# Energy Innovation Needs Assessment


## Sub-theme report: Carbon capture, utilisation, and storage

Commissioned by the Department for Business, Energy & Industrial Strategy

October 2019


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*The views expressed in this report are the authors' and do not necessarily reflect those of the Department for Business, Energy and Industrial Strategy.*

# Acronyms and abbreviations

Table 1. **Key acronyms and abbreviations**

| Acronym/abbreviation | Definition |
|---|---|
| **ACT** | Accelerating CCS Technologies |
| **AGR** | Acid Gas Removal |
| **ATR** | Auto Thermal Reformer |
| **ASU** | Air Separation Unit |
| **BECCS** | Bioenergy with Carbon Capture, Utilisation, and Storage |
| **BEIS** | Department for Business, Energy & Industrial Strategy |
| **CAPEX** | Capital Expenditure |
| **CCGT** | Combined Cycle Gas Turbine |
| **CCUS** | Carbon Capture, Utilisation, and Storage |
| **EINA** | Energy Innovation Needs Assessment |
| **EOR** | Enhanced Oil Recovery |
| **EGH** | Exhaust Gas Circulation |
| **EPCm** | Engineering, Procurement, and Construction Management |
| **ESC** | Energy Systems Catapult |
| **ESME** | Energy System Modelling Environment |
| **GDP** | Gross Domestic Product |
| **GHG** | Greenhouse Gas |
| **GHR** | Gas Heated Reformer |
| **GVA** | Gross Value Added |
| **HMG** | Her Majesty's Government |
| **IEA** | International Energy Agency |
| **IGCC** | Integrated gasification combined cycle |
| **IP** | Intellectual Property |
| **ITM** | Ion Transport Membrane |
| **LCOE** | Levelised Cost of Energy |

| | |
|---|---|
| **OPEX** | Operating Expenditure |
| **MBC** | Modern Building Chemicals |
| **MCFC** | Modern Carbonate Fuel Cells |
| **MDEA** | Methyl diethanolamine |
| **MEA** | Monoethanolamine |
| **MMV** | Measuring, Monitoring, and Verification |
| **RPB** | Rotation Pack Bed |
| **RCA** | Revealed Comparative Advantage |
| **ROV** | Remotely Operated Underwater Vehicle |
| **RD&D** | Research, Development and Demonstration |
| **SCPC** | Supercritical Pulverised Coal |
| **TINA** | Technology Innovation Needs Assessment |
| **TRL** | Technology Readiness Level |
| **OFS** | Oil Field Services |

# Glossary

Table 2. **Key terms used throughout this report**

| Term | Definition |
|---|---|
| **Learning by doing** | Improvements such as reduced cost and/or improved performance. These are driven by knowledge gained from actual manufacturing, scale of production, and use. Other factors, such as the impact of standards which tend to increase in direct proportion to capacity increases. |
| **Learning by research, development and demonstration** | Improvements such as proof of concept or viability, reduced costs, or improved performance driven by research, development, and demonstration (RD&D); increases with spend in RD&D and tends to precede growth in capacity. |
| **Sub-theme** | Groups of technology families which perform similar services which allow users to, at least partially, substitute between the technologies.<br>For example, a variety of technology families (heat pumps, district heating, hydrogen heating) have overlapping abilities to provide low carbon thermal regulation services and can provide flexibility to the power system. |
| **System value and Innovation value** | Estimates of change in total system cost (measured in £ GBP, and reported in this document as cumulative to 2050, discounted at 3.5%) as a result of cost reduction and performance improvements in selected technologies. This is the key output of the EINAs and the parameter by which improvements in different technologies are compared.<br>System benefits result from increasing deployment of a technology which helps the energy system deliver energy services more efficiently while meeting greenhouse gas targets. Energy system modelling is a vital tool in order to balance the variety of interactions determining the total system costs.<br>Innovation value is the component of system value that results from research and development (rather than from 'learning by doing'). |
| **Technology family** | The level at which technologies have sufficiently similar innovation characteristics. For example, heat pumps are a technology family, as air-source, ground-source and water-source heat pumps all involve similar technological components (compressors and refrigerants). Electric vehicles are also a technology family, given that the battery is a common component across plug-in hybrids and battery electric vehicles. |
| **Gross Value Add** | Gross Value Add (GVA) measures the generated value of an activity in an industry. It is equal to the difference between the value of the outputs and the cost of intermediate inputs. |

# Introduction

*Box 1.* **Background to the Energy Innovation Needs Assessment**

The Energy Innovation Needs Assessment (EINA) aims to identify the key innovation needs across the UK's energy system, to inform the prioritisation of public sector investment in low-carbon innovation. Using an analytical methodology developed by the Department for Business, Energy & Industrial Strategy (BEIS), the EINA takes a system-level approach, and values innovations in a technology in terms of the system-level benefits a technology innovation provides.[1] This whole system modelling in line with BEIS's EINA methodology was delivered by the Energy Systems Catapult (ESC) using the Energy System Modelling Environment (ESME$^{TM}$) as the primary modelling tool.

To support the overall prioritisation of innovation activity, the EINA process analyses key technologies in more detail. These technologies are grouped together into sub-themes, according to the primary role they fulfil in the energy system. For key technologies within a sub-theme, innovations and business opportunities are identified. The main findings, at the technology level, are summarised in sub-theme reports. An overview report will combine the findings from each sub-theme to provide a broad system-level perspective and prioritisation.

This EINA analysis is based on a combination of desk research by a consortium of economic and engineering consultants, and stakeholder engagement. The prioritisation of innovation and business opportunities presented is informed by a workshop organised for each sub-theme, assembling key stakeholders from the academic community, industry, and government.

This report was commissioned prior to advice being received from the CCC on meeting a net zero target and reflects priorities to meet the previous 80% target in 2050. The newly legislated net zero target is not expected to change the set of innovation priorities, rather it will make them all more valuable overall. Further work is required to assess detailed implications.

[1] The system-level value of a technology innovation is defined in the EINA methodology as the reduction in energy system transition cost that arises from the inclusion of an innovation compared to the energy system transition cost without that innovation.

## The CCUS sub-theme report

**The Carbon Capture Utilisation, and Storage (CCUS) sub-theme analysis focusses on CCS for power, industrial CCS, and utilisation to produce fuels.** CCUS technologies have different deployment timelines and present a variety of important innovation opportunities capable of bringing system benefits. There are three options for capturing emissions: post-combustion, pre-combustion, and oxycombustion. All three have different performance characteristics, integration requirements, and optimal applications.

**Table 3 below describes the sub-areas of focus of this report for Power CCS applications, which includes solid fuel, gas, transport, and storage.** Solid fuel refers to both biomass and coal, which have largely the same considerations for both post-combustion and oxyfuel combustion. There are several challenges that are unique to biomass for pre-combustion capture, but these relate to gasification processes and fall within the scope of the Bioenergy EINA.

Table 3. **Overview of CCS in the power sector sub-areas**

| Sub-area | Description |
|---|---|
| **Solid fuel $CO_2$ capture plants** | |
| **Post-combustion capture** | Post-combustion capture refers to the use of a capture unit attached to a solid fuel-fired power plant that utilises one or more of a range of capture processes for $CO_2$ removal. Capture processes include:<br>- Advanced solvent absorption<br>- Adsorption onto a solid sorbent<br>- Fuel cells, including molten carbonate fuel cells (MCFC)<br>- Membrane separation |
| **Pre-combustion capture** | Pre-combustion capture involves the conversion of a solid feedstock into a combustible gas mixture of $H_2$, $CO_2$, and other gases, typically through integrated gasification combined cycles (IGCC power plant). The $CO_2$ and $H_2$ are separated and the hydrogen-rich gas used as fuel. Separation technologies used in pre-combustion capture include:<br>- Solvent separation processes such as Rectisol and Selexol<br>- Pressure Swing Adsorption<br>- Water enhanced gas-shift |
| **Oxy-combustion capture** | This process avoids the complex separation of $CO_2$ used in pre- and post- combustion capture. Instead, fuel is burnt in pure oxygen, which is isolated from air beforehand using an air separation unit (ASU). This results in a flue gas that is mainly $CO_2$ and water, simplifying the process of obtaining a high purity $CO_2$ that is then ready for compression and transportation. Flue gas can be recirculated in the combustor to further increase the purity of the $CO_2$. |
| **Gas $CO_2$ capture plants** | |
| **Pre-combustion capture** | Pre-combustion carbon capture from natural gas uses chemical absorption and physical adsorption processes, like those described above, to separate the gaseous $H_2$ / $CO_2$ mixture that is produced from steam reformation. |
| **Post-combustion capture** | A similar process to the solid fuel-based system, but with gas as the fuel which changes the flue gas composition slightly. The efficiency of the plant is also characteristically higher, and the costs are typically less dominated by the high capital costs related to solid fuel plants and more by the historically higher price of gas as a fuel. |

| | |
|---|---|
| **Oxy-combustion capture** | A similar process to the solid fuel-based oxy-combustion capture process, with similar process changes to those mentioned above when comparing gas and solid fuel post-combustion capture. |
| **$CO_2$ transport** | The transportation of $CO_2$ has been commonplace for many decades in sectors such as the beverage industry and for the purposes of enhanced oil recovery (EOR). $CO_2$ is compressed and transported as a gas in cylinders or as a liquid through pipelines. |
| **$CO_2$ storage** | |
| **Exploration & appraisal** | This includes the characterisation, modelling, seismic surveys, exploration wells, injection tests, and permitting costs associated with ensuring that a store is viable and secure. |
| **Infrastructure & injection wells** | This primarily relates to the platform/subsea infrastructure, new/re-used injection wells, and legacy well remediation that is necessary for developing a store. |
| **Closure** | The plugging of faults and leaks as well as the decommissioning costs of a store. |
| **O&M** | Day-to-day operation and maintenance costs of a store. |
| **MMV** | Monitoring, measurement, and verification of $CO_2$ flows and the seismicity of the store whilst it is in operation. |

*Source:* *Carbon Trust*

**Industrial applications in this report cover industrial process emissions that cannot be abated through fuel switching.** The capture of $CO_2$ from fossil fuels used in industrial processes is covered within the power sector sub-area. Four energy- and emission-intensive industries are covered: cement, chemicals, iron and steel, and refining. It has been projected that the industrial applications of CCS could reduce global emissions by c. 300 $MtCO_2$ (0-1600 $MtCO_2$) annually by 2050.[2]

**Further examinations of technologies for storage, transport, and use/utilisation that could rapidly be applied to the UK industrial sources are also covered in this report.** There are several ways that captured gas can be utilised in the production of industrial feedstocks or long duration products that do not ultimately release $CO_2$ back into the atmosphere. However, utilisation in this report is limited to the production of fuels given the EINA's focus on the energy system.

**This report has four sections**:

- **CCUS and the whole energy system:** Describes the role of CCUS in the energy system, based on ESME modelling performed by the ESC.
- **Innovation opportunities:** Provides lists of the key innovations within CCUS and their impact on costs and performance.
- **Business opportunities:** Summarises the export opportunities of CCUS, the GVA and jobs supported by these opportunities and how innovation helps the UK capture the opportunities.

[2] International Energy Agency (IEA) (2015), Energy Technology Perspectives.

- **Market barriers to innovation:** Highlights areas of innovation where market barriers are high and energy system cost reductions and business opportunities are significant.

# Key findings

## Priority innovations areas in CCUS

**The main innovations for CCUS are identified below.** The list is not a substitute for a detailed cost-reduction study. Rather, it is a guide for policymakers on key areas to be considered in any future innovation programme design.

The innovation priorities below select individual or groups of the top scoring innovations. Table 4 maps the top scoring innovations to individual technology components, and Table 7 sets out the full list of innovations and their scores.

**The rates of capture and the associated energy penalty are important concepts for CCS.** Technologies and processes that can increase capture rates or reduce energy penalties are applicable across each sub-category and can play a crucial role in helping to overcoming economic barriers to deployment of each capture technology.

### CCS for Power

- **Pre-combustion capture – gas:**
    - Novel reformers: advanced reformer technologies unlock the potential to combine hydrogen production with CCS for power, which opens further opportunities across the energy system. Cost reduction is possible using cheaper and more energy-efficient materials and processes.
- **Post-combustion capture – gas & solid fuels:**
    - R&D into new solvent and absorption processes: lower-cost and improved performance capture can be achieved, whilst also having the potential to reduce regeneration costs, corrosion effects, environmental impact, and product degradation.
- **Oxy-combustion:**
  New technologies for lower-cost air separation in oxy-combustion, including Ion Transport Membranes (ITMs). Ceramic materials that conduct oxygen ions at elevated temperatures are an early-stage technology with significant potential for a step change cost reduction in air separation.
- **Storage:**
    - De-risking the scale-up of stores: technologies that characterise the connectivity of sands and structural features would reduce scale-up risks. R&D into technologies and methods that model, simulate, and appraise stores faster, and with a higher degree of confidence, can support this.

- Post-closure Measuring, Monitoring, and Verification (MMV): improving long-term monitoring techniques and moving towards performance-based standards can have reduced storage risks.

- **CO2 Transport:**
  - Coordination by sharing infrastructure and capacity for transport and $CO_2$ storage would facilitate and enable CCUS innovation in the UK. Similarly, geographical cluster development would enable the identification of lowest-cost infrastructure opportunities in the future.

### Industrial CCS

- Collaborative industrial CCS programmes. These will be important for driving technology demonstration and proving the economic case in key industrial sectors. The clustering of energy-intensive industries with a shared aim can help to accelerate the deployment of CCS by reducing the cost and barriers associated with CCS.
- Investigating the effects of variation in the quality of $CO_2$ streams on capture technologies. New studies and solutions that can improve the understanding of how different capture technology performance is affected by variation in $CO_2$ stream compositions, can benefit the wider deployment of industrial CCS.
- Applied R&D technology programmes to identify the optimum capture solutions for UK industrial sub-sectors. In cement production, for example, post-combustion capture solutions can potentially be used both for new kilns and retrofitted to existing ones. Oxy-combustion for new kilns is also possible, but further R&D is needed to understand the effect changing the atmospheric composition has on the cement products.

## Business opportunities for the UK

**The UK can capture £4.3 billion of GVA per annum from exports by 2050 as the global CCUS market increases from minimal levels today to 6,800 Mt of $CO_2$ captured annually by 2050.** In the business opportunities section below, GVA and jobs results are set out by component (Table 8).

- Around half of the business opportunity is associated with engineering, procurement and construction management (EPCm) services associated with the installation of capture transport and storage infrastructure (not directly captured in Table 4). The UK can leverage its expertise in engineering and oil and gas to export engineering, procurement, and construction management (EPCm) services to CCUS projects around the world, potentially securing £2.1 billion of GVA per annum from the export of these services by 2050.

- Innovative solvents and capture technologies could add £1.5 billion in GVA per annum to the UK economy from exports by 2050, particularly from exports to industrial CCUS projects in the EU and rest of world (RoW) markets.
- Deploying CCUS clusters connected to North Sea storage from the 2020s would be a strong enabler for UK exports globally, building UK CCUS expertise and driving international demand for UK CCUS goods and services.
- For the opportunities considered, export opportunities are expected to be significantly larger than domestic opportunities. This is primarily because of the likely international competitiveness of the UK, and the relative sizes of the global and UK market. Opportunities from the domestic market could plausibly support around £850 million in GVA and nearly 10,000 jobs per annum by 2040 as the UK rapidly deploys CCUS to meet climate targets.

## Market barriers to innovation in the UK

**Opportunities for HMG support exist when market barriers are significant, and they cannot be overcome by the private sector or international partners.** In the market barriers section below, the barriers are set out by component, where possible (Table 11). The main market barriers identified by industry are:

- Policy-dependent demand for CCS and an uncertain policy position on deployment are critical barriers to capture, full systems integration, and storage.
- The lack of insurance frameworks for a very long-term and global liability in case of leakage limits commercial incentives for individual companies to deploy. The uncertainty introduced by an unclear route to deployment limits incentives for investing in innovation in storage technology. Ownership and duration of the liability are undefined, making insurance schemes very expensive and deterring private sector activity.
- Unclear rules for storage site approval introduce uncertainty into future costs. Uncertainty about potentially high future costs limits incentives to innovate. Health and safety regulation and public acceptance requirements associated with leakage add to uncertain future demand.

# Key findings by component

Government support is justified when system benefits and business opportunities are high, and government is needed to overcome barriers.

