents is estimated to take 3-5 years.

Technology area	Barrier 1	Barrier 2	Barrier 3
Hydrogen	**Business model:** Clean hydrogen is currently more expensive than incumbent alternatives, this is likely to continue – particularly as renewable energy currently accounts for 70% of the cost of green hydrogen production. There is also uncertainty around how the enabling infrastructure will be funded, although enablers such as the Hydrogen Storage and Transport Business Models are expected to bring more certainty in this area.	**Enabling infrastructure:** Hydrogen transport and storage infrastructure will be essential, but existing capacity is limited. Large scale storage assets have long lead times, and pipelines can take up to 6-12 months of pre-construction and 3 years for construction or repurposing. For hydrogen produced via electrolysis, manufacturing capacity will need to be scaled up.	**Regulatory environment:** New regulatory frameworks will be needed for depleted gas field storage, and existing regulation for salt caverns will need to adapt to account for faster rates of cycling, and to support both regulated and private assets. For hydrogen transmission, more work needs to be done around purity, pipe specification and safety to achieve a sufficient regulatory framework. The existing regulatory frameworks, unless adapted, can cause delays in deployment, which may stall the development of hydrogen production and transport and storage infrastructure in the coming years. Further clarity expected from an updated UK Hydrogen Strategy.

Technology area	Barrier 1	Barrier 2	Barrier 3
Nuclear	**Availability of investment:** Nuclear power plants require significant upfront investment in research, design and construction. The combination of capital cost with long delivery time can be a barrier to deployment.	**Skills and training:** The workforce is currently insufficient to deliver the UK's 2050 nuclear power targets. This is compounded by the aging workforce, as a significant proportion of the civil nuclear workforce are nearing retirement.	**Supply chain:** Nuclear plants require a number of specialist components, but there is currently a limited number of vendors in the UK with advanced manufacturing capabilities to meet these demands.
Heating and buildings (specific to heat pumps)	**Availability of consumer investment:** Relative to incumbent gas boilers, upfront costs for heat pumps, enabling works and operational costs contribute to a challenging financial proposition for consumers.	**Supply chain:** The UK currently has a limited domestic heat pump manufacturing sector, meeting only 30% of UK demand. Additionally, global supply chain pressure on semiconductors, and high energy prices, are contributing to the limited UK supply chain.	**Skills and training:** There is a limited number of installers in the UK, and the existing market is fragmented, generally characterised by small companies or sole traders. There is a need to increase the number of installers.

Technology area	Barrier 1	Barrier 2	Barrier 3
Carbon management	**Business model viability**: Market and revenue certainty is seen as a medium or high barrier for most CCUS and GGR technologies since carbon prices are currently too low to incentivise investments in projects at scale without additional interventions.	**Enabling infrastructure**: Common factors identified for CCUS and GGR projects included the availability of CO_2 transport and storage infrastructure or non-pipeline transport for capture plants away from clusters. For DACCS, access to low-carbon heat and/or electricity (including grid connection) and water is also needed.	**Supply chains:** Common factors identified included establishing supply chains from a very limited base for low TRL technologies, such as DACCS, and scaling up supply chains, whilst overcoming constraints and bottlenecks, to be able to deploy projects at scale within the timescales envisaged.
Energy storage	**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 are not fully utilised, while longer duration energy storage has limited market mechanisms in place which do not fully capture its system benefits (e.g. Capacity Market).	**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.

Technology area	Barrier 1	Barrier 2	Barrier 3
Networks[5]	**High costs and commercialisation**: Many technologies face high costs of materials, installation, and maintenance. This barrier is prevalent in second-generation cables, HVDC converter hubs, distributed feeder technologies, and subsea cables. Reducing these costs is essential for widespread adoption and deployment.	**Regulatory challenges**: Regulatory hurdles and the need for supportive policies are common barriers for technologies such as distributed feeder technologies, Dynamic Line Rating (DLR), and islanded architecture of critical infrastructure. Establishing clear regulatory frameworks and policies is crucial to encourage innovation and integration.	**Technical integration**: Integrating new technologies with existing infrastructure poses significant challenges. This barrier is more heavily seen in HVDC converter hubs, distributed feeder technologies, and islanded architecture of critical infrastructure. Developing robust integration strategies and technologies is necessary to ensure seamless operation and efficiency.

[5] The networks and industry technology EINAs followed a different methodology to the other technology themes, so the results for the barriers analysis align with different categories.

Technology area	Barrier 1	Barrier 2	Barrier 3
Industrial Decarbonisation[6]	**Economic viability:** All options detailed require significant upfront investment by prospective users, irrespective of technology maturity, primarily relating to project development and capex, with capex for First-of-a-Kind (FOAK) technologies typically higher than alternative options.	**Enabling infrastructure and supply chains:** Current electricity supply is insufficient to support a full transition to electrified industry. At a site level, new distribution network infrastructure and new connections may be needed. Currently, the supply of hydrogen for use in industry is limited.	

[6] The networks and industry technology EINAs followed a different methodology to the other technology themes, so the results for the barriers analysis align with different categories.

System benefits from innovation

Introduction and methodology

System modelling to assess the potential impact of innovation in key net zero technologies was conducted for the EINAs primarily using UK TIMES, a least cost 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, three levels of innovation were developed representing a low, medium and high innovation case for the technology. The low innovation level broadly aligns with DESNZ current technology cost and performance estimates, representing a business-as-usual case where innovation is limited, whilst the high innovation case represents significant innovation in the technologies 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 the Minimally Constrained, High Hydrogen and High Diversification scenarios. They do not represent government policy. They help us to understand how the potential value of technology innovation might be sensitive to the future evolution of the energy system. A summary of each is presented below; more in-depth descriptions can be found in the EINAs Methodology report.

1. **Minimally Constrained:** Designed to show the largest potential impacts from innovation investments and least cost route to Net Zero by minimising the number of constraints on the energy system. UK Government data assumptions are used across the scenario.
2. **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 hydrogen demand ranges in the DESNZ Hydrogen transport and storage networks pathway policy paper published in 2023, and provisional figures from DESNZ sector teams collected in late 2024 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.
3. **High Diversification:** Based on the Minimally Constrained scenario, this scenario aims to be more energy secure through two approaches, 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 and network 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 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 nine UK nodes (Figure 3) and nine European nodes, to give insight into the innovation value of energy storage and energy networks technologies. To ensure consistency with the rest of the EINAs outputs, HighRES uses outputs from UK TIMES EINA runs as inputs. Details of this calibration can be found in the EINAs Methodology report.

Figure 3: Spatial zones for the UK used in the HighRES model (Source: UCL)

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 were modelled in highRES as standalone snapshots for the Minimally Constrained and High Diversification scenarios. The High Hydrogen scenario 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 was carried out for a typical weather year (2012 data) and an adverse weather year (2010 data, with a period of low wind coinciding with low temperatures).

How to interpret results:

The results presented below, for both UK TIMES and HighRES, demonstrate the potential impact of innovation for a specific technology or group of technologies 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 lower-cost technology increases while the deployment of more expensive alternatives decreases, a reduction in overall system cost reduction will be realised. This cost reduction will be lower than the direct cost reduction that would have occurred if the new technology had already been used at lower innovation levels. More profound changes could also occur across the energy system, for example changes in total electricity consumption or in the relative rate of decarbonisation between sectors of the economy.

The results are shaped by the defined scope of the model and the set of technologies investigated in the project. Therefore, system impacts for each technology should be interpreted in terms of their role within the energy system and scenario context, rather than as definitive outcomes for the specific technologies considered in the EINAs system modelling. For instance, a high impact from DACCS innovation indicates that reducing their costs has significant value to the energy system for offsetting hard-to-abate emissions—this could be achieved through innovation and deployment of DACCS or other viable alternatives. While the EINAs analysis focused on a selected set of known technologies, new options may emerge, and alternative decarbonisation routes may be identified. High-potential, low-TRL technologies are noted in the disruptive technologies section of reports but are not included in the system modelling as their future costs and performance are not yet understood well enough to be able to represent them appropriately.

We have not considered rebound effects where lower costs of energy due to innovation investments lead to higher energy service consumption. An elastic demand version of UK TIMES could be used to explore potential rebound effects of innovation investments in the future.

All UK TIMES results are presented as cumulative costs in real 2022 values. For HighRES, results are presented as annualised cost figures, in 2022 real values. This differs from UK TIMES results, where cumulative 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 technologies assessed by the EINAs as outlined above. It should be noted that given these results are an output of the systems modelling and the three hypothetical scenarios developed for the EINAs, and do not reflect UK government deployment targets and ambitions.

The results presented below provide summary insights from UK TIMES based on model runs for individual technology innovation levels. The results of model runs for a broader range of technologies / technology families can be found in their respective reports. Summary results for energy storage and networks, modelled using HighRES, are also presented below.

