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Energy Innovation Needs Assessment: Carbon Management

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Authors

The 2025 Energy Innovation Needs Assessment: Carbon Management was commissioned by the Department for Energy Security & Net Zero (DESNZ) and delivered by a consortium led by the Carbon Trust, including Mott MacDonald, UCL and Pengwern Associates.

Mott MacDonald was the lead technical author for the carbon management technology theme report.

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

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Abbreviations

ASU	Air Separation Unit
AD	Anaerobic Digestion
BECCS	Bioenergy with Carbon Capture and Storage
BiRCS	Biomass with Carbon Removal and Storage
CAGR	Compound annual growth rate
CCC	Climate Change Committee
CCSA	Carbon Capture and Storage Association
CCGT	Combined Cycle Gas Turbine
CCU	Carbon Capture and Usage
CCUS	Carbon Capture, Usage and Storage
CDR	Carbon Dioxide Removal
CHP	Combined Heat and Power
CfD	Contracts for Difference
DACCS	Direct Air Carbon Capture and Storage
DOC	Direct Ocean Capture
DPA	Dispatchable Power Agreement
ECC	East Coast Cluster
EfW	Energy from Waste
EOR	Enhanced Oil Recovery
FOAK	First Of A Kind
GGR	Greenhouse Gas Removal
GVA	Gross Value Added
HD	High Diversification

HH	High Hydrogen
IPCC	Intergovernmental Panel on Climate Change
IEA	International Energy Agency
LCOE	Levelised Cost Of Electricity
MOFs	Metal-Organic Frameworks
MC	Minimally Constrained
MMV	Monitoring, Measurement and Verification
MRV	Monitoring, Reporting and Verification
NESO	National Energy System Operator
NZIP	Net Zero Innovation Portfolio
NZT	Net Zero Teesside
NPT	Non-Pipeline Transport
NEP	Northern Endurance Partnership
NOAK	Nth Of A Kind
OCGT	Open Cycle Gas Turbine
O&M	Operation and Maintenance
PCC	Post Combustion Capture
R&D	Research and Development
SAF	Sustainable Aviation Fuel
TRI	T&S Regulatory Investment
TRL	Technology Readiness Level
T&S	Transport and Storage
UKCS	UK Continental Shelf
UKETS	UK Emissions Trading Scheme
VCMs	Voluntary Carbon Markets

Key findings

The Energy Innovation Needs Assessments (EINAs) have been developed and updated to identify key innovation needs across the UK's energy system, to provide an evidence base for the prioritisation of investment and support for clean energy innovation. This report summarises the analysis and findings from the EINAs across the carbon management sub-theme, focusing on carbon capture, usage and storage (CCUS) and greenhouse gas removal (GGR) technologies.

A range of CCUS and GGR technologies are assessed in this update, at different stages of development and commercialisation. The technologies assessed in this EINAs report are:

- Combined Cycle Gas Turbine (CCGT) with Post Combustion Capture (PCC) (gas CCS)
- Bioenergy with carbon capture and storage (BECCS)
- Direct air carbon capture and storage (DACCS)
- Geological storage of CO2

Other relevant technologies are assessed in separate technology EINAs reports, including CCUS-enabled hydrogen production (see the Hydrogen EINAs report) and industrial carbon capture and usage (see the Industry EINAs report).

Energy system modelling to assess the potential impact of innovation in key net zero technologies was conducted using UK TIMES. Technologies were assessed at 3 levels of innovation (low, medium and high) and across three hypothetical scenarios: Minimally Constrained, High Hydrogen and High Diversification.[1] The key results from EINAs system modelling suggests that:

- BECCS: System modelling suggests that BECCS is integral to decarbonising the UK. This is driven by its role in providing negative emissions which are valuable in addressing residual emissions in hard to abate sectors such as aviation, while also providing energy at the same time. BECCS deployment remains broadly consistent across innovation levels when other technologies are innovated, suggesting limited sensitivity to innovation in other technologies that were assessed. Significant cost savings could be realised through innovation of the technology, with high innovation in BECCS delivering cumulative system cost savings of between £55.5 billion and £75.8 billion between 2025 and 2050, compared to a low-innovation case.
- DACCS: System modelling suggests that DACCS is also integral to decarbonising the UK, particularly to offset greenhouse gas emissions (GHG) that cannot be avoided easily. Across the three core scenarios, medium innovation and high innovation DACCS runs increase CO_2 captured from DACCS in 2050 by a factor of 1.4–1.7 and 2.1–2.8 respectively (from a 10Mt annual GHG removal in the low innovation baseline). DACCS

[1] These scenarios do not represent government policy but were selected due to their differing constraints which provide a diverse set of outputs and insights. More information on the scenarios can be found in the Innovation Analysis section of this report and in the EINAs Methodology report.

deployment only decreased when other GHG removal technologies (e.g. BECCS) achieved high innovation, showing sensitivity to alternatives for decarbonising hard to abate sectors. Significant savings could be realised through innovation in DACCS. Cumulative savings via high levels of innovation in DACCS, compared to the low-innovation case, reaches £61.8 billion in the High Diversification scenario in 2050 compared to £39.9 billion in the High Hydrogen scenario and £31.2 billion in the Minimally Constrained scenario.

- Geological CO_2 storage: Innovation in geological storage does not significantly alter or accelerate its adoption indicating that the base scenarios already heavily rely on geological storage. Cumulative savings from high levels of innovation by 2050, range from £6.7 billion (for the High Hydrogen scenario) to £4.8 billion (for the High Diversification scenario).
- CCGT with PCC: Due to the limited temporal resolution of UK TIMES (it does not model on a short-term or hourly basis), the dispatchable value of the technology is not adequately captured, and consequently there is no generation across model runs. Separate modelling undertaken by NESO demonstrated that low-carbon dispatchable power plants (e.g. gas CCS and hydrogen-to-power) play a vital role on the system by operating flexibly to match demand during periods of low renewables or stored energy.

The tables below summarise the key innovation opportunities across the technology areas assessed, included on the basis of potential cost and barrier reduction impacts. Further detail on these, including relatively lower impact innovations needs, are provided in the Carbon Management innovation opportunities section of the report.

Table 1: Innovation opportunities for 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, reducing financing risks once technology considered proven, with transferable benefits to BECCS and industry.

Table 2: Innovation opportunities for 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 1.
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 3: Innovation opportunities for 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 4: Innovation opportunities for 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).

CCUS and GGR technologies will interact closely with the rest of the energy system and support energy security. Flexible gas CCS and power BECCS can provide dispatchable, lower carbon generation to help maintain security of electricity supplies by balancing intermittent renewables and energy storage. Production of low-carbon fuels such as hydrogen and

Sustainable Aviation Fuel (SAF) from BECCS can contribute to security of fuel. Linking DACCS to intermittent renewables can potentially support grid flexibility by utilising surplus renewable energy.

In addition to technology innovation, key barriers and enablers to the deployment of CCUS and GGR technologies were identified including:

- **Market and revenue certainty:** Investors need clear sight of long-term revenue models to support investment decisions. Carbon prices are currently too low to incentivise investments in CCUS and GGR at scale without additional interventions. Many GGR companies participate in Voluntary Carbon Markets (VCMs); however, the size of future demand for credits from GGR projects is uncertain. In the UK, government is rolling out a suite of CCUS business models to support projects participating in the CCUS Cluster Sequencing process.
- **Availability of CO_2 Transport & Storage (T&S) infrastructure:** This is essential to allow investment in carbon capture projects. Over time, non-pipeline transport (NPT) can connect capture projects to existing clusters where pipelines are not technically or commercially feasible; this could be by road, rail or ship. This could also enable international CO_2 storage. Instead of geologically storing CO_2, it can be utilised in various products such as synthetic fuels, chemicals and building aggregates. However, whether it qualifies as greenhouse gas removal depends on how long the CO_2 is retained in the product.
- **Supply chains:** Although the UK CCUS supply chain is well developed, it cannot currently support the volume of projects planned to meet current CCUS targets in the UK. Constraints reported include those in the manufacturing and engineering workforces, UK fabrication yard capacity, logistics constraints and planning bottlenecks. In the DACCS sector, building up a supply chain from a small base will require significant global expansion. For BECCS, the availability of sustainable biomass will be a constraint, including the availability of land and water to grow feedstocks, competition with other uses, and supply chains to harvest, process and transport biomass. However, constraints are also an opportunity for UK supply chains to develop and capture a significant global share of the CCUS sector.

Overall, the key results from the business opportunities calculator, which covers five carbon management technologies, suggest the following potential business opportunities[2]:

- Substantial Gross Value Added (GVA) growth across all scenarios with a compound annual growth rate (CAGR) of between 10% and 13% between 2025 and 2050 with, depending on the scenario, GVA reaching between £2.6 and £4.3bn by 2050.

[2] The calculators only adequately cover five carbon management technologies: BECCS (electricity), BECCS (hydrogen), BECCS (Fischer Tropsch), DACCS and geological storage technologies. As a result, the carbon management sector as a whole will likely support more jobs and GVA than the figures reported here. Power CCS, while being part of the EINA technologies, were excluded in the results due to limitations with the UK TIMES model (see innovation analysis section for more detail).

- Over 60% more GVA supported by 2050 in the High Diversification scenario than in the Minimally Constrained and High Hydrogen scenarios as a result of the substantially higher rates of Power BECCS and DACCS deployment in that scenario.
- Power BECCS followed by geological storage make the largest contribution to GVA in 2040 with DACCS and BECCS (H2) becoming increasingly important by 2050. This is consistent across scenarios. However, lower technology maturity and time to deployment at scale (15+ years) also suggest high uncertainty on technology mix and overall deployment levels.
- Supported total employment (direct and indirect jobs) rises from 2,000 to 6,000 jobs in 2025 to between 49,000 and 81,000 jobs by 2050, which implies a growth rate between 11% and 14% depending on the scenario. In line with GVA estimates, by 2050, there are over 60% more jobs supported with High Diversification than in the other two scenarios.
- Across scenarios, around 48-49% of supported jobs are direct jobs in 2025, rising to approximately 56-58% by 2050.
- The domestic market is expected to support the majority of jobs in the sector with 59-78% of jobs supported by domestic deployment in 2040 rising to approximately 80-90% in 2050. The size of the export market is expected to be relatively constant between 2035 and 2050, contributing over 10,000 jobs across the period.
- As the sector matures and the ratio of new capacity to existing capacity falls, a shift from GVA and jobs being driven by construction activity to increasingly being driven by operations and maintenance.
- An employment profile that, by 2050, is predominantly supporting high skilled science, research and engineering and technology professional occupations, as well as director/managerial jobs.

Introduction

The Energy Innovation Needs Assessments

Achieving the UK's ambitious Clean Power 2030 ambition and 2050 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 provide an evidence base for the prioritisation of investment and support for clean energy innovation. The 2025 publications reflect an update on the 2019 exercise, accounting for the significant changes and progress both in the clean energy sector and the wider economy. To complement and build on the UK's Net Zero Research and Innovation Framework, the updated EINAs will inform key decisions on clean energy innovation funding through a structured evidence base that quantifies and assesses the role and scale of opportunities. The evidence enables comparison across technologies and takes account of wider factors that may impact deployment and scale-up.

The methodology followed is detailed in the EINAs Methodology report, and is summarised below.

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

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

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

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

This report summarises the findings across the carbon capture, usage and storage (CCUS) and Greenhouse Gas Removal (GGR) sub-themes.

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

Scope and limitations of the EINAs:

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

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.

The carbon management sub-theme

Carbon Capture and Storage (CCS) involves the capture of CO_2 from large point sources such as power plants and industrial facilities. Greenhouse Gas Removal (GGR) is the capture of CO_2 directly or indirectly from the atmosphere. In both cases, the captured CO_2 is compressed and transported to be stored deep underground, or for use as a feedstock in a variety of applications.

Carbon capture from power and industry

Between 1990 and 2023 electricity supply emissions in the UK have fallen by 78%. Nevertheless, in 2023, emissions from electricity supply still accounted for 11.5% of all UK greenhouse gas emissions[3]. Globally, power remains the largest emitter of CO_2 in the energy sector[4]. Emissions from existing fossil fuel power plants can be reduced by retrofitting carbon capture technologies; this reduces emissions ‘lock-in’ (future greenhouse gas emissions from existing assets or products). In systems with a large and/or growing share of intermittent renewables, flexible gas power with carbon capture can provide dispatchable, low-carbon power to meet demand during periods of low renewables or high demand.

In addition to the power sector, CO_2 can also be captured from industrial and waste facilities, for example, from cement, steel, pulp and paper, chemicals, hydrogen production and natural

[3] DESNZ (2024) 2023 UK greenhouse gas emissions, provisional figures
[4] IEA (2020) The role of CCUS in low-carbon power systems

gas processing plants, and from Energy from Waste (EfW) plants. As with power plants, carbon capture plants can be retrofitted onto existing sites or applied to new-build facilities.

Carbon capture technologies come in a variety of forms, including pre-combustion, post-combustion and oxyfuel. Pre-combustion involves the conversion of fuel into hydrogen and CO_2; the CO_2 is captured whilst the hydrogen can be utilised without CO_2 emissions. Post-combustion is the separation of CO_2 from exhaust flue gases, with first generation approaches using amine-based solvents, and next generation approaches including hot potassium carbonate solvents and solid sorbents such as Metal-Organic Frameworks (MOFs). Oxy-fuel uses oxygen, produced in an Air Separation Unit (ASU), instead of air in the combustion process; the exhaust gas is mainly water vapour and CO_2, which can be more easily separated than a flue gas containing combustion products such as NOx.

Greenhouse gas removal

GGR is an umbrella term for techniques that capture greenhouse gases from the air and store or chemically convert them with some degree of permanence[5]. It is also known as negative emissions, or in the case of carbon dioxide CO_2 specifically, Carbon Dioxide Removal (CDR).

More precisely, the Intergovernmental Panel on Climate Change (IPCC) defines CDR as: 'Anthropogenic activities removing carbon dioxide (CO_2) from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products…'[6].

To deliver negative emissions, a technique must remove more CO_2 than it emits during its lifecycle (net negative). This can be demonstrated through a comprehensive Lifecycle Analysis (LCA) of a project showing the expected capture rate and associated lifecycle emissions from all materials and substances required, and all energy and fuel requirements.

The Intergovernmental Panel on Climate Change (IPCC)[7], the UK's Climate Change Commission (CCC)[8] and others consider that the use of GGR is unavoidable to achieve net zero climate targets because, even with aggressive emissions reduction, there will be remaining greenhouse gas emissions from hard-to-decarbonise sectors such as aviation, agriculture and industry.

GGR methods broadly fall into two groups: nature-based methods such as afforestation, habitat restoration and soil carbon sequestration; and engineered removals such as Direct Air Carbon Capture and Storage (DACCS), Bioenergy with Carbon Capture and Storage (BECCS), carbon in building materials, biochar, enhanced weathering and ocean-based removals. This report focuses on engineered removals and in particular on DACCS and BECCS. These two technologies were prioritised due to their importance in multiple, published net zero pathways (e.g. IEA Net Zero Roadmap[9]). However, the GGR sector is nascent and

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[5] CO2RE (Accessed: 2025) What is Greenhouse Gas Removal?
[6] Based upon IPCC definition of CDR: IPCC Glossary
[7] IPCC (2022) Climate Change 2022: Mitigation of Climate Change
[8] CCC (2025) The Seventh Carbon Budget
[9] IEA (2023) Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach

therefore the likelihood of other technologies emerging or maturing is greater than in some other sectors.

Technologies included in this assessment

A shortlisting and prioritisation exercise was carried out to determine the CCUS and GGR technologies to be modelled and studied in detail in this update of the EINAs. This followed a framework which considered the following factors:

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

Approximately 25 separate CCUS and GGR technologies and applications were shortlisted and then filtered. The prioritised technologies and applications are outlined in Table 5.

Table 5: Technologies in the carbon management sub-theme prioritised for EINAs assessment

Technology	Description
Combined Cycle Gas Turbine (CCGT) with Post Combustion Capture (PCC) (gas CCS)	CCGT is a core component of the current power grid with around a quarter of all capacity. Importantly, it is dispatchable and can be used to meet demand during periods of low renewables/storage or high demand. Post-combustion carbon capture (PCC) can be fitted to new or existing CCGTs to capture around 95% of the CO_2 in the flue gas. The most established PCC technologies use amine-based solvents and are rated at a Technology Readiness Level (TRL) of 8-9[10]. Next generation approaches include using hot potassium carbonate solvents or solid sorbents such as Metal-Organic Frameworks (MOFs). PCC can also be used to capture CO_2 from the industrial and waste sectors. There are currently no commercial scale, operational gas CCS power plants using PCC, although there are coal CCS power plants in the US (Boundary Dam and Petra Nova) and, in the UK, Tata Chemicals captures 40,000 tpa CO_2 from a gas Combined Heat and Power (CHP) plant to use in the manufacture of sodium bicarbonate[11] (CCU). Several commercial scale gas CCS projects are under development in the UK, including Net Zero

[10] Global CCS Institute (2021) Technology Readiness and Costs of CCS
[11] Tata Chemicals Europe (Accessed: 2025) Carbon capture and utilisation

Technology	Description
	Teeside (NZT) Power which is an 860MW CCGT plant being developed by bp and Equinor, targeting operation from 2028[12].
Bioenergy with Carbon Capture and Storage (BECCS)	BECCS is the conversion of sustainable biomass into power or fuels, while also capturing and storing the CO_2 generated during the conversion process. Sustainable biomass feedstocks may include energy crops, agricultural residues, hydrocarbon wastes and wood from short-rotation coppicing and forestry. There are several different BECCS pathways including but not limited to: • Power BECCS, which is the generation of electricity via combustion of biomass with capture of CO_2 from the flue gas (TRL 8-9[13]); • Hydrogen BECCS, including the gasification of biomass to produce a synthetic gas from which CO_2 is removed (TRL 6-7[13]); • A wide variety of other BECCS processes including the production of bioethanol, which is regarded as one of the most mature BECCS technologies (TRL 9[14]); and • The production of Sustainable Aviation Fuel (SAF) (biokerosene) from gasification with CCS and Fischer-Tropsch, which is less mature (TRL 4-6[15]). The IEA reports that around 2 Mtpa CO_2 are currently captured from BECCS facilities, mainly from bioethanol plants in the US[16]. In the UK, biomass power without carbon capture accounted for 11% of total generation in 2022, with much of this from Drax (2.6GW capacity). Drax has planned to retrofit carbon capture to at least one of its four biomass power plant units; the four units combined have the potential to achieve approximately 16 Mtpa gross removals[17]
Direct Air Carbon Capture and Storage (DACCS)	DACCS is the removal of CO_2 directly from the air using chemicals or minerals. There are multiple approaches being developed by at least 100 startups[18]. In most methods, atmospheric air is brought into contact with a liquid solvent or solid sorbent that captures CO_2, which is later released

[12] Net Zero Teesside (Accessed: 2025) Net Zero Teesside Power
[13] DESNZ (2022) Next Generation Carbon Capture Technology: Technology Review
[14] IEA Bioenergy (2023) How bioenergy contributes to a sustainable future

[15] IEA Bioenergy (2020) The Role of Renewable Transport Fuels in Decarbonizing Road Transport
[16] IEA (2024) Bioenergy with Carbon Capture and Storage
[17] Baringa for Drax (2021) Value of Biomass with Carbon Capture and Storage (BECCS) in Power
[18] O.Geden et al. (2024) The State of Carbon Dioxide Removal: A global, independent scientific assessment of Carbon Dioxide Removal

Technology	Description
	by heating, varying pressure and/or electrochemical methods. TRLs vary but are up to 7-8 for the most advanced methods. The only existing plants in the UK are at pilot scale, including those funded by the UK Government's Direct Air Capture and other Greenhouse Gas Removal Innovation programme[19], which was part of the Net Zero Innovation Portfolio (NZIP). Globally, the largest existing plant is owned by Climeworks in Iceland and is expected to capture 36 ktCO_2pa[20]; construction is underway by 1PointFive and Carbon Engineering in the US to build a plant capable of capturing up to 500 ktCO_2pa[21].
Geological storage	Geological storage is the permanent storage of CO_2 deep underground, either onshore or offshore, trapped within a porous reservoir by an impermeable cap rock. The underground CO_2 plume is monitored using a range of techniques to verify the permanence of the storage. TRLs have been assessed as up to TRL 9 for storage in saline aquifers and depleted oil and gas fields[10]. The UK has significant geological storage capacity, estimated at 78 billion tonnes[22], which could potentially meet the UK's needs for hundreds of years. CO_2 injection for enhanced oil recovery is commonplace in North America but does not always qualify as permanent storage. There are limited industrial scale CO_2 storage projects for sequestration in operation; one example is the Sleipner CCS facility in the North Sea (Norway). In the UK, several storage projects are under development including the HyNet cluster which will store CO_2 in depleted gas fields in the Irish Sea, and the East Coast Cluster (ECC) which will store CO_2 in saline aquifers in the southern North Sea. Lower TRL approaches include storage in basalt and ultra-mafic rocks, where CO_2 is stored via mineralisation. As an example, CO_2 captured by the Climeworks project in Iceland is stored in basalt rock using a mineralisation process developed by its partner Carbfix[23]. These approaches in general have been assessed as TRL 2-6[10].

Other technologies were assessed but de-prioritised as they did not score as highly against the four key criteria (known net zero priority, energy security, UK relevance, TRL). Some technologies were prioritised but not modelled in UK TIMES due to the uncertainty and/or lack

[19] Department for Energy Security and Net Zero (2022) Direct Air Capture and Greenhouse Gas Removal Innovation Programme (closed to applications)
[20] Climeworks (2024) Climeworks switches on world's largest direct air capture plant
[21] 1pointfive (Accessed: 2025) Capturing CO_2 and storing it securely underground
[22] Oil and Gas Authority (2020) UKCS Energy Integration: Annex 2 Carbon Capture and Storage
[23] Carbfix (Accessed: 2025) Carbfix

of availability of sufficient data, or difficulties modelling within UK TIMES, but were assessed qualitatively:

- Industrial CCS
- CO_2 Usage (CCU) – also see EINA Industrial Decarbonisation report
- Emerging and disruptive engineered GGR technologies such as biochar and ocean removals

Nature-based GGR methods were not analysed due to the technology focus of the EINAs, but were modelled according to known government ambition (e.g. expected afforestation).

Carbon management and the energy system

The CCUS and GGR landscape in the UK

Current deployment of CCUS and engineered GGR in the UK is mainly limited to pilot-scale projects, with no large-scale projects in operation. However, the government has previously announced ambitions to capture 90 to 170 Mtpa of CO_2 by 2050, including up to 75 to 81 Mtpa of engineered GGRs[24]. The government intends to realise these short-term ambitions through the roll out of four CCUS 'clusters'[24] whereby capture projects located close to a cluster can feed into the same CO_2 T&S infrastructure. Clusters and capture projects are being selected through the UK government's CCUS Cluster Sequencing process[25]. The government has recently confirmed £21.7 billion (2021 prices) of funding over 25 years[26] towards the development of projects that form part of the 'Track 1' clusters: the East Coast Cluster at Teesside and the HyNet cluster at Merseyside. The first projects reached financial close in December 2024 are now in the execution phase; these are Northern Endurance Partnership (NEP) (T&S infrastructure) and Net Zero Teesside (NZT) Power (gas CCS power plant), both part of the East Coast Cluster[27]. Additionally, in December 2023, the government opened applications for CCUS and engineered GGR projects wanting to take part in the 'Track-1 expansion' of the HyNet cluster[28].