Table 4. **Cost and performance in Carbon Capture, Utilisation, and Storage (see key to colouring below)**

**Overall statistics for CCUS: System value = £4.0 billion (range £1.8-7.4 billion), 2050 export opportunity (GVA) = £4.3 billion, 2050 potential direct jobs supported by exports = 48,000**

| Component | Example innovation | Business opportunity | Market barriers | Strategic assessment |
|---|---|---|---|---|
| **Gas & Solid fuel (biomass and coal) Post-Combustion capture** | Cheaper absorbers | High (summing across all capture equipment) | Low | Advanced technologies can capture more $CO_2$ with more compact technologies, but significant cost reduction around these technologies is needed. Supporting the deployment technologies in this area at scale can help to demonstrate a business case and unlock wider benefits. There are potentially large export opportunities associated with exporting capture equipment. |
| **Gas Pre-Combustion capture** | Novel reformers (gas) | | | The UK is among the leaders in this field and has a competitive advantage in hydrogen production with significant know-how, for instance in fuel cell technologies. There is an opportunity to take advantage of low-emission hydrogen production, which needs novel reformer innovations to increase both hydrogen production and carbon capture. There are potentially large export opportunities associated with exporting capture equipment. |
| **Gas and Solid fuel Oxy-Combustion** | Ion Transport Membranes to produce cheaper oxygen | Low | | Improved processes for air separation, such as Ion Transport Membranes, can give high-purity oxygen separation for oxy-combustion. Technologies are currently at a relatively early stage of development, presenting an opportunity to support R&D innovations in this area. The UK does not currently manufacture large turbines, and is unlikely to capture a significant market share. |
| **$CO_2$ Storage: Exploration, characterisation and optimisation** | Optimising liabilities and insurances, particularly in re-thinking approaches for how CCS is characterised in this context | NA (indirectly assessed within wider EPCm services) | Severe | Without government intervention, innovation in $CO_2$ storage will occur far below the optimal level and with few commercial examples. Key areas of innovation lie in characterising the connectivity of sands and structural features; developing technologies and methods that would model and appraise stores faster to reduce risk and unlock development. Using O&G expertise, service export opportunities are likely to be significant. |
| **$CO_2$ Storage: Infrastructure & injection wells** | Potential for storage cost reduction in legacy wells through re-characterising abandoned old wells | | | There are several barriers and challenges associated with the re-characterising of legacy wells for storage purposes, including those in the North Sea. Innovation support in this area is needed to cost-effectively overcome technical barriers and long characterisation lead times of these storage sites. Without support, innovation in this area will happen slower than the optimal levels that are required. Using O&G expertise, service export opportunities are likely to be significant. |

| Overall statistics for CCUS: System value = £4.0 billion (range £1.8-7.4 billion), 2050 export opportunity (GVA) = £4.3 billion, 2050 potential direct jobs supported by exports = 48,000 | | | | |
|---|---|---|---|---|
| **Component** | **Example innovation** | **Business opportunity** | **Market barriers** | **Strategic assessment** |
| **$CO_2$ Storage: MMV** | Cost-effective robust long-term monitoring techniques for Post-closure Measuring, Monitoring, and Verification (MMV) | Medium-Low (for equipment) | | Government support has the potential to unlock more accurate monitoring of $CO_2$ pathways and seismicity for a better understanding of how leaks may happen, which is highly needed. There are various business opportunities associated with equipment export and wider EPCm service delivery for storage projects. |
| **$CO_2$ Transport** | $CO_2$ pipeline network and infrastructure | Low | Low | Transport of $CO_2$ is well established with limited technology innovation required. For large-scale CCUS deployment, support is needed in scaling up of the required $CO_2$ transport network infrastructure. Increased deployment will likely occur without government intervention, but below optimal levels. |
| **Industrial CCS** | Post-combustion and oxycombustion capture for cement kilns | High (summing across all capture equipment) | N/A | A large portion of Industrial $CO_2$ emissions are fundamental to the industrial processes, meaning there is limited scope for reduction through increased efficiency or fuel switching. Government intervention is required to support plants to demonstrate and implement CCUS at a cost that does not impact the competitive position within the industry. Export opportunities associated with capture equipment are generally assessed (for power and industry) and are likely to be high. |

*Source:* *Vivid Economics, Carbon Trust*

*Note:* *The main innovations per component are the innovations that score highest in the innovation inventory. This table only includes component-specific market barriers. Cross-cutting barriers are included in the market barriers section below.*

Table 5. **Key to colouring in the key findings by component**

| **Business opportunities** | **Market barriers** |
|---|---|
| **High:** more than £1 billion annual GVA from exports by 2050 | **Critical:** Without UK Government intervention, innovation, investment and deployment will not occur in the UK. |
| **Medium-High:** £600-£1,000 million annual GVA from exports by 2050 | **Severe:** Without UK Government intervention, innovation, investment and deployment are significantly constrained and will only occur in certain market segments / have to be adjusted for the UK market. |
| **Medium-Low:** £200-£600 million annual GVA from exports by 2050 | **Moderate**: Without UK Government intervention, innovation, investment and deployment will occur due to well-functioning industry and international partners, but at a lower scale and speed. |
| **Low:** £0-200 million annual GVA from exports by 2050 | **Low:** Without UK Government intervention, innovation, investment and deployment will continue at the same levels, driven by a well-functioning industry and international partners. |

*Source: Vivid Economics, Carbon Trust*

*Box 2.* **Industry workshop**

A full-day workshop was held on 8th February 2019 with key delegates from the energy sector: industry, academic community, and research agencies. Key aspects of the EINA analysis were subjected to scrutiny, including innovation opportunity assessment, and business and policy opportunities assessment. New views and evidence were suggested; these have been incorporated into an update of the assessments.

The views of the attendees were included in the innovation's assessment. In addition, several contextual issues were raised at the workshop:

- There is a role for government in providing public support to develop a CCUS market and for de-risking scale-up and protecting legacy infrastructure, such as wells in the case of the power sector.
- Unlocking finance mechanisms to encourage capture in the industrial sector should be prioritised to facilitate investment in CCUS.
- For Power CCS, advanced technologies in solvents, absorbents, and reformers are viewed as key enablers of cost reduction of technical innovation. Further scale projects are needed to stimulate investment in CCUS components.
- A concern around the full chain of carbon transport was raised and whether there is enough transport network infrastructure and capacity to support increased CCS deployment across the UK.

These overarching messages, while not necessarily fitting within the limited scope of the EINA framework, are important for consideration in setting innovation policy.

# CCUS and the whole energy system

## Current situation

**CCUS could have an important role to play in helping the UK meet the remaining challenges associated with achieving the targeted 80% reduction in emissions compared to 1990 levels**. HMG has an ambition to ensure the UK has the option to deploy CCUS at scale during the 2030s, subject to the costs coming down sufficiently. The *UK Carbon Capture Use and Storage Deployment Pathway: An Action Plan* was launched alongside creation of the *CCUS Cost Challenge Taskforce* to enable the UK's first CCUS facility to be commissioned in the mid-2020s.[3]

**Within the action plan, the important role that investing in CCUS innovation can play in supporting deployment is highlighted**, including the announcement of CCUS innovation programmes worth £45 million. There is a wider recognition that a successful CCUS facility and carbon dioxide infrastructure network could enable innovation and help bring economies of scale to an integrated decarbonisation solution suitable for a wide range of industries.

**Existing industry clusters in the UK have the potential to form key assets for the deployment of CCUS, which in turn can support wider national deployment.** Deployment in industrial clusters can benefit from having several different CCUS applications connecting to shared CO2 infrastructure to reduce both costs and risks. Teesside is an example of a UK industrial cluster and hosts 58% of the UK's chemicals industry. Teesside is home to the proposed Clean Gas Project, a project which seeks to develop a commercial scale CCUS project including power generation and industrial CCUS.[4] The project builds on the work of the Teesside Collective, a partnership between the local combined authority and local businesses, which seeks to position the region as the UK's first CCUS-equipped industrial zone.

**CCS can unlock cost-effective production of low carbon hydrogen in the UK.** Hydrogen could play an important role in decarbonising the energy system, which is covered in more depth within the Hydrogen and Fuel Cells EINA. The most established process for hydrogen production is through steam reforming of fossil fuels, giving $CO_2$ as a by-product. HyNet North West and H21 North of England are

[3] BEIS (2018) Clean Growth: The UK Carbon Capture Usage and Storage deployment pathway: an Action Plan. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/759637/beis-ccus-action-plan.pdf

[4] OGCI (2018) OGCI Climate Investments announces progression of the UK's first commercial full-chain Carbon Capture Utilization and Storage Project. https://oilandgasclimateinitiative.com/climate-investments-announces-progression-of-the-uks-first-commercial-full-chain-carbon-capture-utilization-and-storage-project/

examples of projects aimed at creating low-carbon hydrogen production and distribution networks.[5]

**Negative emissions technologies, such as CCS with bioenergy (BECCS), can have an important role to play in achieving decarbonisation targets.** A Royal Society and Royal Academy of Engineering study found that even with very stringent emissions reductions, negative emissions technologies will need to account for around 130Mt$CO_2$/year for 2050 net zero emissions to be achieved in the UK.[6] It is recognised that BECCS could be among the highest value uses for biomass in a future energy system, with the different uses discussed in more detail in the Bioenergy EINA.

## Future deployment scenarios

**The EINAs High-Innovation scenario estimates 19GW Combined Cycle Gas Turbine (CCGT) CCS deployed by 2050.** Power CCS is a core component in decarbonising the electricity system in the ESME model run. ESME's modelling assumes that the default $CO_2$ capture rate for CCS technologies is 95% of the $CO_2$ emitted, the main exception being waste gasification with CCS where a 90% capture rate is assumed. The energy penalty associated with CCS varies according to the technology but is typically between 8%-12%. ESME finds system-optimal deployment levels of circa 2GW by 2030, 16 GW by 2040, and 19GW by 2050.[7]

## Sub-theme system integration: Benefits, challenges and enablers

**Large-scale deployment of CCS has the potential to offer the energy security benefits of continued fossil fuel combustion,** whilst reducing greenhouse gas (GHG) emissions and their contribution to climate change. If the UK energy system is to meet decarbonisation targets without the use of CCS, it will require a significant increase in reliance on nuclear and offshore wind.

**CCS has the potential of acting as a flexible enabler for low carbon energy**, either through continued use of fossil fuels for electricity or by enabling industrial decarbonisation and the production of hydrogen to be used flexibly in a wide range of end uses.

**Bio-energy with CCS (BECCS) is an important negative $CO_2$ emissions technology** that will be critical to cost-effectively meeting the UK's 2050 carbon

[5] Global CCS Institute (2018) The Global Status of CCS: the creation of the CCUS Cost Challenge Taskforce.
[6] The Royal Society and Royal Academy of Engineering (2018). Greenhouse Gas Removal. https://royalsociety.org/topics-policy/projects/ greenhouse-gas-removal/
[7] Energy Systems Catapult (2018). Estimates based on the ESME whole-systems modelling tool following BEIS' EINA methodology.

targets. There are several constraints and assumptions that will influence the role of BECCS in the UK's future energy system. These include the amount of sustainable biomass that is available, as well as the cost and performance trajectories of all other technologies. Analysis by the Energy Technologies Institute (ETI) into 2050 decarbonisation pathways suggest that a consistent biomass feedstock planting rate of 30,000 hectares per annum, combined with moderate imports, would be enough to meet the required negative emissions targets.[8]

**Deployment of CCS will be essential to achieving the deep emission cuts that are required in high-emitting heavy industries.** The steel and cement industries are also key to a decarbonised future, as they are required for the building of new renewable energy technology manufacturing infrastructure. The scope of emission reductions through efficiency improvements and fuel switching is limited in many of these industries to around 30%.[9] In contrast to the power sector, additional challenges arise from the global nature of industrial sectors. This can have the effect of leaving organisations that invest in CCS exposed to cheaper overseas competition.

**Economies of scales in CCUS can be achieved through coordination between different sectors and industries.** Workshop delegates confirmed that coordination by sharing infrastructure and capacity for transport and $CO_2$ storage would facilitate and enable CCUS innovation in the UK. Similarly, geographical cluster development would enable the identification of lowest-cost infrastructure opportunities in the future.

**CCS (most notably CCGT-CCS) is deployed significantly in the EINA methodology using ESME in both the baseline and high-innovation cases, detailed below.** Its appearance in the baseline case demonstrates its criticality to the delivery of a lowest-cost UK decarbonisation pathway to 2050.

**The innovation impact analysis summarised by ESME (see Box 3) shows that there is also value to the UK in continued (and accelerated) innovation in CCS**.

[8] ETI (2016) The Evidence for Deploying Bioenergy with CCS (BECCS) in the UK. https://www.eti.co.uk/insights/the-evidence-for-deploying-bioenergy-with-ccs-beccs-in-the-uk
[9] International Energy Agency (n.d.) Industrial Applications of CCS. https://www.iea.org/topics/ccs/industrialapplicationsofccs/

*Box 3.* **System modelling: CCUS in the UK energy system**

Following the BEIS EINA methodology, whole energy system modelling was conducted using the ESME$^{TM}$ Version 4.4 to estimate where innovation investments could provide most value to support UK energy system development.

ESME is a peer-reviewed whole energy system model (covering the electricity, heat and transport sectors, and energy infrastructure) that derives cost-optimal energy system pathways to 2050 meeting user-defined constraints, e.g. 80% greenhouse gas (GHG) emissions reduction.[10] The model can choose from a database of over 400 technologies which are each characterised in cost, performance and other terms (e.g. maximum build rates) out to 2050. The ESME assumption set has been developed over a period of over 10 years and is published.[11] ESME is intended for use as a strategic planning tool and has enough spatial and temporal resolution for system engineering design.

Like any whole system model, ESME is not a complete characterisation of the real world, but it is able to provide guidance on the overall value of different technologies, and the relative value of innovation in those technologies.

The EINA Methodology prescribes the approach to be taken to assess the system-level value of technology innovation. This involves creating a baseline energy system transition without innovation (from which a baseline energy system transition cost is derived), and on a technology-by-technology basis assessing the energy system transition cost impact of "innovating" that technology. Innovation in a technology is modelled as an agreed improvement in cost and performance out to 2050.

For the EINA analysis, the technology cost and performance assumptions were derived from the standard ESME dataset[10] as follows:

- In the baseline energy system transition, the cost and performance of all technologies is assumed to be frozen at their 2020 levels from 2020 out to 2050.
- The "innovated" technology cost and performance for all technologies are assumed to follow the standard ESME dataset improvement trajectories out to 2050 (these are considered techno-optimistic).
- In the case of CCUS technologies, the assumed "innovated" installed cost reduction is above 50% by 2050. This compares to reductions in other sectors of 59% for fixed offshore wind, 51% for floating offshore wind, 38% for tidal stream, 16% for nuclear Gen III, and 25% for nuclear small modular reactors (SMR).

Whole system analysis using the BEIS EINA methodology described above shows that there is significant value to the UK in continued (and accelerated) innovation in CCUS.

- The innovation value of CCUS is £4.0 billion cumulatively to 2050 (discounted at 3.5%). The ESME modelling was made using the assumptions that when considering the cost of Integrated Gasification Combined Cycle (IGCC) Biomass with CCS, the capital cost of CCGT with CCS would decrease from £3,500 /kW to ~ £2,600/kW and from ~£1,250/kW to £1,000/kW respectively by 2050. It appears that the baseline case demonstrates that CCS is critical to the delivery of a lowest-cost UK decarbonisation pathway 2050.
- Other analysis and modelling (Committee on Climate Change (CCC), ETI) has shown that the cost of delivering the UK 2050 targets without CCS would increase by several £10s of billions.[12] The ETI modelling estimates that a delay to the baseline case of CCS deployment in the early 2020s will add £1-2 billion per year to the otherwise best achievable cost for reducing carbon emissions throughout the 2020s. Longer-term costs are also predicted to significantly increase, with delay adding an estimated £4-5 billion per year to otherwise best achievable cost in 2040.

Further work is required to estimate the value of innovations in CCUS, or how these estimates may change in the case of different energy system scenarios.

[10] More details of the capabilities and structure of the ESME model can be found at eti.co.uk/programmes/strategy/esme. This includes a file containing the standard input data assumptions used within the model.
[11] The ESME assumption set has been developed is published with data sources at https://www.eti.co.uk/programmes/strategy/esme
[12] Imperial College for The Committee on Climate Change: CCS in the UK: A new strategy. https://www.theccc.org.uk/wp-content/uploads/2016/07/CCS_Advisory_Group_-_CCS_in_the_UK.pdf; Energy Technologies Institute (2016): Letter to Chair on Future of CCS. https://s3-eu-west1.amazonaws.com/assets.eti.co.uk/legacyUploads/2016/01/ETI-letter-to-Chair-on Future of-CCS.pdf

*Box 4.* **Learning by doing and learning by research**

The total system value follows from two types of technology learning:

- **Learning by doing:** Improvements such as reduced cost and/or improved performance. These are driven by knowledge gained from actual manufacturing, scale of production, and use. Other factors, such as the impact of standards, which tend to increase in direct proportion to capacity increases.
- **Learning by research:** Improvements such as proof of concept or viability, reduced costs, or improved performance driven by research, development, and demonstration (RD&D). It increases with spend in RD&D and tends to precede growth in capacity.

The EINAs are primarily interested in learning by RD&D, as this is the value that the government can unlock as a result of innovation policy. Emerging technologies will require a greater degree of learning by RD&D than mature technologies. Academic work suggests[13] that for emerging technologies around two-thirds of the learning is due to RD&D, and for mature technologies it contributes around one-third.

To reach a quantitative estimate of the system value attributable to RD&D, these ratios are applied to the innovation value. This implies that, as an emerging technology, around £2.8 billion of the £4.0 billion innovation value for CCUS follows from RD&D efforts. Note, this is an illustrative estimate, with the following caveats:

- The learning-type splits are intended to apply to cost reductions. However, in this study, they are applied to the system value. As system value is not linearly related to cost reduction, this method is imperfect.
- In practice, learning by research and learning by doing are not completely separable. It is important to deploy in order to crowd-in investment to more RD&D, and RD&D is important to unlock deployment.

These estimates are used in the EINA Overview Report to develop a total system value that results from innovation programmes across the energy system.

[13] Jamasb, Tooraj (2007) Technical Change Theory and Learning Curves, The Energy Journal 28(3).

# Innovation opportunities within CCUS

## Introduction

*Box 5.* **Objective of the innovation opportunity analysis**

The primary objective is to identify the most promising innovation opportunities within CCUS and highlight how these innovations may be realised and contribute to achieving the system benefit potential described above. This section provides:

- A breakdown of the costs within CCUS across key components and activities.
- A list of identified innovation opportunities, and an assessment of their importance to reducing costs and deployment barriers.
- Deep dives into the most promising innovation opportunities.

**There are important learning opportunities from both innovation and the demonstration of CCUS in the UK.** Despite significant benefits to the energy system and potential for reducing GHG emissions, there is no full-scale demonstration of the CCS technology chain in the UK. There is a critical need to learn from full-scale systems in order to realise cost reductions through both learning by doing and learning by research in the UK.[14]

**Analysis from the Energy Technologies Institute suggests that the key to reducing the cost of CCS** is through the delivery of a small number of large-scale projects sequentially. The study further suggests that the risk reduction through sequential deployment using existing technologies could reduce output energy costs by as much as 45%.[15]

[14] CCUS Cost Challenge Taskforce (2018), Delivering Clean Growth: CCUS Cost Challenge Taskforce Report
[15] Energy Technologies Institute (2016): Letter to Chair on Future of CCS. https://s3-eu-west1.amazonaws.com/assets.eti.co.uk/legacyUploads/2016/01/ETI-letter-to-Chair-on Future of-CCS.pdf

## Cost breakdown

### Power CCS

BEIS[16] estimations split the cost breakdown of Power CCS into cases including those listed below, which were set to capture at least 90% of the $CO_2$ arising within the process. Natural gas- and coal-fired cases were developed with a target net electrical power output in the range 800-1200 MW:

1. Natural gas CCGT with post-combustion carbon capture
2. Natural gas reformation with pre-combustion carbon capture
3. Coal Supercritical Pulverised Coal (SCPC) with post-combustion carbon capture
4. Coal SCPC with oxy-combustion carbon capture
5. Coal IGCC with pre-combustion carbon capture
6. Oxy-fired supercritical gas power generation with carbon capture
7. Natural gas CCGT with Molten Carbonate Fuel Cell carbon capture

**Studies estimate that Levelised Cost of Energy (LCOE) contribution to power cases vary between £70/MWh and £204/MWh**. Coal IGCC with pre-combustion carbon capture's total LCOE is at £120.8/MWh compared to natural gas CCGT with post-combustion carbon capture at £69.9/MWh. Capital cost represents 42% of the total LCOE contribution cost for coal pre-combustion IGCC while for natural gas CCGT fuel costs are the largest component, representing 61%.

[16] BEIS (2018), Assessing the Cost Reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology: Benchmarking State-of-the-Art and Next Generation Technologies.