Results: UK TIMES (all EINAs technologies excluding storage and networks)

The UK TIMES analysis demonstrates the potential of innovation to significantly reduce the cost of transitioning to a Net Zero energy system by 2050. Relative to a low innovation baseline, high levels of innovation across all EINAs technologies (excluding storage and networks) have the potential to reduce systems costs by between £5–£8bn per annum by 2035, and between £21bn–£30bn by 2050 (using real 2022 figures), equivalent to about 5%–6.5% of system costs in 2050. This equates to a cumulative system cost saving of between £203bn–£348bn by 2050, depending on the scenario. Medium innovation levels in the Minimally Constrained and High Hydrogen scenarios reduce systems costs (cumulatively to 2050) by £133bn and £155bn, respectively (£14bn–£19bn annually in 2050, equivalent to approximately 3.5%–4.2% of system costs that year). High innovation in these scenarios demonstrate savings of £203bn and £230bn respectively. Innovation in the High Diversification scenario offers the highest potential cost reductions, with savings of £158bn in 2050 with medium innovation and £348bn with high innovation, as demonstrated in Figure 5.

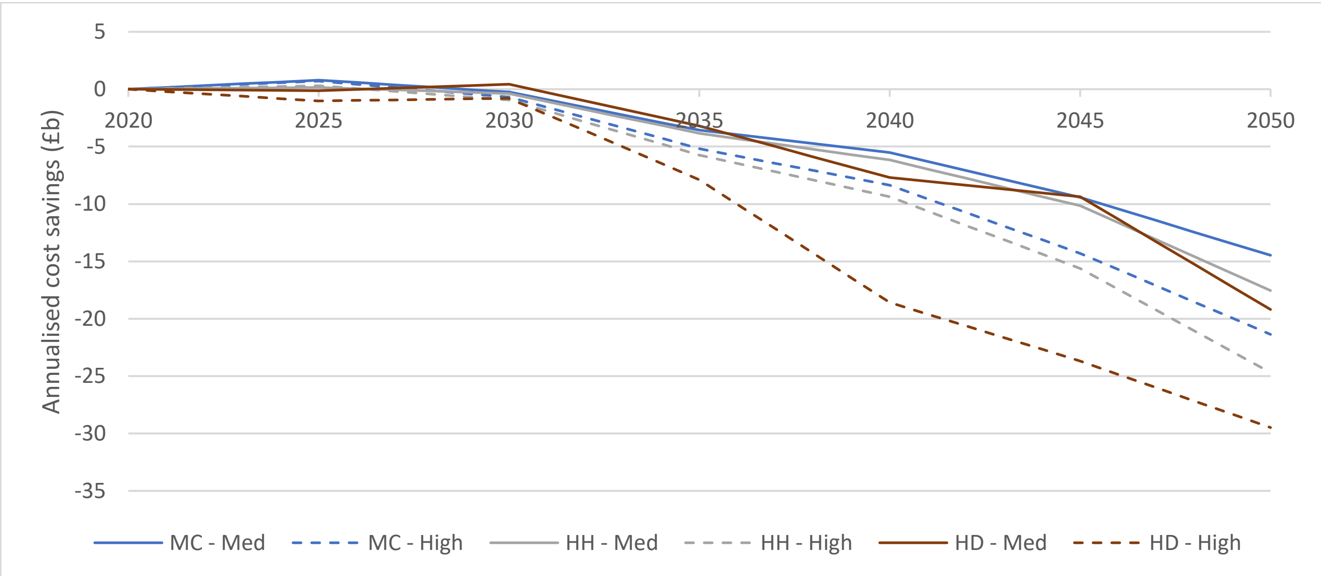

Figure 4: Relative annualised cost savings (in real 2022 £bn) at medium and high innovation levels in all the EINAs technologies, relative to the base (low innovation) case in the Minimally Constrained (MC), High Hydrogen (HH) and High Diversification (HD) scenarios.

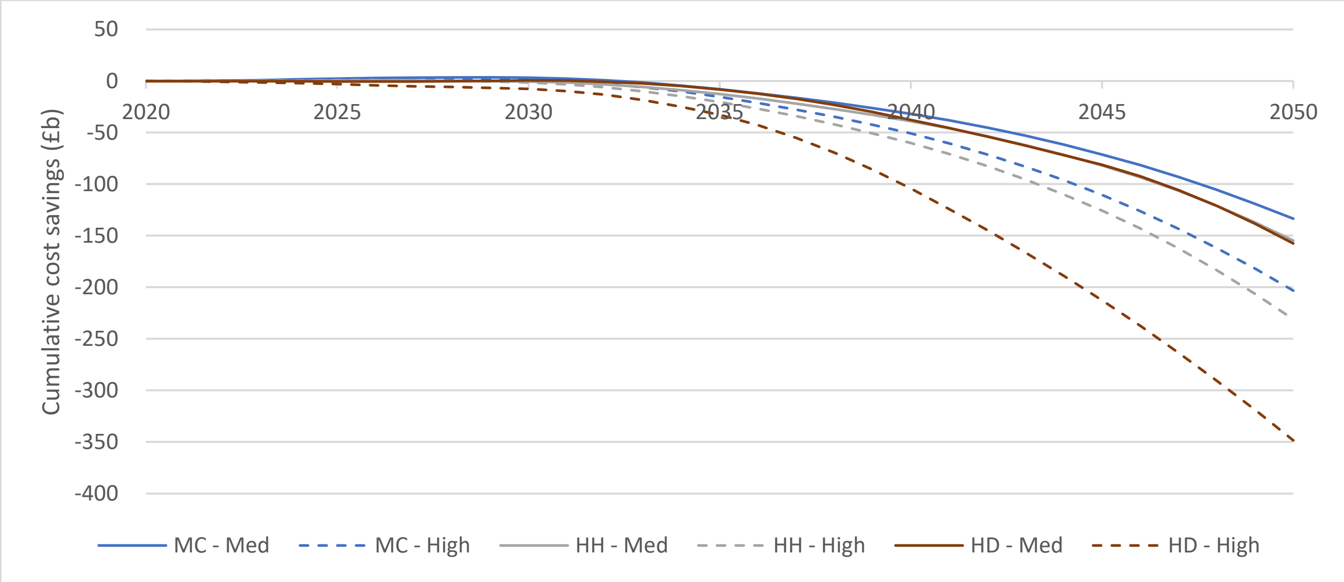

Figure 5: Relative cumulative cost saving (in real 2022 £bn) at medium and high innovation levels in all the EINAs technologies, relative to the base (low innovation) case in the Minimally Constrained (MC), High Hydrogen (HH) and High Diversification (HD) scenarios.

Across the Minimally Constrained, High Hydrogen and High Diversification scenarios, innovation in BECCS, DACCS, air-source heat pumps and offshore wind lead to significant reductions in total energy system costs compared to the respective low innovation cases. High innovation runs for each of the four technologies reduce total cumulative costs (2025–2050) by up to £41bn (offshore wind), £62bn (DACCS), £76bn (BECCS), and £111bn (air-source heat pumps) (using real 2022 figures). Each equates to approximately 1% to 2% annualised reduction in system costs in 2050, going up to 3% of annualised system cost reduction in High Diversification for DACCS. Each of these maximum potential systems cost savings arise in the High Diversification scenario, with lower but still significant potential savings in the Minimally Constrained and High Hydrogen scenarios (see **Figure 7**). These reductions in system cost are a consequence of the importance of these technologies to reaching Net Zero with high levels of deployment which has a multiplicative effect on the cost savings from innovation.

BECCS is a key technology driven by its role in providing negative emissions and energy at the same time, whilst DACCS is required to offset greenhouse gas emissions that cannot easily be avoided. Innovation in BECCS delays and reduces the need for DACCS slightly across results from all three scenarios due to them both providing negative emissions. Offshore wind is heavily deployed as it is a critical technology to decarbonise ever increasing demands for electricity generation whilst being the cheapest way of generating power. It is closely interconnected with the innovation of other EINA technologies. Technologies that rely on low-carbon electricity downstream, including electrolysis and heat pumps, increase the value of offshore wind and accelerate its deployment in the energy system, whilst BECCS and DACCS innovation sensitivities reduce the need for offshore wind so is scaled to meet demand accordingly. Deployment of air-source heat pumps reaches the assumed maximum feasible yearly installation level in most innovation runs, meaning that the technology is highly valuable to the energy system and is often used to the maximum extent the model is allowed to.

In the Minimally Constrained scenario, innovation in geological CO_2 storage, nuclear, electrolysis, autothermal reforming, wall insulation, hydrogen transmission and distribution, and WSHP for heat networks cause modest cost savings compared to the low innovation case. Innovation in the remaining technology families including tidal stream, natural gas CCS, depleted gas storage, roof and floor insulation and ground-source heat pumps (GSHP) for heat networks showed marginal or no cost savings in UK TIMES compared to the reference case (all reducing costs by no more than £0.05bn in 2050). Such results do not imply lack of decarbonisation significance from the named technologies, rather limited system impacts from the higher levels of cost and performance improvements suggested within available literature. In some instances results are impacted by technology modelling limitations, as in the case WSHP and GSHPs in relation to heat networks. Further detail on specific technologies can be found in the relevant technology theme reports.