Outside of the UK, notable progress has been made in the US and EU. The US previously announced funding opportunities worth $1.7 billion for carbon capture and $1.2 billion for DACCS under the 2021 Infrastructure and Investment Jobs Act The EU has issued around $1.5 billion for CCUS projects under the latest Innovation Fund round, and $500 million for T&S projects under the Connecting Europe Facility programme[29].

Globally, the International Energy Agency (IEA) has identified around 45 commercial CCUS and engineered GGR facilities capturing around 50 Mtpa CO_2[29]. Large-scale projects include the Petra Nova post-combustion carbon capture facility in the US which is a retrofit to an existing coal-fired plant that can capture up to 1.4 Mtpa CO_2 for Enhanced Oil Recovery (EOR). There are around 700 further projects in various stages of development which could contribute an additional 385 Mtpa by 2030. Examples include the Brevik cement works CCS project in Norway, which recently achieved mechanical completion[30] and aims to capture 400 ktpa of CO_2, to be stored by Northern Lights in a saline aquifer under the North Sea[31].

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[24] DESNZ (2023) Carbon capture, usage and storage: a vision to establish a competitive market
[25] DESNZ (2021) Cluster sequencing for carbon capture, usage and storage (CCUS) deployment: Phase-1
[26] DESNZ (2024) Government reignites industrial heartlands 10 days out from the International Investment Summit
[27] DESNZ (2024) Contracts signed for UK's first carbon capture projects in Teesside
[28] DESNZ (2024) Carbon capture, usage and storage (CCUS) deployment: Track-1 expansion: HyNet cluster
[29] IEA (Accessed: 2025) Carbon Capture, Utilisation and Storage
[30] Heidelberg Materials (2024) Brevik CCS reaches mechanical completion
[31] Equinor (Accessed: 2025) Northern Lights

Future deployment of CCUS and GGR

The Climate Change Committee (CCC), in its recommendations to government for the UK's Seventh Carbon Budget[8], sees CCS used in the chemicals and cement and lime industries, for dispatchable power and in manufacturing low-carbon hydrogen. It also sees engineered GGR playing a crucial role in offsetting residual emissions. In its Balanced Pathway scenario:

- Around 9 Mtpa of CO_2 will be captured and stored from industry by 2050;
- There will be 38GW of low-carbon dispatchable power by 2050, from gas CCS and hydrogen-to-power (e.g. hydrogen-fired turbines), to provide security of supply during periods of low renewables;
- Engineered GGR reaches around 36 Mtpa by 2050, including from power BECCS (around 10 Mtpa), BECCS from EfW (5 Mtpa), other BECCS (10 Mtpa), DACCS (8 Mtpa) and with some enhanced weathering and biochar (together up to 3 Mtpa).

The National Energy System Operator (NESO), in its advice to government on achieving clean power by 2030, also sees gas CCS and hydrogen-to-power important in the shorter term, delivering up to 2.7 GW by 2030[32].

Globally, the IEA, in its Net Zero Roadmap to limit the global temperature rise to 1.5°C[33], sets out a global pathway to net zero by 2050 which includes capturing 6 Gtpa of CO_2 in 2050 including around 2 Gtpa from industry, 1 Gtpa from DACCS, 0.8 Gtpa from fossil fuel power, 0.8 Gtpa from hydrogen and 0.4 Gtpa from BECCS power. This includes 89 GW of gas CCS capacity and 114 GW of BECCS capacity by 2050.

Costs are expected to fall for all CCUS technologies, although the size of fall differs between technologies, potentially increasing their deployment in the future. For example, levelised costs for gas power generation (point source) CCS projects have been estimated to fall by around 5% between 2030 and 2040[34] whereas costs for DACCS projects have been estimated to fall by up to 75% by 2050[35].

CCUS and GGR technologies will interact closely with the rest of the energy system. For example, gas CCS can provide flexibility to the grid by offering dispatchable power to balance intermittent renewables or high demand, which will be necessary to decarbonise the power system. In industry, carbon capture will be needed to reduce emissions in some sectors such as chemicals, lime and cement and Energy from Waste (EfW) and, in other industrial sectors, can complement (or may compete with) other decarbonisation approaches such as fuel switching and electrification to reduce emissions. DACCS and other novel technologies are likely to play a key contribution to meeting net zero targets if costs fall as projected. Linking DACCS to intermittent renewables can potentially support grid flexibility by utilising surplus renewable energy, thereby indirectly supporting energy security.

[32] NESO (2024) Clean Power 2030
[33] IEA (2023) Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach
[34] BEIS (2020) BEIS Electricity Generation Costs (2020)
[35] IEAGHG (2021) Global Assessment of Direct Air Capture Costs

Carbon management innovation opportunities

Gas CCS with Post Combustion Capture (PCC)

This section outlines the technology and associated key innovation opportunities to reduce costs, support commercialisation and scale up of Gas CCS using Post Combustion Capture (PCC).

Gas power plants account for 77.5% of CO_2 emissions from the UK's electricity supply, and around 9.85% of the UK's total annual CO_2 emissions.[36] Gas power plants burn natural gas (generally) in gas turbines to generate power. Open Cycle Gas Turbines (OCGT) plants comprise one or more gas turbines coupled to a generator(s). In a Combined Cycle Gas Turbine (CCGT) plant, hot exhaust gases from the gas turbine drives a steam turbine to generate additional power and increase the overall efficiency. CCGTs are a core component of the current power grid with 31 GW installed, which is around a quarter of all capacity, although many plants are close to the end of their design lives and may close over the next ten years[37]. Importantly, CCGT and OCGT are dispatchable, which means they can start up, shut down or vary load at speeds required by the grid for short- and long-term stability, and can be used to meet demand during periods of low renewables/storage or high demand.

Post-combustion carbon capture (PCC) can be fitted to new or existing CCGT and OCGT plants to capture at least 95% of the CO_2 in the flue gas during normal operating conditions[38]. The most established PCC technologies use amine-based solvents. The capture plant requires steam and power from the main CCGT plant, thus reducing its overall output and efficiency. The CO_2 delivered from the capture plant is compressed and purified to meet the specifications of the T&S network. Gas CCS therefore provides a low-carbon, dispatchable power option, which is expected to be needed to balance the grid and achieve rapid decarbonisation to meet the government's Clean Power 2030 ambition[39].

Gas power plants are well proven, having been in commercial operation for over 30 years in the UK, and innovation opportunities on the power side are therefore limited. This report therefore focuses on innovation opportunities in PCC which, in the most part, are also likely to be applicable to the waste and industrial sectors.

Substantial improvements will need to be made to the solvents used for PCC to drive down costs and improve environmental impact. In the short term, advanced solvents could improve performance by reducing regeneration energy consumption and/or degradation, whilst in the longer term, non-amine-based solvents and non-aqueous solvents could become commercially

[36] DESNZ (2025) Provisional UK greenhouse gas emissions statistics 2024
[37] DESNZ (2023) Assessing the deployment potential of flexible capacity in Great Britain – an interim report
[38] Environment Agency (2024) Post-combustion carbon dioxide capture: emerging techniques
[39] National Engineering Policy Centre (2024) Rapid decarbonisation of the GB electricity system

viable. Additionally, modularisation of systems or individual components could help to ease deployment due to improved supply chains.

Process improvements including optimisation of flue gas pre-treatment and flue gas recycling, as well as demonstrating the ability of PCC plants to match flexible operation of CCGT plant could reduce costs and allow gas CCS to play a more flexible role on the grid respectively.

Allam-Fetvedt cycle

An alternative approach to PCC is the Allam-Fetvedt cycle which involves oxy-fuel combustion with natural gas and the use of the produced CO_2 as the working fluid to drive a turbine. This allows close to 100% CO_2 capture and potentially improved overall efficiencies relative to PCC[13]. The technology has a lower TRL but has been demonstrated by NET Power at a 50MWth test facility in Texas with plans for a First of a Kind (FOAK) 300MWe project from 2029[40].

Work is also underway to demonstrate the combustion of blue hydrogen in gas turbines, which would move the location of the CO_2 capture from the power plant to the blue hydrogen facility. Hydrogen burns without producing CO_2, so carbon capture is not required at the power plant.

Table of innovation needs

This section details key components and areas of technology innovation required to reduce cost and accelerate the deployment of the technologies assessed in this report. This section draws from the previous EINAs research with updated assessments. The table details the direct technology impacts of innovations, as well as the other EINAs technologies that could benefit from innovation in these areas. Each innovation is assessed according to its likely impact on cost reduction and deployment for the relevant technology, with a qualitatively assessed 1 (very low) – 5 (very high) impact rating. The timeframe column refers to the time period within which the innovation could be expected to have material implications for the UK energy system and Net Zero with investment and innovation. Column descriptors within the table are defined as following:

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

[40] Business Wire (2025) Net Power Reports Fourth Quarter 2024 Results and Provides Business Update

Table 6: Innovation needs for gas CCS with Post Combustion Capture[41], [13], [10], [42], [13], [43]

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Capture	R&D and demonstration of advanced solvents that improve performance by reducing regeneration energy consumption, reducing losses, and reducing thermal and oxidative degradation	PCC	Transferable to BECCS, DACCS, waste and industrial sectors where reduction in energy (steam) consumption is important	4 – Reduced energy consumption, which is a key contributor to lifecycle costs (fuel costs), as well as solvent management and replacement costs; potentially allows the use of smaller capture modules with more standard materials to reduce capital costs.	3 – Reduction in costs can contribute to greater market certainty and public acceptance; potential environmental benefits	2025-2030

[41] DESNZ (2019) Energy Innovation Needs Assessment: Carbon capture, utilisation and storage
[42] HM Government (2021) UK Net Zero Research and Innovation Framework
[43] FOCUSS (Accessed: 2025) TERC Current Projects

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Capture	R&D and demonstration of next generation solvents such as hot potassium carbonate solvents, other non-amine-based solvents and non-aqueous solvents	PCC	May be transferrable to BECCS, waste and industrial sectors	4 - Potentially reduced energy consumption, which is a key contributor to lifecycle costs (fuel costs); potentially allows the use of smaller capture modules with more standard materials to reduce capital costs.	3 - Potential environmental benefits compared to amine-based solvents; reduction in costs can contribute to greater market certainty and public acceptance	2030s
Capture	R&D and demonstration of next generation technologies such as solid sorbent (e.g. MOFs), pressure swing, rotating packed beds, fuel cell and membrane-based capture technologies (e.g. polymeric membranes), and their applicability to CCGT plants	PCC	May be transferrable to BECCS, DACCS, waste and industrial sectors	4 - Potentially reduced energy consumption, which is a key contributor to lifecycle costs (fuel costs), and capex	3 – Reduction in costs can contribute to greater market certainty and public acceptance; potential environmental benefits	2030s

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Capture	R&D on the environmental impact of solvent emissions from PCC and subsequent atmospheric degradation products	PCC	Transferable to BECCS, DACCS, waste and industrial sectors	1 - Unlikely to contribute meaningfully to cost reductions	3 – Potential environmental benefits and improved public acceptance	2025-2030
Capture	R&D and demonstration of modularisation of entire systems or individual components	All capture technologies, membranes and fuel cells may be best suited[13]	Transferable to DACCS, BECCS, waste and industrial sectors	2 – Facilitates scaling up, quicker construction, mass manufacture of modular components, simplified plant designs; potential reductions to capex	4 – Can help establish supply chains quicker	2040s
Capture	R&D and demonstration of approaches to reduce water consumption	Predominantly liquid solvent-based approaches which have higher water consumption	DACCS, green hydrogen production and other water intense technologies	2 – The cost of water is not normally a key contributor to lifecycle costs	4 – The availability of water may limit the locations that particular technologies can be deployed	2030s

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Process	R&D and demonstration of process improvements including optimisation of flue gas pre-treatment, Exhaust Gas Recirculation (EGR) and Selective Exhaust Gas Recirculation (S-EGR), heat integration, integration of CCGT and capture plant	CCGT, PCC	BECCS	4- Potentially reduced energy consumption, which is a key contributor to lifecycle costs (fuel costs)	3 – Reduction in cost can contribute to greater market certainty and public acceptance, increase in capture rates can contribute to public acceptance	2025-2030
Process	R&D and demonstration of ability of PCC plant to match flexible operation of CCGT plant including impact on capture rates	CCGT, PCC	Limited application outside gas CCS	1 – Potentially limited impact on cost reduction but may reduce solvent management costs and operational costs.	4 – Required to allow gas CCS to play a flexible role on the grid	2025-2030
Conditioning	R&D and demonstration of advanced CO_2 polishing technologies (H_2O and O_2)	All	All CCS	2 – Not normally a key contributor to lifecycle costs	4 – May reduce T&S infrastructure opex	2025-2030

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Waste disposal	Demonstration of improved approaches to minimise disposal costs from reclaimer waste and direct contact cooler effluent.	PCC	Transferable to BECCS, waste and industrial sectors	2 – Reduced waste disposal costs; potential environmental benefits.	2 – Potential environmental benefits; reduction in costs can contribute to greater market certainty and public acceptance	2025 - 2030
All	R&D and demonstration of alternative approaches to low-carbon dispatchable power including Allam-Fetvedt technology and the combustion of hydrogen in gas turbines	Gas CCS	Potentially transferable to BECCS and industrial sectors	1 – Uncertain	3 – Potential environmental benefits through lower air emissions	2030s
All	Construction of mid-scale demonstration facilities; sustained reliable operation to remove uncertainties	All	N/A	3 – Can facilitate scaling up, and capex and opex reduction	4- Can reduce financing risks once technology considered proven	2025-2035

Components and costs

Given gas power plant technology is proven, opportunities for significant cost reductions are more likely to be related to the capture plant. The levelised cost of electricity (LCOE, £/MWh generated) for CCGT CCS projects has been estimated to fall by around 5% between 2030 and 2040. Percentage contribution figures used in this section are estimated based on several sources [34 44 10 45].

Capex: Capex includes project development, project management, engineering, procurement, construction, commissioning and connection to a T&S network, including treatment equipment to ensure the CO_2 meets the network or end user specifications. Capex reduction could be achieved through the use of emerging technologies, scaling up to exploit economies of scale, longer plant lifetimes, modularisation and mature supply chains. Capex has been estimated to contribute to around 20% of the total LCOE.

Opex: Fixed and variable operation and maintenance (O&M) costs (opex) are estimated to contribute around 10% of the LCOE. Fixed opex includes staffing, insurance and administration costs, and are incurred whether or not the plant is operating. Variable opex is driven by how often the carbon capture plant operates and includes solvents, other consumables, maintenance and spare parts.

Fuel: The cost of natural gas to operate the CCGT plant is estimated to contribute around 60% of the LCOE. More natural gas is needed to operate a CCGT plant with carbon capture, on a per MWh generated basis, since the capture plant requires steam and power from the main CCGT plant, thus reducing its overall output and efficiency. Reductions in fuel costs related to the capture plant including through the use of advanced solvents or next generation (non-solvent) technologies that reduce regeneration energy consumption, or process improvements.

CO_2 Transport and Storage (T&S): This includes the cost of transporting the captured CO_2 to the final geological storage site or the point of use (CO_2 usage). Transportation is most likely to be through onshore and offshore pipelines, but may also be non-pipeline transport (NPT) methods such as shipping, road or rail. T&S costs have been estimated to contribute less than 5% of the LCOE; however, this will depend on the specific project. In 'clusters' or 'hubs', T&S costs will be shared amongst several, separate CO_2 emitter/capture projects, significantly reducing the costs placed on an individual project.

[44] Wood (2018), Assessing the Cost Reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology, Assessing the Cost Reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology
[45] IEA (2020) Projected Costs of Generating Electricity

Industrial CCS

Industry contributes around 53 Mtpa CO_2 emissions (or 14%) of total annual emissions in the UK.[46] Major contributors in the UK include the manufacture of iron and steel, chemicals and cement and lime. Emissions arise from the combustion of fossil fuels (e.g. to provide heat to the manufacturing process) or from process emissions arising from reactions other than combustion that are intrinsic to the manufacturing process (e.g. around half the emissions from cement production arise from the calcination of limestone).

Industrial decarbonisation options include energy efficiency, electrification, fuel switching to bioenergy or hydrogen, and CCS. CCS is particularly important for tackling process emissions which cannot be removed through electrification or fuel switching. As such, the CCC has recommended that CCS is targeted at those industries with limited other decarbonisation options (cement and lime, and chemicals) and sees CCS contributing 17% of emissions reduction (around 9 Mtpa CO_2) in the industry sector by 2050[47].

Approaches for decarbonising industrial processes through point source carbon capture vary because of the different types of industrial emissions, with different CO_2 concentrations and partial pressures, and the multiple approaches for capturing CO2[48]. It can be as simple as taking an existing CO_2 stream from a process and drying and compressing it for transportation, to having to build a new plant to accommodate carbon capture. Carbon capture is most effective on flue streams with high CO_2 concentrations.

In the cement and lime industry, there are several carbon capture options available including Post Combustion Capture (PCC), oxy-fuel combustion, chemical and carbonate looping and cryogenic separation of CO_2.

Heidelberg Materials is currently retrofitting an amine-based PCC plant to its Brevik cement facility in Norway, which will use steam generated from waste heat recovery units that recover heat from the hot flue gas from the cement process.[49, 50] Once operational, this will be the world's first industrial scale CCS plant at a cement facility and will capture 400 ktpa CO_2 to be stored by Northern Lights in a saline aquifer under the North Sea[31]. Mechanical completion was achieved in late 2024.

An alternative approach to PCC at cement facilities is oxy-fuel combustion (combustion in an oxygen rich environment) which produces a CO_2-rich flue gas which is relatively simple to capture for onwards transportation and storage. Full oxyfuel allows capture rates above 90% whereas partial oxyfuel, which is easier to implement, achieves lower capture rates at 55-75%[51]. An Air Separation Unit (ASU) is required to provide the large volumes of oxygen needed; this significantly increases electricity requirements and therefore increases the cost of

[46] DESNZ (2025) 2023 UK Greenhouse Gas Emissions, Final Figures
[47] CCC (2025) The Seventh Carbon Budget
[48] AECOM (2022) Review of Next Generation Carbon Capture Technology for Industrial, Waste and Power Sectors
[49] Heidelberg Materials (2024) Brevik CCS reaches mechanical completion
[50] West Welding Oy (2021) CCS project in Brevik, Norway – Manufacturing of Waste Heat Recovery units reaches halfway mark with excellent quality remarks
[51] Global Cement and Concrete Association (Accessed: 2025) Oxyfuel

clinker. Research is underway to bring down costs and to understand the impact that the process has on final product quality. Heidelberg Materials is developing a project to convert an existing cement facility at Geseke, Germany using oxyfuel technology which aims to capture 700 ktpa CO_2, with commissioning planned for 2029[52].

Around half of industrial emissions in the UK are from industrial clusters[53] and may therefore have access to a CO_2 transportation and storage network as part of a CCUS cluster. Significant work has been undertaken to encourage the decarbonisation of industrial clusters, including the Industrial Decarbonisation Challenge delivered by Innovate UK and Engineering and Physical Sciences Research Council (EPSRC) which was backed by £210m of public funding and matched by £261m from industry. This provided targeted support to six of the UK's key industrial clusters[54].

The remaining half of emissions are from dispersed sites, including most cement and lime manufacturing facilities. Dispersed sites may need to access geological storage via Non-Pipeline Transport (NPT) such as road and rail (see Non-Pipeline Transport) or deliver CO_2 for usage in the manufacture of other products (see CO_2 usage).

In the UK, DESNZ is developing an Industrial Carbon Capture business model to provide support to industrial CCS projects participating in the CCUS Cluster Sequencing process (see 'Deep dive 1: Market and revenue certainty' for further details of business models).

As part of the CCUS Cluster Sequencing process, the Padeswood Cement Works CCS project was selected by DESNZ to proceed to negotiations for support through the Industrial Carbon Capture business model[55]. This project is being developed by Hanson (part of the Heidelberg Group) at its existing cement facility at Padeswood, Flintshire. The project is part of the HyNet cluster and will use amine-based PCC technology, similar to that being deployed at Brevik, to capture 800 ktpa CO_2[56], with commercial operation by 2029.

Key innovation opportunities in industrial carbon capture relate to demonstrating technologies at scale, further research and development of emerging technologies, assessing performance of technologies with varying fuels and CO_2 concentrations, reducing costs (particularly through reductions in energy use), integrating CCS with existing manufacturing processes and understanding the impact of CCS on the quality of the final products.

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[52] Heidelberg Materials (Accessed: 2025) Paving the way for a decarbonised cement industry
[53] UKRI (2023) Enabling Net Zero: A Plan for UK Industrial Cluster Decarbonisation
[54] UKRI (2024) Industrial decarbonisation milestone reached as challenge completes
[55] DESNZ (2023) Cluster sequencing Phase-2: Track-1 project negotiation list, March 2023
[56] Heidelberg Materials (Accessed: 2025) Padeswood CCS

BECCS

Overview of BECCS

Bioenergy with Carbon Capture and Storage (BECCS) is the conversion of sustainable biomass into power or fuels, with the capture and storage of CO_2 generated during the conversion process. Biomass feedstocks include wood, agricultural residues and biogenic wastes.

There are several different BECCS pathways including:

- Power BECCS: The generation of electricity via combustion of sustainable biomass with capture of CO_2 from the flue gas (PCC). The TRL has been rated as up to TRL 8-9[99] for advanced amine-based PCC technologies.
- Hydrogen BECCS: For example, the gasification of sustainable biomass to produce a synthetic gas from which the CO_2 is removed and captured, and the syngas is refined to produce hydrogen. The TRL of H_2 BECCS via gasification has been rated at TRL 7-8.
- Biomethane BECCS: The production of biomethane via Anaerobic Digestion (AD); the biogas is upgraded by removing CO_2 which is captured.
- Low-carbon fuel BECCS: There are a wide variety of low-carbon fuel BECCS processes rated up to TRL 9, such as bioethanol production in the US which is regarded as one of the most mature BECCS technologies. The production of Sustainable Aviation Fuel (SAF) (biokerosene) from gasification with CCS and Fischer-Tropsch is at a lower TRL 4-6.

Since biomass absorbs CO_2 from the atmosphere via photosynthesis whilst growing, when it is combusted the carbon contained in biomass can be captured (approximately 90% is captured) meaning that there is a net CO_2 reduction in the atmosphere making BECCS carbon negative. As for all GGR methods, the main significance of BECCS to meeting net zero targets is its ability to deliver net negative emissions to offset the sectors that are most difficult to decarbonise (e.g. aviation, industry, agriculture) and to take back CO_2 that is already in the atmosphere.