Table 6. **Split of LCOE Contribution (£/MWh) for Power CCS**

| LCOE contribution (£/MWh) | Capital Cost | Fuel | Operating Cost | Emissions Price | Storage & Transport | Total |
|---|---|---|---|---|---|---|
| Natural gas post-combustion CCGT | 14.9 | 37.9 | 7.2 | 2.9 | 7.0 | 69.9 |
| Natural gas pre-combustion | 26.6 | 48.5 | 12.2 | 3.8 | 8.9 | 100 |
| Coal post-combustion SCPC | 32.9 | 22.2 | 13.8 | 7.5 | 16.9 | 93.3 |
| Coal oxy-combustion SCPC | 35.3 | 21.7 | 14.7 | 8 | 16.3 | 96 |
| Coal pre-combustion CCGT | 51.1 | 22.8 | 22 | 7.5 | 17.4 | 120.8 |

*Source:* *BEIS (2018) Assessing the cost reduction potential and competitiveness of novel (next generation) UK carbon capture technology: benchmarking State-of-the-Art and Next Generation technologies*

**Costs between coal cases vary greatly and are higher than gas cases partly due to feedstock handling and the more complex process steps needed to produce clean energy.** For Coal-IGCC, for instance, the cost of gasification, carbon monoxide shift, carbon dioxide/hydrogen sulphide capture, and combined cycle are the most expensive. Similarly, operating costs for coal are higher than natural gas cases, due to higher capital and labour costs. But also, higher levels of $CO_2$ emissions require larger volumes of $CO_2$ to be transported, resulting in increased operating costs.

## Industrial CCUS

**Using literature figures of a techno-economic analysis of CCS applied to several industries, an indicative cost breakdown can be analysed.** The total cost of CCS deployment on 80% of plants globally in the cement, iron and steel, and petroleum refining sectors are projected to fall within the range of $190-230 billion by 2050. Estimated annualised costs of CCS are $17.8 billion, $14.8 billion, and $17.3 billion for refineries, cement, and iron/steel respectively. By using calcium looping in the cement industry, the overall cost will be around $28/t$CO_2$ avoided over the course of the time period and $20/t$CO_2$ by 2050. In contrast, the costs in the other two industries are higher; $55/t$CO_2$ for iron and steel and $59/t$CO_2$ for refining.[17]

**Iron and steel industries are the largest emitting industrial sectors, accounting for 31% of industrial emissions.** This comes mainly from 180 large integrated steel mills globally with average emissions of 3.5 Mt per year. There is great potential for reducing emissions associated with these integrated steel mills. On average, blast furnaces produce 2.3 t$CO_2$ per tonne of steel produced, which can be reduced to 1.9 t$CO_2$ using process efficiency improvements. Through the use of post-combustion $CO_2$ capture directly from the blast furnace, emissions can be further reduced to 0.9 t$CO_2$ per tonne of steel produced.[18] The petroleum refining industry is responsible for around 10% of industrial emissions globally, with 65% of these total emissions coming from furnaces and boilers and a further 16% coming from gasifiers and catalytic crackers. In the cement industry, around 1,306 million tonnes of $CO_2$ are emitted each year globally, with 60% of this coming from calcination processes and 40% related to heat generation for the kiln.

## Inventory of innovation opportunities

**Innovation opportunities in CCUS are highly dependent on action from both the public and private sectors.** Public sector support in the demonstration of commercially viable scaled-up CCUS solutions within the UK could help to catalyse private sector investment**.** Cross-cutting innovation opportunities in power and industrial CCUS have the biggest cost and deployment barrier reduction potential. Examples of cross-cutting innovations include those that focus on risk reduction and the unlocking of business models and liabilities for transport and storage.

### Gas and solid fuel post-combustion capture

Gas and solid fuel (biomass and coal) post-combustion $CO_2$ capture plants have high innovation opportunities in the development and demonstration of cheaper absorbers. Absorbers are currently the main component of the capture unit and there

[17] Cost estimations from: D. Lesson et al. (2016): A techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources.
[18] Energy Transitions Commission (2018): Reaching Zero Carbon Emissions From Steel. http://energy-transitions.org/sites/default/files/ETC_Consultation_Paper_-_Steel.pdf

is particularly high value for innovation relating to reducing the cost and increasing the performance of absorbers and other alternative materials, such as solid sorbents.

**Gas pre-combustion capture**
For novel reformers, advanced technologies can unlock the potential to combine hydrogen production with CCS for power and open opportunities across the energy system. Cost reduction and efficiency gains are also possible using technologies that require less energy and fuel, cheaper materials, and reduced $CO_2$ compression.

**Solid fuel pre-combustion capture**
Solid fuel pre-combustion capture has high innovation opportunity for the development and demonstration of cheaper gasification processes, which can reduce both cost and deployment barriers. The UK would benefit from leveraging gasifier technologies that have been developed and deployed elsewhere, in China for example, and focussing on the integration challenge with solid fuel pre-combustion capture plants. Solid fuel pre-combustion capture innovation opportunities for BECCS are covered in more depth within the Biomass and bioenergy EINA.

**Storage**
Several key storage innovation needs have not yet been addressed, particularly in terms of risks associated with storage deployment. There is a high innovation opportunity for $CO_2$ storage in post-closure Measuring, Monitoring, and Verification (MMV), to move towards effective long-term monitoring techniques that are performance-based and dynamic. There is strong potential for storage cost reduction in legacy wells through re-characterising abandoned old wells, such as those in the North Sea. The long lead times of developing such storage sites makes this a priority innovation area. There is also a need for development and demonstration of pressure management technologies that can improve injectivity and increase storage efficiency and reliability.

**Industrial CCUS**
Industrial CCUS innovation opportunities with the highest potential for reducing barrier deployment are related to the de-risking of scaling up the technology. The cement and steel sectors have been identified as having some of the greatest need for collaboration to drive demonstration and prove economic feasibility. Developing a more comprehensive understanding of the optimal application of capture technologies to industrial process emissions is also essential. Different industrial processes have different conditions and requirements which can affect the optimal capture solutions. Furthermore, varying exhaust $CO_2$ stream compositions can influence key performance factors such as capture rates and associated energy penalties.

**Table 7 contains examples of technical innovation opportunities in CCUS. It groups technical innovations by broad category,** describing which technology it applies to and the approximate timeframe for deployment. It is indicative and not exhaustive. It was first developed by the Carbon Trust for the 2015 CCUS Technology Innovation Needs Assessment (TINA) refresh through extensive desktop research and expert consultation. It was updated for the EINAs via expert review from Imperial College London.

**Workshop participants discussed the contents of the table and offered feedback.** The updated table was afterwards circulated amongst workshop delegates with the opportunity to provide further comments, which were included. Prioritisation of cost reduction and barriers to deployment was elaborated by the Carbon Trust to reflect the importance of some innovations in the workshop interaction. The magnitudes of the contribution to cost reduction and reducing deployment barriers are described in qualitative terms relative to other innovation opportunities:

- Significantly above average = 5
- Above average = 4
- Average = 3
- Below average = 2
- Significantly below average = 1

An indicative timeframe for each innovation is provided. The timeframe given relates to the year the technology is deployed commercially at scale (gaining 10-20% market share).

Table 7. **Innovation mapping for CCUS**

| Component | Innovation opportunity | Cost reduction | Deployment barrier reduction | Technology affected | Impact on other energy technology families | Timeframe |
|---|---|---|---|---|---|---|
| **Power:** | | | | | | |
| **Gas post-combustion capture** | Learning about plant integration and balance of plant to unlock innovative cost reductions | 3 | 2 | Any process using thermal regeneration | | 2020s |
| | Development & demonstration of cheaper absorbers | 5 | 4 | Solvent-based processes (e.g. RPB) | | 2025 |
| | R&D, development & demonstration of advanced solvents that can reduce regeneration costs and corrosion effects, and work with industrial applications | 4 | 3 | Solvent-based capture | | 2020s |
| | R&D on water management and waste minimisation | 1 | 2 | | Solvent-based | 2020s |
| | R&D on flexible power generation (part of power plant improvement) | 3 | 3 | | May be particularly useful for gas | 2020s |
| | R&D on Exhaust Gas Recirculation | 4 | 2 | More useful for natural gas | | 2020s |

| | | | | | | |
|---|---|---|---|---|---|---|
| | R&D on safety etc. of degradation products, emissions to the environment e.g. management of wastewater | 3 | 5 | Solvent-based | | 2020s |
| **Component** | **Innovation opportunity** | **Cost reduction** | **Deployment barrier reduction** | **Technology affected** | **Impact on other energy technology families** | **Timeframe** |
| **Gas pre-combustion capture** | Novel reformers e.g. ATR, GHR, also coupling steam heating reformers with CCS (which may include novel solvent, sorption-enhanced water gas shift) | 5 | 5 | | $H_2$ for power and other uses | 2030 |
| **Gas Oxy-combustion capture** | Ion transport membranes | 5 | 3 | Oxy | | 2040s |
| | High-pressure oxy-fuel (high UK content) | 3 | 3 | Oxy | | 2030 |
| | Learning about plant integration and balance of plant to unlock innovative cost reductions | 2 | 2 | All oxy | | 2020s |
| | Development and demonstration of advanced ASUs | 2 | 2 | | | 2020s |
| | Development and demonstration of advanced combustors and exhaust gas recirculation | 3 | 3 | All oxy | | 2020s |
| | Exploring alternative gas processing/ clean-up options pre-transport | 3 | 3 | All oxy | | 2020s |
| | R&D on water management and waste minimisation | 1 | 1 | | | 2020s |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Solid fuel Post-combustion capture** | Learning about plant integration and balance of plant to unlock innovation cost reductions | 3 | 2 | Any process using thermal regeneration | | 2020s |
| | Development & demonstration of cheaper absorbers (same R&D programme as for gas) | 5 | 4 | Solvent-based processes (e.g. RPB, MBC) | | 2040 |
| **Component** | **Innovation opportunity** | **Cost reduction** | **Deployment barrier reduction** | **Technology affected** | **Impact on other energy technology families** | **Timeframe** |
| **Solid fuel Post-combustion capture** | R&D, development & demonstration of advanced solvents that can reduce regeneration costs and corrosion effects, and work with industrial applications | 4 | 3 | Solvent capture | | 2020s |
| | R&D on water management and waste minimisation | 1 | 2 | Solvent-based | | 2020s |
| | R&D on exhaust gas recirculation (EGR) | 2 | 1 | All | | 2020s |
| | R&D on flexible power generation | 3 | 3 | All | | 2020s |
| | R&D on safety of degradation productions, emissions to the environment e.g. management of wastewater | 3 | 5 | Solvent-based | | 2020s |
| **Solid fuel Pre-combustion capture** | Learning about plant integration and balance of plant to unlock innovative cost reductions | 3 | 2 | Any process using thermal regeneration | | 2020s |
| | Development & demonstration of cheaper gasifier and gasification process | 4 | 4 | All gasification-based processes | | 2030 |
| | R&D on water management and waste | 1 | 2 | All gasification | | 2020s |

| | | | | | | |
|---|---|---|---|---|---|---|
| | R&D on polygeneration (hydrogen options) | 3 | 3 | Those which go beyond power | | 2030 |
| **Component** | **Innovation opportunity** | **Cost reduction** | **Deployment barrier reduction** | **Technology affected** | **Impact on other energy technology families** | **Timeframe** |
| **Solid fuel Oxy-combustion** | Learning about plant integration and balance of plant to unlock innovative cost reductions | 2 | 2 | All oxy | | 2020s |
| | Development & demonstration of advanced Air Separation Units (ASUs) | 2 | 2 | NB ASU is mature | | 2020s |
| | Development & demonstration of advanced combustors and EGR | 3 | 3 | All oxy | | 2030 |
| | Exploring alternative gas processing/clean-up options pre-transport | 3 | 3 | All oxy | | 2020s |
| | R&D on water management and waste minimisation | 1 | 2 | All oxy | | 2020s |
| | R&D on flexible power generation | 2 | 2 | All oxy | | 2020s |
| **$CO_2$ Storage: Transport** | R&D on the effects of flexible load following | 2 | 2 | All | | 2020s |
| **$CO_2$ Storage: Exploration, characterisation and optimisation** | De-risking the scale-up of stores (connectivity of sands, structural features, imagining approaches for characterising) | 3 | 5 | All | | 2020s |
| | R&D and development of technologies and methods that can model, simulate, and | 3 | 4 | All | | 2020s |

| | | | | | | |
|---|---|---|---|---|---|---|
| | appraise stores faster with a high degree of confidence | | | | | |
| | Development of sub-sea modules for extended injection testing | 2 | 4 | All | | 2020s |
| | R&D on the connectivity of stores | 2 | 3 | All | | 2020s |
| **Component** | **Innovation opportunity** | **Cost reduction** | **Deployment barrier reduction** | **Technology affected** | **Impact on other energy technology families** | **Timeframe** |
| **$CO_2$ Storage: Infrastructure & injection wells** | Legacy wells- how to develop wells to an adequate standard without a rig | 4 | 4 | All | | 2020s |
| | Development and demonstration of pressure management technologies to increase injectivity | 4 | 4 | All | | 2020s |
| | Deploying sub-sea installations instead of platforms | 4 | 3 | All | | 2030s |
| | Improve resilience of injection wells (especially for less pure $CO_2$ streams) | 2 | 2 | All | | 2020s |
| | Legacy wells- how to make an adequate standard without a rig | 4 | 4 | All | | 2020s |
| **$CO_2$ Storage: O&M** | Deploying sub-sea installations instead of platforms | 2 | 3 | All | | 2030s |
| **$CO_2$ Storage: MMV** | Post-closure – most effective long-term monitoring techniques (move to performance-based standard) | 4 | 4 | All | | 2050s |
| | R&D on $CO_2$ migration pathways and leak assessment | 2 | 3 | All | | 2020 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Standardisation with other countries | 2 | 3 | All | | 2030s |
| | Development and demonstration of advanced technologies – e.g. fibre optic, chemical, gravity monitoring etc, and without the need for wells | 2 | 3 | All | | 2030s |
| **Component** | **Innovation opportunity** | **Cost reduction** | **Deployment barrier reduction** | **Technology affected** | **Impact on other energy technology families** | **Timeframe** |
| **Industrial:** | | | | | | |
| **Cement** | Investigate the effects of varying quality $CO_2$ streams for capture technologies | 3 | 3 | All | | 2020s |
| | Collaborative Industrial CCS programme to drive demonstration and prove economics | 3 | 4 | All | | 2020s |
| **Chemicals** | Investigate the effects of varying quality $CO_2$ streams for capture technologies | 3 | 3 | All | | 2020s |
| | Applied R&D technology programme to identify optimum capture solutions for UK applications by sub-sector | 3 | 3 | All | | 2020s |
| | Collaborative industrial CCS programme to drive demonstration and prove economics | 3 | 4 | All | | 2020s |
| **Iron & steel** | Investigate the effects of varying quality $CO_2$ streams for capture technologies. | 2 | 2 | All | | 2020s |
| | Collaborative industrial CCS programme to drive demonstration and prove economics. | 3 | 4 | All | | 2020s |
| | Applied R&D technology programme to identify optimum capture solutions for UK applications. | 3 | 3 | All | | 2020s |

| Component | Innovation opportunity | Cost reduction | Deployment barrier reduction | Technology affected | Impact on other energy technology families | Timeframe |
|---|---|---|---|---|---|---|
| **Refining** | Investigate the effects of varying quality $CO_2$ streams for capture technologies. | 3 | 3 | All | | 2020s |
| | Applied R&D technology programme to identify optimum capture solutions for UK applications. | 3 | 3 | All | | 2020s |
| | Collaborative industrial CCS programme to drive demonstration and prove economics. | 3 | 4 | All | | 2020s |
| | Investigate the effects of varying quality $CO_2$ streams for capture technologies. | 3 | 3 | All | | 2020s |
| **Use/utilisation** | Expand CCS roadmaps/task forces to look at options for the UK, including building an understanding of the environmental trade-offs versus storage. | 2 | 2 | | | 2020s |
| | Fundamental R&D, including small and medium-sized enterprises (SMEs) support, to develop disruptive technologies and applications. | 3 | 3 | | | 2030 |
| **Fuel production** | Methanol | 2 | 2 | Mostly known technology | | 2020s |
| | Formic acid | 3 | 2 | More innovation potential | | 2020s |
| | Investigate the effects of varying quality $CO_2$ streams for capture technologies. | 3 | 3 | All | | 2020s |
| | Increased capture efficiency | 2 | 4 | All | | 2025 |

| Component | Innovation opportunity | Cost reduction | Deploymen t barrier reduction | Technology affected | Impact on other energy technology families | Timeframe |
|---|---|---|---|---|---|---|
| **Cross-cutting** | Development of finance mechanisms to encourage capture deployment, large-scale innovation would reduce risk. | 4 | 4 | All | | 2020s |
| | Explore innovative business models and liabilities for transport and storage | 3 | 5 | All | | 2020s |

*Source: Frazer-Nash, Carbon Trust, Vivid Economics, expert workshop*

# Innovation opportunity deep dives

**The following five example innovations illustrate cost reduction and deployment barrier opportunities for CCUS technologies.**

## Pre-combustion

**The high cost of novel reformers was highlighted as a problem by workshop participants.** For natural gas pre-combustion capture, novel reformers such as Auto Thermal Reformers (ATR) and Gas Heated Reformers (GHR) have a considerable advantage compared to Steam Heating Reformers (SHR). These advanced technologies can produce purer hydrogen and capture $CO_2$ in larger quantities. Further cost reductions can be achieved through more energy-efficient processes with reduced fuel requirements, cheaper materials, and reduced gas compression.

**Workshop participants also highlighted the potential for CCS deployment to unlock the UK's hydrogen energy system.** Hydrogen is a very important and closely aligned sector with high potential across power, transport, and industries for the use of hydrogen as a fuel. The hydrogen economy is highly dependent on the development of CCS for low-emission hydrogen production. This further reinforces the need for supporting novel reformer innovations that can both increase hydrogen production and carbon capture. In addition to this, the UK is among the leaders in this field, with a competitive advantage in hydrogen production and significant know-how, for instance in fuel cell technologies. The Shell Quest Project in Canada is an example of CCS deployment in hydrogen production. By using 3 steam methane reformers, the company can capture 1.2 million tonnes of $CO_2$ per year. Through an amine-based chemical absorption process, the company can capture highly pure $CO_2$, at over 99%.[19]

## Post-combustion

**Developments in advanced solvent processes that can reduce regeneration costs and corrosion effects have a high potential for cost reduction in gas and solid fuel post-combustion capture.** The benefits of these new solvents include reduced environmental impact and product degradation. R&D into innovative concepts around advanced solvents can help to reduce the energy penalty of the capture process and thus bring down costs further. One example is a Rotating Pack Bed (RPB) system, which can intensify the process by capturing more $CO_2$ through

[19] Shell (2010); Quest Carbon Capture and Storage Project. https://www.cslforum.org/cslf/sites/default/files/documents/Warsaw2010/Spence-TG-QuestPresentation-Warsaw1010.pdf

more compact technologies, although significant cost reductions are still needed. Other innovations in this area are around solvents that can replace monoethanolamine (MEA) and looking further ahead to new processes such as solid adsorption, which could reduce costs further.  Earlier-stage innovations may require significant changes to more established capture systems that are based upon well proven technologies, which can present a higher risk.