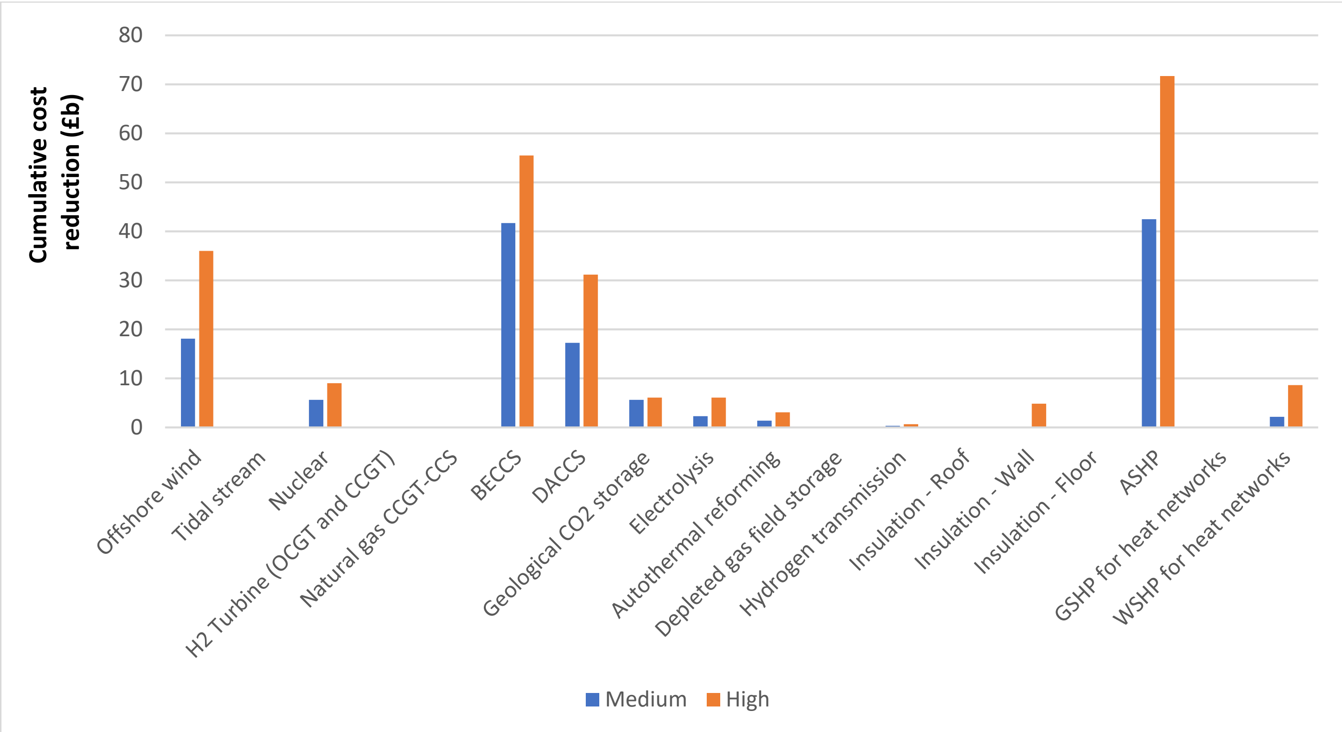

Figure 6: Relative cumulative system cost saving (£bn) at medium and high innovation levels compared to the low innovation baseline in the Minimally Constrained scenario.

Conversely, in the High Hydrogen and High Diversification scenarios some technology families with limited influence in the Minimally Constrained scenario become considerably more significant in reducing total energy system costs. This suggests that the innovation potential of some technologies is sensitive to the decarbonisation pathway. The figure below illustrates the differences in the cumulative system costs saving (2020–2050) for the Minimally Constrained, High Hydrogen and High Diversification scenarios, compared to their respective low innovation baseline, for each respective individual technology high innovation run. It should be noted that whilst the total savings are highest in high diversification, the baseline total system cost in 2050 is also higher. Total annualised systems cost for the Minimally Constrained scenario is £419bn, the High Hydrogen scenario is £429bn and the High Diversification scenario is £456bn in 2050.

This reflects the different constraints of each scenario which enforces and limits deployment of certain technologies impacting the total system cost.

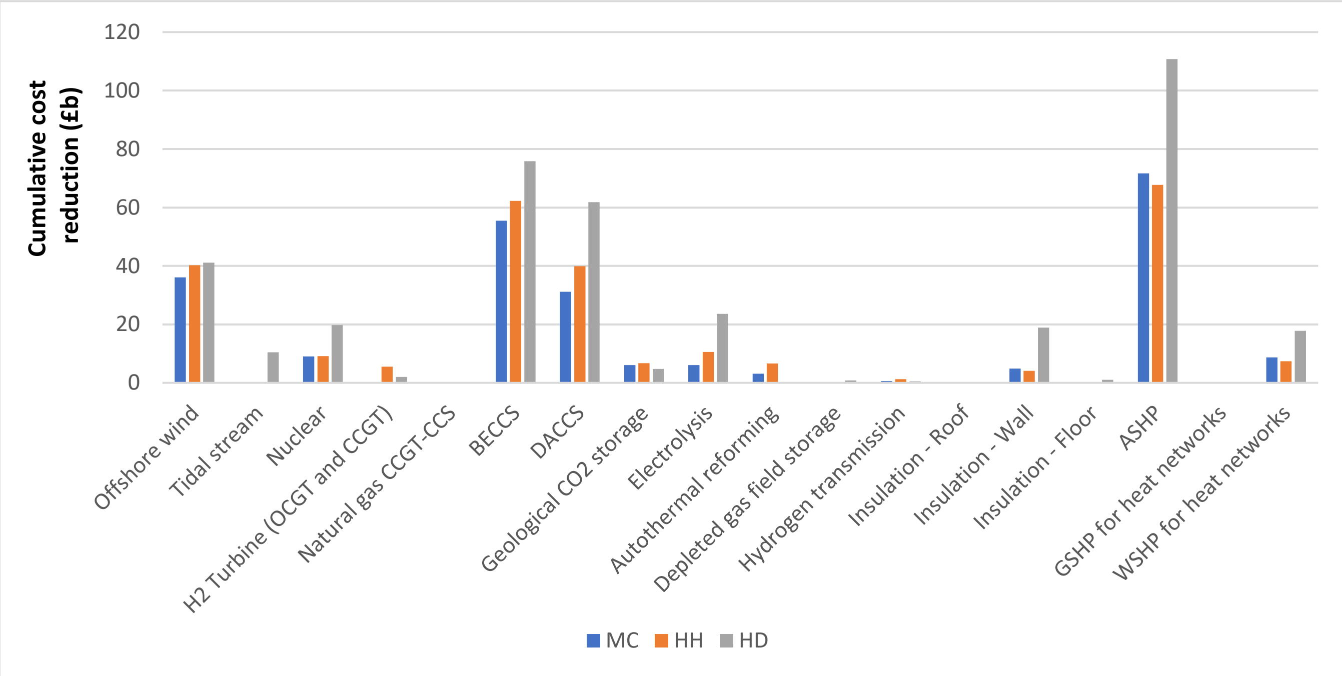

Figure 7: Relative cumulative system costs saving (£bn) between 2025-2050 for all three scenarios at the high innovation level compared to the respective low innovation baseline

Impacts of innovation on carbon prices in UK TIMES:

In the Minimally Constrained scenario, increasing innovation substantially reduces the carbon price (based on the marginal abatement cost in achieving given yearly carbon targets in UK TIMES) in 2050 from about £1000/tCO_2e to under £400/tCO_2e. The high price in the low innovation case reflects the models' need to draw on more expensive technologies to meet Net Zero under modelled scenarios. Increasing DACCS availability in the higher innovation cases (with DACCS sequestration limited to 18 Mt under low innovation) gives the model more flexibility and so greatly reduces the carbon price. High innovation in other EINA technologies does not materially affect the carbon price in 2050. Prior to 2050, innovation investments have only a small impact on carbon price.

The High Hydrogen and High Diversification scenarios are constrained to a greater extent than the Minimally Constrained scenario so have higher carbon prices with a Net Zero target. Carbon prices are similarly reduced substantially in 2050 in the alternative scenarios as a result of innovation, from £1200/tCO_2e to under £400/tCO_2e for the High Hydrogen scenario and from £1500/tCO_2e to under £500/tCO_2e for the High Diversification scenario.

It is important to note that these carbon prices do not reflect and should not be confused with UK ETS or long-term carbon valuation estimates. Rather they are specific to the UK TIMES scenario set-up and technology assumptions and choices within the EINAs, which do not consider carbon trading or wider potential system changes outside of project scope.