A thorough life cycle analysis is required to determine whether, and to what extent, net negative emissions removal has been achieved. This includes the sustainability of the biomass, supply chain losses and emissions from the later combustion of BECCS products such as low-carbon fuels. Literature indicates the greenhouse gas removal efficiency of BECCS to be around 65-85%[57].

The production of biomass has several environmental challenges including land requirements (direct and indirect land-use change), high water requirements to grow biomass and potentially negative impacts on forest carbon stocks, depending on the feedstock. In its Biomass Strategy in 2023, the previous government set out an intention to further strengthen the UK’s biomass sustainability criteria[58].

Public perceptions of BECCS often question the validity of the technology to deliver net negative emissions[99]. To help address this, governments and third parties are developing Monitoring, Reporting and Verification (MRV) frameworks that projects can follow to demonstrate net negativity. Compliance can then be independently verified and certified.

The State of Carbon Dioxide Removal (2nd edition) reported that 0.51 Mtpa CO_2 was captured from BECCS projects globally in 2023, much of this from the Illinois Industrial CCS Project in the US which has captured between 0.43 to 0.52 Mt CO_2 per year during bioethanol production since 2017[18]. The IEA reports that BECCS projects currently under various stages of development globally, if realised, could reach around 60 Mtpa by 2030[57].

Deploying BECCS at scale to meet climate targets requires the ramp-up in production of sustainable biomass. However, there is a limit to the availability of biomass and other sectors compete for its use as a feedstock. Modelling has indicated that prioritising BECCS when allocating biomass will maximise the contribution of biomass to net zero targets[58].

Power BECCS

Biomass power plants are a mature technology: biomass is burnt in a boiler to raise steam which is fed to a steam turbine to generate electricity. In the UK, biomass power accounted for 11% of total generation in 2022, with much of this from Drax (2.6GW capacity) and Lynemouth (420MW) which both use imported wood pellets. Smaller plants in the UK use domestic fuels such as waste wood (Steven's Croft, 46MW) and straw (Ely, 40MW)[59].

Similar to gas CCS, PCC can be fitted to new or existing biomass power plants to capture over 90% of the CO_2 in the flue gas[60]. Drax has piloted carbon capture technology at its biomass power plants using C-Capture technology in 2019 and at a second pilot facility using MHI technology in 2020. It now plans to retrofit carbon capture to at least one of its biomass power plant units[61].

Power BECCS does not have as short start-up times as gas CCS, although it can still be partially dispatchable to contribute to meeting demand during periods of low renewables/storage or high demand and power decarbonisation targets.

Capturing CO_2 from Energy from Waste (EfW) plants can also deliver net negative emissions, from the biogenic portion of the waste. It has been estimated that 5-8 Mtpa negative emissions can be captured from the UK EfW fleet[62], although not all EfW plants are close to planned T&S networks necessary for CO_2 storage. Projects under development include the retrofit of carbon capture to Viridor's Runcorn EfW plant, which is in negotiation with the government for Track 1 funding as part of the HyNet cluster[63].

[57] IEA (2024) Bioenergy with Carbon Capture and Storage
[58] DESNZ (2023) Biomass Strategy
[59] DESNZ (2024) Digest of UK Energy Statistics (DUKES): electricity
[60] DESNZ (2023) The ability of BECCS to generate negative emissions: Task and Finish Group Report
[61] Drax (Accessed: 2025) BECCS and negative emissions
[62] Oxford Institute for Energy Studies (2024) Carbon capture from energy-from-waste (EfW): A low-hanging fruit for CCS deployment in the UK?
[63] DESNZ (2023) Cluster sequencing Phase-2: Track-1 project negotiation list, March 2023

Table of innovation needs

This section details key components and areas of technology innovation required to reduce cost and accelerate the deployment of the technologies assessed in this report. This section draws from the previous EINAs research with updated assessments. The table details the direct technology impacts of innovations, as well as the other EINAs technologies that could benefit from innovation in these areas. Each innovation is assessed according to its likely impact on cost reduction and deployment for the relevant technology, with a qualitatively assessed 1 (very low) – 5 (very high) impact rating. Column descriptors within the table are defined as following:

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

Table 7: Innovation needs for power BECCS

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
All	Construction of mid-scale demonstration facilities; sustained reliable operation to remove uncertainties	All	N/A	3 – Can facilitate scaling up and cost reduction; potential reductions to capex and opex	4- Can reduce financing risks once technology considered proven	2030s
Capture	Advanced solvents that improve performance by reducing regeneration energy consumption, reducing losses, and reducing thermal and oxidative degradation	PCC	Transferable to power CCS, waste and industrial sectors where reduction in energy (steam) consumption is important	4 – Reduced energy consumption, which is a key contributor to lifecycle costs (fuel costs), as well as solvent replacement costs	3 – Reduction in costs can contribute to greater market certainty and public acceptance; potential environmental benefits	2030s
Capture	Emerging solvents such as hot potassium carbonate solvents, other non-amine-based solvents and non-aqueous solvents	PCC	May be transferrable to gas CCS, waste and industrial sectors	4- Potentially reduced energy consumption, which is a key contributor to lifecycle costs (fuel costs)	3- Potential environmental benefits compared to amine-based solvents; reduction in costs can contribute to greater market certainty and public acceptance	2030s

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Capture	Next generation technologies such as solid sorbent, pressure swing, rotating packed beds, fuel cell and membrane-based capture technologies, and their applicability to biomass plants	PCC	May be transferrable to gas CCS, waste and industrial sectors	4- Potentially reduced energy consumption, which is a key contributor to lifecycle costs (fuel costs); potentially allows the use of smaller capture modules with more standard materials to reduce capital costs.	3 – Reduction in costs can contribute to greater market certainty and public acceptance; potential environmental benefits	2030s
Capture	Modularisation of entire systems or individual components	All capture technologies, although membranes and fuel cells may be best suited[13]	Transferable to gas CCS, waste and industrial sectors	2 – Facilitates scaling up, quicker construction, mass manufacture of modular components, simplified plant designs; potential reductions to capex	4 – Can help establish supply chains quicker	2040s
Capture	R&D on the toxicity of solvent emissions from PCC and subsequent atmospheric degradation products	PCC	Transferable to gas CCS, waste and industrial sectors	1- Unlikely to contribute meaningfully to cost reductions	3 – Potential environmental benefits	2030s

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Capture	R&D and demonstration of approaches to reduce water consumption	Predominantly liquid solvent-based approaches which have higher water consumption	DACCS, green hydrogen production and other water intense technologies	2 – The cost of water is not normally a key contributor to lifecycle costs	4 – The availability of water may limit the locations that particular technologies can be deployed	2030s
Process	R&D and demonstration of process improvements including optimisation of flue gas pre-treatment, flue gas recycling, heat integration, integration of biomass and capture plant, re-use of waste heat to dry biomass	Biomass power, PCC	Gas CCS	4- Potentially reduced energy consumption, which is a key contributor to lifecycle costs (fuel costs)	3 – Reduction in cost can contribute to greater market certainty and public acceptance	2030s
Process	R&D and demonstration of techniques to mitigate risks in capture plant associated with impurities in flue gases from biomass burning	Biomass power, PCC	Limited applications outside BECCS	4 – Potentially improve availability (improvement in revenues) and reduce maintenance costs	3 – Reduction in cost can contribute to greater market certainty and public acceptance	2030s
Conditioning	R&D and demonstration of advanced CO_2 polishing technologies (H_2O and O_2).	All	All CCS	2 – Not normally a key contributor to lifecycle costs	4 – May reduce T&S infrastructure opex	2030s

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
All	R&D and demonstration of use of biomass as an alternative fuel in industrial facilities (e.g. cement kilns) coupled with carbon capture to achieve BECCS	Steel, cement, paper and chemicals	Potentially other industries	1 - Uncertain	1 - Limited	2030s
MRV	Development of technology-specific MRV to enable robust carbon accounting and assignment of credits to support carbon market	All DACCS	Other GGRs	1 – Limited potential for cost reduction	4 – Can increase confidence in quality of removals contributing to market certainty and public acceptance	2030s

Sources: [39], [13], [10], [40], Mott MacDonald

Components and costs

Given that unabated biomass power plant technology is proven, opportunities for significant cost reductions are more likely to be related to the capture plant. The LCOE (£/MWh generated) for power BECCS has been estimated to fall by around 5% between 2030 and 2040. Percentage contribution figures used in this section are estimated based on several sources [34] [64] [65] [66].

Capex: Capex includes project development, project management, engineering, procurement, construction, commissioning and connection to a CO_2 Transport and Storage (T&S) system, including treatment equipment to ensure the CO_2 meets the system specifications. Capex reduction could be achieved through the use of emerging technologies, scaling up to exploit economies of scale, longer plant lifetimes, modularisation and mature supply chains. Capex has been estimated to contribute to around 25% of the total LCOE.

Opex: Fixed and variable O&M costs (opex) are estimated to contribute around 10% of the LCOE. Fixed opex includes staffing, insurance and administration costs, and are incurred whether or not the plant is operating. Variable costs include consumables, maintenance and spare parts.

Fuel: The cost of biomass to operate the power plant is estimated to contribute around 50% of the LCOE. More feedstock is needed to operate a biomass power plant with carbon capture installed, on a per MWh generated basis, since the capture plant requires steam and power from the main power plant, thus reducing its overall output and efficiency. The use of advanced solvents that reduce regeneration energy consumption, or process improvements to improve overall efficiency could reduce the amount of biomass required, and therefore costs.

CO_2 Transport and Storage (T&S): This is the cost of transporting the captured CO_2 to the final geological storage site. Transportation is most likely to be through onshore and offshore pipelines, but may also be NPT methods such as shipping, road or rail. T&S costs have been estimated to contribute around 15% of the LCOE for biomass CCS plants, but this will depend on the specific project and could contribute higher in some estimates. In ‘hubs’ or ‘clusters’, T&S costs will be shared amongst several, separate CO_2 emitter/capture projects, significantly reducing the costs placed on an individual project.

Hydrogen BECCS

Hydrogen BECCS is the production of hydrogen from biogenic feedstocks via gasification or an alternative pathway, combined with CCS.

Hydrogen BECCS covers different technologies and approaches at different TRLs. In its 2023 Biomass Strategy[33], the previous government identified multiple biomass pathways that rely on

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[64] Wood (2018), Assessing the Cost Reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology
[65] IEA (2020) Projected Costs of Generating Electricity
[66] Ricardo (2020) The Potential of Bioenergy with Carbon Capture

gasification, including hydrogen production, and noted that gasification is a priority area for innovation.

The government's £31 million Hydrogen BECCS Innovation Programme and £60m Direct Air Capture and other Greenhouse Gas Removal Innovation programme (both part of NZIP) have supported several gasification-based projects including that led by Compact Syngas Solutions, together with alternative pathways such as dark fermentation (led by Biorenewables Development Centre) and thermal catalytic conversion (led by CATAGEN).[67]

In a review of advanced gasification technologies for government in 2021, a specific hydrogen BECCS process based on gasification and syngas treatment technologies currently under development was studied. The studied process uses biomass pellets as a feedstock (1 Mtpa) and so is at a much larger scale than current demonstration projects.[68] In general, gasification-based projects (for syngas production and power) have historically suffered from poor plant availability, particularly during the early years of operation. The study assumed 85% availability for a FOAK hydrogen BECCS plant but also noted that real life gasification-based installations have achieved much lower availabilities. There are several reasons for these low availabilities including: a drive to use cheaper waste fuels which are more difficult to process (compared to clean biomass pellets) and are more variable meaning it is harder to produce syngas of consistent quality; feedstock that is incompatible with the installed equipment; poor quality construction and a lack of redundancy; system integration issues; contamination and fouling challenges; poorly performing main units such as gasifiers and syngas treatment units. Integration with all the downstream processes required for hydrogen BECCS also adds additional technical risks to the project and further potential to negatively impact the level of availability that can be achieved. Therefore, an important area of development is the demonstration of sustained levels of high availability in commercial operation conditions.

Table of innovation needs (hydrogen BECCS)

This section details key components and areas of technology innovation required to reduce cost and accelerate the deployment of the technologies assessed in this report. This section draws from the previous EINAs research with updated assessments. The table details the direct technology impacts of innovations, as well as the other EINAs technologies that could benefit from innovation in these areas. Each innovation is assessed according to its likely impact on cost reduction and deployment for the relevant technology, with a qualitatively assessed 1 (very low) – 5 (very high) impact rating. The timeframe column refers to the time period within which the innovation could be expected to have material implications for the UK energy system and Net Zero with investment and innovation. Column descriptors within the table are defined as following:

- Technology: technologies where the innovation is applicable.
- Other impacts: other technology families that are indirectly impacted by this innovation.

[67] BEIS (2022) Hydrogen BECCS Innovation Programme
[68] BEIS (2021) Advanced Gasification Technologies - Review and Benchmarking

- Cost reduction: how the innovation opportunity can reduce the overall costs of the technology, rated from 1 (low) to 5 (high).
- Barrier reduction: how the innovation opportunity can contribute to reducing barriers to deployment, rated from 1 (low) to 5 (high).
- Time frame: period over which the innovation could feasibly be adopted and start scaling.

Table 8: Innovation needs for hydrogen BECCS

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
All	Construction of mid scale demonstration facilities; sustained reliable operation to remove uncertainties	All	N/A	3 – Can facilitate scaling up and cost reduction (capex and opex)	5 - Can reduce reputational and financing risks once technology considered proven	2030s
Feedstock	Using cheaper waste fuels (with biogenic content for BECCS); will need to overcome negative impacts on plant reliability, e.g. waste feedstocks are generally more variable making it more difficult to produce syngas of consistent quality, waste feedstocks may contain contaminants that can form slag or cause equipment damage	Syngas production	Transferable to other low-carbon fuel production, EfW	4 – Reduced feedstock costs (potentially negative gate fees), which is a key contributor to lifecycle costs, but may increase capex and opex	4 – Reduction in costs can contribute to greater market certainty and public acceptance; greater fuel flexibility	2030s
Feedstock	Improved sorting and pre-processing of heterogenous waste fuels to reduce costs and improve gasification performance	Feedstock handling	Transferable to other low-carbon fuel production, power BECCS, EfW	4 – Reduced feedstock costs, which is a key contributor to lifecycle costs, but may increase capex and opex	3 – Reduction in costs can contribute to greater market certainty and public acceptance	2030s

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Gasification	Improvements to gasifier designs to allow improved feedstock flexibility, reduced maintenance requirements and improved syngas quality	Syngas production	Transferable to other low-carbon fuel production, EfW	3 – Potentially allows reduced feedstock costs and greater availabilities	3 – Reduction in costs can contribute to greater market certainty and public acceptance; potential greater fuel flexibility	2030s
Gasification / Biomass conversion technology	Alternative gasification methods such as entrained flow gasification which may achieve higher efficiencies and cost reductions through larger scale units; will need to overcome lower calorific values and ash fusion temperatures of biomass feedstocks, as well as feedstock variability	Syngas production	Transferable to other low-carbon fuel production, potentially EfW	4 – Reduced feedstock consumption, which is a key contributor to lifecycle costs; improved yields; potential reductions in capex	3 – Reduction in costs can contribute to greater market certainty and public acceptance; potential environmental benefits	2030s

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Gasification	Replacement of Air Separation Unit (ASU) to produce oxygen with a membrane unit or similar next generation technology	Syngas production	Transferable to other low-carbon fuel production, potentially EfW, other sectors such as steel and ammonia production	2 – Reduced consumables costs	2 – Reduction in costs can contribute to greater market certainty and public acceptance	2030s
Syngas treatment and reforming	Improved syngas treatment technologies to control contaminant concentrations and reduce energy requirements	Syngas cleanup	Transferable to other low-carbon fuel production, potentially EfW, other sectors such chemicals sector	3 – Potentially reduced feedstock consumption (or improved yields) and reduced opex, potentially improved availability (improvement in revenues)	2 – Reduction in costs can contribute to greater market certainty and public acceptance	2030s
Syngas treatment and reforming	Improved syngas upgrading technologies to improve hydrogen yield and which can be combined with CCS	Hydrogen production	Transferable to other low-carbon fuel production, potentially EfW, other sectors such chemicals sector	2 – Potentially improved yields (improvement in revenues)	2 – Increase in revenues can contribute to greater market certainty and public acceptance	2030s

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Syngas treatment and reforming	Catalysts with improved performance and lower costs	Hydrogen production	Transferable to other low-carbon fuel production, potentially EfW, other sectors such chemicals sector	2 – Potentially reduced opex	2 – Reduction in costs can contribute to greater market certainty and public acceptance	2030s
CO_2 capture	Advanced solvents that improve performance by reducing regeneration energy consumption, reducing losses, and reducing thermal and oxidative degradation	CCS	Transferable to gas CCS, waste and industrial sectors where reduction in energy (steam) consumption is important	4 – Reduced energy consumption, which is a key contributor to lifecycle costs (fuel costs), as well as solvent replacement costs	3 – Reduction in costs can contribute to greater market certainty and public acceptance; potential environmental benefits	2030s
CO_2 capture	Next generation solvents such as hot potassium carbonate solvents, other non-amine-based solvents and non-aqueous solvents	CCS	May be transferrable to gas CCS, waste and industrial sectors	4- Potentially reduced energy consumption, which is a key contributor to lifecycle costs (fuel costs)	3- Potential environmental benefits compared to amine-based solvents; reduction in costs can contribute to greater market certainty and public acceptance	2030s

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
CO_2 capture	Next generation technologies such as solid sorbent, pressure swing adsorption, rotating packed beds, pressurised water absorption, fuel cell and membrane-based capture technologies, and other innovations, and their applicability to hydrogen BECCS plants	CCS	May be transferrable to gas CCS, waste and industrial sectors	4- Potentially reduced energy consumption, which is a key contributor to lifecycle costs (fuel costs), improvements in hydrogen purity allowing sales to wider markets (improved revenues)	3 – Reduction in costs can contribute to greater market certainty and public acceptance; potential environmental benefits	2030s
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.	All	Transferable to other BECCS processes	4- Reduction in consumables cost, which is a key contributor to lifecycle costs	3 – Reduction in cost can contribute to greater market certainty and public acceptance	2030s

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Waste disposal	Approaches to minimise production of hazardous solid residues; use of inert materials as secondary aggregates	Waste treatment	All BECCS, chemicals sector, EfW	3 – Reduced waste disposal costs; potential environmental benefits	3 – Potential environmental benefits; reduction in costs can contribute to greater market certainty and public acceptance	2030s
Waste disposal	Approaches to reduce amount of tars and other hazardous material in effluent stream; improvements to on-site effluent treatment systems	Waste treatment	All BECCS	3 – Reduced waste disposal costs; potential environmental benefits	3 – Potential environmental benefits; reduction in costs can contribute to greater market certainty and public acceptance	2030s
All	Modularisation of entire systems or individual components	All	Transferable to gas CCS, waste and industrial sectors	2 – Facilitates scaling up, quicker construction, mass manufacture of modular components, simplified plant designs; potential reductions in capex	4 – Can help establish supply chains quicker	2030s

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
All	Improve reliability across the entire process chain allowing reduced downtime, e.g. by improving integration, adding redundancy, pre-processing feedstock to improve compatibility with installed equipment, increased operational experience	All	Transferable to other low-carbon fuel production, potentially EfW, other sectors such chemicals sector	3 – Improved availabilities (improvement in revenues)	5 - Can reduce reputational and financing risks once technology considered proven	2030s
All	Novel hydrogen BECCS technologies other than gasification, e.g. fermentation, wastewater treatment, reforming of biogas from anaerobic digestion, bio-electrochemical systems	Hydrogen production	May be transferable to other low-carbon fuel production, and other sectors such as water and waste sectors	2 – Potential reduced feedstock costs	3 – Potential environmental benefits; reduction in costs can contribute to greater market certainty and public acceptance	2030s
MRV	Development of technology-specific MRV to enable robust carbon accounting and assignment of credits to support carbon market	All	Other GGRs	1 – Limited potential for cost reduction	4 – Can increase confidence in quality of removals contributing to market certainty and public acceptance	2030s

Components and costs

Percentage figures in this section are from the Advanced Gasification Technologies Review and Benchmarking study (2021)[69], for a FOAK, large scale 1Mtpa wood pellet plant with rich CO_2 stream capture only.

- Capex: Capex includes project development, engineering, procurement, construction and commissioning. Capex reduction could be achieved through scaling up to exploit economies of scale, modular designs and common fabrication techniques. Capex has been estimated to contribute around 25% of the total levelised cost of hydrogen.
- Fuel: The cost of biomass pellets in the specific process analysed in the 2021 study is estimated to contribute around 35% of the levelised cost of hydrogen. Reductions in biomass costs (or increases in hydrogen yields) may be achieved through process improvements and new catalysts to improve reaction efficiencies. Fuel costs can also be achieved using cheaper waste fuels, albeit this may require higher capex and opex.
- Fixed opex: Fixed opex is estimated to contribute around 15% of the levelised cost of hydrogen. Fixed opex includes staffing, administration costs and maintenance.
- Variable opex: Variable opex is estimated to contribute around 30% of the levelised cost of hydrogen in for the specific process analysed in the 2021 study. Variable opex for this process includes consumables, predominantly oxygen (used as a fluidising medium along with steam in a fluidised bed gasifier) and imported electricity (to run the process). Variable opex reduction could be achieved through recovery of waste heat to generate some or all of the electricity requirements for the plant, or to generate oxygen.

BECCS Fuel: Sustainable aviation fuel from gasification and Fischer-Tropsch

The UK government is set to introduce a Sustainable Aviation Fuel (SAF) mandate from 2025 that will require 2% of UK jet fuel demand to be met by SAF in 2025, increasing to 10% in 2030 and 22% in 2040[70]. SAF can be produced using a range of technologies including hydro-processed esters and fatty acids (HEFA), alcohol-to-jet (AtJ), gasification/Fischer-Tropsch (gasification/F-T); and power-to-liquid (PtL)[71].

Gasification/F-T can be considered a form of BECCS since CO_2 can be captured from the process and stored. However, it is not a form of GGR as, when burned, SAF releases CO_2 emissions similar to those from fossil fuels. Whilst not net-negative, it has been estimated that SAF from gasification/F-T can reduce lifecycle greenhouse gas emissions of jet fuel by 85% to 94% compared to fossil fuels[71].

The gasification/F-T process involves several steps. First, a syngas is produced from the gasification of biomass. The syngas undergoes Fischer-Tropsch synthesis to create liquid hydrocarbons, which are subsequently refined into biokerosene (aviation/jet fuel). CO_2 can be

[69] AECOM & Fichtner (2021) Advanced Gasification Technologies - Review and Benchmarking
[70] Department for Transport (2024) Sustainable aviation fuel initiatives
[71] World Economic Forum (2020) Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation

captured from the CO_2 rich stream extracted from the shifted syngas; CO_2 can also be captured from the flue gas, albeit at a higher cost per tonne captured compared to the rich stream.