Beyond advanced solvents, post-combustion $CO_2$ separation costs for gas can be reduced through Exhaust Gas Recirculation (EGR), where exhaust $CO_2$ is recirculated through a gas turbine to increase flue gas $CO_2$ concentration and reduce the burden of separation. Other post-combustion capture processes, including fuel cells (e.g. molten carbonate fuel cells), are also being explored. However, these technologies are generally at an earlier stage of development and are likely limited in scope to small- and medium-sized plants.

## Oxy-combustion

**Advances in air separation using ITM**: ITM is a technology with high potential for reducing the cost of air separation in both oxygen and syngas production. Success could lead to a step change cost reduction as the technology is able to produce large volumes of higher purity oxygen than conventional technologies. ITM is based on ceramic materials that conduct oxygen ions at high temperature, with 100% selectivity. Hot high pressure is supplied to one side of the membrane and a pure oxygen product is recovered from the permeate side.[20] Compared to other air separation processes, the extraction efficiency of oxygen from air is significantly improved, but there remain several challenges around membrane durability. These may limit suitability to small- and medium-sized applications.

## Storage

**For innovations relating to $CO_2$ storage, improved characterisation and optimisation technologies and processes can address concerns on the risk of stores' scale-up.** No market or business case has been developed to address the inherent uncertainty of storage appraisal, which presents a considerable challenge when the long lead times of storage site appraisals are considered. Technologies and methods that can characterise the connectivity of sands and structural features would reduce this risk and unlock deployment. This would also be supported by further R&D into technologies and methods that model, simulate, and appraise stores faster and with a higher degree of confidence. Closely aligned to this is the need for innovative approaches to optimising liabilities and insurances, including re-thinking approaches for how CCS is characterised in this context. For storage developers, there is no guaranteed return on their significant investment if the stores

[20] Anderson et al. (2015) Advances in ion transport membrane technology for oxygen and syngas production.

they appraise prove to be inadequate or CCS deployment and the associated market fails to grow in the UK. Aquifer storage sites were identified by workshop attendees as an example of where significant R&D into new technologies is needed, particularly around the modelling physics of injection and migration of the $CO_2$ plume.

**There is a need for cost-effective robust long-term monitoring techniques.** Post-closure Measuring, Monitoring, and Verification (MMV) represents a significant cost and deployment barrier. An example of these challenges can be seen in the ETI £5.4m collaborative innovation programme for the development of a marine monitoring system for underwater CCS sites.[21] Innovation in finding alternatives to the current technologies were prioritised during the workshop session. Improving long-term monitoring techniques and moving towards performance-based standards could have the knock-on effect of reducing $CO_2$ storage-related risks. This could involve the more accurate monitoring of $CO_2$ pathways and seismicity to provide a better understanding of how leaks may happen. There is also a need for research into improving the metering systems and technologies that are used in $CO_2$ pipeline systems. Highly accurate quantitative and qualitative metering hardware and software would build greater confidence in the operation of $CO_2$ transport networks.

[21] Energy Technologies Institute; Measurement, Monitoring and Verification of $CO_2$ Storage (MMV). https://www.eti.co.uk/programmes/carbon-capture-storage/measurment-modelling-and-verrfication-of co2-storage-mmv

# Business opportunities within CCUS

## Introduction

*Box 6.* **Objective of the business opportunities analysis**

The primary objective is to provide a sense of the relative business opportunities against other energy technologies. To do so, the analysis uses a consistent methodology across technologies to quantify the 'opportunity'; in other words, what *could* be achieved by the UK. The analysis assumes high levels of innovation but remains agnostic about whether this is private or public. This distinction is made in the final section of the report. The two key outputs provided are:

- A quantitative estimate of the gross value added, and jobs supported associated with CCUS technology, based on a consistent methodology across technologies analysed in the EINA. Note, the GVA and jobs supported are *not* necessarily additional, and may displace economic activity in other sectors depending on wider macroeconomic conditions.
- A qualitative assessment of the importance of innovation in ensuring UK competitiveness and realising the identified business opportunities. Note, the quantitative estimates for GVA and jobs supported cannot be fully attributed to innovation.

The following discussion details business opportunities arising both from exports and the domestic market. An overview of the business opportunities, and a comparison of the relative size of export and domestic opportunities, across all EINA sub-themes is provided in the overview report.

More detail on the business opportunities methodology is provided in the Appendix.

**The global CCUS industry is still in its infancy, but significant growth is expected.** There are 18 operational CCUS projects worldwide, with most related to gas processing and enhanced oil recovery (EOR). Of these, 14 use the captured $CO_2$ for enhanced oil recovery and 4 send the captured $CO_2$ into dedicated geological storage (Sleipner and Snohvit $CO_2$ Storage in Norway, Quest in Canada, and Illinois Industrial CCS in the US). There are only two operational large-scale CCUS power plants globally (Boundary Dam CCS in Canada, operational since 2014, and Petra Nova Carbon Capture in the US, operational since 2017).[22] Despite being in its infancy now, CCUS is expected to play a key role in mitigating climate

[22] Global CCS Institute, Facilities Database, 2019. https://co2re.co/FacilityData

change, primarily in the power sector (to enable continued use of coal and gas with low emissions) and in hard-to-treat industries such as in cement, chemicals, refining, and iron and steel. The IEA expects rapid growth in CCUS, estimating 6,785 Mt of captured $CO_2$ in 2050, split approximately evenly between industry and power.[23]

**The UK has an emerging carbon capture and storage industry that has the potential to scale domestically and export internationally.** Although the UK lacks operational large-scale (>0.8Mt$CO_2$ per annum) CCUS plants, there are operational demonstration projects (Drax bioenergy carbon capture pilot plant), test facilities (UK Carbon Capture and Storage Research Centre Pilot-scale Advanced Capture Technology) [24] and active research programmes (such as at Imperial College London and the University of Edinburgh). The UK has also made significant past investment in the design of projects such as Whiterose, and is developing new CCUS projects at Teesside, Grangemouth, and St. Fergus.[25] Furthermore, given the significant skills and engineering overlap, the UK can leverage its existing oil and gas industry to lead the initial deployment of CCUS.[26]

**To estimate the CCUS-related business opportunity to the UK, our analysis primarily considers generation equipment, equipment for $CO_2$ capture, transport and storage, and key CCUS services.** CCUS is a complex process, with a broad variety of goods and services required. This analysis focusses on the goods and services directly related to CCUS and does not assess indirect benefits, such as enabling of low carbon industrial or syntenic fuel production.[27] Nor does this analysis assess direct air capture, though this technology could plausibly be similar in market size to power CCUS. Fuel inputs for power CCUS, such as biomass production, are not assessed.[28] Key areas of focus are:

- **Carbon capture and air pollution control equipment:** Relevant for power and industry. Components include air pollution controls such as specialty solvents, flue gas desulphurisation, and air separation and compression equipment.
- **Generation equipment:** Relevant for power only. Components include gas, coal, or biomass combined cycle turbines and specialty oxyfuel turbines.

[23] IEA 2-degree scenario, see IEA, Energy Technology Perspectives, 2017. https://www.iea.org/etp2017/
[24] Global CCS Institute, Facilities Database, 2019. https://co2re.co/FacilityData
[25] Ibid.
[26] For a discussion of the oil and gas skills overlap, see HM Government, Clean Growth: The UK Carbon Capture Usage and Storage deployment pathway, 2018. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/759637/beis-ccus-action-plan.pdf and Poyry and Teesside Collective, A Business Case for A UK Industrial CCS Support Mechanism, 2017. http://www.teessidecollective.co.uk/wp-content/uploads/2017/02/0046_TVCA_ICCSBusinessModels_FinalReport_v200.pdf
[27] Synthetic fuels are covered in the Disruptive EINA.
[28] Biomass fuels for BECCS are covered in the Bioenergy EINA.

- **Transport and storage components:** Relevant for power and industry. Components include both the associated capital equipment, such as pipelines and injection equipment, and the potential opportunity to store $CO_2$ as a service for other countries.
- **Measuring Monitoring and Verification (MMV):** Relevant for power and industry. Components include instruments related to measuring, monitoring, and verification of $CO_2$ capture, transport, and storage.
- **Engineering, procurement, and construction management (EPCm) services:** Relevant for power and industry. Includes engineering, procurement, and construction management services for CCUS projects.[29]

The business opportunities analysis is set out as follows

- An overview of the global market, with a focus on markets for exports
- A discussion of the UK's competitive position, with a focus on exports
- A discussion of the business opportunities from exports
- A discussion of the UK business opportunities in the UK's domestic market, including a comparison of the relative importance of export and domestic opportunities

[29] EPCm services do not include financial, insurance, legal, or regulatory services.

*Box 7.* **The UK's current CCUS industry**

- UK strengths: EPCm services; capture and air pollution control components, including innovative solvents; and MMV instruments.
- Notable UK companies: BP and Shell, which have the technical expertise and the balance sheet to finance, engineer and operate large-scale CCUS, ventures; C-Capture and Carbon Clean Solutions, which are specialty $CO_2$ capture solvent manufacturers;[30] Heatric, a specialist manufacturer of advanced heat exchangers that employs over 200 people.
- Key competitors include: the US, Germany, China, and Japan in generating turbines; Japan as a competitor in capture technology, where Mitsubishi and Kansia Electric Power have partnered; the US is a particularly strong competitor in EPCm services, including multiple major oil companies and oilfield service providers such as Schlumberger, Haliburton, and Baker Hughes, which cumulatively controlled 48% of the global oilfield service market in 2017.[31]

## Market overview

**The global CCUS market is expected to grow to a multi-billion-pound market by mid-century, characterised by substantial capital expenditure.** The IEA 2-degree scenario projects around 650 GW of power CCUS capacity deployed worldwide for power generation by 2050.[32] CCUS power stations are characterised by high levels of capital expenditure, with the capital cost of a typical project being between £0.8 billion - 2.2 billion.[33] By 2050, accounting for projected cost reductions, the global market for power CCUS is expected to be worth £24 billion per year in turnover. The global markets for industry CCUS and $CO_2$ transport and storage components are expected to be substantially larger, at £181 billion and £54 billion per annum in turnover by 2050 respectively.[34]

[30] Shell has acquired CANSOLV, now Shell CANSOLV, which is a speciality solvent manufacturer based in Canada.
[31] Rystad Energy, Global Service Report: Well Services and Commodities: Drilling Tools and Services, 2018. https://www.rystadenergy.com/products/OFS-Solutions/Oilfield-Service-analytics/Oilfield-Service-Report/
[32] This capacity is expected to generate more than 12 times the amount of electricity the UK generated in 2017.
[33] BEIS and Wood, Assessing the Cost Reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology: Benchmarking State-of-the-Art and Next Generation Technologies, 2018. Doc no 13333-8820-RP-001. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/730562/BEIS_Final_Benchmarks_Report_Rev_3A__2_.pdf
[34] This estimate includes the total turnover from capital expenditure, though not all turnover is tradable. Tradability is discussed below and the total tradeable market is estimated at £15 billion in 2050.

**The trade of goods and service in the CCUS market is not well established due to the immaturity of the market, though trade in similar markets offers guidance on likely global trade patterns.**[35] The component market is expected to be highly traded regionally (within Europe), while the EPCm service and MMV markets are expected to be highly traded globally. Accordingly, our analysis assumes 100% of EPCm value is tradable globally across power, industry, and transport. For components, our analysis assumes that nearly 100% of capex is tradeable in Europe across CCUS applications, while approximately 75% of capex is tradable for power and industry, and 25% of storage and transport capex is tradable in the rest of the world (RoW). There are few tradability frictions in the EU market as a result of proximity and the likely deployment of CCUS around the North Sea, facilitating relatively easy maritime transport. In the RoW, high-value components, such as generating turbines, solvents, heat exchangers, and MMV instruments are likely to be highly traded while low-value bulk components, such as steel pipes, steel frames, or concrete, are likely to be sourced regionally.

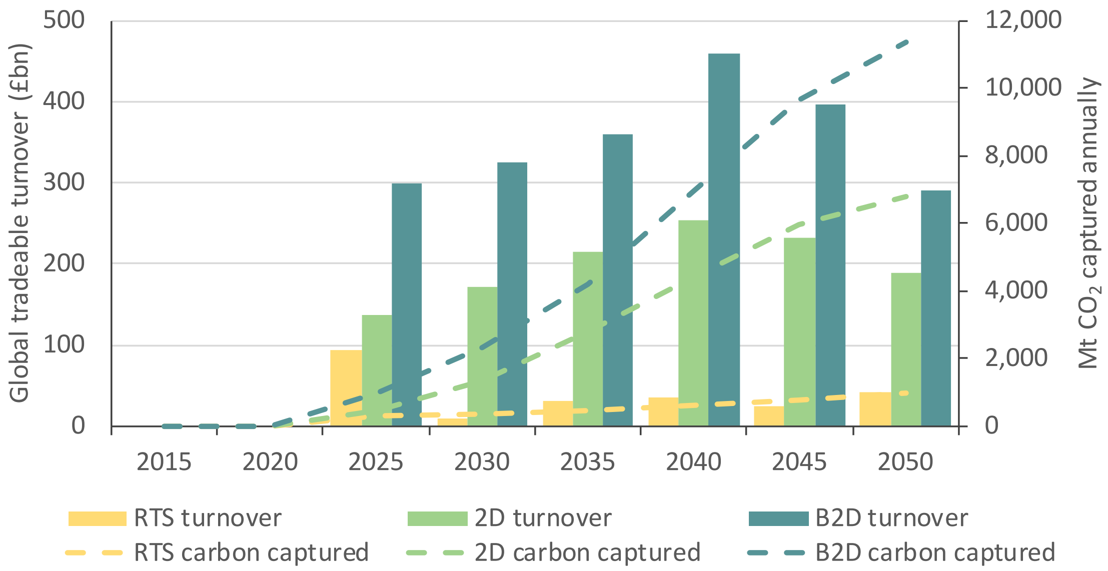
**CCUS market flows are expected to mirror the oil and gas component and service markets with large established supply chains to countries with relatively small CCUS industries and expertise.** Complex energy engineering projects, such as CCUS projects, often require bespoke expertise that is not readily available in middle-income economies. This is likely to be the case in the ASEAN region where the IEA 2-degree (2D) scenario projects 24 GW of coal CCUS, 20 GW of gas CCUS, and 8 GW of biomass CCUS to be deployed by 2050, requiring the transport and storage of 325 Mt of $CO_2$ per year.[36] Despite the distance, the growth of the ASEAN and like markets presents an opportunity for the UK to export expertise and speciality components, such as solvents and MMV instruments, and EPCm services that are likely to source bulk components closer to the location of the project.

**Although the power CCUS market is immature today, rapid growth is expected to 2050, particularly after 2030**. Our estimate of global tradeable turnover in power CCUS grows from minimal levels today to a peak of £53 billion annually by 2040 as deployment accelerates. Growth of CCUS deployment decelerates by 2045, reflected by £19 billion in annual tradeable turnover by 2050. The acceleration in deployment to 2040 is driven by the need to reduce $CO_2$ emissions in order to meet climate targets. This estimate assumes a 2-degree (2D) scenario. However, the CCUS deployment projections are uncertain and sensitive to the level of global climate action. For example, a beyond-2-degree (B2D) scenario could increase CCUS power deployment by 13%, while in a business-as-usual (RTS) scenario, global CCUS deployment to 2050 is only 24 GW. The timing of the turnover peak is

[35] Identification and assessment of similar markets is set out in the following section.
[36] IEA, Energy Technology Perspectives, 2017. https://www.iea.org/etp2017/

also sensitive to the level of global climate action. For example, delaying climate action could shift the turnover peak closer to 2050. Figure 1 displays total global tradeable turnover and annual carbon captured by scenario.

Figure 1 **CCUS tradeable market size by IEA scenario**




*Note:* *Global tradeable turnover includes power, industry, and transport and storage. Bars reflect global tradeable turnover and dashed lines reflect Mt of $CO_2$ captured annually.*

*Source:* *Vivid Economics*

**The industry CCUS market is also expected to grow rapidly in order to meet climate targets.** Our analysis estimates global tradeable turnover of £182 billion annually in industry CCUS by 2040 as deployment in industry outpaces power to meet climate targets. As deployment decelerates after 2040, annual global tradeable turnover declines to £149 billion by 2050, though the total quantity of $CO_2$ captured annually increases to 3,621Mt per annum as the fleet of industrial plants with CCUS continues to increase to 2050. In the EU market, deployment of industry CCUS outpaces power CCUS substantially, with £13.3 billion in annual industry CCUS turnover compared to £1.7 billion in annual power CCUS turnover by 2050. The market for industry CCUS is also particularly sensitive to the level of global climate action. In a B2D scenario, the deployment of industrial CCUS nearly doubles, while under a BAU scenario industry CCUS declines by 78% compared to the 2D scenario.

**Widespread deployment of power and industry CCUS are expected to create a substantial market for $CO_2$ transport and storage.** By 2050, the IEA estimates the carbon captured from power and industry to reach 6,785 Mt per year. However, this estimate is sensitive to global climate action and increases by two-thirds to 11,343Mt per year in a B2D scenario. Our analysis estimates global tradeable turnover in the $CO_2$ transport and storage market to reach £21 billion annually by 2050 under the 2D scenario, despite annual turnover of £54 billion. The gap between tradeable turnover and total turnover is a function of the type of components involved in $CO_2$ transport and storage, such as steel pipes and $CO_2$ injections rigs, which are more likely to be sourced regionally than equivalent industry or power CCUS components. However, EPCm services for $CO_2$ transport and storage are likely to be highly traded. This could present an opportunity for UK industry, dependent on the successful development of carbon storage in the North Sea.