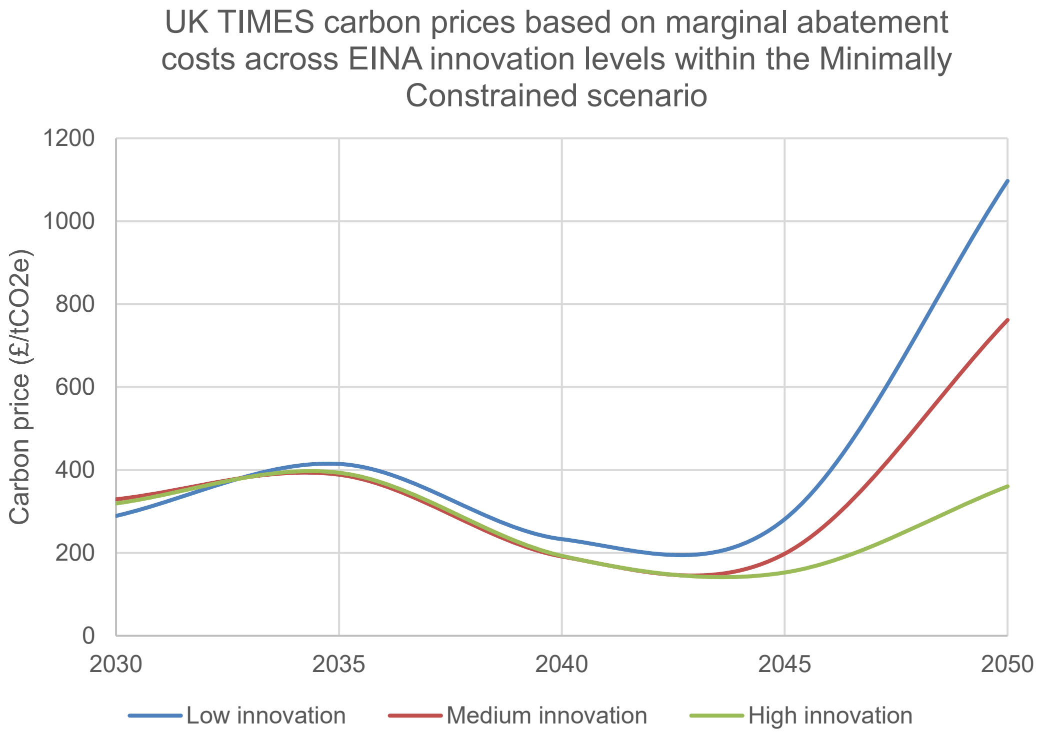

Figure 8: Carbon price with innovation investments in all technologies in the Minimally Constrained scenario

Innovating in all or only single technologies has only a minor influence on the relative rate of decarbonisation between key sectors. The principal technologies that affect decarbonisation rates are BECCS and DACCS, for which innovation leads to earlier deployment of those technologies, allowing slower decarbonisation in end-use sectors so total emissions are unchanged.

To a lesser extent, hydrogen production technology innovation enables the residential sector decarbonisation to be accelerated a little. There is an assumed limit on the growth of heat pump deployment over time, to account for delivery capacity and other barriers, and some dwellings that cannot adopt heat pumps early in the transition due to this limit can use hydrogen instead.

Results: HighRES (energy storage and networks technologies)

Of the energy storage technologies investigated, innovation in hydrogen storage – via salt caverns storage and OCGT or CCGT energy generation – plays the greatest role in reducing system costs, compared to the baseline all low innovation model run, reducing system costs by up to £5.4bn a year in 2050 in the Minimally Constrained scenario and up to £4.8bn 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 interseasonal scale, therefore, the value of innovation in hydrogen storage could be understated here.

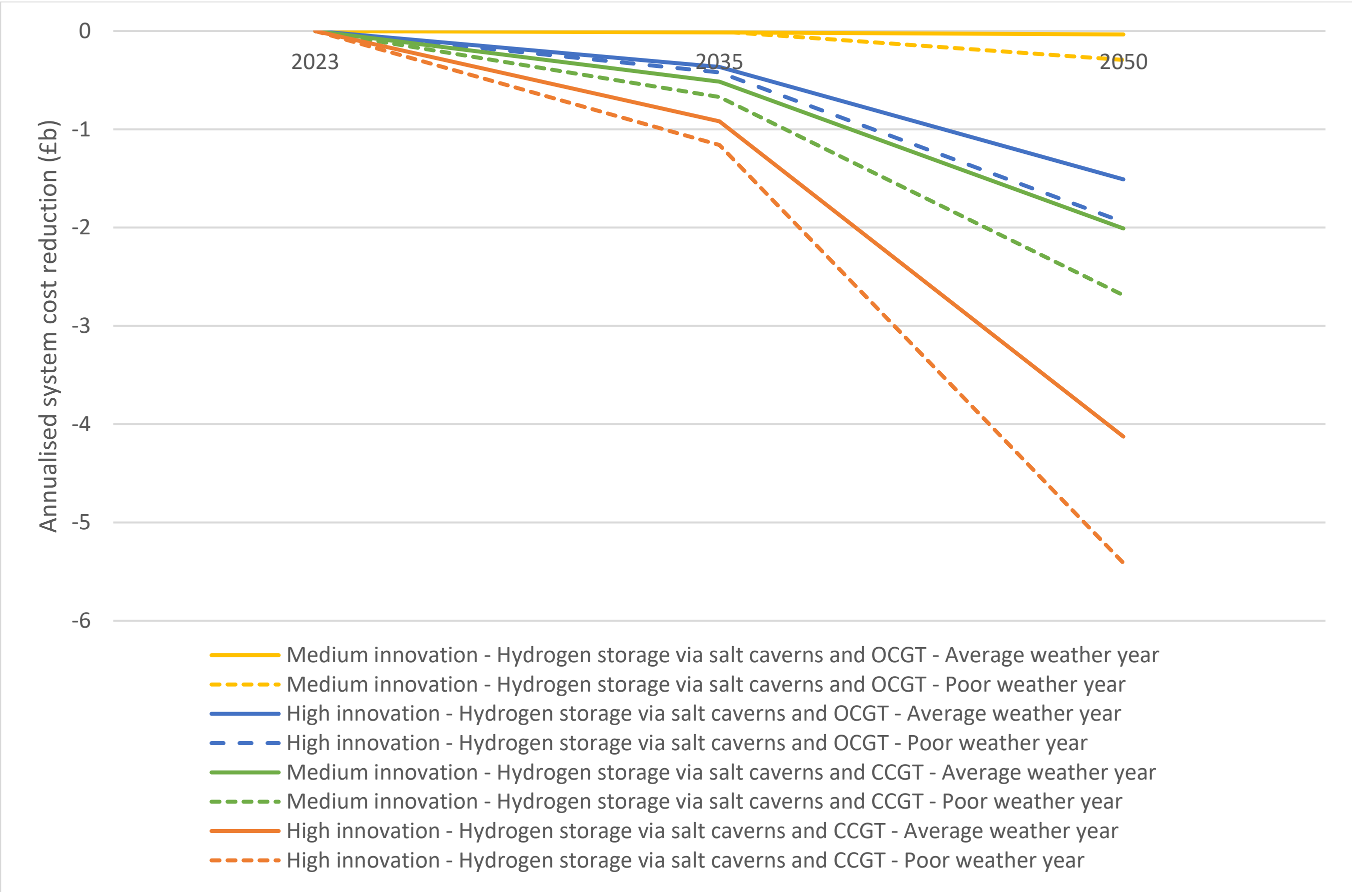

Figure 9: System cost difference from innovation levels (medium, high) for hydrogen storage technologies (H2 salt caverns to OCGT/CCGT) compared to All Low innovation baseline, in the <u>Minimally Constrained scenario</u>. Results from poor weather years are shown in dotted lines.