While gasification and Fischer-Tropsch as individual processes have been considered commercial for some time, their integration for SAF production using biogenic feedstocks[72] has not been demonstrated at commercial scale[73]. The largest gasification/F-T plant to date was Fulcrum Bioenergy's Nevada plant which began operation in late 2022 but shut down in May 2024 before the company filed for bankruptcy[74]. RedRock Biofuels also suffered setbacks; its Oregon plant was closed in 2023 before construction was complete. Ongoing planned projects include Velocys' Bayou Fuels facility in Mississippi and Altalto facility in the UK[75].

Many of the same innovation opportunities that apply to hydrogen BECCS also apply to SAF from gasification/F-T as they share similar process steps up to the production of syngas, discussed in the table in section 3. Additional innovation opportunities related to the F-T process may include R&D and demonstration of catalysts that have a higher selectivity towards the jet fraction, and R&D and demonstration of improved reactor designs[73].

[72] Note that SAF produced from energy crops is not eligible under the SAF Mandate.
[73] IEA Bioenergy (2024) Progress in Commercialization of Biojet/Sustainable Aviation Fuels (SAF): Technologies and policies
[74] Chemical and Engineering News (2024) Fulcrum BioEnergy abandons trash-to-fuel plant in Nevada
[75] Velocys (Accessed: 2025) Sustainable Aviation Fuel is critical to achieving net zero carbon aviation

DACCS

Overview of DACCS

Direct Air Carbon Capture & Storage (DACCS) is the removal of CO_2 directly from the air, typically using chemicals or minerals. There are multiple approaches being developed by at least 100 startups[18]. In most methods, atmospheric air is brought into contact with a liquid solvent or solid sorbent that captures CO_2, which is later released by heating, varying pressure and/or electrochemical methods. First generation liquid solvent approaches (e.g. Carbon Engineering) tend to require higher temperature energy inputs, whereas solid sorbent approaches (e.g. Climeworks) tend to require lower temperatures but have greater non-energy operating costs since lifecycle solid adsorbent costs can be high. However, within each of the liquid and solid categories, there are diverse approaches with varying energy requirements and cost structures. Additionally, many second generation DACCs approaches do not neatly fit into the liquid-high temperature/solid-low temperature categorisation, e.g. technology pursued by Holocene employs a liquid solvent operating at low temperatures[76], Heirloom's technology is based upon the reactivity of calcium oxide (lime) with CO_2 in the atmosphere[77]. The Technology Readiness Level (TRL) varies but is up to 7-8 for the most advanced methods.

The only existing plants in the UK are at pilot scale, including those funded by the UK government's £60m Direct Air Capture and other Greenhouse Gas Removal Innovation programme[78] which was part of the Net Zero Innovation Portfolio (NZIP).

Globally, the largest existing plant is owned by Climeworks in Iceland ('Mammoth') and is expected to capture 36 ktCO_2pa[79] using a solid sorbent approach; Climeworks is also developing a larger facility at the 'Project Cypress' DAC hub in Louisiana, US. Construction is also underway by 1PointFive in the US to build a plant ('Stratos') capable of capturing up to 500 ktCO_2pa[80] using Carbon Engineering's liquid solvent technology. Heirloom is developing a facility alongside Climeworks at the Project Cypress DAC hub, with an ambition to achieve 100 ktpa by 2027[81].

The definition of DACCS is still evolving. As well as liquid solvent- and solid sorbent-based approaches, it often includes processes that involve rapid mineralisation of CO_2 at the earth's surface, sped up by industrial processes, which are referred to as mineral carbonation (e.g. Heirloom's technology). It generally excludes certain engineered ocean-based GGR methods, sometimes referred to separately as Direct Ocean Capture (DOC).

[76] The Holocene (2023) DAC via a liquid, low-temp system
[77] Heirloom (Accessed: 2025) Heirloom Carbon Technology
[78] DESNZ (2022) Direct Air Capture and Greenhouse Gas Removal Innovation Programme (closed to applications)
[79] Climeworks (2024) Climeworks switches on world's largest direct air capture plant
[80] 1pointfive (Accessed: 2025) Stratos
[81] Heirloom (Accessed: 2025) Driving investment in America's energy capital

As for all GGR methods, the main significance of DACCS to meeting net zero targets is its ability to deliver net negative emissions in order to offset the sectors that are most difficult to decarbonise (e.g. aviation, industry, agriculture) and to take back CO_2 that is already in the atmosphere.

Table of innovation needs

This section details key components and areas of technology innovation required to reduce cost and accelerate the deployment of the technologies assessed in this report. This section draws from the previous EINAs research with updated assessments. The table details the direct technology impacts of innovations, as well as the other EINAs technologies that could benefit from innovation in these areas. Each innovation is assessed according to its likely impact on cost reduction and deployment for the relevant technology, with a qualitatively assessed 1 (very low) – 5 (very high) impact rating. The timeframe column refers to the time period within which the innovation could be expected to have material implications for the UK energy system and Net Zero with investment and innovation. Column descriptors within the table are defined as following:

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

Table 9: Innovation needs for DACCS. Sources: [82], [83], [84], [85], Mott MacDonald

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
All	Demonstration of a range of DACCS approaches at scale to provide real-world data to verify performance and remove uncertainties	All DACCS	N/A	3 – There are currently at least 100 DACCS startups; demonstration at scale would allow the market to converge on the most successful approaches, potentially facilitating scaling up and cost reduction (capex and opex)	3 – Reduction in costs can contribute to greater market certainty and public acceptance	2030s
Capture	R&D and demonstration of novel liquid solvents and solid sorbents with improved capture performance, reduction in energy required to release CO_2 (regeneration), reduced degradation rates and harmful degradation products	Liquid solvents/solid sorbent approaches	May be transferrable to other carbon capture applications such as in power, waste and industrial sectors	4 – Performance impacts cost of energy for DACCS, which is a key contributor to lifecycle costs, as well as the cost of the solvent/sorbent itself	4 – Reduction in costs can contribute to greater market certainty and public acceptance	2030s

[82] IEAGHG (2021) Global Assessment of Direct Air Capture Costs.
[83] Energy Systems Catapult (2023) DACCS
[84] IEA (2022) Direct Air Capture: A key technology for net zero
[85] Oxford Institute for Energy Studies (2023) Scaling Direct Air Capture (DAC): A moonshot or the sky's the limit?

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Capture	R&D and demonstration of novel air contactors such as passive air flow that rely on wind or natural airflow, to reduce costs	All DACCS	May be transferrable to other carbon capture applications such as in power, waste and industrial sectors	2 – Performance impacts cost of energy for DACCS, which is a key contributor to lifecycle costs	2 – Reduction in costs can contribute to greater market certainty and public acceptance	2030s
Capture/resources	R&D and demonstration of emerging DAC technologies such as electrochemical regeneration methods, which could require less energy, mineral carbonation and membrane-based technologies	All DACCS	May be transferrable to other carbon capture applications such as in power and industrial sectors	5 – Performance impacts cost of energy for DACCS, which is a key contributor to lifecycle costs	5 – Reduction in costs can contribute to greater market certainty and public acceptance	2030s

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Resources	R&D and demonstration of 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	Approaches requiring high-temperature heat, predominantly liquid solvent-based approaches	May be transferrable to fuel switching applications for industrial decarbonisation	3 – Performance impacts cost of energy for DACCS, which is a key contributor to lifecycle costs	3 – Reduction in costs can contribute to greater market certainty and public acceptance	2030s
Resources	R&D and demonstration of integration of large heat sources for DACCS such as from nuclear generation, Energy from Waste (EfW) plants, or emerging heat sources such as geothermal or low-grade waste heat from heat networks.	Approaches that require low-temperature heat, predominantly solid sorbent-based approaches	N/A	5 – Performance impacts cost of energy for DACCS, which is a key contributor to lifecycle costs	5 – Reduction in costs can contribute to greater market certainty and public acceptance	2030s

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Resources	Research on optimal location of DACCS projects with access to low-carbon energy (renewables, waste heat), CO_2 transport and storage, land and water, and suitability of the UK's climate	All DACCS	N/A	4 – Optimising locations has been shown to reduce overall DACCS costs (e.g. energy costs, T&S costs)	5 – Potential environmental benefits; reduction in costs can contribute to greater market certainty and public acceptance	2030s
Resources	R&D and demonstration of approaches to reduce water footprint including use of lower-quality water	Predominantly liquid solvent-based approaches which has higher water consumption than solid sorbent-based approaches	Green hydrogen production and other water-intense technologies	1 – The cost of water is not normally a major contributor to lifecycle DACCS costs	4 – The availability of water may limit the locations that particular DACCS technologies can be deployed at	2030s

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Process	R&D and demonstration of flexible DACCS plants to match variable renewable generation (e.g. rapid start up and shut down and optimisation of operation/cycles) to reduce curtailment of renewable energy.	All DACCS	May be transferrable to other applications such as in power, waste and industrial sectors	1 – Potentially limited impact on DACCS cost reduction, but potential reductions in overall system costs.	2 – Required to allow DACCS to play a flexible role in the system	2030s
Construction	R&D and demonstration of modularisation of entire systems or individual components, e.g. solid sorbent filters	All DACCS although more likely to be applicable to low-temperature, solid sorbent-based approaches	May be transferrable to other applications such as in power, waste and industrial sectors	2 – Facilitates scaling up, quicker construction, mass manufacture of modular components, simplified plant designs; potential reductions in capex.	4 – Facilitates quicker development of supply chains for modular components	2030s
MRV	Development of technology-specific MRV to enable robust carbon accounting and assignment of credits to support carbon market	All DACCS	Other GGRs	1 – Limited potential for cost reduction	2 – Can increase confidence in quality of removals contributing to market certainty	2030s

Components and costs

DACCS is currently a relatively expensive technology. However, since the technology remains in the nascent stages, there is significant scope for cost reduction. There is uncertainty around how low DACCS costs may fall in the future. In some independent studies, costs for DACCS projects have been estimated to fall by around 75% between 2030 and 2050[82], although many vendors claim even greater falls are achievable. Areas for cost reduction areas including reduced energy costs and capex.

Capex: Capex includes project development, project management, engineering, procurement, construction, commissioning and connection to a T&S network, including treatment equipment to ensure the CO_2 meets the network specifications. Capex reduction could be achieved through novel techniques, scaling up to exploit economies of scale, longer plant lifetimes, modularisation to allow for mass production and mature supply chains. Capex, together with financing costs, have been estimated to contribute to around 25% of the total cost of capture ($/t$CO_2$ captured) in a Nth-of-a-kind (NOAK) plant[82].

Energy: Energy is needed primarily for regeneration of the solvent/sorbent (to release CO_2), but also to operate air contactor fans and balance of plant. Access to low-cost, low-carbon energy is often cited as a key factor determining economic viability. This could be wind energy in the UK or, globally, solar PV. For processes requiring only low-temperature heat, energy costs can be reduced by using waste heat from large sources, such as nuclear power and Energy from Waste (EfW) plants, particularly where output is consistent to maximise the load factor of the DACCS plant and CO_2 capture. Energy costs can also be reduced by improving the efficiency of DACCS processes, for example, through the use of better performing capture chemicals, novel air contactors or novel regeneration methods. The contribution of energy costs to the total cost of capture ($/t$CO_2$) depends heavily on the DACCS technology and the source of energy; it has been estimated to contribute around 40% of the total cost of capture for high-temperature liquid solvent-based approaches, and around 20% for low-temperature solid sorbent-based approaches[82].

Non-energy opex: This includes the cost of staffing, regular inspections of equipment, maintenance and replacement parts. Current solid sorbent-based approaches also require the frequent replacement of sorbents, which is one of the technologies key cost contributors. Total non-energy opex (including sorbent/solvent replacement) has been estimated to contribute around 40% of the total cost of capture for solid sorbent approaches, whereas this is only around 20% for liquid solvent-based approaches.

CO_2 Transport and Storage (T&S): This includes the cost of transporting the captured CO_2 to the final geological storage site or point of use (utilisation). Transportation is most likely to be through onshore and offshore pipelines, but may also be via shipping, road or rail. In ‘hubs’ or ‘clusters’, T&S costs may be shared amongst several, separate CO_2 emitter/capture projects, significantly reducing the costs placed on an individual project. T&S costs have been estimated to contribute around 10% of the total cost of capture for DACCS[82].

In principle, DACCS can be installed anywhere, although optimal siting of projects requires several factors to be considered including the availability of low-cost, low-carbon energy, and the location of CO_2 T&S infrastructure. Modelling by Energy System Catapult indicated that large heat sources (such as nuclear power plants, including small modular reactors), are favoured as the primary source of heat; a small number of large DACCS plants is favoured in order to reduce new build infrastructure and grid reinforcement costs; this leads to the conclusion that lowest-cost DACCS can be achieved at very large DACCS sites co-located with waste heat sources[86], and with access to shared T&S infrastructure.

Geological storage

Overview of geological storage

Geological CO_2 storage is the process of permanently storing captured CO_2 deep underground, either onshore or offshore. Storage requires connected, underground pore spaces that together form a reservoir with an impermeable cap rock to contain the CO_2 within the reservoir. The underground CO_2 plume is monitored using a range of Measurement, Monitoring and Verification (MMV) techniques to verify the permanence of the storage.

The UK has significant geological storage capacity: the UK Continental Shelf (UKCS) has an estimated theoretical CO_2 storage capacity of 78 billion tonnes in saline aquifers or depleted oil and gas fields[22], which could potentially meet the UK's needs for hundreds of years.

In saline aquifers and depleted oil fields, CO_2 must be compressed to high pressures and stored over 800m underground in its dense phase to ensure pressure is maintained. Depleted gas fields are lower pressure, so the CO_2 is stored in its gas phase during the early life of the reservoir.

As well as suitable geology, the UK benefits from technical skills, capabilities and supply chains from the oil and gas sector.

There are only a handful of industrial scale CO_2 storage projects for sequestration in operation (although CO_2 injection for enhanced oil recovery is commonplace in North America but does not always qualify as permanent storage). One project is the Sleipner CCS facility in the North Sea (Norway). The UK does not currently have any operational CO_2 storage sites, although several are under development as part of Tracks 1 and 2 of the UK government's CCUS Cluster Sequencing process, including the HyNet cluster which will store CO_2 in depleted gas fields in the Irish Sea, the East Coast Cluster (ECC) which will store CO_2 in saline aquifers in the southern North Sea, the Acorn cluster in Scotland and the Viking cluster in the Humber region. The Northern Endurance Partnership (NEP) Track 1 project, which will transport and store CO_2 for the ECC, reached financial close in December 2024 and is expected to start up from 2028[87].

[86] Energy Systems Catapult (2023) DACCS
[87] Northern Endurance Partnership (2024) Northern Endurance Partnership greenlights UK's first CO2 transportation and storage infrastructure project

Non-Pipeline Transport (NPT)

Non-Pipeline Transport (NPT) is the transportation of CO_2 using road, rail and/or shipping.

NPT will be important for capture projects outside the CCUS clusters, where a pipeline is technically and/or commercially unfeasible. It has been estimated that roughly half of the industrial emissions in the UK sit outside industrial clusters, and not all clusters have direct access to geological storage (e.g. South Wales). Capture projects in the UK using NPT could potentially capture around 15 Mtpa CO_2 by 2035[88].

NPT can also help unlock a market in cross-border CO_2 T&S and in unconventional sources of capture, such as HVAC GGRs. For example, by establishing CO_2 shipping and port facilities, NPT can open cross-border CO_2 transport networks to neighbouring countries, providing access to the UK's large offshore geological storage capacity. The CCSA's CCUS Delivery Plan 2035 estimates that the UK has sufficient storage to import around 20Mtpa CO_2 by 2035 from neighbouring countries[89].

It is therefore important to demonstrate NPT technically and commercially to bring down costs.

[88] DESNZ (2024) CCUS: non-pipeline transport and cross-border CO2 networks - call for evidence
[89] CCSA (2022) CCUS Delivery Plan 2035

Table of innovation needs

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

Table 10: Innovation needs for geological storage

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Exploration, appraisal and characterisation	R&D of technologies and methods that can model, simulate, and appraise stores faster with a high degree of confidence	All storage	Limited	3 – Reduces appraisal and characterisation time; potential reductions in project development costs	1 – Limited direct impacts; reduction in costs can contribute to greater market certainty and public acceptance	2025-2030
Infrastructure	Development and demonstration of pressure management technologies to increase injectivity	All	Limited	4 – Reduces cost per tonne CO_2 stored (capex and opex)	4 – Limited direct impacts; reduction in costs can contribute to greater market certainty and public acceptance; better T&S availability reduces barriers for capture plants	2025-2030

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Infrastructure	Deploying sub-sea installations instead of platforms	Offshore storage	Limited	4 – Reduction in capex costs	3 – Limited direct impacts; reduction in costs can contribute to greater market certainty and public acceptance	2030s
Infrastructure	Improve resilience of injection wells (especially for less pure CO_2 streams)	All	Limited	2 – Reduction in opex	2 – Limited direct impacts; reduction in costs can contribute to greater market certainty and public acceptance; reduces barriers for capture plants	2030s
MMV	Development and demonstration of advanced technologies – e.g. fibre optic, chemical, gravity monitoring etc, and without the need for wells	All	Limited	2 – Reduction in MMV costs, although MMV contributes a relatively small proportion of overall storage costs	3 – MMV improvements increases certainty in safe and stable storage potentially increasing public acceptance	2030s

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Reservoir	R&D and demonstration of unconventional storage such as in ultra-mafic and basalt rocks, including CO_2 monitoring tools	Favourable geologies	Limited	2 – Uncertain	2 – Uncertain, but may open up additional storage sites in some areas of the UK (e.g. Scotland, Northern Ireland[90])	2040s
Infrastructure	R&D and demonstration of 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)	All	May also benefit onshore CO_2 processing equipment and for CO_2 transportation	4 – Can contribute to capex and opex reductions	2 – Limited direct impacts; reduction in costs can contribute to greater market and public acceptance	2030s
Exploration, appraisal and characterisation /MMV	R&D and demonstration of novel sensors to reduce appraisal and storage monitoring costs	All	May also benefit CO_2 detection at onshore CO_2 processing and transportation	2 – Reductions in MMV costs, although MMV contributes a relatively small proportion of overall storage costs	3 – MMV improvements increases certainty in safe and stable storage potentially increasing public acceptance	2030s

[90] Carbfix (Accessed: 2025) Carbfix Atlas

Component	Innovation opportunity	Technology	Other impacts	Cost reduction	Barrier reduction	Time frame
Exploration, appraisal and characterisation /MMV	R&D and demonstration of methods to process and interpret large volumes of monitoring data, predictive analysis, automation and other digital innovations to improve reservoir management	All	Potential applications within a wide range of sectors	2 – Reductions in MMV costs (although MMV contributes a relatively small proportion of overall storage costs)	3 – MMV improvements increases certainty in safe and stable storage potentially increasing public acceptance	2025-2030
MMV	R&D and demonstration of CO_2 monitoring techniques outside of the storage formation into either the surrounding geology or atmosphere	All	May also benefit CO_2 detection at onshore CO_2 processing and transportation	2 – Reductions in MMV costs (although MMV contributes a relatively small proportion of overall storage costs)	3 – MMV improvements increases certainty in safe and stable storage potentially increasing public acceptance	2025-2030

Sources: [41], [91], [10], [92], [42], Mott MacDonald

[91] IEAGHG (2020) Value of Emerging and Enabling Technologies in Reducing Costs, Risks and Timescales for CCS
[92] IEAGHG (2020) Monitoring and modelling of CO2 Storage: The Potential for Improving the Cost-Benefit Ratio of Reducing Risk

Components and costs

Geological storage costs vary significantly depending on the specific storage site. In an early study carried out by the IEAGHG and Zero Emissions Platform (ZEP) on the costs of CO_2 storage, estimated costs ranged significantly depending on the storage scenario assessed (by as much as 400%)[93]. Site factors that contribute to this large range include:

- Offshore storage is more expensive than onshore
- Large capacity sites with higher injection rates requiring fewer injection wells reduce capex on a £ per tonne stored basis
- Well characterised sites with significant, reliable existing data (e.g. depleted oil and gas fields) are less expensive than sites that have not been explored
- In certain cases, existing infrastructure such as pipes and wells can be re-used reducing capex.

Pre-FID activities: These may include site appraisal studies, seismic studies, injection testing, reservoir characterisation, permit application and general project development activities. The scope of studies required during this phase will depend on how much data is already available.

Capex: This includes the construction or refurbishment of off-shore structures, drilling of new wells and/or refurbishment of legacy wells.

Opex: This includes operations and maintenance, mainly related to the operating injection wells and offshore structures.

Monitoring, measurement and verification (MMV): MMV is required to address risks related to injectivity, capacity, containment and public acceptance[92]. Activities may include the drilling of monitoring wells, deployment and operation of sensors, MMV operating costs, operational and final seismic surveys and post-closure MMV costs. Although the overall contribution of MMV to costs is less than capex and opex, MMV potentially has greater scope for future cost reduction including through optimisation of MMV techniques from other industries for CO_2 monitoring[10].

Close down: This phase may include decommissioning of injection wells and offshore structures.

Deployment of multiple, large scale storage sites over time is also expected to contribute to the reduction in overall costs, e.g. as CO_2 appraisal becomes routine, and CO_2 corrosion resistant steel, cement and other components are manufactured at scale[10].

[93] IEAGHG (2010) The Costs of CO2 Storage: Post-demonstration CCS in the EU

CO_2 usage

CO_2 usage is the capture and repurposing of CO_2 for useful purposes. Usage of CO_2 minimises emissions and maximises the reuse, recycling, and removal of carbon to create a sustainable carbon cycle. Climate benefits depend on the source of the CO_2 (fossil, biogenic or air-captured), the product that is being displaced and how long the CO_2 is retained in the product.

Worldwide, CO_2 is already being used in several industries with the majority being used for urea/fertiliser production and enhanced oil recovery. Other industries include food processing, carbonated drinks, chemicals production, metals and agriculture.

As CO_2 becomes more abundant with the construction of carbon capture projects, there will be more opportunities for the usage in addition to geological storage of CO_2, particularly at dispersed sites. CO_2 use for synthetic fuels is considered a key route. Others include chemicals production, CO_2 mineralisation, horticulture and industrial applications.

In an earlier study assessing the potential for CO_2 usage in the UK, the TRLs of the potential usage activities were judged as follows[94]:

- Bauxite residue carbonation – TRL 9
- Carbonisation of aggregates from different industrial wastes – TRL 4-9
- Concrete curing – TRL 7-8
- Novel cements – TRL 3-6
- Horticulture – TRL 9
- Polymer processing – TRL 8
- Synthetic methane – TRL 7-8
- Synthetic methanol – TRL 8
- Formate and formic acid for agricultural applications – TRL 5-8
- Proteins for aquaculture and agriculture feed – TRL 3-7
- Omega-3 for aquaculture feed – TRL 6-7
- Proteins as human food substitutes – TRL 5-7
- Ethanol as a chemical intermediate – TRL 5-7
- Algae growth for biofuels – TRL 5-7
- Nano-carbon materials for advance engineering – TRL 5-6
- Precipitated carbon minerals – TRL 5-6

[94] Imperial, ECOFYS (2017) Assessing the potential of CO2 utilisation in the UK

Notable CO_2 usage projects from carbon capture in the UK include the UK's first PCC facility installed on a gas turbine at Tata Chemicals Europe facility near Northwich. This is designed to capture up to 40ktpa of CO_2, which is then dehydrated and purified into food grade CO_2 for the production of pharmaceutical grade bicarbonate of soda[11].