Figure 2 **The current and future CCUS market**

**Current market for CCUS**

- *Production:* Deployment of CCUS today is minimal with 18 operational large-scale projects globally, of which only two are power CCUS
- *Trade:* Given the immaturity of the market, global trade in CCUS goods and services is minimal today
- *Markets:* The UK has 5 CCUS projects in early development, while the US leads deployment with 9 operational CCUS facilities. China and Australia also have numerous CCUS projects in development

**Tradability of market**

- *Goods:* High-value CCUS components, such as solvents and turbines, are highly tradeable, while low-value components, such as pipes and steel frames, are expected to be sourced locally
- *Services:* EPC services are highly tradeable, similar to the trade in oilfield services today, and are aided by successful domestic CCUS deployment
- *Trends:* CCUS trade patterns are expected to resemble trade in similar goods today

**Trends in deployment**

- *Global:* Power CCUS deployment is expected to reach 650GW and industry CCUS is projected to capture 3,621Mt of $CO_2$ annually by 2050.
- *Growth pattern:* Markets outside of the EU are expected to drive CCUS growth, with RoW deploying more than 10x the EU by 2050
- *Uncertainty:* Deployment could decrease by 86% by 2050 under BAU or increase by 67% under the beyond 2°C scenario compared to the 2°C scenario

**Tradeable market size to 2050**

- *Growth trend:* Substantial growth out to 2050 to meet climate targets. Sales growth is projected to slow following 2040 as deployment of CCUS in power and industry decelerates
- *Key markets:* EU market is expected to total £18 billion, with the rest of the world expected to be £170 billion by 2050

*Source: Vivid Economics*

## UK competitive position

**UK firms face substantial competition domestically and internationally in the manufacture of key CCUS equipment but could be strong in specialist products and broader CCUS related services.** The UK supply chain lacks a major (>400MW) gas or coal turbine manufacturer to compete with the US, Germany, Japan, or China in the market for CCUS conversion and generation equipment. However, the UK is likely competitive relative to its size in capture and pollution control (solvents, air pollution control) and measuring, monitoring, and verification (MMV) instruments, obtaining a 7-8% EU27 market share and 3-8% ROW market share respectively of related goods today.[37] Given substantial competition in mid-value manufacturing and significant distance from relatively large prospective Asian and American CCUS markets, the UK is unlikely to capture a large share of global CCUS component sales**.** However, the UK could capture a sizeable share of EPCm services given the UK's comparative advantage in EPCm services, as evident from the sale of similar EPCm services today, notably in the oil and gas sector.

**The UK's expertise is in engineering, procurement, construction, and project management, which it currently successfully exports in related industries.** The UK's engineering and oil and gas industries are well suited to lend their expertise to CCUS projects and these industries are highly competitive. For example, in 2016, the UK captured 11.8% of the global oilfield services (OFS) market, worth £36 billion in turnover,[38] despite the UK's 1.1% share of world oil production.[39] This positions the UK to move first on large-scale carbon capture and storage projects and use the challenging conditions, yet favourable geology, of the North Sea to build expertise in the delivery of complex CCUS projects combining power, industry, and carbon transport and storage.

**The UK is also moderately competitive in capture and pollution control and MMV instrument manufacturing.** The UK could capture a sizeable share of the CCUS solvent market if innovative solvent companies scale-up operations.[40] Measuring, monitoring, and verification instruments are another competitive opportunity for the UK given market shares of similar goods today. Successful deployment and operation of these instruments in the North Sea, could offer an effective proving ground to drive international sales.

**The US, Germany, Japan, and China are leading exporters of generating turbines and are likely CCUS competitors.** The UK ceased manufacturing large power turbines in 2014,[41] though some UK companies continue to manufacture specialty smaller power turbines.[42] Given the lack of large conventional power

[37] Capture and pollution control potential market shared based on UNCOMTRADE data for HS codes: 381400, 731100, 842139 and 842199. MMV potential market share based on UNCOMTRADE data for HS codes: 901580, 902610, 902620 and 902690.
[38] Three year average applied to calculate market share and turnover (2014-2016).
[39] BP, Statistical Review of World Energy, 2018. https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html
[40] Shell CANSOLV is a speciality solvent manufacturer based in Canada. Shell's acquisition of CANSOLV could allow for speciality solvent knowledge spillovers in the UK.
[41] Rolls-Royce, Rolls-Royce signs agreement to sell its Energy Gas Turbine and Compressor business to Siemens, 2014. https://www.rolls-royce.com/media/press-releases/2014/060513-energy-agreement-siemens.aspx
[42] These are typically gas-powered turbines for oil rigs, manufactured by companies such as Rolls-Royce or Centrax.

turbine manufacturers, the UK is unlikely to be competitive in the manufacture and export of power turbines for CCUS projects. Countries with established large power turbine manufacturers, such as the US, Germany, Japan, and China, are more likely to capture a substantial share of the CCUS generating turbine market. Toshiba has moved first into the oxyfuel turbine market by designing and demonstrating a 50MW gas-fuelled supercritical oxy-combustion turbine for NET Power's La Porte, Texas demonstration project.[43] The IEA's 2-degree scenario projects the US to deploy 57GW of coal CCUS and 59GW of gas CCUS by 2050, placing the US in a position to leverage its domestically deployed CCUS to competitively export CCUS generating turbines and related goods.[44]

**Germany and the US are the key competitors in EPCm services, and particularly the US in EPCm services related to the oil and gas industry.** The US is a strong competitor in EPCm services, including multiple multinational energy companies and oilfield service providers that could offer EPCm services for CCUS projects. US companies cumulatively controlled 48% of the global oilfield service market in 2017.[45] They are likely to remain strong competitors as the US increases oil production and develops new CCUS facilities.[46]

**Demonstrated domestic CCUS projects would be a strong enabler for UK exports globally.** Successful deployment of CCUS technology would enhance the UK's export position by demonstrating the UK's supply chain can deliver a complex engineering project that combines internationally sourced carbon capture components and integrates $CO_2$ transport and storage infrastructure. Major UK oil and gas companies can contract leading UK engineering firms and contractors to deploy CCUS at scale. Once an initial first-of-a-kind project and the corresponding infrastructure is operational, the project can serve as a hub to attract additional CCUS projects. This would potentially enable a CCUS cluster that would further lift international demand for UK CCUS expertise.

**UK export opportunities could exist without domestic deployment of CCUS, but these would be limited by a lack of proven experience.** Lacking the deployment of a large-scale CCUS power or industry facility in the UK, the business case for an international CCUS project to source UK components or EPCm services is diminished. However, niche component suppliers, such as specialty solvent manufacturers, could still be in a competitive position to export. In addition,

[43] Toshiba, Toshiba Successfully Achieves First Fire of 50MWth Commercial-scale Combustor at the NET Power Demonstration Plant, 2018. https://www.toshiba-energy.com/en/info/info2018_0615.htm
[44] IEA, Energy Technology Perspectives, 2017. https://www.iea.org/etp2017/
[45] Rystad Energy, Global Service Report: Well Services and Commodities: Drilling Tools and Services, 2018. https://www.rystadenergy.com/products/OFS-Solutions/Oilfield-Service-analytics/Oilfield-Service-Report/
[46] The US is likely to deploy additional CCUS facilities as a result of the increase in captured carbon tax credits (45Q tax credits) to $50/t$CO_2$ under the Bipartisan Budget Act of 2018.

multinational companies with a UK presence, such as multinational energy and heavy industry companies, are likely to be involved in CCUS projects abroad.

**The UK is likely to be more competitive in gas and biomass CCUS than coal CCUS.** International competitiveness is enhanced by successful domestic deployment and the UK is likely to deploy substantial quantities of gas CCUS and some biomass CCUS. Gas is the likely fuel choice for domestic CCUS given the UK's large gas power station fleet. In 2017, gas generated 137 TWh of electricity (40.4% of total) while coal only generated 23 TWh (6.7% of total).[47] Given the current industry mix, the UK looks unlikely to deploy coal CCUS. In contrast, China is projected to deploy a sizeable domestic coal CCUS power station fleet and become a key competitor in coal CCUS. The IEA's 2-degree scenario expects China to deploy 163 GW of coal CCUS, which is nearly 50% of projected global coal CCUS deployment by 2050. Accordingly, our analysis assumes the UK does not export EPCm services for coal CCUS.

[47] BEIS, Digest of United Kingdom Energy Statistics, 2018. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/736148/DUKES_2018.pdf

Figure 3 **The UK's competitive position in trade in CCUS goods**

**Current UK competitiveness**

- *Market shares (of relevant goods trade):*
  *EU (excl. UK) ~ 5%*
  *Rest of World ~ 3%*
- *Strengths: Capture and pollution control components, MMV instruments, sizeable oil and gas sector*
- *Weaknesses: No large power turbine manufacturers, no operational large-scale CCUS projects*

**Key competitor - US**

- *Market shares (for relevant goods trade) :*
  *EU ~ 7%*
  *Rest of World ~ 14%*
- *Strengths: Key player in large power turbines, capture and pollution control components, large oil and gas sector, multiple operational large-scale CCUS facilities*
- *Weaknesses: Limited exports of CCUS equipment to date*

**Key competitor - Germany**

- *Market shares (for relevant goods trade) :*
  *EU ~ 21%*
  *Rest of World ~ 6%*
- *Strengths: Key player in EU market for capture and pollution control components, large power turbines, and MMV instruments*
- *Weaknesses: Small oil and gas sector, no large-scale CCUS projects under development, public opposition to $CO_2$ storage*

**Key competitor – China**

- *Market shares (for relevant goods trade):*
  *EU ~ 6%*
  *RoW ~ 15%*
- *Strengths: Capture and pollution control components, multiple large-scale CCUS projects under development*
- *Weaknesses: Limited export of CCUS equipment to date*

*Note:* *Market shares based on UN COMTRADE data using HS codes: 281121, 381400, 730411, 730419, 730511, 730512, 731100, 841480, 841490, 842139, 842199, 890520, 901580, 902610, 902620 and 902690*

*Source:* *Vivid Economics*

*Box 8.* **Industry workshop feedback regarding business opportunities**

- The UK's comparative advantage is in engineering, designing, and assembling CCUS projects, while the UK is less competitive in the manufacture of CCUS components.
- First-mover advantage is crucial for international competitiveness in the sector. If the UK can successfully deploy several large-scale CCUS projects, it is more likely to successfully compete for EPCm contracts.
- The equipment to deploy CCUS is ready. The main challenge is the economics of the project given the price of carbon today.
- There is an opportunity for UK firms to lead in $CO_2$ transport and storage. In order to store the quantities of $CO_2$ IEA CCUS deployment projections entail, a 30 to 50 times increase in project scale is required.
- If the UK leads on storage, there is a substantial corresponding market for information and data gathered from storage activities.
- The UK can offer complementary services for CCUS projects, such as financing, insurance, legal, regulatory, and educational services and the licensing of intellectual property (IP).

Table 8. **Export market shares and innovation impact - CCUS**

| Component | Tradeable market 2050 (£bn) | Current market share of related goods and services | 2050 outlook with strong learning by research: Market share* | Captured turnover (£m) | GVA from exports (£m) | Rationale for the impact of innovation |
|---|---|---|---|---|---|---|
| Capture and pollution control | **EU: 11** RoW:102 | **EU: 8%** RoW: 3% | **EU: 8%** RoW: 3% | **EU: 860** RoW: 3,500 | **Total: 1,500** | Innovation could drive the development of cost-effective pre- and post-combustion $CO_2$ capture technologies, such as innovative solvents, that allow the UK to capture the same market shares in the EU and RoW that it captures for related air pollution control technologies today. |
| Conversion and generation | **EU: 0.9** RoW: 9.3 | **EU: 0%** RoW: 0% | **EU: 0%** RoW: 0% | **EU: N/A** RoW: N/A | **Total: N/A** | The UK lacks a major power turbine manufacturer and it is unlikely a UK firm will enter this market in the short- or medium-term. Accordingly, the UK is not expected to compete in this market. |
| $CO_2$ transport components | **EU: 1.3** RoW: N/A | **EU: 2%** RoW: 1% | **EU: 2%** RoW: 1% | **EU: 23** RoW: N/A | **Total: 6** | Innovation is unlikely to have a substantial effect on the UK's competitiveness in $CO_2$ transport components. There is unlikely to be significant trade in this category as materials are usually sourced regionally. Given these constraints, the UK can expect to have a similar market share to related transport goods (e.g. pipes) today. |

| Component | Tradeable market 2050 (£bn) | Current market share of related goods and services | 2050 outlook with strong learning by research | | | |
|---|---|---|---|---|---|---|
| | | | Market share* | Captured turnover (£m) | GVA from exports (£m) | Rationale for the impact of innovation |
| $CO_2$ storage components | **EU: 1.6**<br>RoW: 11 | **EU: 3%**<br>RoW: 2% | **EU: 3%**<br>RoW: 2% | **EU: 51**<br>RoW: 198 | **Total: 100** | Innovation, driven by learning from large-scale (>0.8mtpa) North Sea carbon storage projects, could allow UK firms to capture a market share in $CO_2$ storage like the market share the UK enjoys in related goods, such as injection equipment, today. |
| Measuring, monitoring, and verification (MMV) | **EU: 1.3**<br>RoW: 17 | **EU: 7%**<br>RoW: **8%** | **EU: 7%**<br>RoW: **8%** | **EU: 97**<br>RoW: 1,312 | **Total: 590** | The UK is a strong competitor in MMV equipment related to CCUS, such as oceanographic surveying equipment. Innovation, driven by learning from domestic deployment of CCUS projects, could allow the UK to capture a similar market share of CCUS MMV equipment as it captures in related MMV equipment today |
| EPCm services | **EU: 2.4**<br>RoW: 31 | **N/A** | **Global: 12%** | **EU: 280**<br>RoW: 3,600 | **Total: 2,100** | With strong learning by doing in CCUS engineering and construction, and by leveraging expertise from the oil and gas sector, UK firms could export CCUS project EPCm services and capture a similar global market share as UK oilfield service companies capture today. |

Note: *Future market shares are not a forecast, but what UK business opportunities could be. The possible market share of the UK, and rationale for the impact of innovation, are based on stakeholder input gathered in 2 workshops. Table is based on IEA scenario from the 2017 Energy Technologies Perspective. The scenario used in this table is the 2 degrees scenario, which is the standard reference throughout the business opportunities section. The methodological annex sets out how market shares are estimated.*

Source: *Vivid Economics*

## UK business opportunities from exports markets

*Box 9.* **Interpretation of business opportunity estimates**
The GVA and jobs estimates presented below are *not* forecasts, but instead represent estimates of the potential benefits of the UK capturing available business opportunities. The presented estimates represent an unbiased attempt to quantify opportunities and are based on credible deployment forecasts, data on current trade flows, and expert opinion, but are necessarily partly assumption-driven. The quantified estimates are intended as plausible, but optimistic. They assume global climate action towards a 2 degree world and reflect a UK market share in a scenario with significant UK innovation activity.[48] More information on the methodology, including a worked example, is provided in Appendix 2, and a high level uncertainty assessment across the EINA subthemes is provided in Appendix 3.

**Growth of UK CCUS exports could support £4.3 billion in GVA and 48,000 jobs per annum by 2050.** The export growth is driven by the export of EPCm services and capture and pollution control components, worth £2.1 billion and £1.5 billion in GVA per annum by 2050 respectively. Given that there are only 18 large-scale CCUS projects globally, GVA and job estimates are driven by IEA CCUS deployment projections. The export of EPCm services is also driven by the key assumption that the UK can deploy several large-scale CCUS projects over the next decade and capture approximately the same share in EPCm services for CCUS projects[49] as the UK currently captures in oilfield services, an 11.8% global market share.

**UK exports and business opportunities are likely greatest in the 2040s, as the rate of power and industry CCUS deployment increases in order to meet climate targets, adding £5.1 billion in GVA and supporting around 62,700 jobs per annum** (see Figures 4 and 5). This increase in the rate of deployment is driven by IEA projections consistent with a scenario where the world limits global temperature increases to 2°C. As deployment increases rapidly from 2025-2040, the UK can benefit throughout the supply chain and will especially benefit from capturing considerable levels of EPCm contracts and supplying greater quantities of pollution control components, such as innovative solvents. To obtain a better sense of the market size, in 2040, the projected peak of CCUS annual deployment, our analysis

[48] Note, other IEA climate scenarios were also used as a sensitivity. Where the level of global climate action has a meaningful impact on market size, this is highlighted in the market overview section. Full results are available in the supplied Excel calculator.
[49] The UK is assumed to capture an 11.8% share of EPCm services for all industry CCUS projects, all $CO_2$ transport and storage projects, and only gas and biomass power CCUS projects.

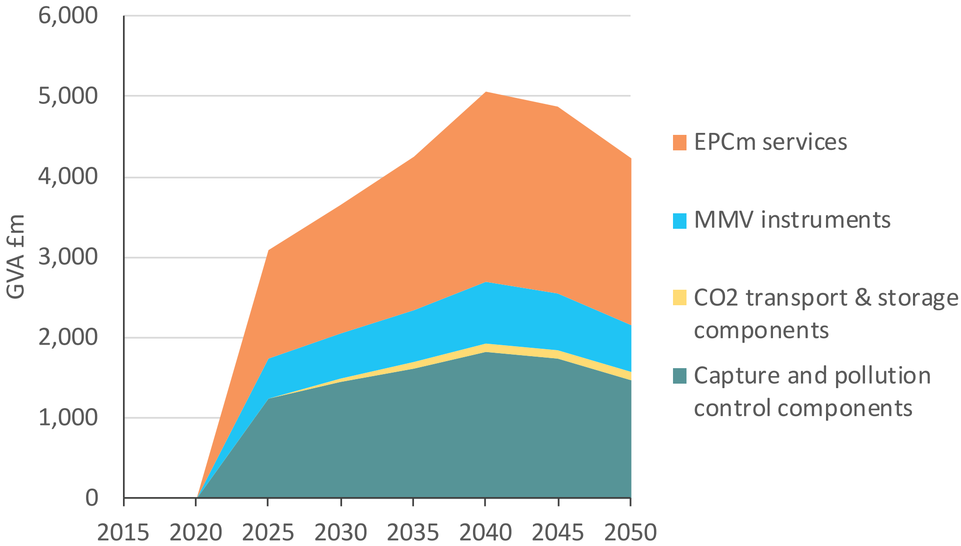
estimates the UK can capture £11.9 billion annually in turnover. This is approximately a third of the £36 billion in turnover the UK captured from oilfield services in 2016.

**UK export growth is dominated by exports for industry CCUS, followed by $CO_2$ storage and transport.** UK exports for industry CCUS are estimated at £3.4 billion in GVA per annum in 2050, considerably larger than exports for $CO_2$ transport and storage or power CCUS, worth £0.1 billion and £0.3 billion in GVA per annum by 2050 respectively. Exports for industry CCUS projects also support a disproportionately large number of jobs, 39,400 annually, compared to $CO_2$ transport and storage and power CCUS, supporting 6,000 and 3,000 jobs per annum respectively. The export of goods and services for industry CCUS is dependent on the assumption that the UK deploys a number of industry CCUS projects domestically during the next decade. This would further expertise in innovative solvents and build project experience to capture the same share of EPCm services for industry CCUS projects globally as the UK currently holds in OFS. Connecting these domestic industry CCUS facilities to North Sea storage could also deliver the expertise required to capture a similar market share of EPCm services in the global $CO_2$ transport and storage market.