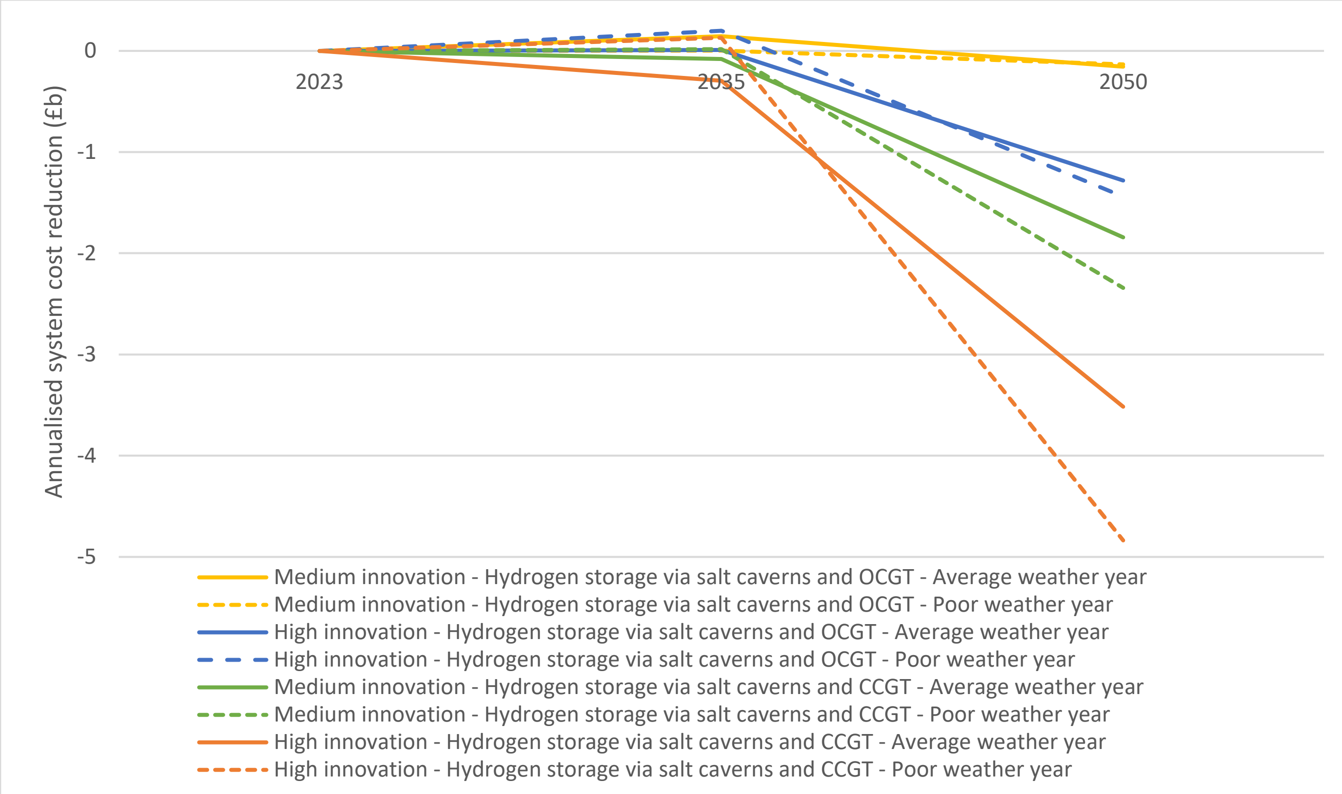

Figure 10: System cost difference from innovation levels (medium, high) in hydrogen storage technologies (H2 salt caverns to OCGT/CCGT) compared to All Low innovation baseline, in the High Diversification scenario. Results from poor weather years are shown in dotted lines.

Innovation in BESS and CAES were also modelled but were found to play a more modest role in system cost reduction. Savings through innovation in BESS are up to £191m a year in the Minimally Constrained scenario and up to £472m a year in High Diversification in 2050. Poor weather conditions combined with high innovation levels in batteries result in the greatest potential for reduction in system costs in the High Diversification scenario.

Savings through innovation in CAES reach up to £706m a year in the Minimally Constrained scenario and up to £474m a year in High Diversification in 2050. Cost reductions for CAES are greatest when tested under average weather conditions, for both time periods. In 2035, this cost reduction is driven by reduced natural gas capex and opex. In 2050, this cost reduction is driven by a reduction in storage capex and opex, alongside a reduction in nuclear opex and transmission costs. However, in the HD scenario, this is offset by higher interconnector costs. These results are explained in further detail in the Energy Storage EINAs report.

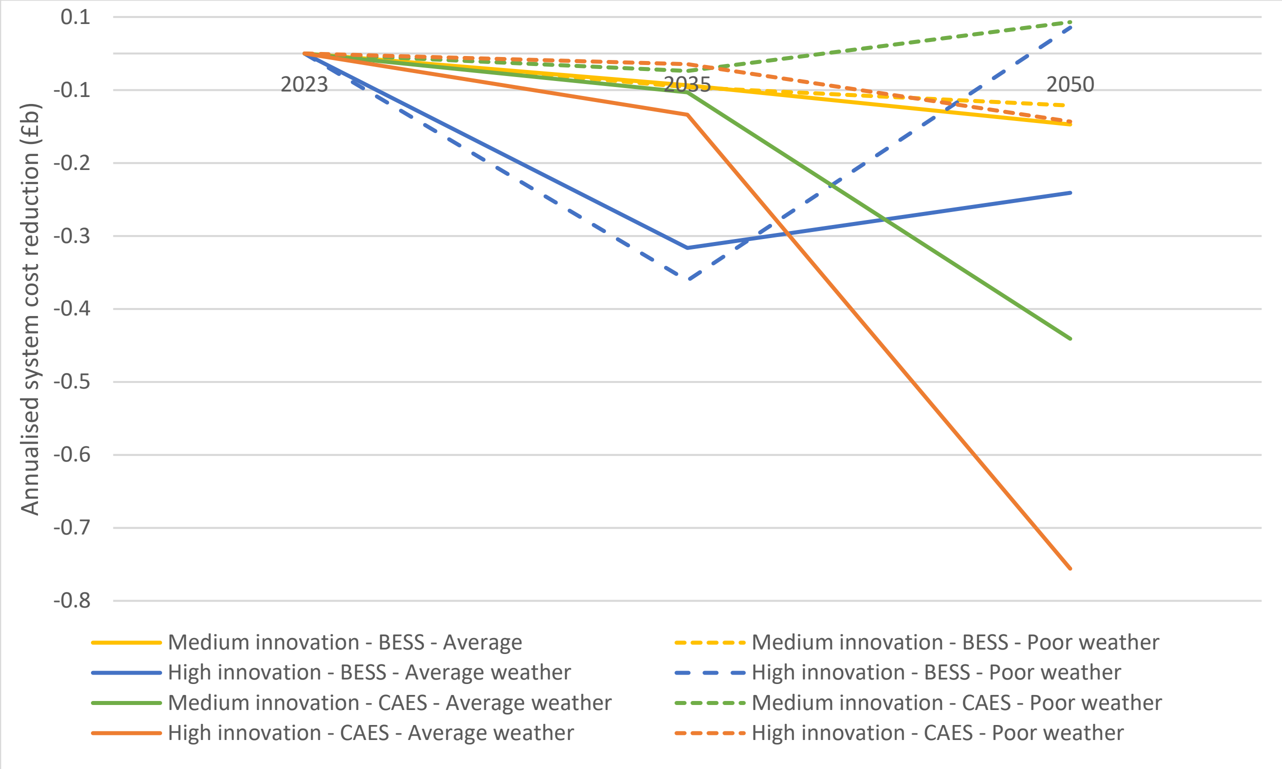

Figure 11: Systems cost difference from innovation levels (medium, high) for BESS and CAES storage technologies compared to All Low innovation baseline, in the Minimally Constrained scenario. Results from poor weather years are shown in dotted lines

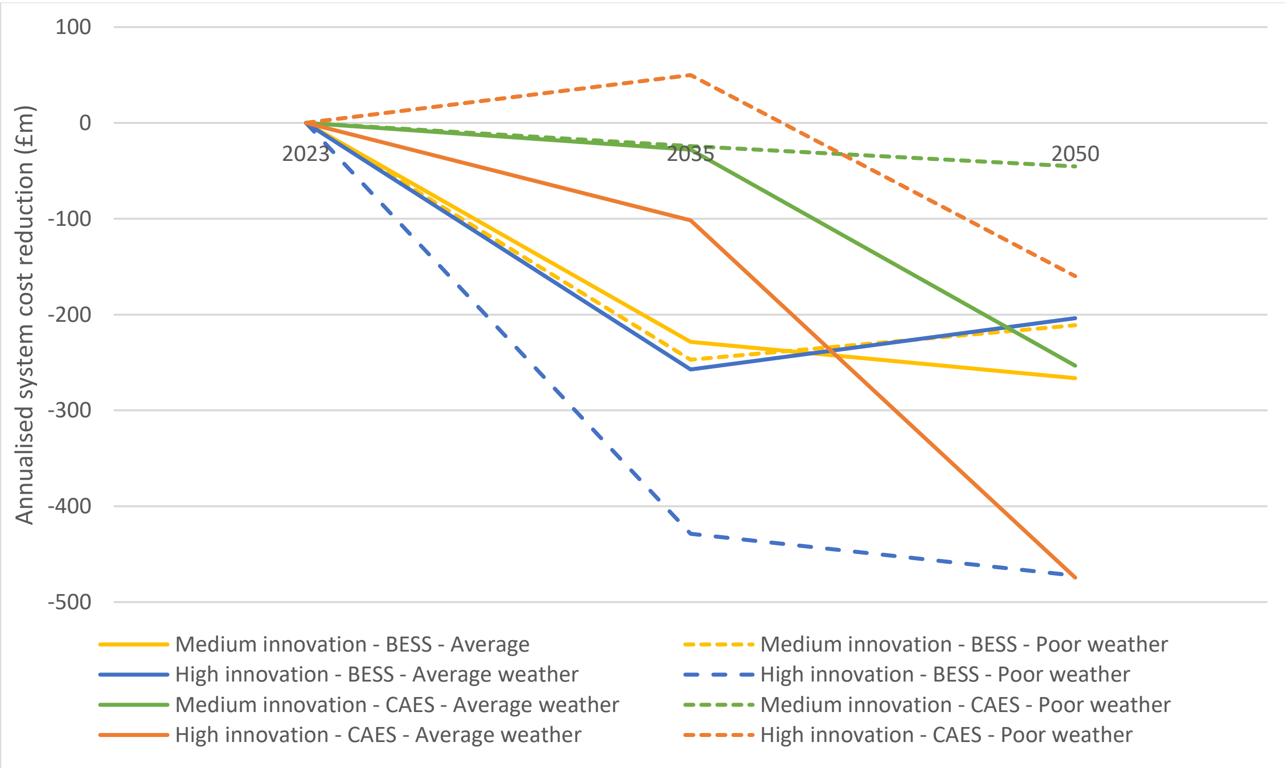

Figure 12: System cost difference from innovation in BESS and CAES storage technologies compared to All Low innovation baseline, in the High Diversification scenario. Results from poor weather years are shown in dotted lines

Regarding networks, innovation across considered technologies can significantly reduce the size and cost of required transmission infrastructure. While scenarios vary, higher levels of innovation generally lead to lower costs and less infrastructure needed, especially in typical weather years. High innovation across EINA technologies causes electricity transmission cost reductions of 6% to 10%. Total transmission annualised cost in the scenarios and innovation cases modelled ranges between £1.6 and £2.1bn in 2050. By 2050, the highest transmission capacity required is observed under a Minimally Constrained scenario with low innovation across EINA technologies in a typical weather year, reaching 172GW, compared to 164GW with high innovation. Given the range of required transmission infrastructure is relatively narrow, the network buildout required will remain largely consistent irrespective of generation and storage technology innovation. Additionally, the increasing necessity to transport renewable energy from Scotland to demand centres located further south, zones UK2, UK3, and UK4 (Scotland to North/Central East England) are projected by the model to experience the highest transmission network capacity requirements in both 2035 and 2050.