Several CO_2 usage projects participated in the CCUS 2.0 Innovation Competition, part of the NZIP innovation programme, including projects to investigate the use of CO_2 to create net-zero concrete (led by Concrete4Change) and the use of CO_2 as a raw material in the production of surfactants (led by Econic Technologies). Additionally, Mission Zero Technologies, a direct air capture developer that participated in the NZIP innovation programme, are partnering with OCO Technology to ultimately supply CO_2 to OCO for the manufacture of carbon negative aggregate[95]. Other companies, such as CarbonCure in North America, are developing and commercialising carbonated concrete production.

Once CO_2 is more abundant, slipstreams may be taken from the capture/transportation networks and cleaned up and utilised on location or transported to the usage site via road or rail.

It is expected that the market size for CO_2 usage will remain limited compared to dedicated storage[96]. However, the use of air-captured and biogenic CO_2 for usage has the potential to decarbonise other industries and replace the fossil carbon molecules in fuels and products.

Many of the potential uses of CO_2 are niche and/or do not utilise large amounts of CO_2. Key drivers to encourage the growth of existing and upcoming usage technologies will be include the cost of the products of utilised CO_2 compared to the existing alternatives. For instance, the cost of producing sustainable aviation fuel from biogenic CO_2 and green hydrogen can be reduced by requiring less heat, or by improving the yield of kerosene compared to diesel from the Fisher Tropsch process (see call-out box in BECCS section above). Many of the usage technologies listed above are not yet at TRL 9 and so innovation and demonstration at scale of each of these technologies is required to determine the technologies that can be cost effective, and reduce capex and opex (including reducing the energy required) to make the products cost competitive.

Innovation opportunities include reducing energy costs during the conversion of CO_2, development of advanced conversion routes, and demonstrating the reliability of CO_2-based construction materials and permanence of carbon stored within them (e.g. through long term trials).

Opportunities for cost savings could include co-locating the usage technologies close to sources of CO_2 such as the UK transportation and storage clusters, to reduce transport and storage costs. This could also apply to CO_2 captured at locations away from transport and

[95] OCO (2022) OCO Technology moves to pilot plant for next stage of DAC programme
[96] IEA (Accessed: 2025) Carbon capture and utilisation

storage clusters, such as the UK's CHP, EfW, biomass and industrial emitters that are dispersed around the UK.

The production of fuels with CO_2 and hydrogen from domestic sources has the ability to secure hydrocarbons for industries and sectors that are hard to abate, and also support energy security.

Major barriers to deployment include the availability of captured CO_2, the ability to transport the CO_2 from the emitter to the utiliser and the cost impact on the products being made with the utilised CO_2 (including competitiveness with current CO_2 suppliers).

Manufacturing key chemicals and materials from captured CO_2 can also increase the UK's security of supply and reduce dependence on imported natural gas.

Government policies targeting CO_2 usage include the Sustainable Aviation Fuel (SAF) mandate, which aims to decarbonise aviation fuel.

System benefits from innovation in carbon management technologies

System modelling to assess the potential impact of innovation in key net zero technologies was conducted using UKTIMES, an energy system model of the UK that was developed by UCL and the UK Department of Business, Energy and Industrial Strategy (now the Department for Energy Security and Net Zero or DESNZ). For each of the selected technologies, 3 levels of innovation were developed representing a low, medium and high innovation case for the technology. The low innovation level represents a business-as-usual case where innovation follows recent trends or is generally limited, whilst the high innovation case represents significant innovation in the technology to decrease costs and improve efficiencies.

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

- Minimally Constrained (MC): Designed to show the largest potential impacts from innovation investments by minimising the number of constraints on the energy system. UK Government data assumptions are used across the scenario.
- High Hydrogen (HH): 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 H2 demand ranges in the DESNZ Hydrogen transport and storage networks pathway policy paper published in 2023, and provisional figures from DESNZ sector teams that are set to be refined further for CB7. A maximum hydrogen consumption in each sector and a minimum overall level of consumption is applied in each year from 2035 to 2050.
- High Diversification (HD): Based on the Minimally Constrained scenario, this scenario aims to be more energy secure through two means, 1) limiting imports of key commodities to reduce UK reliance on overseas resources, and 2) diversifying resource and technology use across the economy to limit the impacts of any supply interruptions, price rises or technology failures.

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

- Direct consequences are a reduction in cost or an improvement in the quality of the energy service supplied by the technology. Only cost reductions are examined in the UK TIMES energy system model.
- Indirect consequences are changes to the wider system caused by a relative change of cost of a technology relative to other technologies. If the deployment of a technology increases due to a lower cost and the deployment of alternative technologies reduces then a cost reduction will be realised. This cost reduction will be lower than the direct cost reduction 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.

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.

The below analysis refers only to the technologies presented in this report. It should be noted that given these results are an output of the system modelling and the three hypothetical scenarios developed for the EINAs that they do not reflect UK government deployment targets and ambitions.

Gas CCS with Post Combustion Capture (PCC)

The technology has no generation across all runs in all three scenarios, even when its cost is reduced. However, it is important to note that this is because UK TIMES has limited temporal resolution and does not model on a short-term or hourly basis, in this case not accounting for the value of grid stabilisation that gas CCS can provide.

Separate modelling undertaken by NESO showed that low-carbon dispatchable plants (gas CCS and hydrogen-to-power) play an important role in the system by operating flexibility to match demand during periods of low renewables or stored energy. In its advice to government on achieving clean power by 2030, NESO sees gas CCS and hydrogen-to-power as important in the short term, delivering up to 2.7GW by 2030[32]. Furthermore, the CCC, in its recommendations to government for the UK’s Seventh Carbon Budget, sees 15GW of low-carbon dispatchable power by 2040 and 38GW by 2050[8].

BECCS

On a systems level and based on UK TIMES modelling, BECCS related technologies are integral for UK decarbonisation. The provision of negative emissions by BECCS, which are valuable in addressing residual emissions in hard to abate sectors such as aviation, is a key factor in driving uptake in the model. Hydrogen BECCS and power BECCS are the main deployed technologies in this category, whilst BECCS-fuel (biokerosene production through Fischer-Tropsch synthesis in particular) does not deploy at significant levels when based on cost-optimisation, assumed biomass availability and cost data available at the time of the analysis. There is uncertainty on the relative cost of hydrogen BECCS versus BECCS-fuel given limited data, which impacts whether the model chooses to prioritise available biomass for hydrogen or biokerosene production.

BECCS deployment remains broadly consistent when other technologies are innovated, suggesting limited sensitivity to cost and efficiency in other assessed technologies as well as high significance to the system. Biomass availability used in the analysis is consistent throughout all runs based on the ambitious supply scenario from the government's Biomass Strategy (2023)[97]. It should be noted that there are uncertainties around overall availability of biomass and market barriers which needs to be overcome for these levels of deployment to be to be achieved (see the barriers and enablers section for more detail). Innovation runs for offshore wind and ASHP slightly delay BECCS deployment, which suggests that faster residential sector decarbonisation reduces the use of BECCS to meet emission limits prior to 2050. The lowest BECCS deployment level across model runs is observed when only DACCS is innovated, in this case with noticeable impact in the High Diversification scenario but limited impact (relative to innovation in other technologies) in the other two scenarios.

[97] Department for Energy Security and Net Zero (2023) [Biomass Strategy 2023]

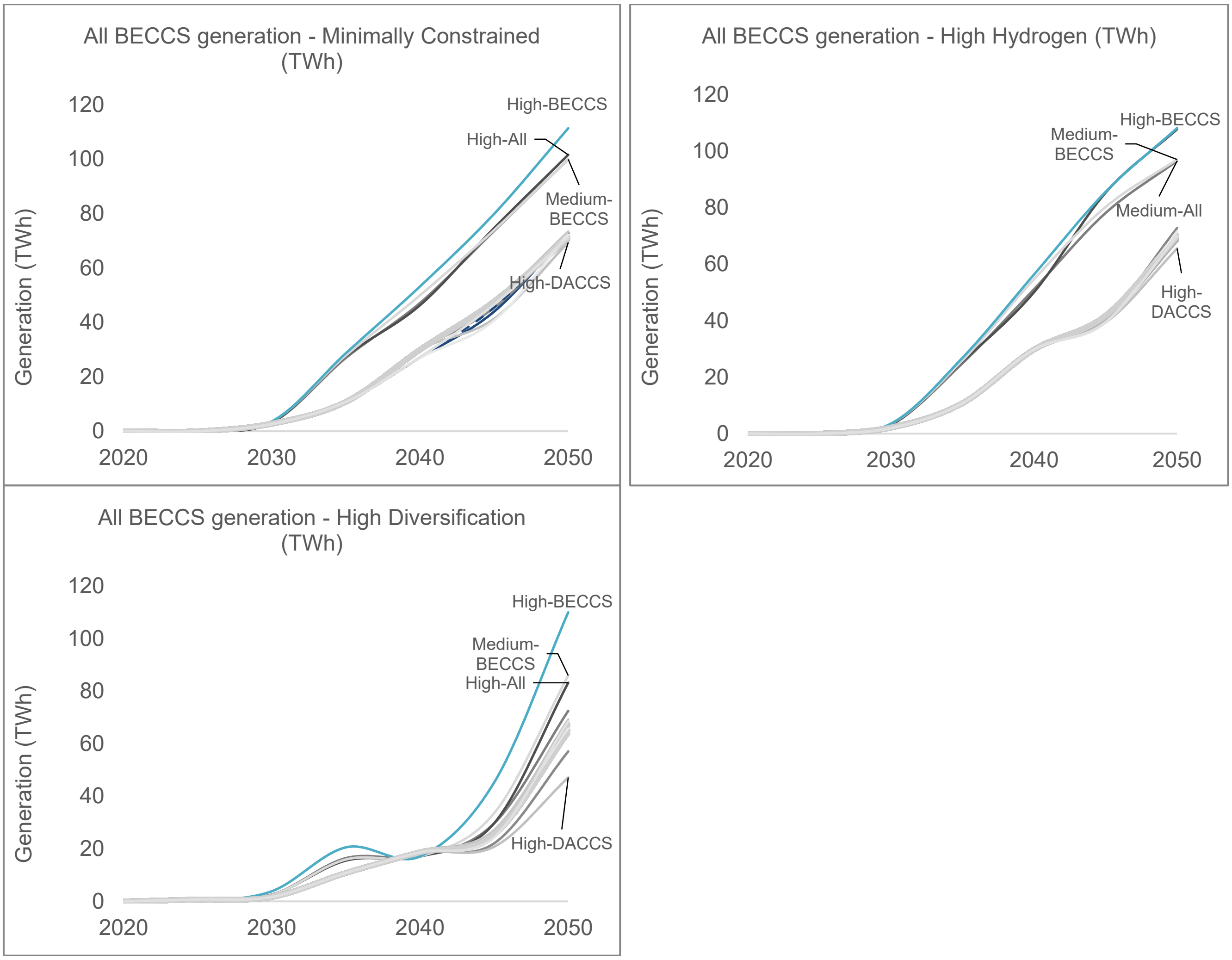

Figure 1: BECCS generation (TWh) over time across different innovation runs (low, medium and high levels for each technology) in all scenarios

Installed capacity of BECCS (cumulative of all BECCS technologies) is highest in the High Diversification scenario, reaching 23GW in the medium and high innovation runs for the technology. This is compared to 17GW to 18GW for both levels of innovation in the High Hydrogen and Minimally Constrained scenarios.

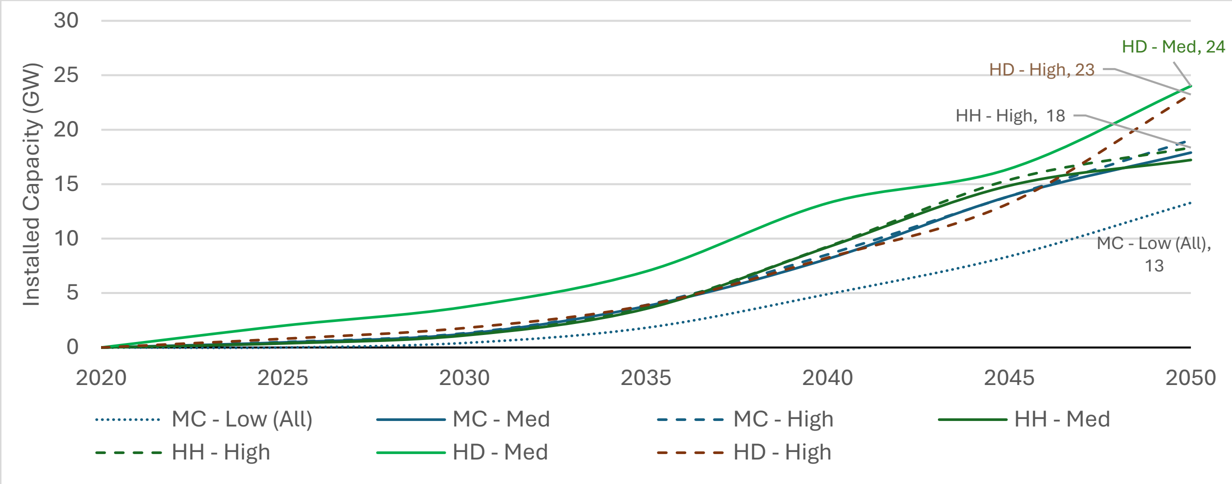

Figure 2: Installed capacity (GW) of BECCS (cumulative) by innovation level and scenario

Given the relatively consistent deployment of BECCS across innovation levels for all technologies, significant cost savings could be realised through innovation of the technology across differing future states of the UK energy system. Cumulative cost savings of between £55.5 billion and £75.8 billion could be realised at the high innovation level across the 3 scenarios compared to a cost saving of between £22.4 billion and £46.2 billion for the medium innovation levels, as shown in Figure 3: Cumulative cost savings (in real 2022 £) to 2050 for differing levels of innovation in BECCS technologies, compared to base all low innovation case.

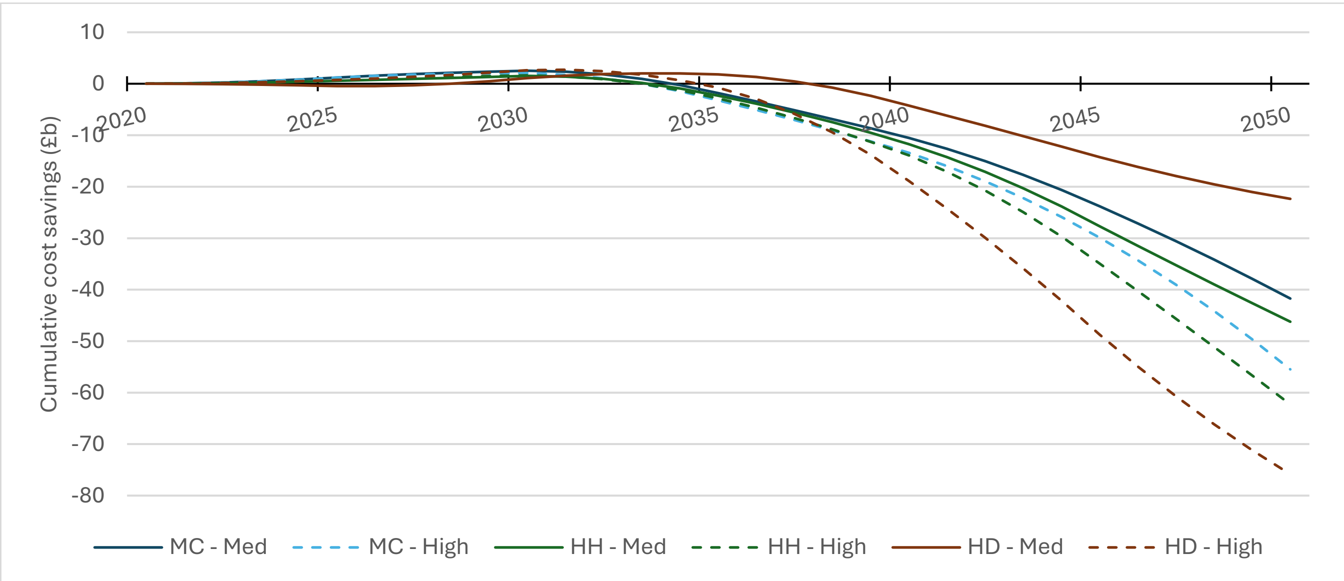

Figure 3: Cumulative cost savings (in real 2022 £) to 2050 for differing levels of innovation in BECCS technologies, compared to base all low innovation case

As shown in Figure 4, innovation in BECCS significantly reduces offshore wind generation and electrolyser use within the Minimally Constrained scenario in 2050. On the other hand, geological storage increases to accommodate for additional CO_2 storage needs while hydrogen transport use increases due to the increased biogenic hydrogen generation.

Innovation in BECCS also reduces the need for DACCS, as higher levels of BECCS deployment reduce the need for other negative emission technologies.

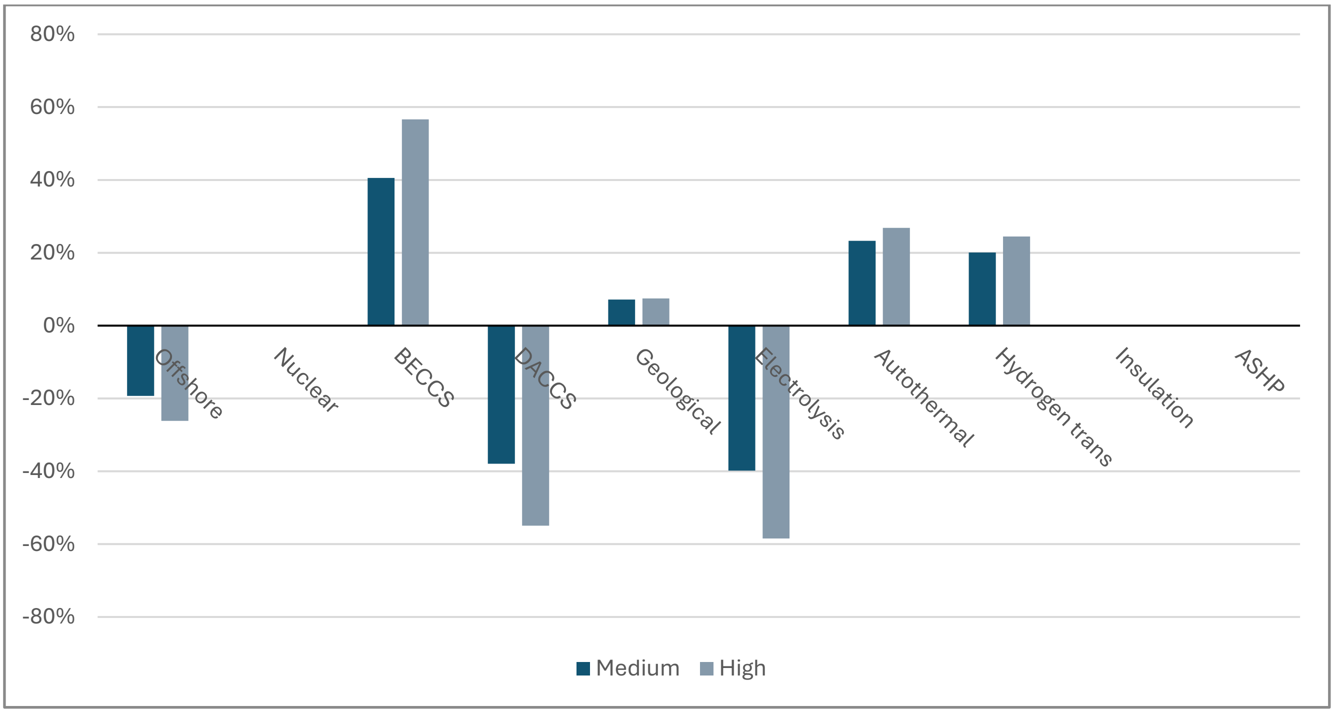

Figure 4: Impact of innovation in BECCS technologies on generation / deployment of other technologies in 2050 compared to low innovation level run for Minimally Constrained
Note – tidal, depleted gas field storage, gas-CCS, H2 turbines, and GSHP have all been excluded as their generation / deployment is either zero or too limited to provide meaningful comparison. Additionally, short and medium storage system modelling is performed using the HighRES model and so are also excluded.

DACCS

Similar to BECCS, DACCS is an integral technology within the UK TIMES model as it offsets hard to abate greenhouse gas emissions. Across the three modelled scenarios, medium innovation and high innovation DACCS runs increase CO_2 captured from DACCS by a factor of 1.4–1.7 and 2.1–2.8, respectively. DACCS deployment remains broadly consistent across innovation levels across the majority of technologies. This reflects the constraint on DACCS deployment at the low innovation level, and low sensitivity to innovation in other technologies. A significant exception is high innovation within BECCS, which noticeably diminishes DACCS removals. This suggests that while highly valuable as source of carbon offset, other technologies providing a similar carbon removal function (e.g. BECCS or other GGR technologies) could significantly impact DACCS deployment if more cost competitive and able to scale.