**Business opportunities from CCUS exports are dominated by EPCm services and capture and pollution control components, as shown in Figures 4 and 5.** The role of innovation in unlocking these business opportunities is summarised above in Table 8.

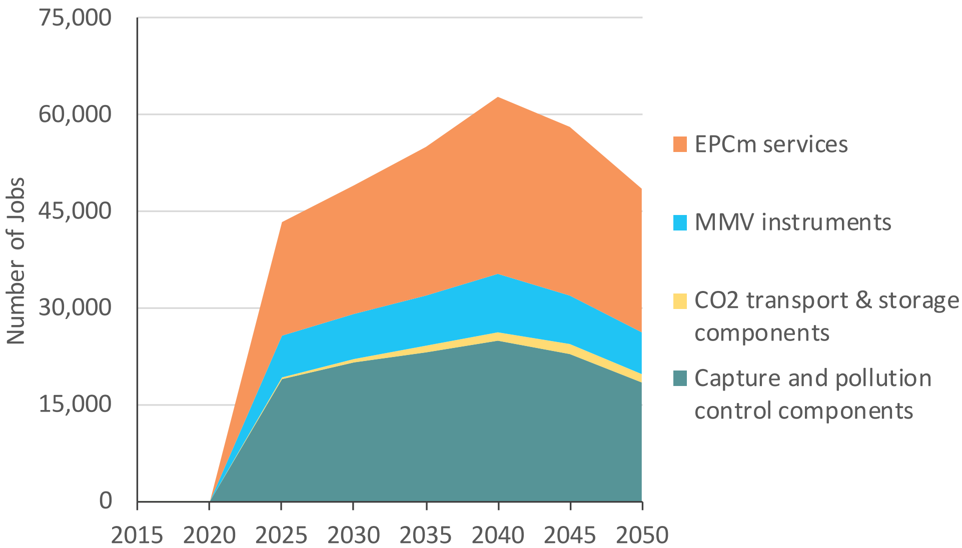
- Capture and pollution control components can support £1.5 billion in GVA and over 18,000 jobs per annum by 2050, after peaking at around £1.8 billion in GVA and 25,000 jobs per annum in 2040.
- EPCm services are expected to generate £2.1 billion in GVA and support approximately 22,000 jobs per annum by 2050. This depends on UK leadership in CCUS by deploying multiple CCUS projects in the 2020s in order to master the engineering and construction challenges, readying the sector for export.
- Monitoring, measuring, and verification instrument exports could lead to £0.6 billion in GVA per annum on average from 2035-2045, supporting around 6,300 jobs per annum.

Figure 4 **GVA from export markets by component – CCUS**




*Source: Vivid Economics*

Figure 5 **Jobs supported from export markets by component – CCUS**




*Source: Vivid Economics*

## UK business opportunities from domestic markets

**The export opportunities in CCUS are significantly larger than the domestic business opportunities.** This is driven by the large expected scale of global CCUS deployment, and the potentially significant opportunity to export associated services. Domestically, the UK has an emerging CCUS industry but lacks a large-scale

(>0.8Mt$CO_2$ per annum) CCUS facility,[50] which could enhance UK technological and commercial leadership. Despite the immature deployment of CCUS today, CCUS is expected to play a key role in helping the UK meet its carbon budget by reducing $CO_2$ emissions from power generation, and in hard-to-treat industries such as cement, chemicals, refining and iron and steel.

**Domestic CCUS business opportunities differ in two key aspects from export opportunities**

1. Installation and construction and operations and maintenance (O&M) services are a significant aspect of domestic opportunities for UK businesses. The domestic analysis includes installation and construction and O&M services associated with CCUS facilities that were excluded in the export analysis due to their low tradability.
2. The transport and storage of $CO_2$ associated with hydrogen production is likely to play a larger role in the domestic analysis.[51] The business opportunities arising from the transport and storage of carbon captured from domestic hydrogen production is considered here.

**CCUS is a cross-cutting decarbonisation technology.** For the purpose of the EINA, some CCUS applications, such as BECCS or hydrogen production with CCS, are covered in other subthemes. Table 9 sets out the division of CCUS applications across EINA subthemes. There could be a large potential market for utilisation of $CO_2$ for use in the production of fuels, building materials and chemicals.[52] However, capturing this potential market would require substantial innovation and cost reductions. Given this uncertainty and the immaturity of utilisation today, the opportunities of $CO_2$ utilisation are noted, but not sized.

Table 9. **CCUS applications and EINA subthemes**

| EINA subtheme | CCUS applications | 2050 GVA per annum (£m) |
|---|---|---|
| CCUS | Power | 170 |
| | Industry | 140 |
| | $CO_2$ transport and storage (including $CO_2$ captured in the production of hydrogen) | 280 |

[50] Global CCS Institute, Facilities Database, 2019. https://co2re.co/FacilityData
[51] The transport and storage of CO2 associated with hydrogen production is also considered in the export analysis. However, the domestic opportunity plays a larger role given the greater quantities of hydrogen production estimated in ESME modelling compared to the IEA ETP scenario, which was used in the export analysis.
[52] Carbon180 estimates a total available market of nearly $6 trillion per year, which includes most hydrocarbon fuels in use today. See Carbon180, A Review of Global and US Total Available Market for Carbontech, 2018. https://static1.squarespace.com/static/5b9362d89d5abb8c51d474f8/t/5c0028d270a6ad15d0efb520/1543514323313/ccr04.executivesummary.FNL.pdf

| EINA subtheme | CCUS applications | 2050 GVA per annum (£m) |
|---|---|---|
| Hydrogen | Hydrogen production from natural gas with CCS (not included in this report) | 570 |
| Biomass and bioenergy | Hydrogen production from biomass with CCS (not included in this report) | 930 |
| Heating and cooling | Hydrogen boilers fuelled by hydrogen produced using CCS (not included in this report) | 1,400 |

*Note:* *See hydrogen, bioenergy and heating and cooling subthemes for more detail*
*Source:* *Vivid Economics*

**The share of the domestic market captured by UK firms is expected to be high for services and lower for components, driven by UK competitiveness in services and the high tradability of components.** Given the immaturity of the CCUS market, future UK market shares of the domestic market are inherently uncertain. Indicative market shares are estimated using UK domestic market shares of similar goods and services today. Across the components considered within CCUS, market shares are outlined in Table 10 and detailed below:

- **Carbon capture and air pollution control equipment:** An assessment of similar goods, including solvents and pollution control equipment, indicates a domestic market share of 64% is plausible.[53]
- **Conversion and generation equipment:** The UK lacks a major power turbine manufacturer and is assumed to capture a negligible share of conversion and generation equipment in the domestic market.
- **Transport components:** Analysis of similar goods, including the type of steel pipes used for the transport of oil and gas, suggests a domestic market share of 15% is plausible.[54]
- **Storage components:** An assessment of goods similar to carbon storage, including, for example, compression equipment, indicates a domestic market share of 64% is plausible.[55]

[53] Based on PRODCOM analysis of UK production, exports and imports of 8 digit SIC codes: 20302273, 20302279 and 25291110.
[54] Based on PRODCOM analysis of UK production, exports and imports of 8 digit SIC code:24201110.
[55] Based on PRODCOM analysis of UK production, exports and imports of 8 digit SIC codes: 20111230, 28132670, 28132753 and 28132755.

- **Measuring Monitoring and Verification (MMV):** An assessment of similar goods, indicates a domestic market share of 37% is plausible.[56]
- **Engineering, procurement, and construction management (EPCm) services:** Given the skills overlap between CCUS and oilfield services (OFS), the UK is expected to capture the same share of the domestic market for CCUS as the UK currently captures in the domestic OFS market, a market share of 77%.[57]
- **Installation and construction services:** Installation and construction services are the labour intensive inputs required to build a CCUS facility. Activities in this category include the actual construction of facilities (e.g. cement laying, welding) and the installation of CCUS equipment (e.g. pipe fitting, installation of electrical equipment). Installation and construction services are not highly traded, and the UK is assumed to capture a 95% share of the domestic market.
- **Operation and maintenance (O&M) services:** Like installation and construction services, O&M services are not highly traded, and the UK is assumed to capture a 95% share of the domestic market.

**Rapid growth of the domestic market for CCUS good and services is anticipated as the UK deploys CCUS to meet carbon targets.** Our estimate of annual domestic turnover peaks in 2040 at £4.3 billion per annum as the UK rapidly deploys nearly 17GW of gas power CCUS from 2025. Growth of CCUS deployments decelerates after 2040 as domestic turnover declines to £1.8 billion per annum in 2050, which reflects a sizeable decline in capital expenditure and moderate increase in transport and storage and operational expenditure.

**Deployment projections are uncertain and sensitive to the level of UK climate action.** Our assessment of domestic business opportunities is based on ESME deployment estimates, which are consistent with an 80% reduction in UK GHG emissions by 2050. For power, ESME estimates 21.5GW of gas CCUS is deployed by 2050, requiring 62Mt of $CO_2$ storage per annum, while industry captures and stores 12Mt of $CO_2$ per annum by 2050. Carbon captured from the production of hydrogen adds an additional 114Mt of $CO_2$ per annum by 2050, which also requires transport and storage.[58] According to the CCC, if the UK pursues a net zero

[56] Based on PRODCOM analysis of UK production, exports and imports of 8 digit SIC codes: 26515235, 26515255, 26515279,26515283 and 26516330.
[57] The UK oilfield service market share is estimated based on EY (2017): https://www.ey.com/Publication/vwLUAssets/EY-review-of-the-UK-oilfield-services-industry-January-2017/$FILE/EY-Review-of-the-UK-oilfield-services-industry-January-2017.pdf, and Oil & Gas UK (2017): https://oilandgasuk.co.uk/wp-content/uploads/2017/09/Economic-Report-2017-Oil-Gas-UK.pdf
[58] This includes carbon captured from hydrogen production using natural gas reforming with CCS, coal gasification with CCS and biomass gasification with CCS. See hydrogen and biomass subthemes for hydrogen production quantities.

pathway, industry would need to capture and store 24Mt of $CO_2$ per annum by 2050. Under this scenario, the turnover peak could shift and total turnover would increase from the doubling of industrial CCUS.[59]

**Domestic business opportunities in CCS could add around £850 million in GVA and support nearly 10,000 jobs per annum by 2040.** The largest domestic UK opportunities are within capture and pollution control components, EPCm services and transport and storage components, contributing over £150 million in GVA and supporting 2,000 jobs per annum each by 2040 (see Figures 8 and 9). O&M GVA and jobs increase rapidly to 2040 and then steadily to 2050 as CCUS capacity rapidly increases to meet climate targets. Table 10 depicts UK captured GVA in the domestic market by component in 2040 and 2050, total market turnover estimates and the UK market share of the domestic market in 2050.

**Export opportunities are considerably larger given the growth of CCUS in the rest of the world to 2050, particularly in the United States and Asia.** This is driven by the UK's ability to capture a modest share of the substantial global market for EPCm services and capture and pollution control components. However, unlike the domestic market, export opportunities exclude labour services with low tradability, such as installation and construction and O&M services. Figures 6 and 7 depict the difference in relative opportunity between the domestic and export markets.

[59] CCC, Net Zero Technical Report, 2019. https://www.theccc.org.uk/publication/net-zero-technical-report/

Table 10. **Domestic market shares and innovation impact - CCUS**

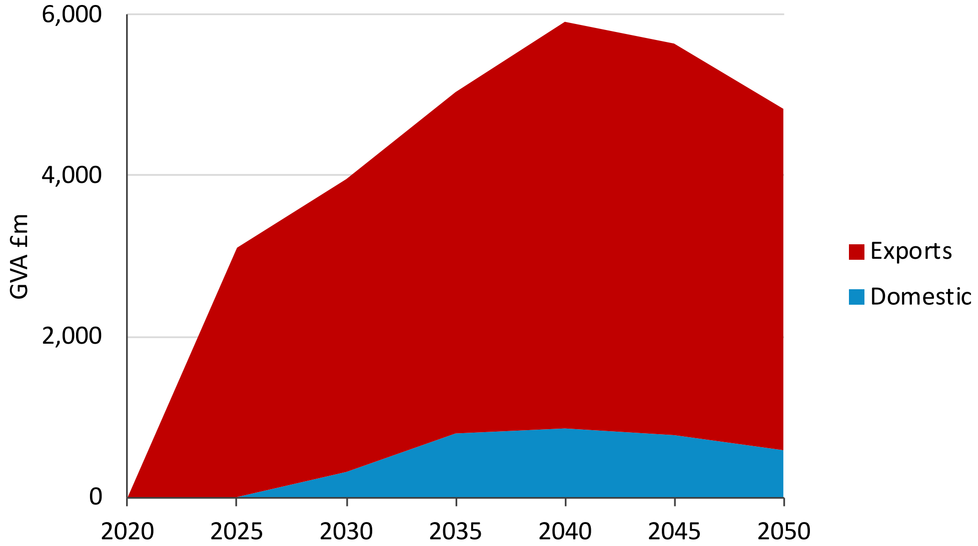
| Technology | Domestic market 2050 (£m) | Current market share of related goods and services | 2050 outlook with strong learning by research | | | |
|---|---|---|---|---|---|---|
| | | | Market share* (%) | Domestic turnover captured (£m) | GVA (£m) | Rationale for the impact of innovation on domestic deployment of related equipment and services |
| Capture and pollution control | **2040: 750** 2050: 280 | 64% | 64% | **2040: 480** 2050: 180 | **2040: 160** 2050: 60 | Innovation could drive the development of cost-effective pre- and post-combustion $CO_2$ capture technologies, such as innovative solvents. An assessment of similar goods today, indicates a domestic market share of 64% is plausible. |
| Conversion and generation | **2040: 680** 2050: 60 | 0% | 0% | **2040: N/A** 2050: N/A | **2040: N/A** 2050: N/A | The UK lacks a major power turbine manufacturer and it is unlikely a UK firm will enter this market in the short- or medium-term. Accordingly, the UK is not expected to compete in this section of the domestic market. |
| $CO_2$ transport components | **2040: 610** 2050: 650 | 15% | 15% | **2040: 80** 2050: 100 | **2040: 20** 2050: 25 | Innovation is unlikely to have a substantial effect on the UK's competitiveness in $CO_2$ transport components. Materials are likely to be sourced from the lowest cost producers regionally. Given these constraints, the UK can expect to have a similar market share to related transport goods (e.g. pipes) today. |
| $CO_2$ storage components | **2040: 610** 2050: 650 | 64% | 64% | **2040: 390** 2050: 420 | **2040: 160** 2050: 175 | Innovation, driven by learning from large-scale (>0.8mtpa) North Sea carbon storage projects, could allow UK firms to capture a market share in $CO_2$ storage similar to the market share the UK enjoys in related goods, such as injection equipment, today. |
| Measuring, monitoring and | **2040: 110** 2050: 40 | 37% | 37% | **2040: 40** 2050: 15 | **2040: 20** 2050: 6 | The UK is a strong competitor in MMV equipment related to CCUS, such as oceanographic surveying equipment. Innovation, driven by learning from domestic deployment of CCUS projects, |

| Technology | Domestic market 2050 (£m) | Current market share of related goods and services | 2050 outlook with strong learning by research | | | |
|---|---|---|---|---|---|---|
| | | | Market share* (%) | Domestic turnover captured (£m) | GVA (£m) | Rationale for the impact of innovation on domestic deployment of related equipment and services |
| verification (MMV) | | | | | | could allow the UK to capture a similar market share of CCUS MMV equipment as it captures in related MMV equipment today. |
| EPCm services | **2040: 530**<br>2050: 290 | 77% | 77% | **2040: 410**<br>2050: 230 | **2040: 220**<br>2050: 120 | With strong learning by doing in CCUS engineering and construction, and by leveraging expertise from the oil and gas sector, UK firms could capture a similar domestic market share as UK oilfield service companies capture today. |
| Installation and construction services | **2040: 310**<br>2050: 80 | N/A: not highly traded | 95% | **2040: 290**<br>2050: 70 | **2040: 130**<br>2050: 30 | Innovation is unlikely to have a substantial effect on the UK's competitiveness as installation and construction services are typically sourced from local construction companies. |
| O&M services | **2040: 690**<br>2050: 830 | N/A: not highly traded | 95% | **2040: 660**<br>2050: 790 | **2040: 150**<br>2050: 180 | Innovation is unlikely to have a substantial effect on the UK's competitiveness as operations and maintenance services are typically sourced from locally available labour. |

*Note:* ** Future market shares are not a forecast, but what UK business opportunities could potentially achieve. The possible market share of the UK, and rationale for the impact of innovation, are based on PRODCOM analysis and additional market research. N/A indicates data is not available.*