The business opportunities of innovation

Introduction to the business analysis

This analysis explores the potential scale of the business opportunities for UK-based businesses associated with the national and global development of the EINA technologies. This section provides a summary of the key results from each of the EINAs business opportunities calculators, focusing on the total GVA and employment that the deployment of EINAs technologies could support in the period to 2050. More detailed analysis is provided in the individual technology EINA reports.

In examining these results, it is important to be clear about how they should be interpreted. They represent the results of an analytical exercise that integrates projections of domestic deployment of the technologies, derived from the systems modelling described above, with assessments of the UK's potential market share[7] in overseas markets, informed by global modelling and literature reviews. These are further combined with assumptions about the cost structure and employment intensity of the different activities required for each technology. As such, they are estimates of the potential economic impact that might be associated with a given set of modelling outputs.[8] They should not be regarded as forecasts of the most likely future outcomes, nor as a reflection of the UK Government's objectives/ambitions either in terms of deployment or the business opportunities that might be realised.

There is a high degree of uncertainty in estimating individual technology impacts, given projections span decades and are impacted by multiple assumptions, such as global market developments. Estimates on GVA and jobs will vary across similar analytical exercises depending on the underlying assumptions and modelling used. Given the reliance on system modelling based on UK TIMES, the EINAs assessment is particularly useful in understanding potential longer-term impact of technologies which are currently still at early commercialisation stage, or which still have scope for significant improvements through innovation.

It is important to stress that the results do not represent overall clean energy opportunities in the UK, which already add up to approximately 440,000 jobs supported as of 2023[9]. Similarly, opportunities within each EINA technology theme are specific to the particular technologies that are the focus of each report (as specified in table 15 below), rather than the GVA and employment for the wider sector within which these technologies may sometimes be categorised. For instance, within the EINA Nuclear technology theme, only the construction and operation/maintenance of SMRs and HTGRs is considered. Therefore, impacts from the

[7] UK market share is defined as the share of total activity in a given market related to the production of a certain good or the fulfilment of a certain activity which is met by UK-based entities.
[8] Importantly, the analysis also relies on system modelling outputs to estimate business opportunities in 2025. While there have been efforts to calibrate the results of the systems modelling outputs for these years with outcomes observed in the market, some discrepancies remain due to data availability at the time of modelling.
[9] Department for Energy Security and Net Zero (2025) Clean Energy Jobs Plan: Creating a new generation of good jobs to deliver energy security

wider sector, such as construction and operation of third generation reactors (e.g. Hinkley and Sizewell C), are not included. Some important clean energy sectors, such as solar PV, are not covered at all given the technology prioritisation criteria used for this analysis. Please refer to the methodology report for more information.

Gross Value Added (GVA)

The analysis explores the value of the potential business opportunity in terms of GVA that the technologies could support across the three different scenarios in the systems modelling - Minimally Constrained, High Hydrogen and High Diversification - and the three different levels of innovation considered in the analysis (Low, Medium and High), resulting in nine different sets of results for most technologies.[10]

To understand the potential aggregate business opportunity offered by the EINA technologies across these different scenarios, Figure 13 below takes the median result for direct GVA in each technology from each of the nine scenario and innovation level combinations and sums them to consider a potential value for total direct GVA in 2025, 2040 and 2050. It shows that the business opportunity offered by these technologies (the total real GVA that these technologies could support) grows to over £19bn in 2050 (all in 2022 values). This represents a compound annual growth rate (CAGR) of 7 - 8.6% over the period depending on scenario used.

[10] For storage technologies, including hydrogen storage, systems modelling results were not developed for the High Hydrogen scenario. Systems modelling was not used to generate deployment projections for networks and industry. For networks, the analysis only distinguished between a low/medium/high level of innovation. In the aggregations presented below, the single set of estimates for Networks by innovation level are used for each of the three scenarios (Minimally Constrained, High Hydrogen, High Diversification). Likewise, for industry, the same results are applied to each of the three scenarios. Further, industry results consist of the sum of 'deep decarbonisation' and 'energy efficiency' industrial technologies. There is only one set of deployment assumptions for deep decarbonisation. For energy efficiency, the 'business as usual' scenario is aggregated with the low innovation level for other technologies, the 'policy ambition' aggregated with the medium innovation level and the 'Max Tech' matched with the high innovation level.

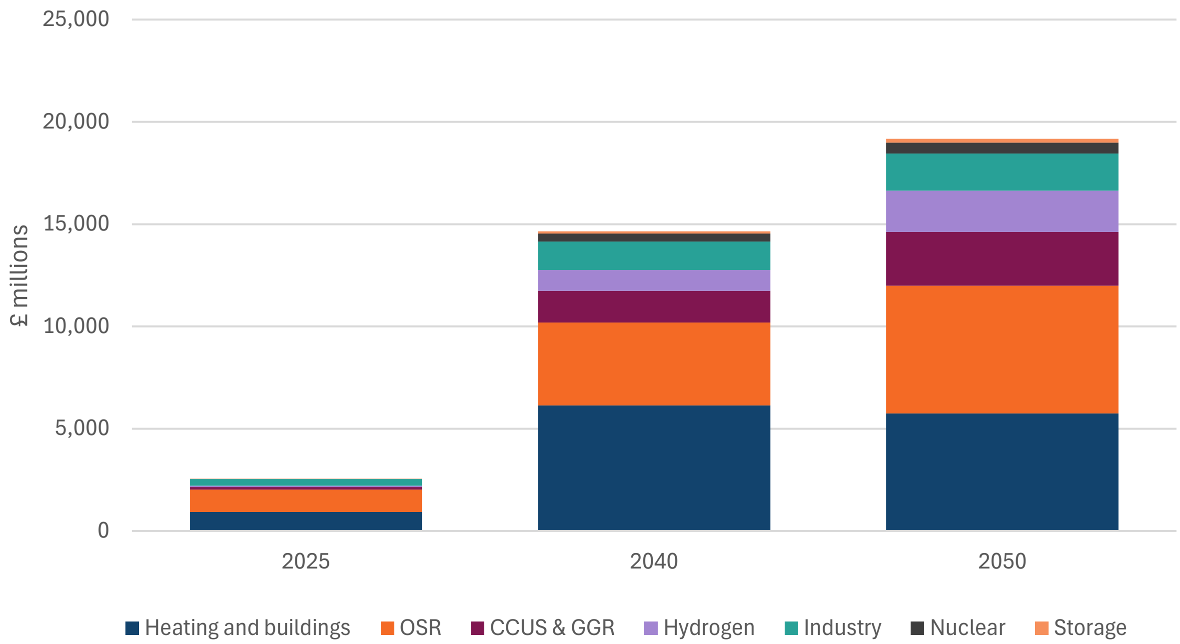

Figure 13: Potential aggregate GVA supported by EINA selected technologies, 2025-2050
Note: The scenario and innovation level combination that generates the median level of GVA for each technology in each year will differ. Only EINA selected technologies are considered, therefore categories such as "storage" or "nuclear" do not refer to overall sectors.

Figure 13 shows that some technology areas are expected to offer greater business opportunities than others. The areas that, according to the modelling and included technologies, can support the highest GVA by 2050 are, in order, heating and buildings, offshore renewables (OSR) and carbon management technologies**,** with hydrogen and industry also supporting a relatively high proportion of the estimated total business opportunity by the end of the period. The main factors driving the differences between the technology areas are:

- The overall deployment of these technologies to meet demand in the UK and in international trading partners.[11] For example, the systems modelling analysis suggests that, by 2050, there may be between 87 and 109GW of offshore renewables deployed in the UK. By comparison, it anticipates between 5 and 11GW of the nuclear technologies of focus for the EINAs.
- The extent to which the economic activities associated with these technologies are subject to international trade. For example, service-based activities such as the installation and operation and maintenance are inherently less tradable than the manufacture of high-value products and components such as turbines or batteries. For some technologies, a greater proportion of the total business opportunity is linked to the service-based activities of installation, operation and maintenance where trade is inherently limited (e.g. heating and buildings): in these cases, UK-based companies will

[11] In estimating the potential deployment of these technologies, the analysis has generally made use of scenarios that deliver ambitious emission reduction goals aligned to the goals of the Paris Agreement. The specific assumptions used for each technology depends on the data available for each technology. More detail is available in the individual technology theme reports.

be able to capture most or all of the domestic market opportunity but will have fewer export opportunities.