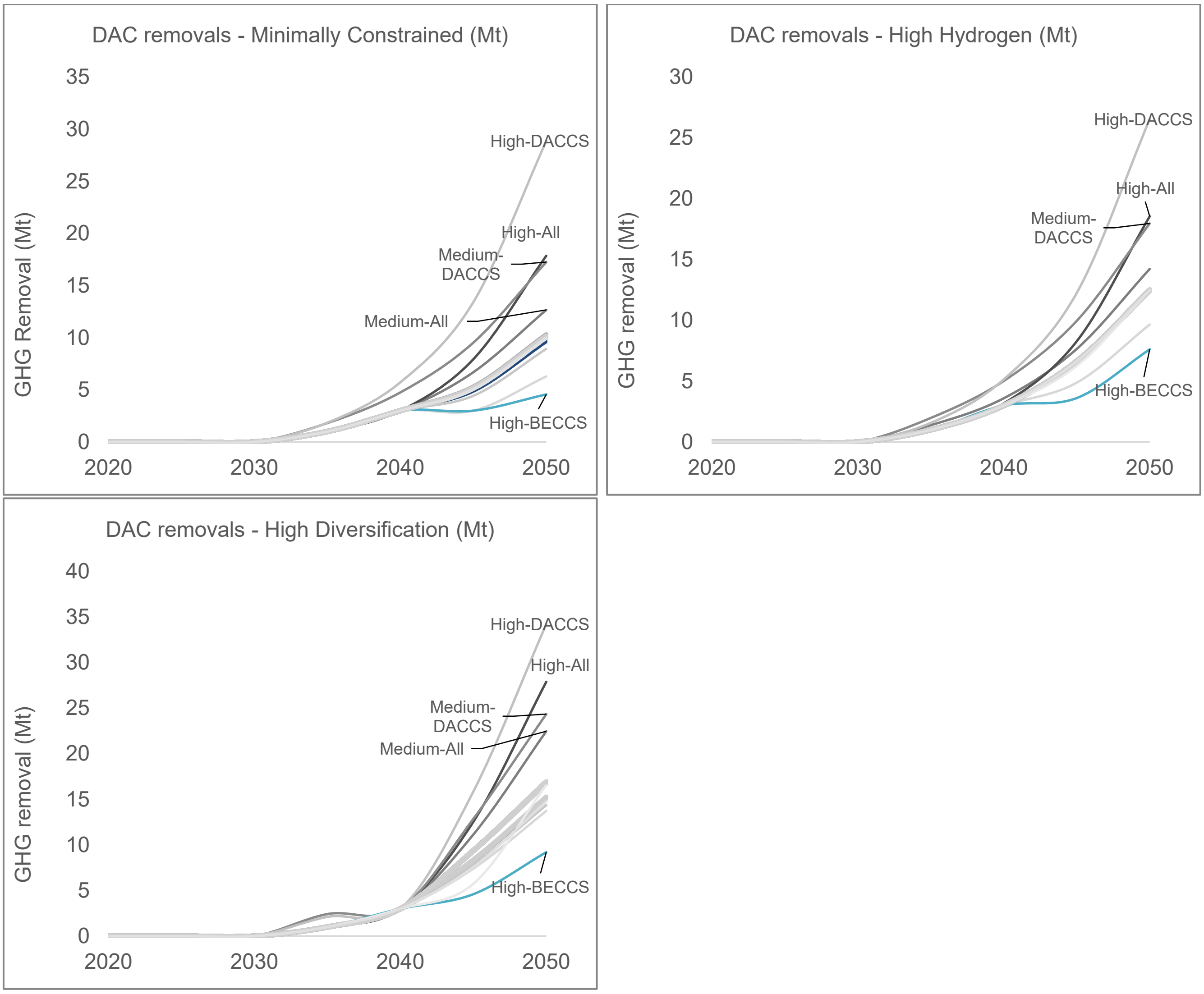

Figure 5: DACCS removals (Mt) over time across different innovation runs (low, medium and high levels for each technology) in all scenarios

Significant savings could be realised through innovation in DACCS due to its necessity to reaching net zero targets. Cumulative savings via innovation in DACCS, compared to the low innovation case, reaches £61.8 billion in the High Diversification scenario in 2050 compared to £39.9 billion in High Hydrogen and £31.2 billion in Minimally Constrained. The financial benefits of these savings starts from around 2040 as the DACCS deployment ramps up. The elevated savings also suggests potential high impact where innovation directly or indirectly addresses emissions from hard to abate sectors (e.g. faster and more cost-effective aviation decarbonisation reducing need for carbon removals), however this could not be considered in more detail in the analysis given the technology scope of the EINAs.

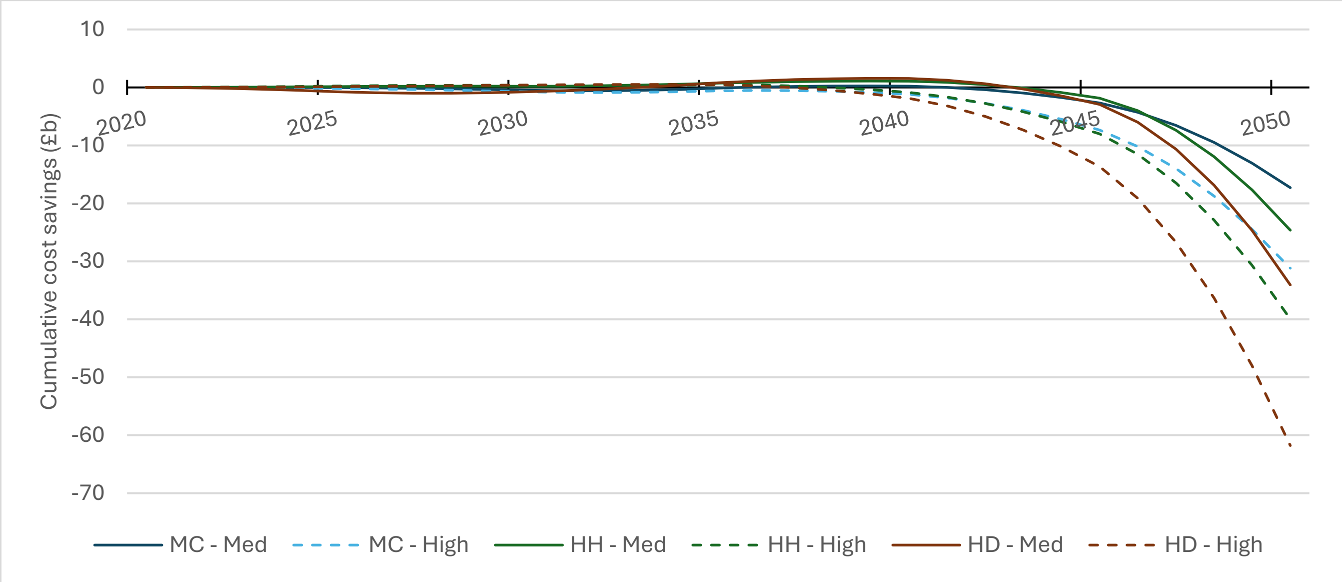

Figure 6: Cumulative cost savings (in real 2022 £) to 2050 for differing levels of innovation in DACCS technologies, compared to base all low innovation case

Geological storage

Innovation in geological storage does not significantly alter or accelerate its adoption compared to all low innovation runs, indicating that the base scenarios already heavily rely on geological storage across all three scenarios. Innovation in negative emissions technologies, BECCS and DACCS, increases the need for geological storage by 2050. This is particularly for High Diversification innovation runs for DACCS, requiring 5–7 Mt additional CO_2 storage by 2050.

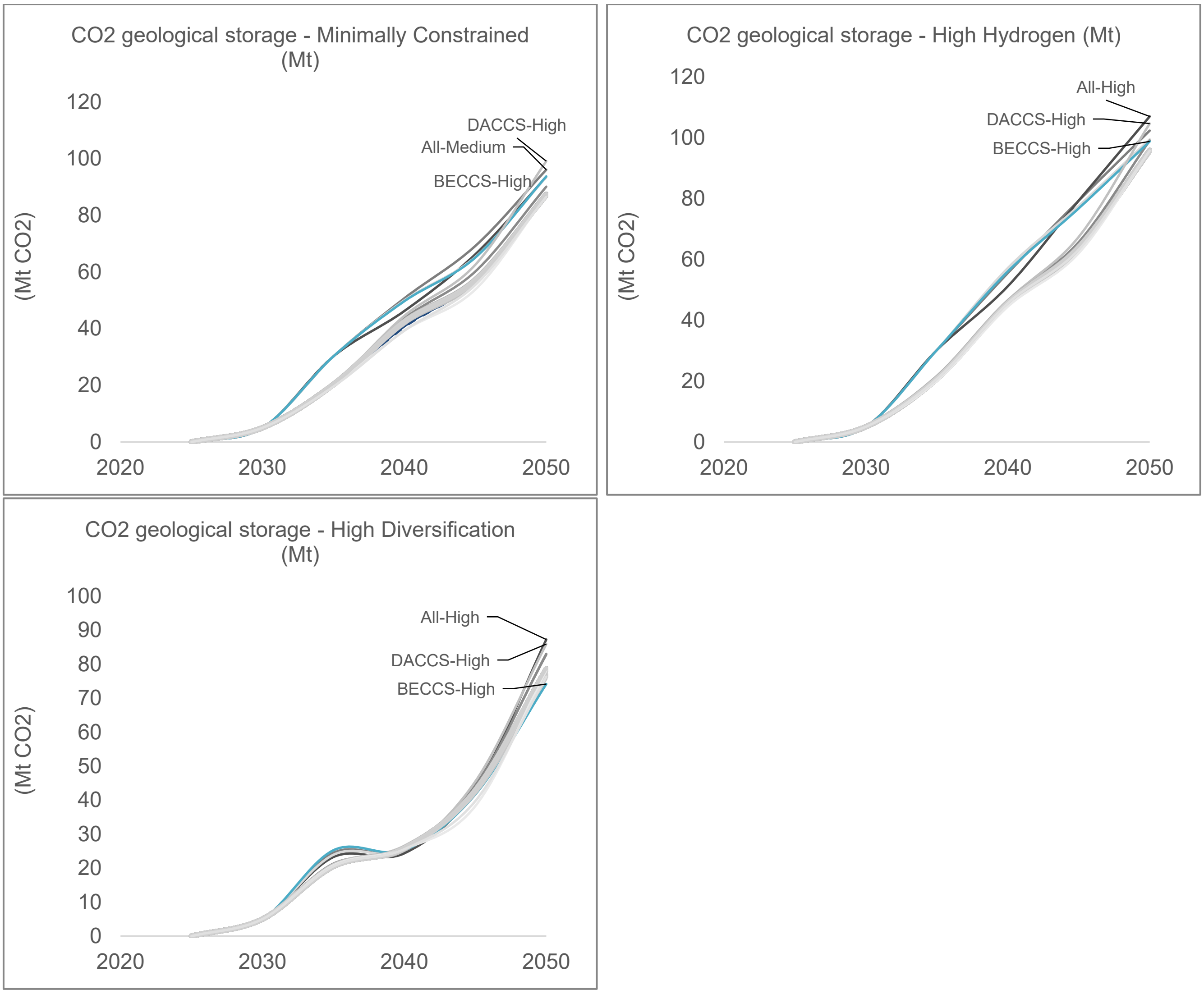

Figure 7: Geological storage (Mt) over time across different innovation runs (low, medium and high levels for each technology) in all scenarios

Due to the relatively consistent deployment of geological storage across all scenarios, the cumulative cost savings across all three do not vary to a large extent. Cumulative savings for High Hydrogen reaches £6.7 billion in 2050 for the high innovation scenario, compared to £4.8 billion in the High Diversification scenario.

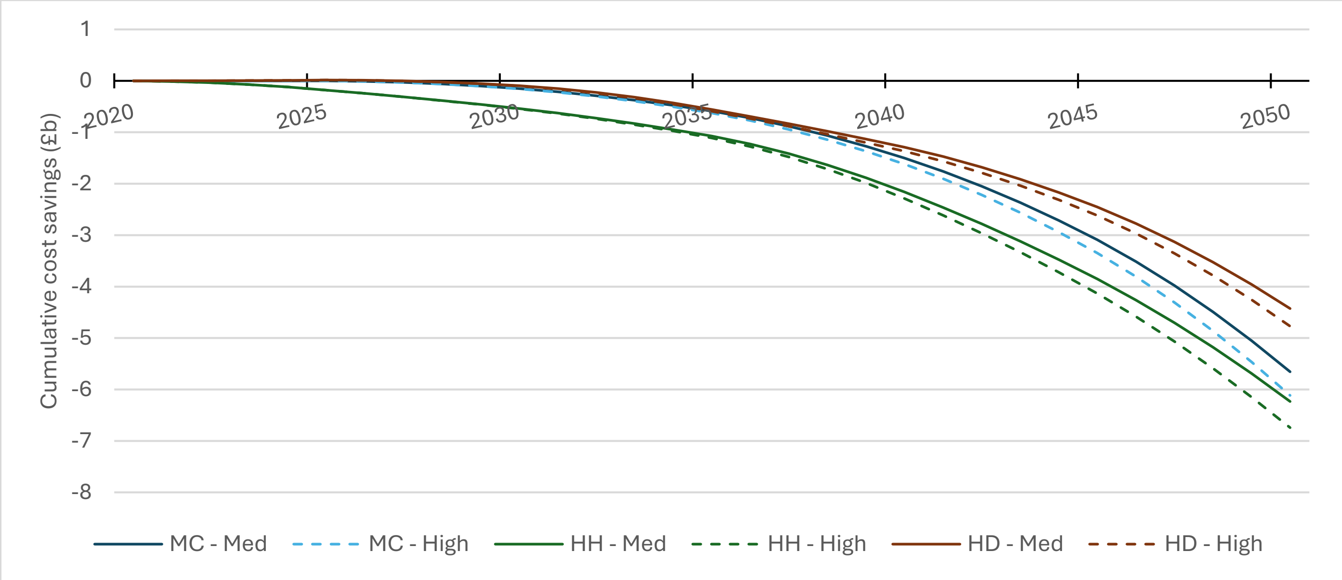

Figure 8: Cumulative cost savings (in real 2022 £) to 2050 for differing levels of innovation in geological storage, compared to base all low innovation case

Disruptive technologies

This section highlights key findings from DESNZ-commissioned research into emerging and potentially disruptive technologies additional to the primary EINAs assessment. The purpose of the disruptive technologies research is to:

- Provide insight on emerging technologies outside of the core EINAs scope and explore the potential impacts of deployment on the future energy system; and
- Provide options for further exploration as a supplementary evidence base to inform prioritisation of future government support for clean energy innovation.

The selection of emerging technologies and summarised insights presented was informed by independent qualitative sub-sector analyses and targeted engagement with stakeholders in the academic community, industry, and government.

The technologies highlighted in this section serve as illustrative examples drawn from a long-list of emerging or alternative approaches with the potential to contribute to net zero if successfully deployed at scale.

This section provides an overview of the key findings into novel GGR technologies, in particular on Biomass with Carbon Removal and Storage approaches (BiCRS). Emerging ocean-based carbon removal methods were noted to offer significant potential for scalable and outsized impact. However, these methods, such as ocean alkalinity enhancement and coastal blue carbon restoration, have not been covered in this report due to limited available data, but they are the subject of ongoing research exploring their carbon sequestration potential. These approaches warrant further investigation as part of a broader assessment of ocean-based GGR pathways.

These technologies offer a similar system function as DACCS and BECCS in UK TIMES, in that they allow removal of hard to abate emissions as the model approaches net zero in 2050. Given the high system cost savings observed when innovating BECCS and DACCS in the EINA analysis, ability by novel GGR technologies to compete in cost and scale could therefore have very significant system cost saving impacts.

Table 11: Novel GGR technologies: Biomass with Carbon Removal & Storage (BiCRS)

Overview: Biomass with Carbon Removal & Storage (BiCRS)	
Description of the technology	Biomass with Carbon Removal and Storage (BiCRS) describes a range of processes that use plants and algae to remove CO_2 from the atmosphere and store that CO_2 underground or in long-lived products. BiCRS is a term that has gained prominence in recent years as a more expansive nomenclature, compared to 'BECCS', for long-term storage of biogenic carbon. BiCRS and BECCS are both approaches that utilise biomass for carbon sequestration but differ in their primary objectives and processes.[98] BECCS approaches are focused on the production of a useful energy vector whilst capturing some or all of the biogenic CO_2 emitted in the conversion process. BiCRS approaches focus on ways to store biogenic carbon over long timescales, rather than the production of a useful energy vector. Below, BiCRS approaches prioritising biomass carbon storage over conversion to bioenergy have been explored. • Biochar is a carbon-rich solid produced from the pyrolysis of biomass (heating in the absence of oxygen), proposed as a long-term, stable carbon store. It may be possible to produce biochar, apply it to soil as part of agricultural or forestry activities, and gain dual benefits of improved soil quality and long-term carbon storage. • Bio-oil injection relies on pyrolysis of biomass, as with biochar, though instead here "fast pyrolysis" is performed to produce a greater content of a carbon-rich bio-oil product versus traditional pyrolysis. This bio-oil is then transported to an injection well, and permanently stored underground. • Biomass burying is the concept of collecting biomass, condensing it into dense blocks or bricks, and then storing these blocks underground in conditions under which they will not decompose further. Excludes storage in the typical geological formations associated with CCS. • Biomass slurry fracture injection: It has recently been proposed that biomass could be milled to particulates, mixed with a liquid to create a slurry, and then injected for permanent underground storage. • Biomass sinking: Sinking of terrestrial (e.g. straw) or marine (e.g. macroalgae) biomass in the marine environment where the biomass must reach the deep ocean where the carbon has the potential to be sequestered durably.[99]

[98] Sandalow, David, et al. "Biomass Carbon Removal and Storage (BiRCS) Roadmap.", Jan. 2021. https://doi.org/10.2172/1763937

[99] Smith, S. M., Geden, O., Gidden, M. J., Lamb, W. F., Nemet, G. F., Minx, J. C., Buck, H., Burke, J., Cox, E., Edwards, M. R., Fuss, S., Johnstone, I., Müller-Hansen, F., Pongratz, J., Probst, B. S., Roe, S., Schenuit, F., Schulte, I., Vaughan, N. E. (eds.) The State of Carbon Dioxide Removal 2024 - 2nd Edition. DOI 10.17605/OSF.IO/F85QJ (2024)

Overview: Biomass with Carbon Removal & Storage (BiCRS)	
Impact on the energy system	BiCRS approaches prioritise use of biomass for carbon removal and sequestration.[100] By converting biomass into stable carbon forms like biochar or bio-oil and storing it long-term, BiCRS can effectively remove CO_2 from the atmosphere. While energy production can be a secondary benefit, the primary impact of BiCRS lies in its ability to enhance carbon removal, making it a promising source of negative emissions for the offset of residual emissions in difficult-to-abate sectors.
Timescale	• Biochar production, as a readily available and scalable technology with hundreds of biochar production plants operating worldwide, is considered to be at a high TRL level of 8–9.[101] • Bio-oil injection is being demonstrated in relevant environments, with some early-stage operational deployments. The approach is estimated at TRL 5-7, and could achieve TRL 9 by 2027-2030.[102],[103] • Biomass burying is in the early stages of development, with laboratory research and small-scale field trials being conducted. The approach is estimated at TRL 3-6, with earliest estimates reaching TRL 9 by 2030.[104,105,106] • Biomass slurry fracture injection is in the advanced research and early demonstration phases, with ongoing efforts to validate and optimise the process in relevant environments. The technology is estimated at TRL 4-6, estimated earliest reaching TRL 9 by 2030.[107,108] • Biomass sinking is estimated to be in the proof-of-concept to early prototype testing phases of TRL 3-5, with earliest estimates reaching TRL 9 by 2030-2035.[109]

[100] Sandalow, David, et al. "Biomass Carbon Removal and Storage (BiRCS) Roadmap." , Jan. 2021. https://doi.org/10.2172/1763937
[101] Chiaramonti, D., Lehmann, J., Berruti, F., Giudicianni, P., Sanei, H., & Masek, O. (2024). Biochar is a long-lived form of carbon removal, making evidence-based CDR projects possible. *Biochar*, *6*(1), Article 81. https://doi.org/10.1007/s42773-024-00366-7
[102] The Charm Underground - 2024 Year in Review
[103] New protocol for Bio-oil Geological Storage
[104] Carbon Dioxide Removal (CDR) 2024-2044: Technologies, Players, Carbon Credit Markets, and Forecasts: IDTechEx
[105] Zeng, N., Hausmann, H. Wood Vault: remove atmospheric CO_2 with trees, store wood for carbon sequestration for now and as biomass, bioenergy and carbon reserve for the future. *Carbon Balance Manage* **17**, 2 (2022). https://doi.org/10.1186/s13021-022-00202-0
[106] Graphyte: Looking Back on 2024
[107] Brian F Snyder 2022 Environ. Res. Lett. 17 024013
[108] McKinsey, JPMorgan, Alphabet & Others Sign $58 Million Biomass-Based Carbon Removal Deal Through Frontier - ESG Today
[109] Roadmap — Seafields

Overview: Biomass with Carbon Removal & Storage (BiCRS)	
	However, some sources argue that the underpinning evidence supporting these BiCRS approaches is less mature, with remaining uncertainties in the ecological impacts of biomass production and storage, and long-term effectiveness of the carbon sequestration techniques.[110] For instance, the timescales for reversal of carbon removal upon biochar degradation in soil are not yet determined.[111]
Barriers	Scaled deployment of BiCRS approaches is expected to face challenges associated with competing land use requirements for food crops, forestry and natural habitats, validation of durability of carbon sequestration, and competing uses of biomass, such as for BECCS, biochemicals production, and bio-based construction materials.[112,113,114] Determining the optimal use of limited biomass resources will be important for maximising mitigation potential, as each application has its own benefits and trade-offs. For instance, prioritisation of bioenergy production will see biomass diverted to BECCS approaches which offer high permanence of CO_2 sequestration but with challenges in economic feasibility and land requirements.[115] Determining optimum utilisation of biomass resources will need to emerge through careful consideration of these trade-offs, making it an area of uncertainty in BiCRS deployment.
Key developers of the technology	There are various large scale biochar demonstration projects underway in the UK to enhance the evidence base around biochar benefits over the longer term, such as the Biochar Demonstrator. Bio-oil injection is a process pioneered by Charm Industrial in the USA. As their process is built on existing, working technologies and processes, they have been able to rapidly scale. An example of biomass burying is that taken by Graphyte, a USA based startup backed by Breakthrough Energy Ventures is applying this approach to agricultural wastes, in their "Carbon Casting" approach. Graphyte believe they can scale to billions of tonnes of carbon removal and can currently deliver at a cost below $100/tonne.

110 European Commission (2023). The EU Blue Economy Report. 2023
111 Roads to Removal: Options for Carbon Dioxide Removal in the United States, December 2023, Lawrence Livermore National Laboratory, LLNL-TR-852901.
112 Smith, S. M., Geden, O., Gidden, M. J., Lamb, W. F., Nemet, G. F., Minx, J. C., Buck, H., Burke, J., Cox, E., Edwards, M. R., Fuss, S., Johnstone, I., Müller-Hansen, F., Pongratz, J., Probst, B. S., Roe, S., Schenuit, F., Schulte, I., Vaughan, N. E. (eds.) The State of Carbon Dioxide Removal 2024 - 2nd Edition. DOI 10.17605/OSF.IO/F85QJ (2024)
113 European Commission (2023). The EU Blue Economy Report. 2023
114 Sandalow, David, et al. "Biomass Carbon Removal and Storage (BiRCS) Roadmap.", Jan. 2021. https://doi.org/10.2172/1763937
115 ***Green Chem.***, 2023,**25**, 2930-2957

Overview: Biomass with Carbon Removal & Storage (BiCRS)	
	Vaulted Deep is a carbon removal company focused on biomass slurry fracture injection. Vaulted Deep collects organic waste such as biosolids from municipal waste plants and livestock manure and injects it about a mile deep, at plants in Los Angeles and Kansas USA. In the biomass sinking space, Seafields Solutions is a UK-based aquaculture business conducting trials to sink seaweed bales for carbon removal, aiming to lock away carbon for millennia.