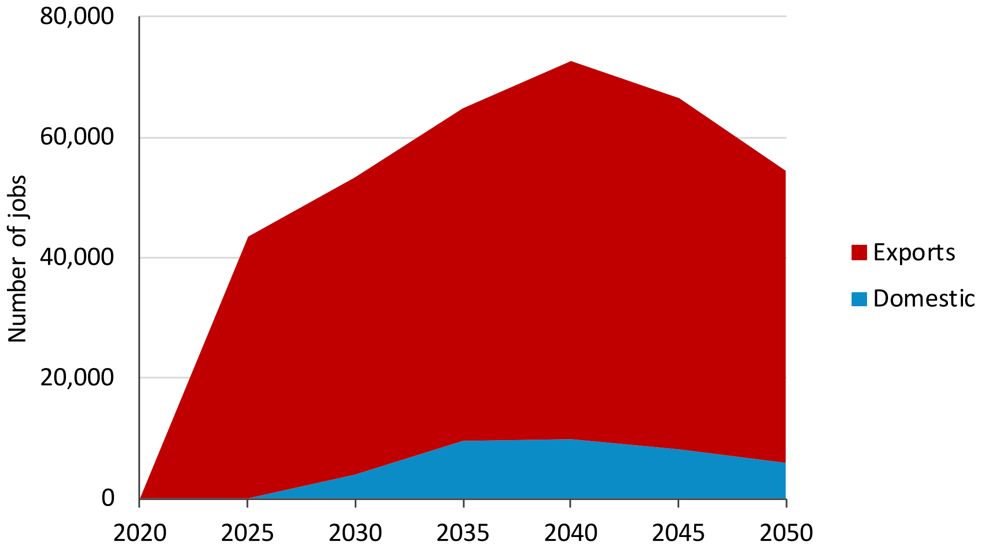
*Source:* *Vivid Economics*

Figure 6 **GVA from export and domestic markets – CCUS**



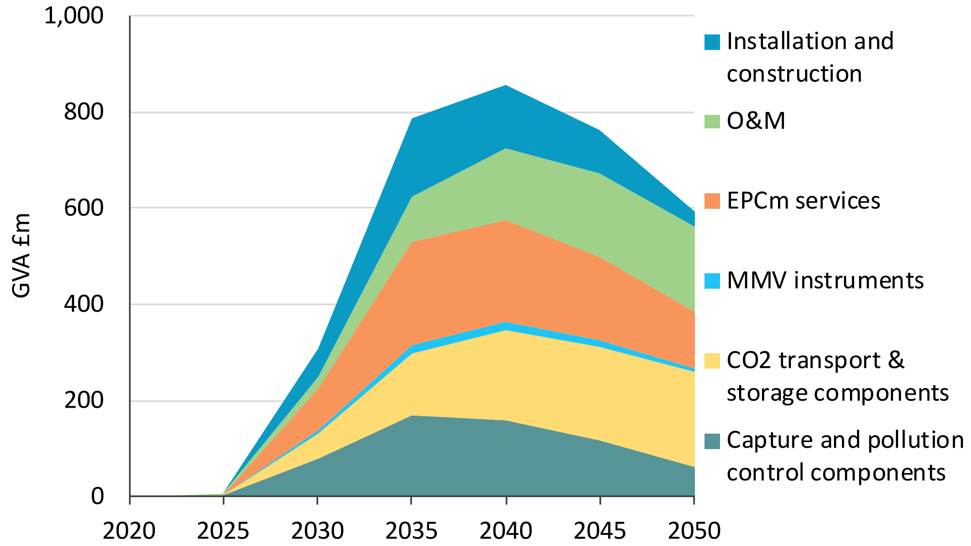

*Source: Vivid Economics*

Figure 7 **Jobs supported from export and domestic markets – CCUS**



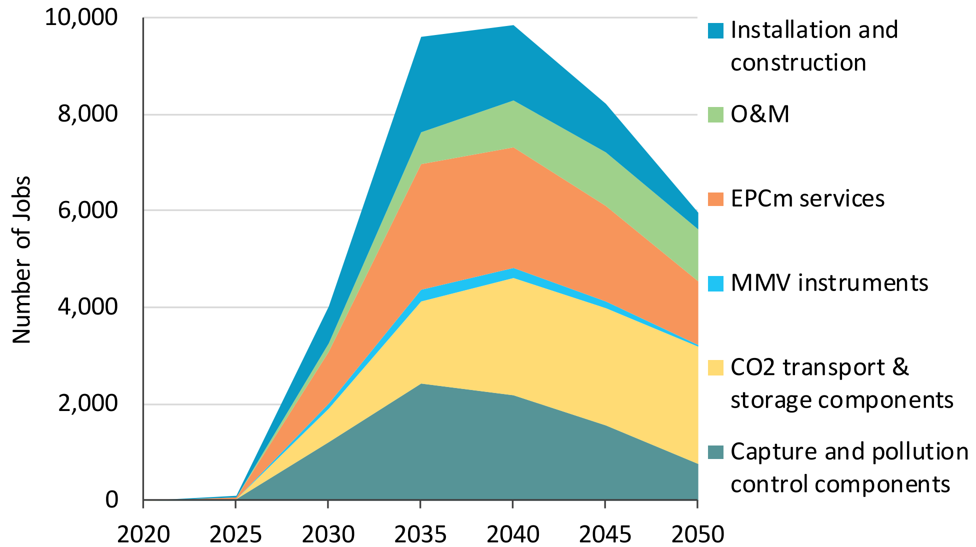

*Source: Vivid Economics*

Figure 8 **GVA from domestic markets by component – CCUS**




*Source:* *Vivid Economics*

Figure 9 **Jobs supported from domestic markets by component – CCUS**




*Source:* *Vivid Economics*

## Business opportunity deep dive: EPCm services

**EPCm services represent a substantial global opportunity for the UK supply chain.** CCUS EPCm services are highly tradeable, allowing the UK to gain a larger market share in fast growing Asian markets than possible with less tradable components. These services are estimated to be 12.9% of total CCUS project cost on average. The EPCm market for CCUS is expected to mirror the market for oilfield services, where the UK holds an 11.8% share globally. Our analysis estimates the global EPCm services market for CCUS to be worth £33.3 billion per year in 2050. However, given low levels of projected coal CCUS deployment domestically, it is unlikely that the UK would be able to capture an 11.8% share of EPCm services for coal CCUS projects. Accordingly, our analysis assumes the UK maintains the oilfield service market share for gas and biomass CCUS projects only, in addition to industry CCUS and $CO_2$ transport and storage, potentially capturing £3.9 billion annually in EPCm contract turnover in 2050, generating £2.1 billion in GVA per annum.

**EPCm services can unlock multiple mid-tier markets, particularly in the Middle East, Africa, and South East Asia.** Mid-tier markets include countries such as the UAE, Oman, Malaysia, Indonesia, and Egypt that demand EPCm services to deploy large complex projects in order to supplement domestic skills. UK energy and oilfield service companies are currently active in many of these markets. Across this set of countries indicative of mid-tier markets, the Department for International Trade (DIT) notes UK export opportunities for refinery efficiency improvements, petrochemical plant development, oilfield services, enhanced oil recovery (EOR) projects, and power generation.[60] Given that CCUS projects are expected to mirror the types of projects identified by DIT in scale and complexity, once mid-tier markets start deploying CCUS it is reasonable to expect that the UK could leverage its past export of EPCm services in related projects to capture EPCm CCUS contracts.

**The UK supply chain could leverage existing EPCm expertise to capture the future CCUS market.** The UK has an existing competitive position in oilfield services, capturing 11.8% of the global OFS market in 2016, worth £36 billion in turnover. Given the significant skills overlap, the UK can leverage its existing oil and gas industry to lead in CCUS EPCm services.[61] If the UK can deploy CCUS domestically before its competitors, it could also gain a first-mover advantage. This

[60] DIT, Doing business in the United Arab Emirates: UAE trade and export guide, 2018. https://www.gov.uk/government/publications/exporting-to-the-united-arab-emirates/exporting-to-the-united-arab-emirates, DIT, Doing business in Oman: Oman trade and export guide, 2015. https://www.gov.uk/government/publications/exporting-to-oman/doing-business-in-oman-oman-trade-and-export-guide, DIT, Doing business in Malaysia: Malaysia trade and export guide, 2015. https://www.gov.uk/government/publications/exporting-to-malaysia/exporting-to-malaysia, DIT, Doing business in Indonesia: Indonesia trade and export guide, 2018. https://www.gov.uk/government/publications/exporting-to-indonesia/exporting-to-indonesia, DIT, Doing business in Egypt: Egypt trade and export guide, 2015. https://www.gov.uk/government/publications/exporting-to-egypt/doing-business-in-egypt-egypt-trade-and-export-guide

[61] For a discussion of the O&G skills overlap, see HM Government, Clean Growth: The UK Carbon Capture Usage and Storage deployment pathway, 2018. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/759637/beis-ccus-action-plan.pdf and Poyry and Teesside Collective, A Business Case for A UK Industrial CCS Support Mechanism, 2017. http://www.teessidecollective.co.uk/wp-content/uploads/2017/02/0046_TVCA_ICCSBusinessModels_FinalReport_v200.pdf

could increase its potential future CCUS EPCm service market share beyond the current market share in OFS.

**EPCm services place the UK in a competitive position across power CCUS, industry CCUS, and $CO_2$ transport and storage projects.** The high tradability of EPCm services globally allows the UK to access substantial markets across power CCUS, industry CCUS, and $CO_2$ storage and transport that are less accessible to component manufacturers.[62] Assuming a similar market share as the OFS market, by 2050 the UK could capture EPCm service contracts worth £0.3 billion from power CCUS, £2.8 billion from industry CCUS, and £0.8 billion from $CO_2$ transport and storage per annum. Combined, these markets could support 22,000 high-GVA jobs (£70,300 GVA/worker).

## Business opportunity deep dive: Importing $CO_2$ for storage in the North Sea

**The favourable geology of the North Sea unlocks the opportunity to import and store $CO_2$.** Aside from Norway and the Netherlands, there are relatively few locations in Europe with suitable geology to store sizeable quantities of $CO_2$.[63,64] Regions without any storage, with relatively more expensive storage options or where there is low public acceptability of storage,[65] such as the Rhine-Ruhr industrial region in Germany, are likely to pursue carbon capture technology, though will face a storage bottleneck.[66] A potential solution is for the UK to import $CO_2$ from Europe by ship or pipeline for storage under the North Sea.

**There is likely to be a large EU27 market requiring $CO_2$ storage.** In order to meet emissions targets, European countries are likely to pursue carbon capture,

[62] Only 25% of $CO_2$ transport and storage project CAPEX is expected to be tradeable. See UK competitive position section for details.
[63] Noordzeeloket, CO2-storage, n.d. https://www.noordzeeloket.nl/en/functions-and-use/co2-opslag/
[64] It is estimated that around 50% of European $CO_2$ storage potential is located under the North Sea. See Element Energy, One North Sea: A study into North Sea cross-border $CO_2$ transport and storage, 2010. http://www.element-energy.co.uk/wordpress/wp-content/uploads/2010/08/OneNorthSea.pdf
[65] SETIS, Dr. Lothar Mennicken talking to SETIS, n.d. https://setis.ec.europa.eu/setis-reports/setis-magazine/carbon-capture-utilisation-and-storage
[66] The Ruhr region in Germany could store $CO_2$ in coal fields, though this option provides limited storage capacity and injection rates. Carbon storage also faces strong opposition from the public and the media in Germany. One proposed solution for storing captured $CO_2$ from the region is to use the Port of Rotterdam as a $CO_2$ collection hub to serve industry installations in the Netherlands, Belgium, and Germany. The $CO_2$ collected in Rotterdam could plausibly be stored in the North Sea. See Geological survey of Denmark and Greenland, Estimates of $CO_2$ storage capacity in Europe, n.d. https://ieaghg.org/docs/Copenhagen/EU_Storage_capacity_KLA.pdf and Fleishman Hillard, Roundtable: Delivering Paris – the difficult part: Decarbonising the EU industry, 2018. https://fleishmanhillard.eu/2018/01/roundtable-delivering-paris-difficult-part-decarbonising-eu-industry/

particularly for industry.[67] Though it is difficult to size the exact market for carbon imports, an example can provide an indicative scale of the market. If the $CO_2$ emissions of North Rhine Westphalia, the state encompassing the Rhine-Ruhr industrial region of Germany, were captured today, this region would have to store 54Mt of $CO_2$ annually.[68] Applying a 2050 carbon price estimate less the cost of $CO_2$ transport and storage, there is a potential £10.8-12 billion market for importing and storing $CO_2$ from this key German industrial region.[69] Competition is expected to be light, with only Norway in a strong competitive position to import and store carbon.[70]

**The UK supply chain could leverage existing maritime and oil and gas industries to facilitate $CO_2$ imports and drive growth in carbon storage.** The UK's leadership in North Sea oil and gas production, including engineering and seismic imaging, can support the development of the North Sea for long-term carbon storage. Existing assets, such as oil and gas pipelines and platforms, can be repurposed to transport and inject carbon in former hydrocarbon fields.[71] Importing $CO_2$ for storage can also improve transport and injection volumes, helping deliver economies of scale for UK-based CCUS projects.

[67] The European Commission acknowledges the role of CCS in meeting EU long-term emission targets. See, DG Climate Action, Low Carbon Technologies: Carbon Capture and Geological Storage, n.d. https://ec.europa.eu/clima/policies/lowcarbon/ccs_en
[68] LANUV, Treibhausgas-Emissionsinventar Nordrhein-Westfalen 2016, n.d. https://www.lanuv.nrw.de/publikationen/details/?tx_cart_product%5Bproduct%5D=907&cHash=dad63a68b0d7e0b7e2fc5224ff05ea19
[69] 2050 carbon price adjusted to 2017£ less the cost of $CO_2$ transport and storage from market size analysis, see DECC, Guidance on estimating carbon values beyond 2050: an interim approach, 2011. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/48108/1_20100120165619_e____carbonvaluesbeyond2050.pdf
[70] Expert opinion from participants at the CCUS workshop.
[71] The Liverpool-Manchester Hydrogen Clusters project is considering repurposing natural gas production facilities and pipelines associated with the Hamilton field within Liverpool Bay for $CO_2$ transport and storage. See Cadent, The Liverpool-Manchester Hydrogen Cluster: A Low Cost, Deliverable Project, 2017. https://cadentgas.com/getattachment/About-us/Innovation/Projects/Liverpool-Manchester-Hydrogen-Cluster/Promo-LMHC-downloads/Summary-report.pdf

# Market barriers to innovation within CCUS

## Introduction

*Box 10.* **Objective of the market barrier analysis**

Market barriers prevent firms from innovating in areas that could have significant UK system benefits or unlock large business opportunities. Market barriers can either increase the private cost of innovation to levels that prevent innovation or limit the ability of private sector players to capture the benefits of their innovation, reducing the incentive to innovate.

Government support is needed when market barriers are significant, and they cannot be overcome by the private sector or international partners. The main market barriers identified by industry are listed in Table 11, along with an assessment of whether HMG needs to intervene.

## Market barriers for CCUS

**In the UK there are currently no full chain, commercial scale CCUS projects in operation or under construction.** Investment at this early stage of maturity is highly dependent on government support, for example by providing long-term investment signals to industry and supporting policy measures. In countries with successful CCUS projects, government supports the sector including via subsidies. The US introduced a stimulus for CCUS in 2018 by providing the 45Q tax credit providing up to $50 per tonne of $CO_2$ permanently stored and $35 per tonne of $CO_2$ used for EOR or other industrial uses. The International Energy Agency (IEA) expects this to result in additional capital investments in the order of $1 billion.[72]

**Table 11 lists the main market barriers in CCUS, along with an assessment of whether the HMG needs to intervene.** For each identified market barrier, an assessment of the need for government intervention is provided. The assessment categories are low, moderate, severe, and critical.

[72] IEA, Carbon capture, utilisation and storage, Policies & Investment, n.d. https://www.iea.org/topics/carbon-capture-and-storage/policiesandinvestment/
IEA, Commentary: US budget bill may help carbon capture get back on track, 2018, https://www.iea.org/newsroom/news/2018/march/commentary-us-budget-bill-may-help-carbon-capture-get-back-on-track.html

- **Low** implies that without government intervention, innovation, investment, and deployment will continue at the same levels, driven by a well-functioning industry and international partners.
- **Moderate** implies that without government intervention, innovation, investment, and deployment will occur due to well-functioning industry and international partners, but at a lower scale and speed.
- **Severe** implies that without government intervention, innovation, investment, and deployment are significantly constrained and will only occur in certain market segments or must be adjusted for the UK market.
- **Critical** implies that without government intervention, innovation, investment, and deployment will not occur in the UK.

Table 11. **Market barriers**

| Market barriers to CCUS | Relevant for | Need for public support |
|---|---|---|
| **Policy-dependent demand and uncertain policy support**, incl. unclear carbon price/ penalty and insufficient incentives, inhibit innovation in capture **from development to full demonstration** | All components | Critical |
| **Long-term, global liabilities difficult to insure against** limiting commercial incentives for individual companies | Storage | Severe |
| **Unclear rules regarding storage site approval** introduce uncertainty into investments and innovation decisions | Storage | Severe |
| **Uncertain infrastructure availability and high cost,** unclear willingness of HMG to underwrite critical infrastructure such as pipelines | Transport | Moderate |
| **Need for support** at earlier stage and breakthrough technologies for capture | Capture | Low |

*Source: Vivid Economics analysis and stakeholder input*

*Box 11.* **Industry workshop feedback**

Industry experts raised several areas that require HMG support:

- **Policy-dependent demand for CCS and an uncertain policy position on deployment are critical barriers, particularly for capture, full systems integration, and storage.** Workshop participants reported deployment support is needed to incentivise innovation. Current incentives in the market are insufficient to drive deployment and a key barrier is a lack of a price or penalty for carbon emissions.

- **The lack of insurance frameworks for a very long-term and global liability in case of leakage limits commercial incentives for individual companies to deploy.** The uncertainty introduced by an unclear route to deployment limits incentives for investing in innovation in storage technology. Ownership and duration of the liability are undefined, making insurance schemes very expensive and deterring private sector activity. Workshop participants cited examples of projects failing due to this barrier.

- **Unclear rules for storage site approval introduce uncertainty into future costs.** Uncertainty about potentially high future costs limits incentives to innovate. Health and safety regulation and public acceptance requirements associated with leakage add to uncertain future demand. For example, the current regulatory regime on environmental impacts requires difficult and costly demonstration of compliance. Environmental impacts and risks are unique to the UK, but there is scope to learn from other countries about the approach to demonstrate compliance and avoid complex demonstration and monitoring requirements. Workshop participants cited Japan and the US as leading in their regulatory approach to environmental compliance.

- **The upfront cost for transport infrastructure is high and investments in networks require substantial coordination.** Industry is hesitant to take ownership of infrastructure due to the limited potential to recoup the investment. It is unclear whether HMG is willing to underwrite critical infrastructure, such as pipelines, and take on a stronger coordinating role. This reduces certainty in the market and discourages innovation in transport technology.