- Among those technologies where there are export opportunities, UK-based firms may be more or less competitive. For example, the UK has arguably established a first-mover advantage in key parts of the offshore wind value chain (part of the offshore renewables technology area). In contrast, global electrolyser manufacturing is heavily dominated by Chinese manufacturers. Differences between sectorial groupings are also a factor of technologies selected for EINA analysis. Given the prevalent focus on innovation opportunities and filtering of more mature technologies (e.g. solar PV), sectorial groupings outlined here are not a reflection of overall sectorial opportunity. In some cases selected technologies were not possible to include due to modelling limitations (e.g. HVDC cables for networks).

Table 15 below clarifies the specific technologies included in these assessments and also provides more detail on the potential range of GVA that might be supported by each of the technology areas in 2040 and 2050.

Table 15: Potential GVA supported by EINA technologies 2040-2050 (values represent median and bracketed values represent the minimum and maximum values from the scenarios investigated)

Technology area	Technologies included	GVA in 2040, £m	GVA in 2050, £m
Offshore renewables	Offshore wind (fixed and floating); Tidal stream	£4,050m *(£3,690 – £4,530m)*	£6,450m *(£6,140 – £7,000m)*
Hydrogen	Electrolysis; Autothermal reforming; Hydrogen transmission and transport; Hydrogen turbine	£550m *(£480m – £1,285m)*	£1,910m *(£1,080 – £3,220m)*
	Hydrogen storage (salt caverns);	£40m *(£30m – £50m)*	£110m *(£90 – £150m)*
Nuclear	Small modular reactors; High temperature gas reactors	£390m *(£370m – £520m)*	£530m *(£480m – £2,110m)*

Technology area	Technologies included	GVA in 2040, £m	GVA in 2050, £m
Heating and buildings	Insulation (roof, wall and floor); Heat pumps (air, ground and water source)	£6,130m *(£3,950m – £10,800m)*	£5,740m *(£5,240 – £7,090m)*
Carbon management)	BECCS (electricity); BECCS (Fischer Tropsch); BECCS (hydrogen); DACCS; Geological CO_2 storage	£1,560m *(£1,480m – £3,150m)*	£2,630m *(£2,470 – £4,930m)*
Storage	4-hour batteries; Compressed air energy storage (CAES/LAES)	£110m *(£80m – £180m)*	£190m *(£170m – £220m)*
Industry	Electrification; Fuel-switching; Resource and energy efficiency technologies	£1,390m *(£1,350m – £1,430m)*	£1,820m *(£1,780m – £1,870m)*
Networks	Dynamic Line Rating; High Temperature Superconductors; Distributed feeder technologies;	£30m *(£10m – £50m)*	£30m *(£10m – £50m)*

Note: All values rounded to the nearest £10m

The table shows that for each technology area there are often significant differences in the business opportunities (amount of GVA they can support) across the different scenarios and innovation levels analysed. Differences between technology theme groupings are often due to the technologies included, therefore comparisons are not representative of whole sectors (e.g. EINA Networks GVA does not cover some of the high capex technologies such as HVDCs or substations due to modelling limitations). Figure 14 considers this in more detail, looking at the three different scenarios explored in the system modelling in 2050 across the 5 largest technology groupings modelled with UK TIMES.[12] The graphs also show the relative importance of the domestic and international market for each technology grouping for each scenario, for those technologies where there was sufficiently robust data to undertake this analysis.[13] For more detail on specific technologies please see relevant technology theme reports where results are explored in more detail.

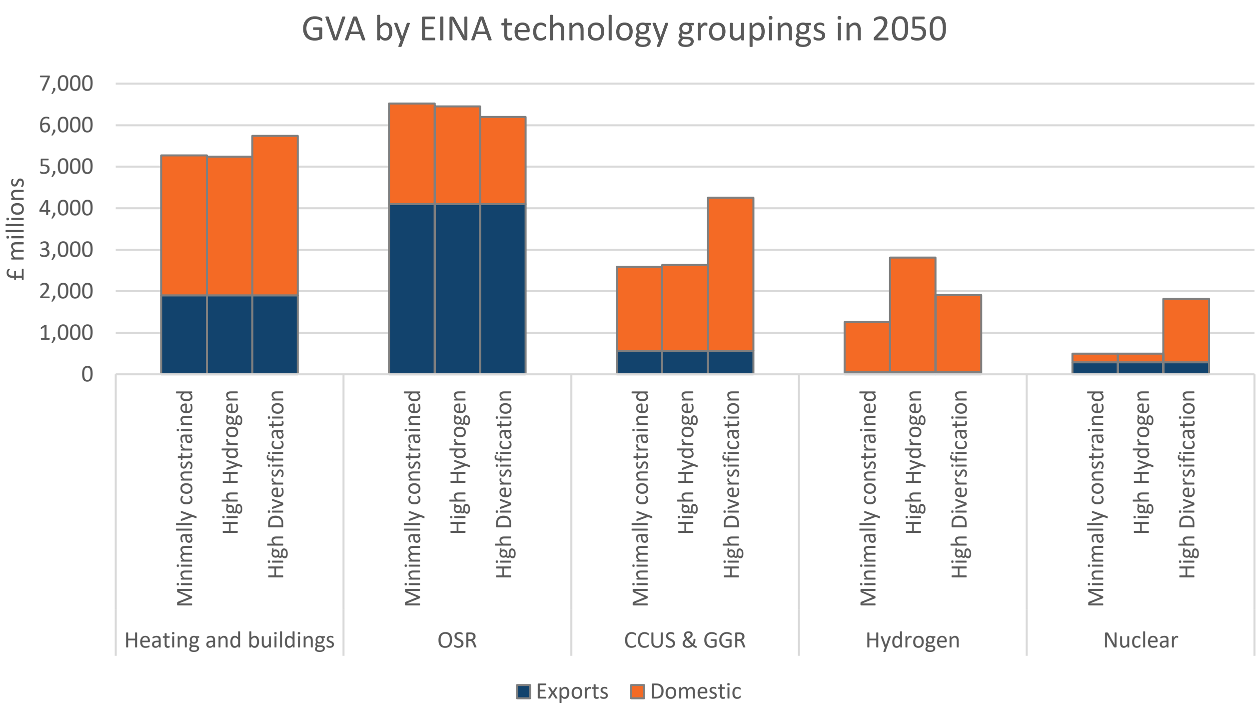

Figure 14: Potential GVA supported by modelled EINA technology groupings at medium innovation levels in 2050 by market.

The figures show that, for most technologies, the High Diversification scenario generates the largest GVA impacts. This reflects that the systems modelling anticipates a greater deployment of the EINA technologies in this scenario; a scenario focused on exploring the implications limiting imports of key commodities and diversifying resource and technology use across the economy. However, this also implies a significant increase in system costs with the High Diversification scenario having the highest baseline total system cost. Two exceptions to this trend are offshore renewables technologies in 2050 where the greatest business opportunity is in the Minimally Constrained scenario, and hydrogen technologies (also in 2050), where the business opportunities are greatest in the High Hydrogen scenario. This also reflects the set-up of the hypothetical scenarios used for the systems modelling: the Minimally Constrained scenario, which focuses on identifying the lowest cost routes to Net Zero with the fewest

[12] A limitation of this analysis is that it was not possible to reliably model the interaction between innovation in the UK and the UK's share of international markets and so this share is assumed to be independent of the level of innovation.

[13] Industry, storage and networks are not included in Figure 14 as the modelling for these technology areas used different scenarios (as explained above) and did not include modelling of potential export markets due to the lack of reliable data on international deployment of these technologies. Hydrogen storage is also excluded from Figure 14 as results for this technology are only available for High Diversification and Minimally Constrained scenarios.

constraints, favours the deployment of low-cost offshore wind; while the High Hydrogen scenario explores the implications of a strong focus on hydrogen use across the economy.

The same charts also show that offshore renewables and heating and buildings are the technology areas where the business opportunities associated with export markets are expected to be substantial in 2050. In the case of offshore renewables, this is driven by export market opportunities in relation to offshore wind, especially fixed-bottom offshore wind. This reflects the strong existing position that UK-based firms have within the supply chain of this technology especially, for example, in relation to development services, blade manufacture and cables.[14] In the case of heating and buildings, the export market opportunities reflect the expected significant worldwide expansion of these technologies, especially air source heat pumps and wall, floor and roof insulation in the next decade. By 2050, exports may continue to be a particularly important driver of business opportunity in the offshore renewables sector, where opportunities in relation to floating offshore wind will become increasingly prominent.

By contrast, the business opportunities from hydrogen and storage throughout the period, and carbon management technologies by 2050, are more heavily reliant on the domestic market. In the case of hydrogen, a global increase in electrolyser manufacturing capacity may limit the UK's export potential in this area. Instead, the main business opportunity is shown to lie in domestic hydrogen production—via electrolysis and autothermal reforming—where high transport costs make UK-based production competitive despite lower production costs abroad. The domestic operation of hydrogen storage capacity will be a further important business opportunity. Within carbon management, while UK-based businesses benefit from some competitive advantages in global markets – including transferable expertise from the oil and gas sector – there are only a limited number of UK-based suppliers that might supply some of the key pieces of equipment as the market scales beyond 2035. As such, there is expected to be more opportunity within the domestic market, especially in relation to power BECCS and geological storage. Business opportunities in the storage technologies are expected to be concentrated in the operation and maintenance of the storage technologies analysed.