Market innovation barrier and enabler deep dives

As part of the EINAs, a barriers and enablers assessment was carried out across the prioritised technologies to understand the factors which should be considered in addition to technology innovation. This included qualitative analysis across eight variables:

- **Enabling infrastructure:** Common factors identified for CCUS and GGR projects included the availability of CO_2 T&S infrastructure or NPT for capture plants away from clusters. For DACCS, access to low-carbon heat and/or electricity (including grid connection) and water is also needed.
- **Regulatory environment:** The development of Monitoring, Reporting and Verification (MRV) frameworks that projects can follow to quantify and verify net negativity are essential to enable funding of GGR projects. Technology specific regulatory factors were also identified such as the need for further research and development of environmental standards and regulations for ocean removals.
- **Stakeholder acceptance:** Common factors identified included public perceptions of CCUS and/or GGR (e.g. whether they are seen as a deterrent to emissions reductions) and public willingness to pay. There are also public concerns around the sustainability of biomass, which is required for BECCS.
- **Availability of funding and investment:** DACCS companies have been particularly successful at attracting private equity in recent years. In general, this is not expected to be a high barrier should other barriers (e.g. business model viability) be removed.
- **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.
- **Resource availability:** The main resource required for BECCS projects is biomass feedstock (and the land and water needed to grow it). There are significant questions around whether sufficient volumes can be sourced sustainably, whilst competing with other potential biomass uses. For DACCS, low-carbon energy is required.
- **Supply chain:** 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.
- **Skills and training:** Skills shortages (to deliver at the scale required) and skills gaps in specific areas (e.g. marine scientists for ocean removals) have been identified as barriers.

Three of the key barriers identified are discussed in further detail in the sections below.

Deep dive 1: Market and revenue certainty

Investors need clear sight of long-term revenue models to support investment decisions. UK Emissions Trading Scheme (UKETS) carbon prices are currently too low to incentivise investments in CCUS and GGR at scale without additional interventions.

Many GGR companies participate in Voluntary Carbon Markets (VCMs) where organisations buy carbon credits as part of their voluntary climate commitments. This market has grown rapidly in recent years; the State of Carbon Dioxide Removal (2nd edition) estimated the purchase of credits for future CO_2 removal through engineered GGR grew to 4.6 Mtpa CO_2 equivalent in 2023, with the average weighted price of those credits ranging from $111 to $1,608 depending on the specific technology[18]. VCMs have played an important role in financing FOAK projects such as those being developed Climeworks and 1PointFive/Carbon Engineering in the DACCS sector. However, the size of future demand for credits from GGR projects is uncertain[18] and may not be large enough to deliver GGR at the Gtpa CO_2 scale needed to support global net zero targets.

Approaches available to policy makers to reduce uncertainty and accelerate deployment at scale include[4]:

- Grant funding for early demonstration projects, such as the Regional DAC Hubs Programme in the US with $3.5 billion of funding to help accelerate the demonstration and deployment of DACCS.[116]
- Public procurement, particularly in countries with state-owned energy companies, where government takes a direct or indirect role in projects, e.g. contracts to purchase power from gas CCS plants.
- Tax credits, such as the 45Q tax credits in the US which provides up to US $85/t CO_2 for dedicated geological storage, and up to $180/t CO_2 for DACCS projects.[117]
- Regulatory standards and obligations, such as a regulated asset base where costs are borne by consumers, or tradeable carbon capture certificates associated with a CO_2 storage obligation.
- Operational subsidies, such as Contracts for Difference (CfD) which cover the difference between higher levelised costs (capex and opex) and market revenues.

Policies will need to be flexible to accommodate changes over time throughout the energy transition. For example; First-Of-A-Kind (FOAK) CCUS projects will have higher capex and opex; gas CCS operating flexibly will need higher payments for power generated during limited running hours; load factors may change over time.

In the UK, government is rolling out a suite of CCUS business models (contracts) including:

[116] US DOE (Accessed: 2025) Regional Direct Air Capture Hubs
[117] IEA (2022) Inflation Reduction Act 2022: Sec. 13104 Extension and Modification of Credit for Carbon Oxide Sequestration

- Dispatchable Power Agreement (DPA), based on a CfD, to support gas CCS deployment
- Power BECCS business model, a dual CfD (for electricity and carbon), to support large BECCS for power >100MW
- Greenhouse Gas Removal (GGR) business model, based on a CfD (versus the price of negative emissions sold in the market), to support the deployment of engineered removals including DACCS and smaller scale BECCS <100MW
- Transport & Storage (T&S) business model (T&S Regulatory Investment (TRI) model), based on a regulated asset base model, to facilitate investment in T&S infrastructure.

In the short term, government intends to award contracts following an assessment process and bilaterial negotiations. This is currently underway for projects participating in Track 1 of the government's CCUS Cluster Sequencing competition. The first Track 1 projects reached financial close in December 2024 are now in the execution phase: Northern Endurance Partnership (NEP) (T&S infrastructure) and Net Zero Teesside (NZT) Power (gas CCS power plant), both part of the East Coast Cluster[118]. Additionally, in December 2023, government opened applications for CCUS and engineered GGR projects wanting to take part in the 'Track-1 expansion' of the HyNet cluster[119], with 6 projects being taken forward to the negotiations phase[120].

From 2030, the government expects to transition to a competitive allocation process[24]. During this phase, deployment will ultimately be constrained by the number and size of contracts that government is willing to award.

Over time, the government expects the evolution of the UKETS to be a key driver of investment in CCUS[24]. The UK ETS is a 'cap and trade' scheme, which caps total greenhouse gas emissions, creating a carbon market with a carbon price to incentivise decarbonisation. The government is currently consulting on how GGRs can be integrated into the UKETS[121].

Deep dive 2: Availability of CO2 Transport & Storage (T&S) infrastructure

The availability of CO_2 Transport and Storage (T&S) infrastructure is essential to allow investment in carbon capture projects such as gas CCS, waste CCS and industrial CCS, and GGR projects that require geological CO_2 storage.

The cost of T&S infrastructure can be shared amongst multiple capture projects close to one another, where each project feeds CO_2 into a network of pipelines that flow into one or more storage sites; this is often referred to as a 'cluster' or 'hub'. This reduces the T&S costs per

[118] DESNZ (2024) Contracts signed for UK's first carbon capture projects in Teesside
[119] DESNZ (2023) Carbon capture, usage and storage (CCUS) deployment: Track-1 expansion: HyNet cluster
[120] DESNZ (2025) HyNet expansion: project negotiation list - GOV.UK
[121] DESNZ (2024) Integrating greenhouse gas removals in the UK Emissions Trading Scheme

tonne of CO_2 captured and reduces the reliance of the T&S network on a single capture project.

Under the UK government's CCUS Cluster Sequencing process, the East Coast Cluster (ECC) at Teesside and the HyNet cluster at Merseyside have been selected as the first clusters to be deployed in the UK, in the mid-2020s, under 'Track 1'. Under 'Track 2', government has commenced engagement with the Acorn cluster in Scotland and the Viking cluster in the Humber region, targeting deployment from 2028 to 2029[122].

Over time, non-pipeline transport (NPT) can connect capture projects to existing clusters where pipelines are not technically or commercially feasible; this could be by road, rail or ship. This could also enable international CO_2 storage.

It should be noted that some engineered GGR approaches do not require geological storage. The production and distribution of biochar stores carbon in soils, although research is underway to understand the longevity of storage. Ocean alkalinity and fertilisation approaches increase the uptake of CO_2 from the atmosphere into the ocean; further work is needed to understand the carbon carrying capacity of the ocean for specific approaches, and the environmental impacts.

An alternative to geological storage of CO_2 is usage (the 'U' in CCUS). Usage is the direct use of CO_2 in various products such as synthetic fuels, chemicals and building aggregates. Emissions reductions depend on how long the CO_2 is retained, e.g. synthetic fuels when burned re-release CO_2. From a storage perspective, due to the limited market sizes, usage is not expected to play a major role; in the IEA's Net Zero Emissions (NZE) scenario, over 95% of CO_2 is stored underground and less than 5% used[123]. However, usage can have wider benefits such as replacing fossil fuel-based raw materials and supporting a circular economy[124]. Tata Chemicals captures 40,000 tpa CO_2 from a gas Combined Heat and Power (CHP) plant to use in the manufacture of sodium bicarbonate[11].

Deep dive 3: Supply chains

Although the UK construction supply chain is well developed, it cannot currently support the volume of projects planned to meet current CCUS targets in the UK[125].

A report assessing the UK CCUS supply chain revealed several constraints including[126]:

[122] Department for Energy Security and Net Zero (2023) CCUS Cluster Sequencing Track-2: Market update December 2023
[123] IEA (Accessed : 2025) Carbon capture and utilisation
[124] IEA (2019) Putting CO2 to use
[125] DESNZ (2023) Future policy framework for power with carbon capture, usage and storage (CCUS): call for evidence
[126] Arup (2023) A Remarkable New Infrastructure System' Opportunities for economic growth in the UK's Carbon Capture and Storage Industry

- Constraints in the construction and engineering workforces to meet demand ahead of 2030, e.g. some classes of welders, design engineers
- UK fabrication yard capacity to meet the demand for manufacture of column vessels, one of the largest items in a capture plant
- Logistics constraints including available storage space and the proximity of fabrication yards to projects
- Planning constraints, exacerbated by resourcing bottlenecks in regulatory authorities.

CCUS markets and equipment suppliers are global. If markets ramp up in several different countries at the same time (e.g. if CCUS opportunities become available simultaneously), there could be constraints on the ability of global equipment suppliers to meet demand. Therefore, early markets adopting CCUS may have an advantage.

Large amounts of commodities such as steel, concrete, copper and aluminium will be needed for CCUS and GGR projects. The availability of these will depend in part on global markets. The ability of the UK to meet the steel demand from CCUS has been identified as a specific constraint, in part due to past global shortages.

In the DACCS sector, building up a supply chain from a small base will require significant global expansion. Whereas some components are already manufactured for other industries, other components are bespoke to DACCS (e.g. solid sorbents) and supply chains at scale do not exist yet[127]. Even with significant investment, there are questions whether supply chains can scale up in time to meet global targets.

For BECCS, the availability of sustainable biomass will be a real constraint, including the availability of land and water to grow feedstocks, competition with other uses, and supply chains to harvest, process and transport biomass. The future availability of sustainable biomass is uncertain and challenging to predict[98]. Public perception of whether a particular biomass source is sustainable (regardless of whether or not it meets government and MRV criteria) may also contribute to constraints.

However, supply chain constraints are also an opportunity for UK supply chains to develop and capture a significant global share of the CCUS sector. The Carbon Capture and Storage Association (CCSA) has published several reports making recommendations to government and industry to focus supply chain strategies including: delivering the first round of CCUS projects under the government's CCUS cluster sequencing process; developing a set of supply chain guiding principles; and greater coordination of skills development[128]. In its Clean Power 2030 Action Plan, the UK government set out actions to build and accelerate the delivery of strong domestic supply chains through convening a new supply chains and workforce industry forum, funding from the National Wealth Fund and support from Great British Energy[129].

[127] Oxford Institute for Energy Studies (2023) Scaling Direct Air Capture (DAC): A moonshot or the sky's the limit?
[128] CCSA (2024) UK CCUS Supply Chain - Initial Forecast 2024: Main Report
[129] Department for Energy Security and Net Zero (2024) Clean Power 2030 Action Plan

Business opportunities in carbon management

Introduction

The purpose of this section is to explore the potential scale of the business opportunities for the UK associated with the national and global development of the CCS & GGR sector (as elsewhere in this report defined as BECCS (electricity), BECCS (hydrogen), BECCS (Fischer Tropsch), DACCS and geological storage technologies). Innovation will be a key driver in supporting the growth of this sector in the UK and realising these business opportunities, and therefore an important element to capture as part of this innovation assessment.

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

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

All results are illustrative of potential business opportunities of technological innovation. They are generated using a particular set of technologies, hypothetical deployment scenarios, modelling outputs and other assumptions to help inform UK Government decision making. Given the lower technological readiness of GGR methods and longer expected scale up timeframe, there is high uncertainty on the deployment level of these technologies and high variability depending on utilised scenario assumptions as well as developments in alternatives. Looking forward, results do not reflect UK government targets/ambitions regarding neither deployment of these technologies nor the economic opportunities that might be realised.

It is also important to stress that the results are specific to the particular technologies of focus for the report, rather than the GVA and employment for the wider sector within which these technologies may often be categorised. As such, care should be taken when comparing the figures presented below with estimations which cover the entire sector, and use different scenarios and models. In particular, **GVA and employment impacts of power or industry CCS are not included in the results shown below**. In the first case because of limited to no deployment of gas-CCS in UK TIMES runs this analysis is based on due to the nature of the model, and the second given that industry CCS is covered within the EINA Industrial Decarbonisation report.

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

Carbon Management (CCS & GGR) market landscape

UK market position

As discussed earlier in this report, CCS & GGR technologies are at a relatively nascent stage of development globally. No global leader has established themselves, although both the EU and the US are well placed, accounting for a significant share of investments in the sector to date. The UK has a particular market opportunity in relation to geological storage where it can benefit from both a large number of suitable sites as well as the existing technical expertise within the oil and gas sector.

Current deployment of CCUS and engineered GGR in the UK is mainly limited to pilot-scale projects, with no large-scale projects in operation.[130] This means that, at present, the UK accounts for a negligible share of the over 50 Mtpa CO_2 currently being captured by CCUS & GGR facilities globally.[131] Going forward, the government has committed £21.7 billion to developing the sector.

Global CCS & GGR market

This positioning puts the UK in a strong position to capture a material share of what is expected to be a rapidly growing global market for CCS & GGR technologies.

- CCS (Power) – IEA (2023) forecasts that the global deployment of natural gas with CCUS could grow to 89 GW by 2050 in a Net Zero 2050 scenario.[132]

[130] The largest operational facility in the UK at the time of writing is the Tata Chemicals Europe facility near Northwich which captures up to 0.04Mtpa of CO_2.
[131] IEA (Accessed: 2025) Carbon Capture, Utilisation and Storage
[132] IEA (2023) Net Zero Roadmap: A global pathway to keep the 1.5ºC goal in reach

- Power BECCS– IEA (2023) forecasts that the global deployment of Power BECCS could grow to 114 GW by 2050 in a Net Zero 2050 scenario.[133]
- BECCS (Hydrogen) – The deployment of BECCS (Hydrogen) could grow to 2.1 EJ by 2050 in a Net Zero 2050 scenario. This estimate is based on a combination of data points. IEA (2023) forecasts that global hydrogen consumption could reach 16 EJ by 2050. The CCC (2020) forecast that, in the UK, biomass will power 13% of hydrogen production by 2050. In absence of better data, it is assumed that the British share is representative of the sector globally.[134][135]
- DACCS – IEA (2023) forecasts that the global deployment of DACCS could grow to 621 Mtpa of CO_2 by 2050 in a Net Zero 2050 scenario.[136]
- Geological storage - IEA (2022) forecasts that the global deployment of geological storage could grow to 5.9 Gtpa of CO_2 by 2050 in a Net Zero 2050 scenario.[137]

Building on this discussion, the quantitative analysis below assumes that the UK can service the majority of its domestic market in these technologies, while also accessing a material share of the global export market. The analysis of market shares varies slightly between technologies but in all cases is based on previous analysis conducted by Ricardo for DESNZ using GEM-E3 modelling.[138] For BECCS (Electricity), DACCS and Geological storage, Ricardo forecast the UK will be able to capture between 55% and 65% of its domestic market and 1.4% of the global market. For BECCS (Hydrogen) and BECCS (Fischer Tropsch), Ricardo forecast that the UK will be able to increase its share of the domestic market from around 43% in 2025 to around 87% in 2050 but that the UK's share of the global market will reduce from approximately 0.2% to 0.1% over the same period.

Carbon Management (CCS & GGR) business opportunity analysis

Gross Value Added (GVA)

The business opportunities calculators suggest that, assuming a 'medium' level of innovation, GVA across analysed carbon management sectors will grow strongly across all modelled scenarios. Figure 9 shows that GVA in real terms grows from between £0.1 to 0.4bn in 2025 to between £2.6 to 4.3bn in 2050 depending on the scenario. The High Diversification scenario demonstrates a substantially higher level of GVA compared to the other scenarios as a result of the increased domestic deployment of Power BECCS and DACCS technologies assumed in this scenario. The divergence between the High Diversification and the other scenarios becomes particularly marked between 2035 and 2040 with the increase in annual GVA being

133 Ibid.
134 IEA (2023) Net Zero Roadmap: A global pathway to keep the 1.5ºC goal in reach
135 Climate Change Committee (2020) The Sixth Carbon Budget: Fuel supply
136 Ibid.
137 IEA (2022) CO2 Storage Resources and their Development
138 The 2024 Ricardo report is title *"Research to quantify the economic opportunities for the UK as a result of the global energy transition"*.

around three times higher in the High Diversification scenario than in the other scenarios in this period. There is little variation between the Minimally Constrained and High Hydrogen scenarios reflecting similar impacts from scenario assumptions for each of the CCS & GGR technologies.

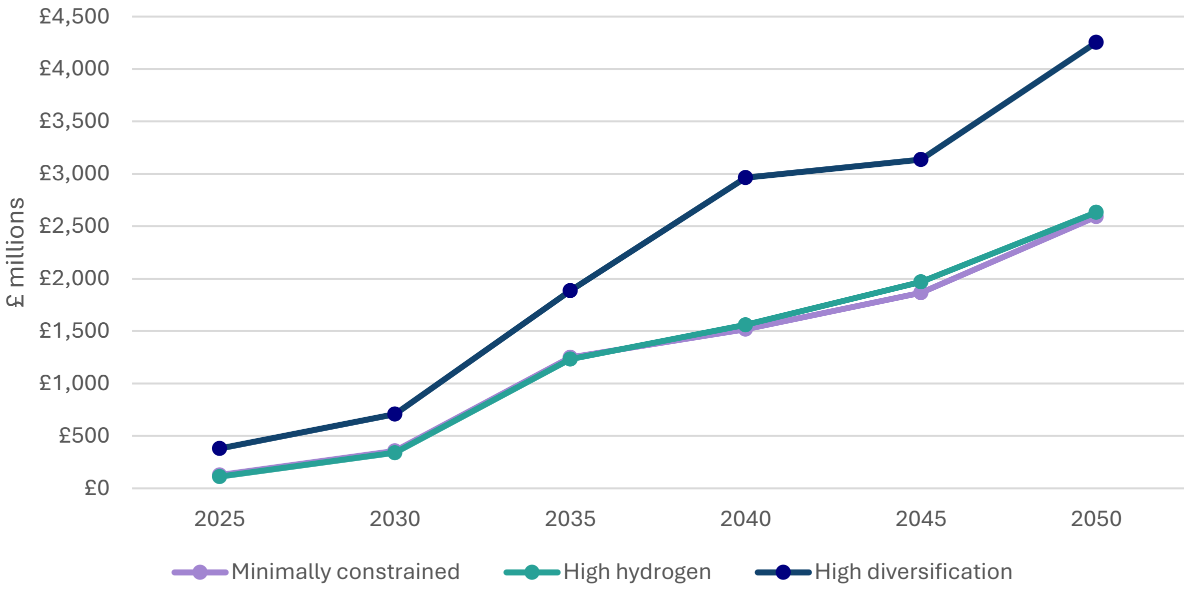

Figure 9: GVA by scenario for technologies assessed in this report
Note: Medium innovation level

As is shown in Figure 10, GVA in the sector is estimated to become increasingly dependent on the domestic market. The domestic market could generate between £0.7 and £1.3 billion in GVA in 2035 (53-69% of the total, depending on the scenario), potentially rising to between £2.0 and £3.7 billion (78-87% of the total, depending on the scenario) by 2050. Exports are expected to be relatively stable between 2035 and 2050, generating between roughly £0.5 and £0.6 billion in GVA per year as global annual additions of capacity are forecast to be relatively consistent across that period. In contrast, the rate of domestic capacity additions is generally increasing over the modelled scenario time periods, driving increased economic activity.

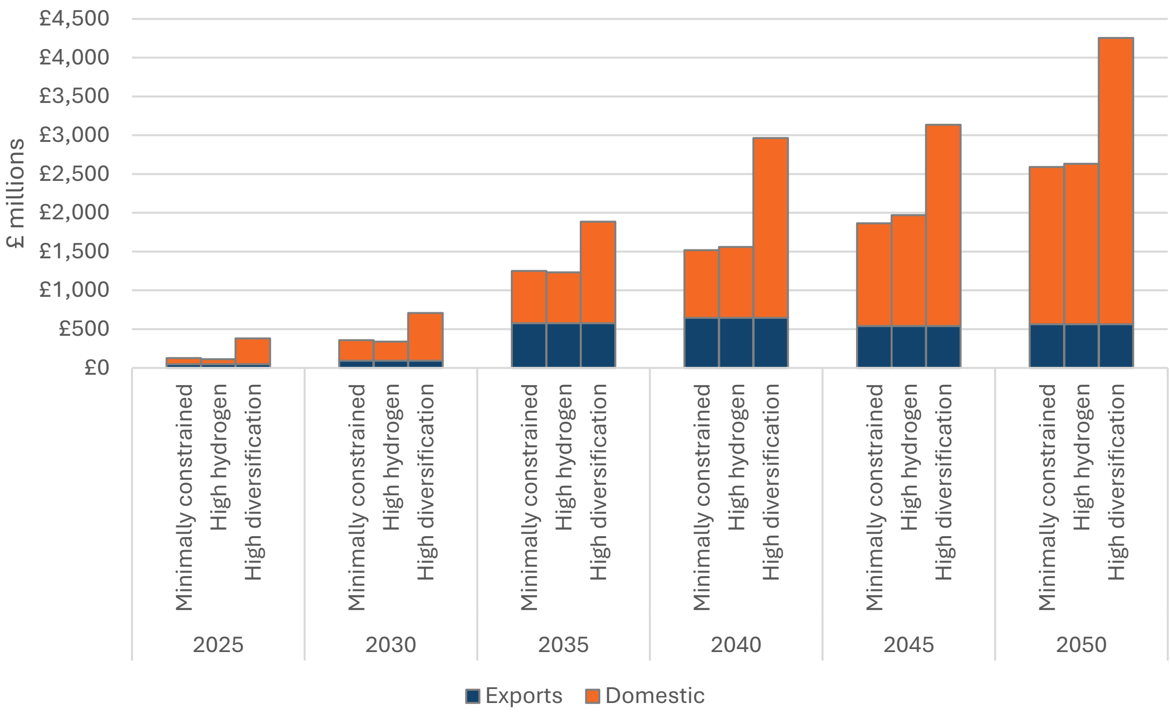

Figure 10: GVA by scenario by market for technologies assessed in this report
Note: Medium innovation level

Figure 11 shows that in the Minimally Constrained and High Hydrogen scenarios, there is a relatively modest difference in GVA between the different innovation levels, with GVA in 2050 varying by only 3% and 13% respectively between the innovation level where GVA is highest and that where GVA is lowest. However, in the High Diversification scenario, there is a lot more variation and this variation increases in absolute terms over time. In the High Diversification scenario, the low innovation level is linked with the highest level of GVA followed by the medium innovation level with the lowest level of GVA displayed in the high innovation level. This counterintuitive outcome is driven by the relationship between costs and economic activity. All else being equal, higher costs, provided they continue to be recovered, mean that the measured value of the economic activity taking place is higher i.e. that the activity makes a higher GVA contribution. The lower costs of high innovation do not lead to a sufficiently large increase in deployment to offset this effect. By 2050, these factors mean that, in the High Diversification scenario, GVA is about 50% higher in the low innovation level than in the high innovation level. This represents a limitation of the methodology, as it does not factor the feasibility of deployment at scale under low innovation, so it should not be concluded that lower innovation translates to greater business opportunities.