- **Direct government RD&D support for capture would be best targeted at select early-stage and breakthrough technologies.**

## International opportunities for collaboration

**There are potential international opportunities to collaboratively innovate, but also threats from international innovation and competition.**

- Long-term insurance schemes for leakage could be addressed in an international effort, for example through the accounting rules specified in international climate legislative frameworks.
- The UK could rely on other countries to innovate some components. However, particularly in areas of niche UK strength or distinct local conditions, such as deep-sea storage, there is a strong case for UK-led innovation and HMG support.
- Several international collaborations exist, and these are important drivers for innovation in CCUS globally and in the UK. Examples are: the Accelerating CCS Technologies (ACT) programme, which funds important research and innovation projects that contributing to safe and cost-effective technology for CCUS;[73] the UK-Norway CCUS Memorandum of Understanding is an example of successful cooperation on innovation for CCUS;[74] the global initiative Mission Innovation, which includes 23 countries and the European Commission, with the goal of accelerating clean energy innovation and its $13 million carbon capture challenge[75]; and academic partnerships for international research in CCUS.[76]

[73] ACT website: http://www.act-ccs.eu/
[74] Link to Memorandum of Understanding: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/775688/Memorandum_of_Understanding_UK-Norway.pdf
[75] Mission Innovation (n.d.) Overview http://mission-innovation.net/about-mi/overview/ ; Mission Innovation (n.d.) IC3: CARBON CAPTURE http://mission-innovation.net/our-work/innovation-challenges/carbon-capture/
[76] UKCCS (2018) UKCCSRC WELL POSITIONED TO SUPPORT THE UK AS A GLOBAL LEAD IN CCUS https://ukccsrc.ac.uk/news-events/news/ukccsrc-well-positioned-support-uk-global-lead-ccus

# Appendix 1: Organisations at expert workshop

- BP
- Carbon Clean Solutions
- Engineering and Physical Sciences Research Council
- Global CCS Institute
- Innovate UK
- Plymouth Marine Laboratory
- Scottish Carbon Capture & Storage
- SGN
- Siemens
- SSE
- Tees Valley Unlimited
- UK Carbon Capture and Storage Research Centre

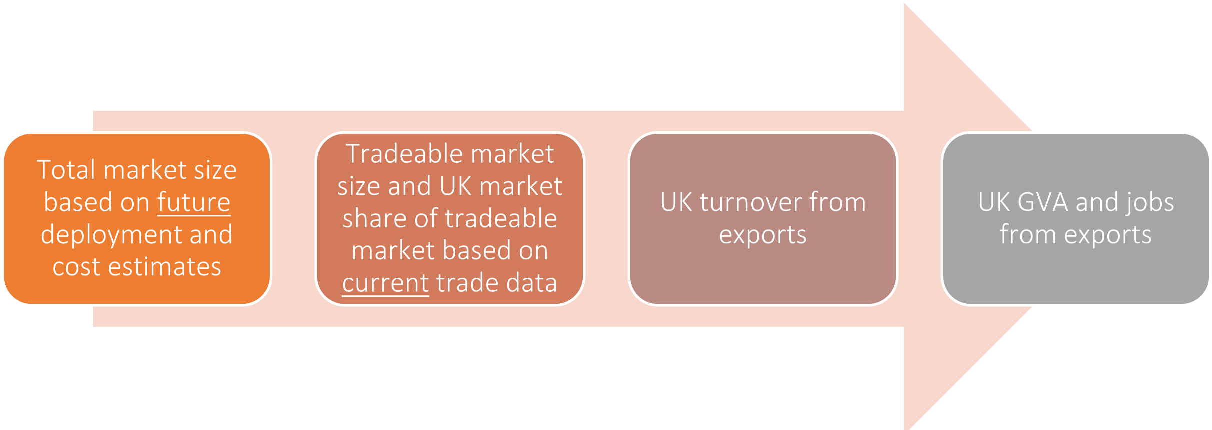
# Appendix 2: Business opportunities methodology

## Methodology for export business opportunity analysis

**In identifying export opportunities for the UK, the EINA process uses a common methodology to ensure comparability of results:**

- The **global and regional markets** to 2050 are sized based on deployment forecasts, which come from the IEA when available. For example, deployment of nuclear power is multiplied by costs to obtain annual turnover for the nuclear market.
- The **tradability** of the market is estimated based on current trade data, where available, and informed by expert judgement. This determines how much of the global market is likely to be accessible to exports and gives a figure for the tradeable market.
- The UK's **market share** under a high-innovation scenario is estimated based on current trade data, research, and expert consultation. The determination of these shares is discussed in more detail below.
- The tradeable market is multiplied by the market shares to give an estimate for **UK-captured turnover**.
- The captured turnover figure is multiplied by a GVA / turnover multiplier which most closely resembles the market to obtain **GVA**. The GVA figure is divided by productivity figures for that sector to obtain **jobs created**.

Figure 10 **Methodology for assessing export opportunities**




*Source:* *Vivid Economics*

For all EINA sub-themes, the assessment of the UK's future competitive position is informed by the UK's existing market share of goods and services, the market share of competitors, industry trends, and workshop feedback.

**Export business opportunities for goods**

- Current market shares of UK goods are evaluated based on existing trade data, where available. If the technology is immature or export levels are low, UK shares are based on trade data from trade in related goods.
- Based on the importance of innovation in unlocking markets, the UK is projected to reach a market share in the EU and RoW by 2050. The potential future market share is intended as an ambitious, but realistic, scenario. It is triangulated using:
    - Market shares of competitor countries, as a benchmark for what is a realistic share if a country is 'world leading'.
    - The maturity of the existing market, which affects the likelihood of market shares changing significantly.
    - The importance of innovation in the technology.
- Market share assumptions are validated at a workshop with expert stakeholders and adjusted based on stakeholder input.

**Export business opportunities for services**

- The EINA focus on service exports directly associated with the technology and innovations considered within the sub-theme. For example, this could include EPCm services around the construction of an innovative CCS plant, but it will not include more generic service strengths of the UK, such as financial services.
- The EINA methodology does not quantify opportunities associated with installation and operation and maintenance as these are typically performed locally. Exceptions are made if these types of services are specialised, such as in offshore wind.
- The key services to consider are based on desk research and verified through an expert workshop.
- The services considered in the CCUS EINA export analysis are EPCm services, transport and storage services.

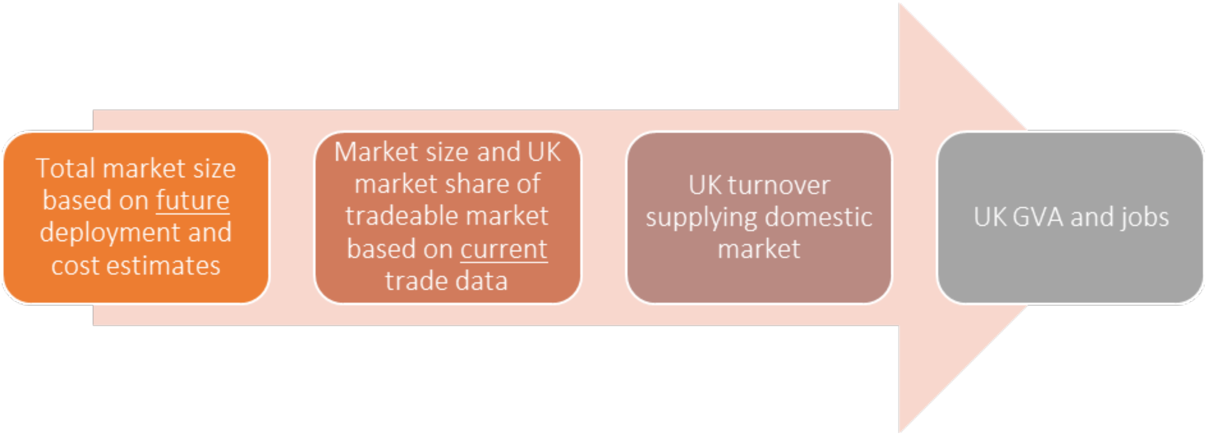
## Methodology for domestic business opportunity analysis

**To estimate the size of domestic business opportunities for the UK, the EINA methodology, as developed to size export opportunities, is adapted.** The domestic analysis leans heavily on insight gleaned from the export analysis, particularly in estimating UK competitiveness and ability to capture market share in its domestic market. To estimate the domestic opportunity, the following methodology is used:

- The **domestic market** to 2050 is sized based on deployment and cost estimates. Deployment estimates are based on ESME modelling used for the EINAs and cost estimates are equal to those from the export work, and based on analysis for each of the EINA sub-themes.[77] For example, deployment of nuclear power is multiplied by costs to obtain annual turnover for the nuclear market.
- The **tradability** of the market is estimated based on current trade data, where available, and informed by expert judgement. This determines how much of the UK's market is likely accessible for foreign firms (e.g. electric vehicles), and how much is likely to be exclusively provided by UK companies (e.g. heat pump installation).
- For the traded share of the UK market, the UK's **market share** under a high-innovation scenario is estimated based on current trade data, research, and expert consultation. The determination of these shares is discussed in more detail below.
- To estimate **UK captured turnover** the traded and non-traded markets are summed.
    - The UK's captured turnover of the UK traded market is estimated by multiplying the tradeable market by the UK's market share.
    - The UK's turnover from the non-traded market is equal to the size of the non-traded market.
- The captured turnover figure is multiplied by a GVA / turnover multiplier which most closely resembles the market to obtain **GVA**. The GVA figure is divided by productivity figures for that sector to obtain **jobs supported**.

[77] For detail on cost estimates used, please refer to the Excel calculators provided for each sub-theme, and the individual sub-theme reports.

Figure 11 **Methodology for assessing domestic business opportunities**




*Source: Vivid Economics*

For all EINA sub-themes, the assessment of the UK's future competitive position is informed by the UK's existing market share of goods and services, the market share of competitors, industry trends, and workshop feedback.

**Domestic business opportunities for goods**

- Current market shares of UK goods are evaluated based on existing trade (import) and domestic production data, where available. If the technology is immature, UK shares are based on trade data from trade in related goods.
- Based on the importance of innovation in unlocking markets, the UK is projected to potentially increase its market share in its domestic market. This estimate is informed by the previously performed export analysis. It is triangulated using:
  - Market shares of competitor countries, as a benchmark for what is a realistic share if a country is 'world leading'.
  - The maturity of the existing market, which affects the likelihood of market shares changing significantly.
  - The importance of innovation in the technology.

**Domestic business opportunities for services**

- The EINA focus on service exports directly associated with the technology and innovations considered within the sub-theme. For example, this could include EPCm services around the construction of an innovative CCS plant, but it will not include more generic service strengths of the UK, such as financial services.
- The domestic assessment explicitly quantifies services such as O&M and installation, which are typically not traded but can support a large number of

jobs associated with e.g. heat pumps. For these services, the estimate of potential service jobs supported is based on:
  - An estimate of the total turnover and GVA associated with the service.
  - A ratio of GVA/jobs (adjusted for productivity increases) in analogous existing service sectors based on ONS data.
- The key services to consider are based on desk research, verified through stakeholder workshops.

## Worked example

1. The **global and regional markets** to 2050 are sized based on illustrative deployment forecasts, which come from ESME when available.[78] For example, deployment of nuclear power (37 GW by 2050) is multiplied by O&M costs (~12% of total plant costs) to obtain annual turnover for the nuclear O&M market (~£2.5 billion by 2050).
2. The **tradability** of the market is estimated based on current trade data, where available, and informed by expert judgement. This determines how much of the global market is likely to be accessible to exports and gives a figure for the tradeable market. In the case of nuclear O&M, tradability is 0% being as it is not tradeable. For the domestic analysis, tradability does not directly feed into our model, but is vital to provide insight on the share of the domestic market UK firms will capture.
3. The UK's **market share** under a high-innovation scenario is estimated based on current trade data, research, and expert consultation. The determination of these shares is discussed in more detail below. For example, for nuclear O&M the UK domestic market share is 100% because the component is not tradeable and therefore foreign firms do not capture some of the value.
4. The tradeable market is multiplied by the market shares to give an estimate for **UK-captured turnover**. For nuclear O&M, market turnover (~£2.5 billion) is multiplied by the UK market share (95%) of O&M to obtain UK-captured turnover (~£2.5 billion by 2050).
5. The captured turnover figure is multiplied by a GVA / turnover multiplier which most closely resembles the market to obtain **GVA**. The GVA figure is divided by labour productivity figures for that sector to obtain **jobs supported**. For example, appropriate Standard Industrial Classification (SIC) codes are chosen for nuclear O&M. This leads to a GVA / turnover multiplier (49%) that is multiplied by market turnover (~£2.5 billion) to isolate GVA (~£1 billion by 2050), which is then divided by labour productivity (~70,000 GVA / worker by 2050) to isolate jobs supported (~16,000 jobs by 2050).

[78] If deployment information is not available from the IEA, alternative projections from, for example, Bloomberg are used. Please see individual sub-theme reports for further detail.

# Appendix 3: Assessment of business opportunities uncertainty

The assessment of business opportunities in the long term, associated with new technologies is uncertain. This assessment does not attempt to forecast what *will* happen. Instead, the business opportunity assessment attempts to provide a realistic and consistent assessment, based on current information, on the business opportunities that *could* be captured by the UK. Whether these opportunities are indeed realised depends on domestic and international developments, political decisions, macro-economic conditions, and numerous other complex variables.

As this assessment is not intended as a full forecast, a formal quantitative sensitivity analysis has not been performed. the below provides a high-level qualitative assessment of the uncertainty associated with the sized opportunity. Note, this is *not* an assessment of how likely the UK is to capture the opportunity, rather it is an assessment of the uncertainty range around the size of the opportunity. The assessment is based on three key factors driving the assessment

1. *The level of future deployment of the technology*. Technologies such as offshore wind are deployed at scale across different energy system modelling scenarios and hence considered relatively certain. In contrast, there is more uncertainty for e.g. hydrogen related technologies. The export analysis is based on 3 IEA scenarios (with numbers provided for the IEA ETP 2 degree scenario). Domestic analysis is based on a single ESME run used across the EINA process.
2. *The potential domestic market share* the UK can capture. This assessment attempts to estimate a plausible market share for the UK across relevant markets. Where this can be based on longstanding trade relationships and industries, this assessment is considered more robust.
3. *Future technology costs and production techniques* are a key driver of the future turnover, gross value added and jobs associated with a technology. For immature technologies for which manufacturing techniques may, for example, become highly automated in future, future costs and jobs supported by the technology may be significantly lower than assessed.

The ratings in the table below are the judgement of Vivid analysts based on the above considerations. The analysts have worked across all sub-themes and the ratings should be considered as a judgement of the uncertainty around the size of the opportunity relative to other sub-themes. As a rough guide, we judge the uncertainty bands around the opportunity estimates as follows:

- **Green**: Size of the opportunity is clear (+/- 20%). Note, this does not imply the UK will indeed capture the opportunity.
- **Amber:** Size of the opportunity is clear, but there are significant uncertainties (+/- 50%).
- **Red:** There are large uncertainties around market structure and whether the technology will be taken up at all in major markets. The opportunity could be a factor 2-3 larger or smaller than presented.

Table 12. **Assessment of uncertainty in business opportunities across sub-themes**

| Sub-theme | Uncertainty rating | Comments |
|---|---|---|
| **Biomass and bioenergy** | | • **Deployment**: Moderate deployment uncertainty; BECCS can produce negative emissions that have high value to the energy system under a deep decarbonisation pathway; there is moderate uncertainty as to whether BECCS will be used for hydrogen production, as in the ESME modelling, or for power generation.<br>• **UK market share:** Speculative market share for immature traded equipment, but majority of business opportunities associated with certain untraded services and feedstocks.<br>• **Costs and production techniques:** Relatively certain costs with most opportunities associated with labour input rather than immature technologies. |
| **Building fabric** | | • **Deployment:** Depends on levels of retrofit that greatly exceed those seen to date.<br>• **Market share:** Speculative for traded. However, majority of market untraded, highly likely captured domestically.<br>• **Costs and production techniques:** High share of labour costs (independent of uncertain tech cost). |
| **CCUS** | | • **Deployment:** Moderate deployment uncertainty; decarbonisation scenarios anticipate rapid uptake of CCUS, though there are few large-scale facilities today.<br>• **Market share:** Moderate market share uncertainty; the UK is likely to be competitive in the storage of CO2 and EPCm services while component market shares are less certain given numerous technology choices and lack of clear competitors.<br>• **Costs and production techniques:** Moderate cost uncertainty; the lack of large-scale facilities today makes estimating future costs difficult. |
| **Heating and cooling** | | • **Deployment**: Expected to be deployed in most UK buildings by 2050.<br>• **Market share:** some uncertainties, immaturity in markets such as for hydrogen boilers.<br>• **Costs and production techniques:** Relatively certain given relative maturity of boilers and heat pumps.<br>• **Deployment of hydrogen boilers or heat pumps** lead to similar opportunities for UK businesses, while heat networks present a 50 per cent smaller opportunity per household. |

| | | |
|---|---|---|
| **Hydrogen and fuel cells** | | • **Deployment**: Highly uncertain future deployment with a wide-range of 2050 hydrogen demand estimates across scenarios, particularly for export markets.<br>• **UK market share**: Speculative market share for immature traded equipment, but majority of business opportunities associated with certain untraded services.<br>• **Costs and production techniques:** Although deep uncertainty in future hydrogen production costs, for example electrolysis, most domestic costs are associated with labour input rather than equipment. |
| **Industry** | | • **Deployment**: Relative certainty in deployment as it is based on the 2050 Roadmaps<br>• **UK market share**: Some uncertainty due to poor quality of trade data that may not be representative of technologies within scope.<br>• **Costs and production techniques:** Some uncertainty in costs, particularly for less mature technologies. |
| **Light duty transport** | | • **Deployment**: Certainty in deployment; low-carbon vehicles will be required in any deep decarbonisation scenario.<br>• **UK market share**: Speculative market share for a relatively immature market; a small number of uncertain future FDI investment decisions generates high uncertainty in overall business opportunities.<br>• **Costs and production techniques:** Highly uncertain future costs, with substantial falls in battery costs a key enabler of BEV uptake. |
| **Nuclear fission** | | • **Deployment**: Moderate uncertainty in future deployment with some proposed nuclear plants recently cancelled<br>• **UK market share**: Relatively certain market shares based on robust estimates of current nuclear activity; market share growth is dependent on uncertain development of UK reactor IP; however, most business opportunities are associated with untraded activity or areas where the UK has existing strength<br>• **Costs and production techniques:** Uncertain costs for nuclear new build, with dangers of construction overrun; deep uncertainty in costs for immature nuclear technologies, for example SMRs and AMRs. |
| **Offshore wind** | | • **Deployment**: Offshore wind will be required in any deep decarbonisation scenario, with clear government commitments.<br>• **UK market share**: Expected growth in current market shares given commitments and progress to date.<br>• **Costs and production techniques:** Costs are relatively certain, with clear pathways to 2050. |
| **Tidal stream** | | • **Deployment**: Global sites for tidal stream are relatively limited, and hence the potential market size well established.<br>• **UK market share**: Although the market is immature, the UK has a an established (and competitive) position.<br>• **Costs and production techniques:** Costs are relatively certain, although the impact of potential scale production is hard to anticipate. |
| **Smart systems** | | • **Deployment**: High deployment uncertainty given immaturity of smart system market today and evolving business models and regulatory framework.<br>• **UK market share**: Moderate uncertainty given immaturity of the market today and scalable nature of digital smart |

| | | |
|---|---|---|
| | | technologies, though there is UK leadership in aggregation services and V2G charging.<br>• **Costs and production techniques**: Moderate uncertainty of cost reductions of batteries and V2G and smart chargers, though costs are expected to continue to fall. |

*Source: Vivid Economics*

Contact us if you have any enquiries about this publication, including requests for alternative formats, at:

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