[14] Offshore Wind Industry Council (2023) UK Supply Chain Industry Analysis

Jobs Supported[15]

Figure 15Figure 15 presents the potential aggregate number of jobs (direct and indirect[16]) that could be supported by the technologies examined in the EINAs calculators on the same basis as Figure 13 (median number of total jobs across all scenarios and all innovation levels). As noted in the introduction, this estimate does not equate to total clean energy jobs which already add up to approximately 440,000 as of 2023, rather it focuses on a narrower grouping with a focus on high innovation potential. It suggests that the total number of jobs that EINA technologies might support by 2050 could be in the region of 470,000. This represents a CAGR of 8.7%, slightly higher than the equivalent growth rate for GVA. This higher growth rate reflects a combination of somewhat faster growth for some of the more labour-intensive technologies plus a switch from investment to operating and maintenance activities, which, especially taking into account supply chain impacts, are typically slightly more labour intensive.

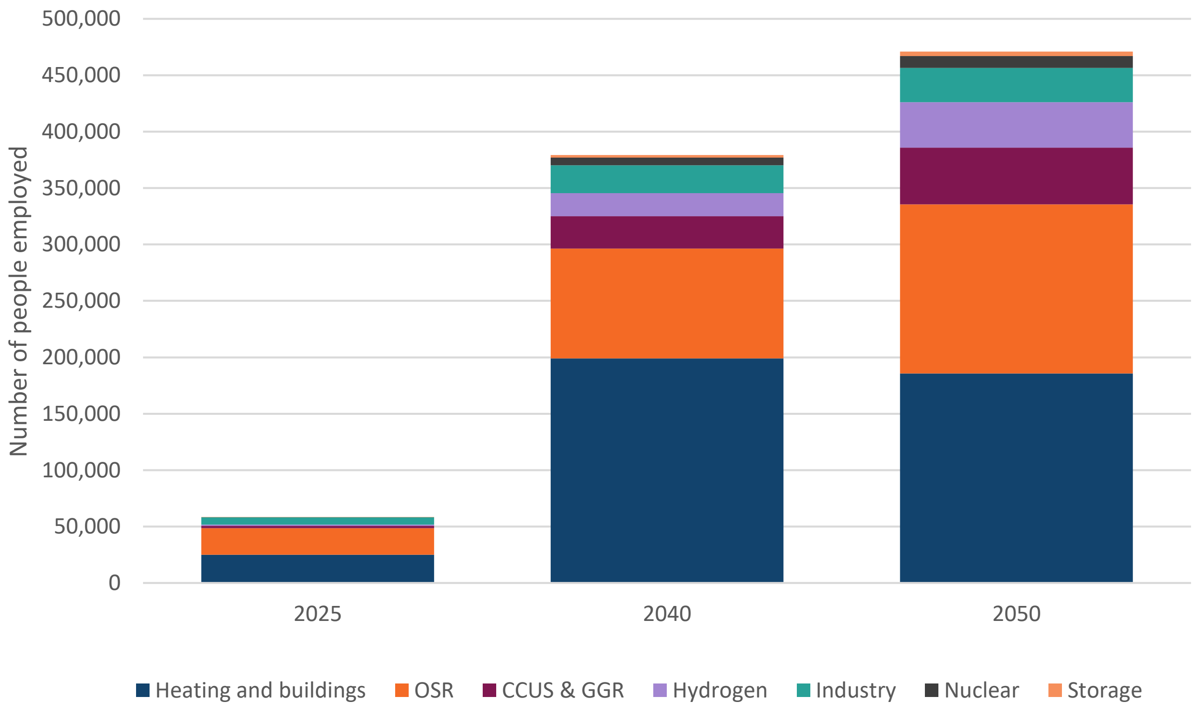

Figure 15: Potential total jobs supported by EINA selected technologies, 2025-2050

Across the different scenarios and innovation levels, the aggregate split between direct and indirect jobs is approximately 1:1. Indirect jobs become modestly more important over the period due to the greater emphasis on operating and maintenance activities, which have slightly more labour-intensive supply chains. Slight exceptions are industry, hydrogen and storage technologies which tend to have a higher proportion of direct jobs (approximately 60%

[15] Many of the key results for jobs – for example, variation by scenario and innovation level follows broadly the same pattern as for GVA. As such, this analysis only focuses on elements of the analysis that are specific to the jobs results.
[16] 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.

in both 2040 and 2050[17]) while, at the other end of the spectrum, supply chain jobs are expected to be relatively more important in the offshore renewable energy technology area.

Finally, Figure 16 provides a breakdown of the potential occupational split of the direct jobs supported by the EINA technologies in 2050 in the medium innovation scenario.[18] It shows that the largest number of jobs are those associated with science, research, engineering and technology professionals, with the EINA technologies potentially supporting over 61,000 people in these occupations by 2050 in the High Diversification scenario. The technologies could also support more than 32,000 jobs associated with skilled construction and building trades and, more generally, between 56,000-63,000 skilled trades jobs by 2050.

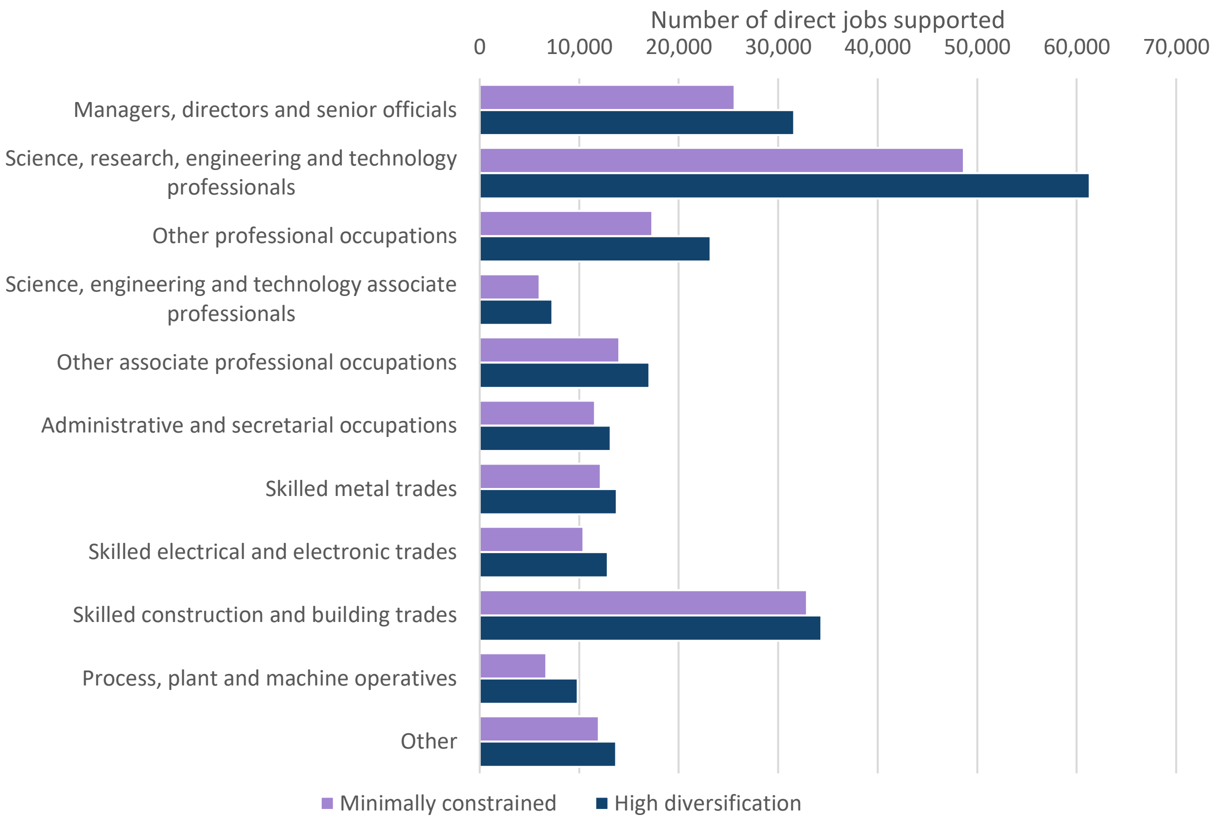

Figure 16: Direct jobs supported by scenario by occupation type in 2050

Note: Medium innovation levels. 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. The heading 'other' covers the following 5 SOC groupings: elementary occupations; other skilled trade occupations; sales and customer service occupations; transport and mobile machine drivers and operatives and; caring, leisure and other service occupations.

[17] Medium innovation level, Minimally Constrained scenario.
[18] The analysis is only provided for the Minimally Constrained and High Diversification scenarios as there was no systems modelling undertaken for storage technologies in the high hydrogen scenario.

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