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

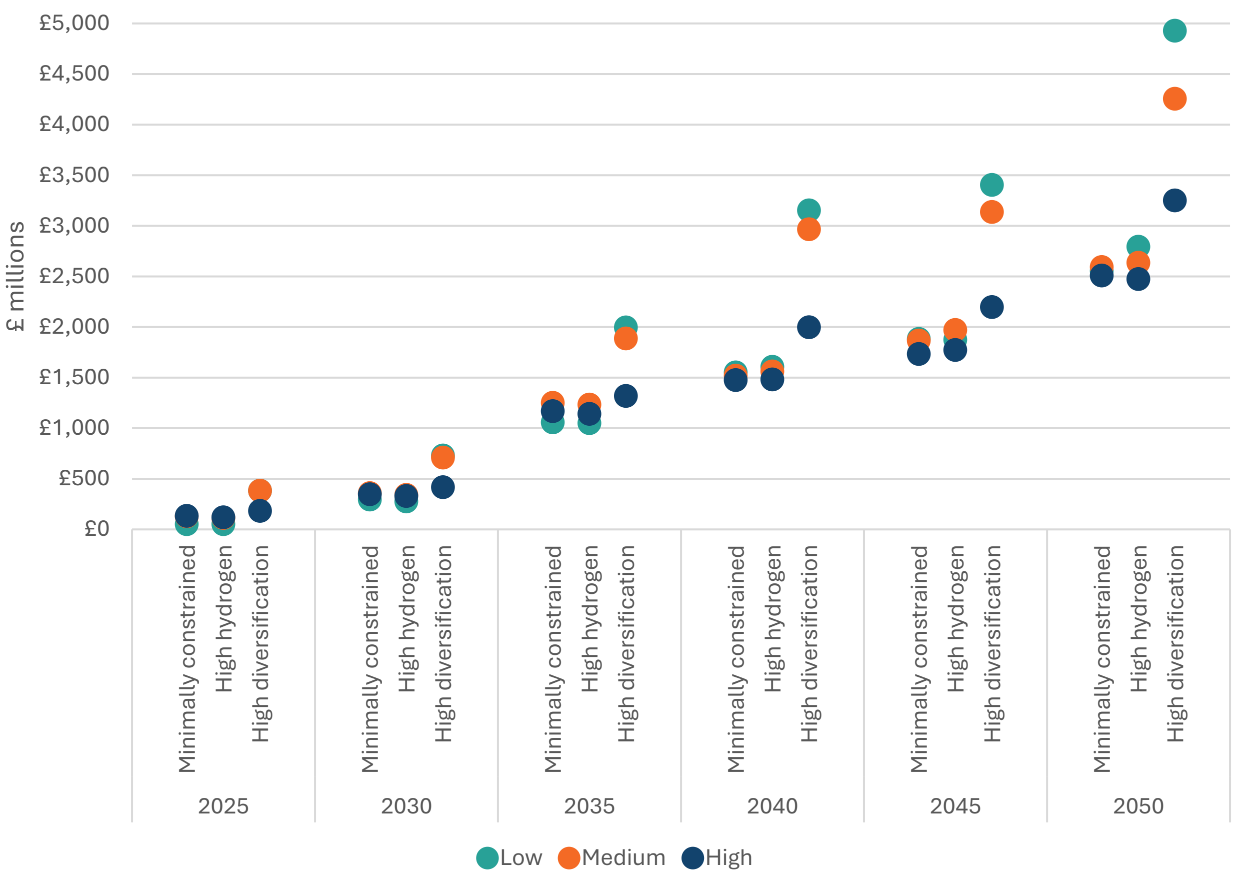

Figure 11: GVA by scenario by innovation level for low, medium and high innovation levels for technologies assessed in this report

Figure 12 shows that in all scenarios modelled, for the 'medium' innovation level, Power BECCS followed by geological storage make the largest contribution to GVA in 2040 with DACCS and BECCS (H2) becoming increasingly important by 2050. In the medium innovation level, CCS (power) and Fischer Tropsch synthesis make a negligible contribution to GVA throughout the period in line with systems modelling output that there is little take up of these technologies in all three scenarios.

For the same underlying deployment reasons, there is little difference in the distribution of GVA across technologies in the Minimally Constrained and High Hydrogen scenarios. In the High Diversification scenario, however, there is a much greater role for Power BECCS than in the other two scenarios. Consequently, by 2050, Power BECCS accounts for 46% of GVA as compared to less than 20% for the other scenarios. The contribution of BECCS (hydrogen) to GVA is also quite different across scenarios. In all cases, the technology has a limited contribution to GVA in 2040 but, in the Minimally Constrained and High Hydrogen scenarios this grows at a Compound Annual Growth Rate (CAGR) of approximately 26-27% to reach over 25% of total GVA by 2050. In the High Diversification scenario on the other hand, BECCS (hydrogen) only accounts for about 8% of total GVA by 2050.

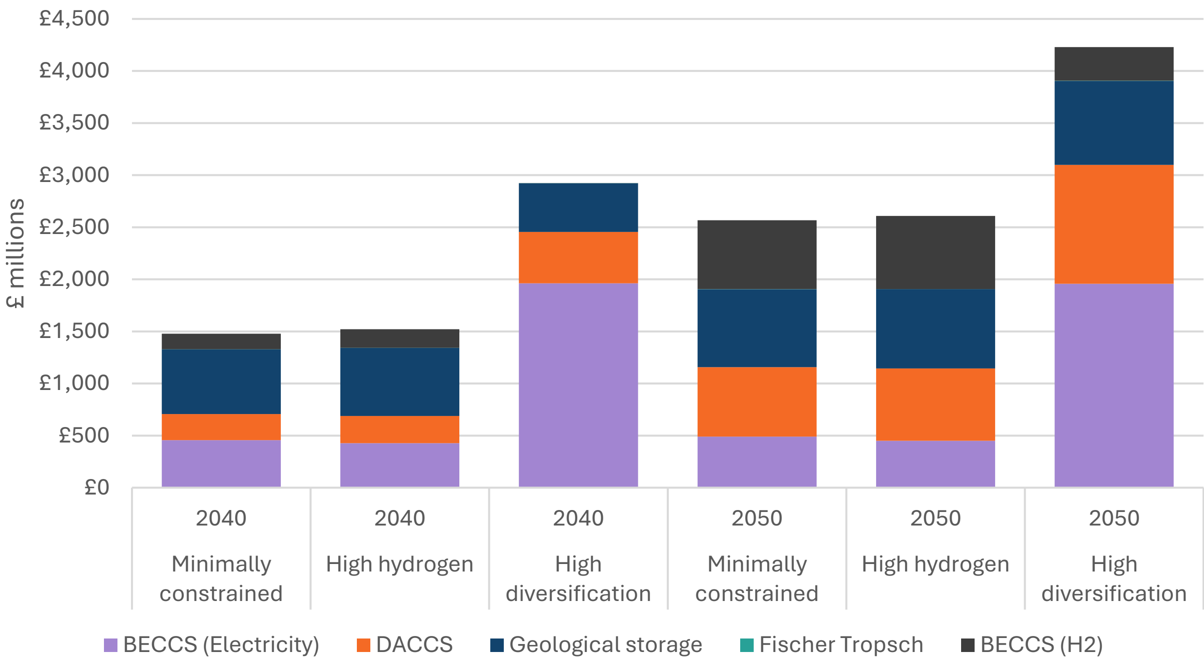

Figure 12: GVA by scenario by technology for technologies assessed in this report
Note: Medium innovation level

Direct and indirect jobs

Supported employment (direct and indirect jobs[139]) follows the rapid growth in GVA. Across the scenarios, supported employment rises from roughly between 2,000 to 6,000 jobs in 2025 to between 49,000 and 81,000 jobs in 2050. Around 48-49% of these jobs are direct jobs in 2025, rising to approximately 56-58% by 2050, as industry activity shifts from construction to operation and maintenance (see also Figure 16 below), the latter having supply chain activities which, for these technologies, are less employment intensive. The ratio of direct to indirect jobs is consistent between scenarios. In line with the GVA results, there is relatively little variation in the expected number of supported jobs between the Minimally Constrained and High Hydrogen scenarios but, for the High Diversification scenario, the higher levels of GVA are also reflected in a higher number of jobs supported. By 2050, there are over 60% more total jobs supported in the High Diversification scenario than in the other two scenarios.

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

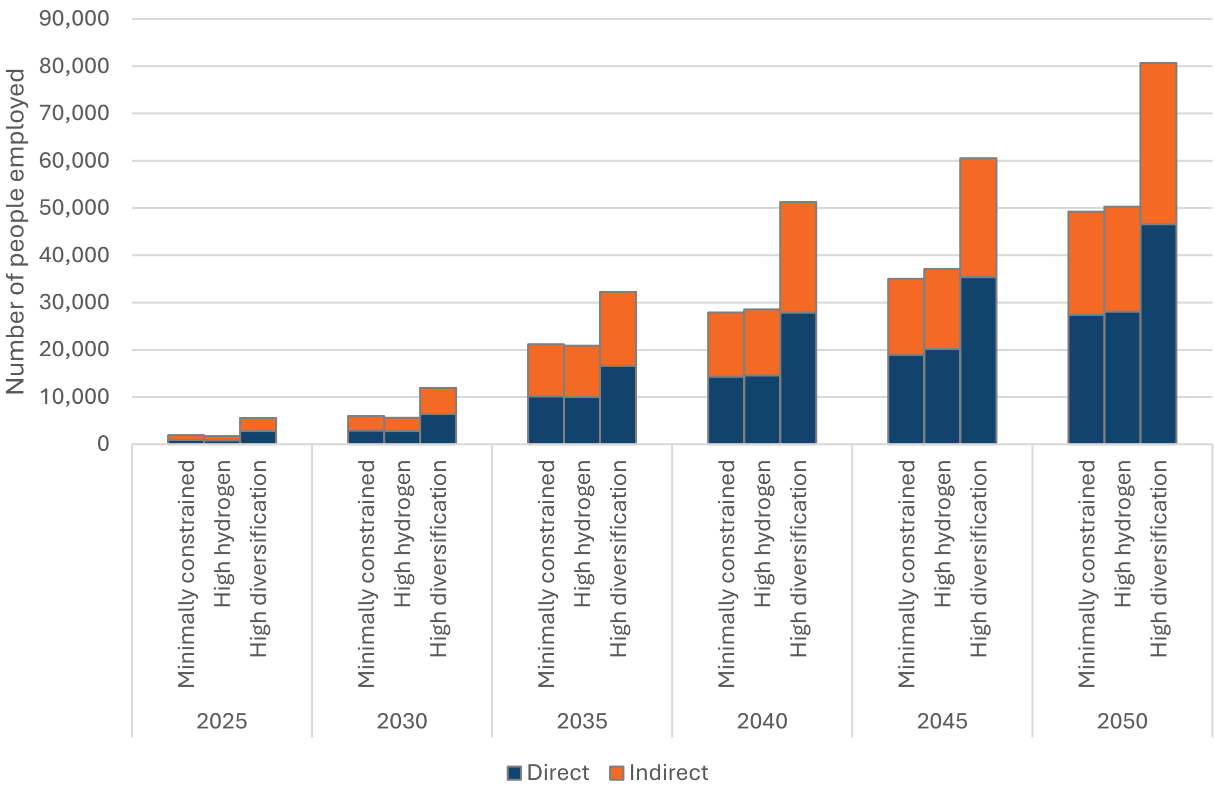

Figure 13: Total jobs supported by scenario by direct vs indirect for technologies assessed in this report
Note: Medium innovation level

Figure 14 and Figure 15 show the breakdown of employment by domestic/export market and across different cost categories i.e. construction, operation & maintenance and decommissioning, respectively.

As is the case for GVA, employment in the sector is projected to become increasingly reliant on the domestic market. The domestic market could support between 16,000 and 40,000 jobs in 2040 (59-77% of the total, depending on the scenario), potentially rising to between 39,000 and 70,000 (79-87% of the total, depending on the scenario) by 2050. The drivers of these trends are the same as those for GVA, a relatively stable rate of global deployment and an accelerating pace of deployment in the UK.

Supported jobs by cost category follow the expected trend with jobs supported by construction activity being relatively more important in 2040 (between 56% and 62% of employment) but jobs supported by operation and maintenance (O&M) activity becoming more important by 2050 (between 60% and 68% of the total). There is no decommissioning activity during this period as no assets are expected to reach the end of their useful life before 2050. The variation between the scenarios is driven by the deployment patterns. In the High Diversification scenario, there is a quicker build-up of CCS & GGR assets than in the other two scenarios, meaning that OPEX jobs become more important more quickly in that scenario.

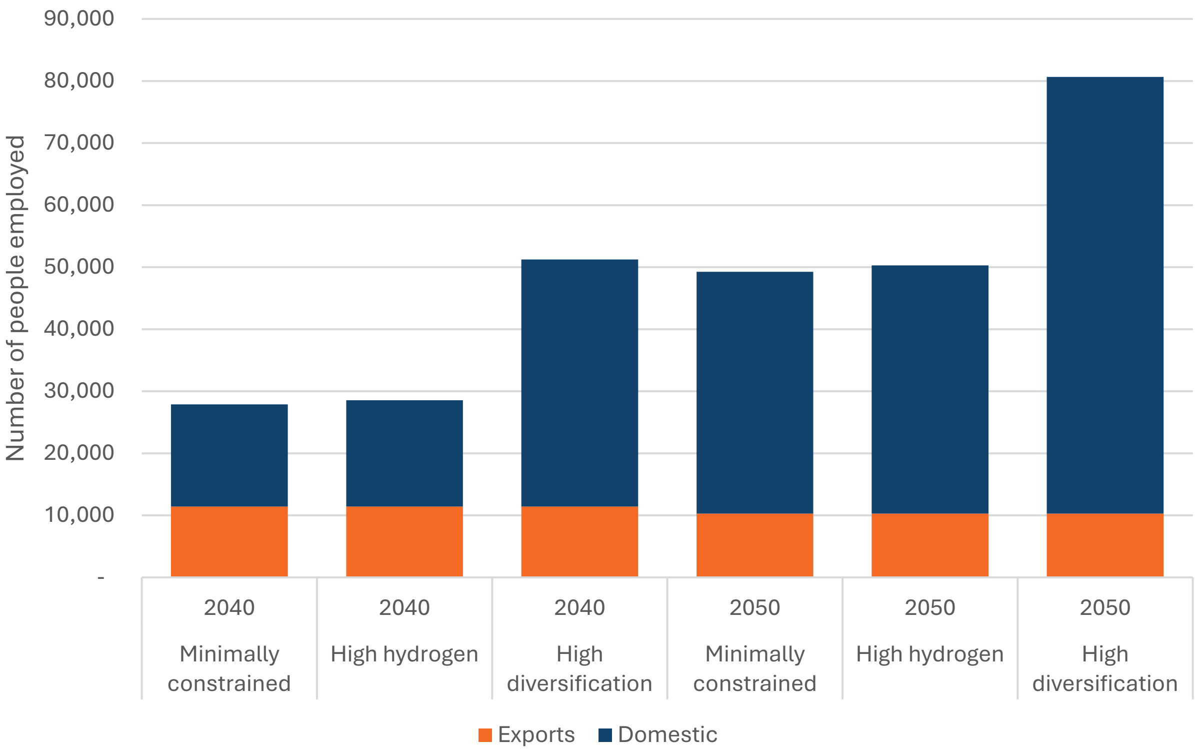

Figure 14: Total jobs supported (direct + indirect) by scenario by market for technologies assessed in this report

Note: Medium innovation level

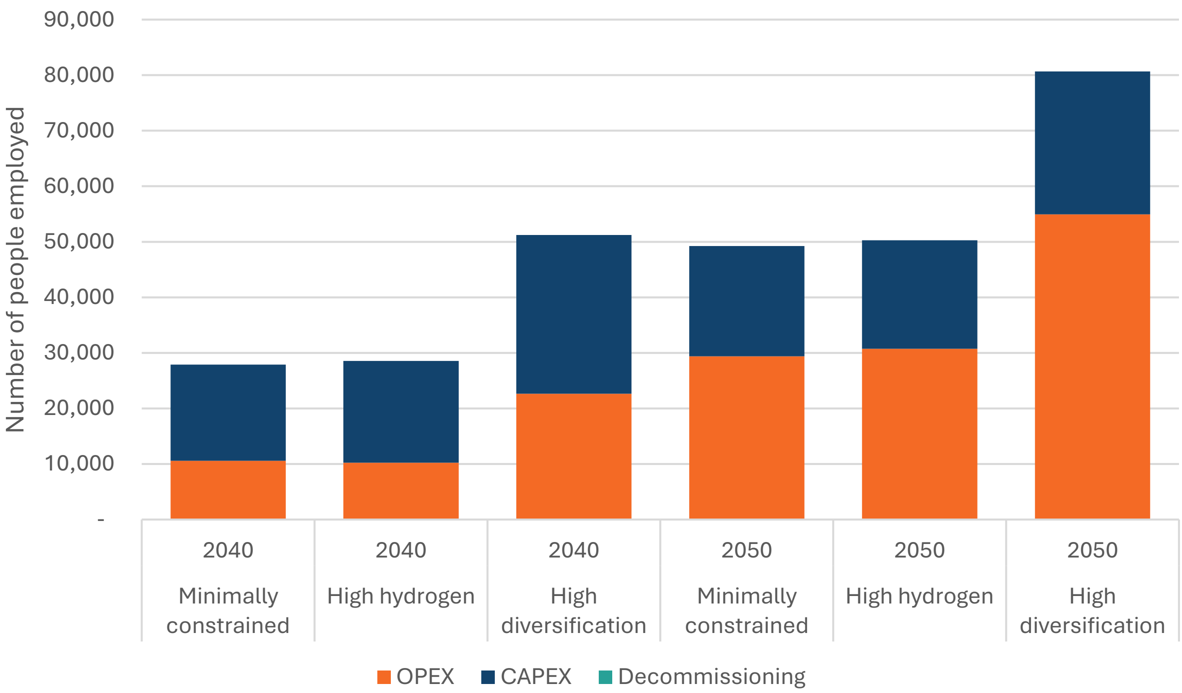

Figure 15: Total jobs supported (direct + indirect) by scenario by cost category for technologies assessed in this report

Note: Medium innovation level

Finally, Figure 16 shows that most of the direct jobs supported by the sector in 2050 are expected to be in high-skilled professional occupations. The occupations that account for the largest number of jobs supported are professionals in science, research, engineering and technology (with an average across scenarios of roughly 11,700 direct jobs), followed by managers, directors and senior officials (with an average of around 4,800 direct jobs) and other professional occupations (with an average of around 4,700 direct jobs). The sector is also expected to support around 3,700 – 5,500 jobs in skilled trade jobs by this date.[140]

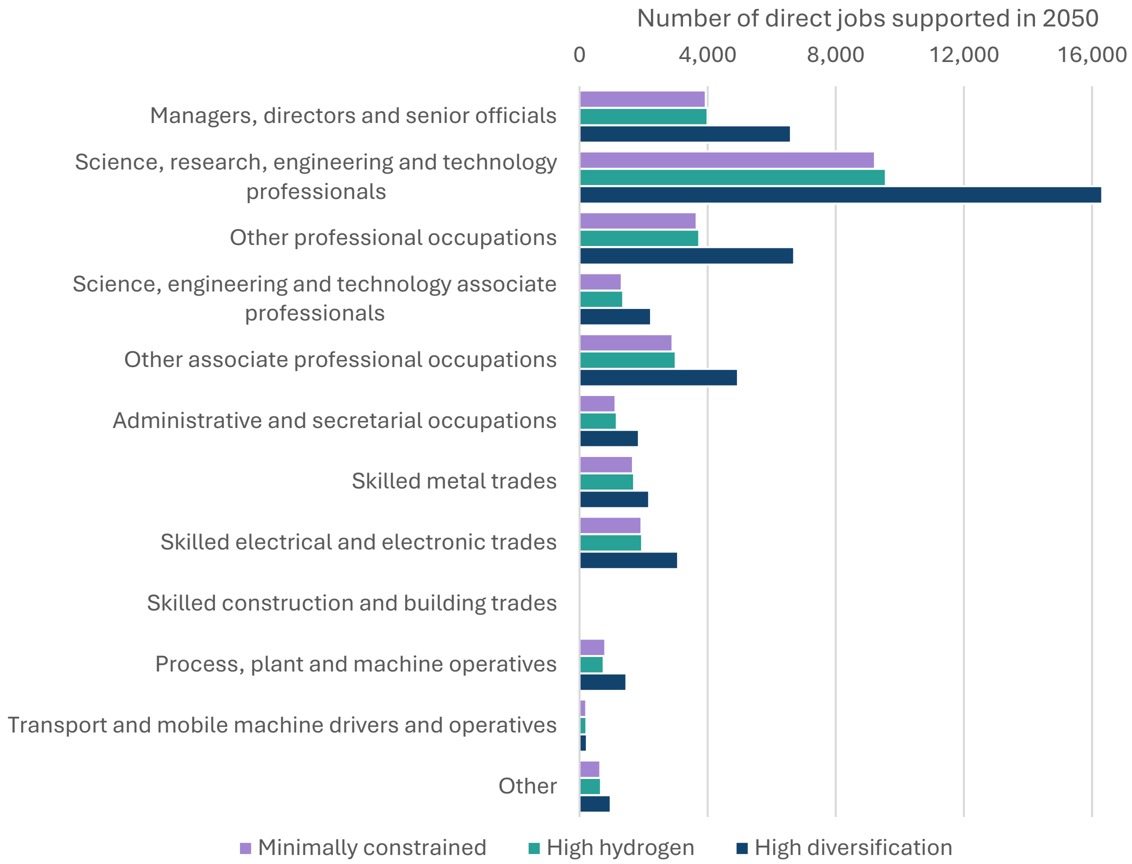

Figure 16: Direct jobs supported by scenario by occupation type in 2050 for technologies assessed in this report

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 note for more details on this aggregation. In *Figure 16the heading 'other' covers the following 4 SOC groupings: elementary occupations, other skilled trade occupations, sales and customer service occupations and caring, leisure and other service occupations*

[140] Note that the zero jobs reported for transport and mobile machine drivers and operatives is the result of data gaps in the ONS data on the distribution of jobs by SOC code for each SIC code. The true value is unlikely to be zero but, in cases where the numbers are small, the ONS determines that the value for a particular SOC code by SIC code combination is too small to be reliable and so it is excluded. This is the case for a number of the SIC codes assigned to components of the offshore renewable technologies. To account for this missing data, the calculators assign a zero when really it will be a small non-zero figure. More generally, the analysis assumes that the same pattern of occupations associated with the construction, operation and maintenance of these technologies persists in the future.

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