# Seizing sustainable growth opportunities from carbon capture, usage and storage in the UK

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## Declaration of conflict of interest

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# Contents

# Foreword by Nicholas Stern

This is a crucial decade for the UK to align its economy with a net-zero future, through the right investments in infrastructure, innovation and skills. These investments will create the opportunity to address several critical and interdependent challenges: delivering a sustainable, resilient and inclusive economic recovery from the COVID-19 pandemic, reducing inequalities and regional disparities, redefining the UK's role in the world, and achieving net-zero emissions of greenhouse gases by 2050. Developing the capacity to capture, transport and permanently store large quantities of carbon dioxide could be a significant part of this transformative, economy-wide investment programme.

There is clear evidence of the need to develop and deploy carbon capture, usage and storage (CCUS) technologies. CCUS presents a potentially cost-effective – and sometimes the only technologically viable – solution for addressing emissions in some of the sectors that are most challenging to decarbonise. In addition, as the most recent report by the Intergovernmental Panel on Climate Change makes clear, it is likely to be extremely difficult to realise the temperature goals of the Paris Agreement without large-scale removal of carbon dioxide from the atmosphere during this century.

The Government has highlighted the potential for investments in CCUS to contribute to sustainable growth across the country through its *Ten Point Plan for a Green Industrial Revolution*, the *National Infrastructure Strategy* and the *Energy White Paper*. This report draws attention to the UK's comparative advantages in production and innovation along the CCUS value chain, which – if realised – can support large numbers of net-zero-aligned jobs in the short and longer term in many regions of the country.

A lack of consistency in previous policies on CCUS has meant that the UK is not now in the prime first-mover position that it could have been. More positively, the commitment in the public and private sectors to CCUS in the UK is now stronger, and demand is growing both domestically and overseas. Policies now need to provide clear and consistent support for the CCUS sector as it seeks to realise its contribution to achieving net-zero and to create new opportunities from further innovation.

As the Climate Change Committee has pointed out, CCUS is a necessity, not an option, for the UK to reach net-zero by 2050. The UK should urgently mobilise investments in CCUS physical infrastructure, innovation and skills during this decade. This will also help the UK to lead by example and create a shared global agenda of investment in a net-zero future among countries at COP26.

**Nicholas Stern**, September 2021

*IG Patel Professor of Economics and Government, and Chair, Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science*

# Abbreviations and glossary

| | |
|---|---|
| BECCS | Bioenergy with carbon capture and storage: the process in which biomass (e.g. waste, energy crops) is used to generate energy where the emitted $CO_2$ is captured and stored, considered a greenhouse gas removal (GGR) technology because it can result in the removal of $CO_2$ from the atmosphere on a net basis if the biomass is supplied sustainably |
| BEIS | Department for Business, Energy & Industrial Strategy [UK Government] |
| Blue hydrogen | Hydrogen produced from natural gas where the $CO_2$ emitted through the production process is captured and stored via carbon capture, usage and storage (CCUS) technology |
| CAPEX | Capital expenditure |
| Carbon footprint | A measure of the $CO_2$ produced by an individual or organisation's activity or activities |
| CCC | Climate Change Committee (formerly Committee on Climate Change): an independent, statutory body established under the UK's Climate Change Act, 2008, with the purpose to advise the UK and its devolved governments on emissions targets and to report to Parliament on progress made in reducing greenhouse gas emissions and preparing for and adapting to the impacts of climate change |
| CCS | Carbon capture and storage |
| CCSA | Carbon Capture and Storage Association |
| CCUS | Carbon capture usage (or utilisation) and storage |
| CfD | Contract for Difference |
| $CO_2$ | Carbon dioxide |
| $CO_2$-e | Carbon-dioxide-equivalent: a measure of how much a gas contributes to global warming, relative to carbon dioxide |
| DACCS | Direct air carbon capture and storage: a process by which $CO_2$ is captured directly from the atmosphere and stored, considered a greenhouse gas removal (GGR) technology because it can result in the removal of $CO_2$ from the atmosphere on a net basis |
| ECITB | Engineering Construction Industry Training Board |
| EINA | Energy Innovation Needs Assessment: a portfolio of work commissioned by BEIS which has produced reports providing analysis on future energy innovation needs in the UK |
| ETC | Energy Transitions Commission |
| ETS | Emissions trading scheme/system |
| GGR | Greenhouse gas removal: technologies that remove greenhouse gases from the atmosphere |
| GHG | Greenhouse gas: any gaseous compound that absorbs and emits radiant energy within the thermal infrared range, causing the greenhouse effect, contributing to global warming |
| IEA | International Energy Agency |

| | |
|---|---|
| Industrial cluster | An area where a number of industrial sites are co-located and that currently typically produces a high level of $CO_2$ emissions |
| IPCC | Intergovernmental Panel on Climate Change |
| GVA | Gross value added |
| MMV | Measurement, monitoring and verification |
| $MtCO_2$-e | Million tonnes of carbon dioxide equivalent |
| MWh | Megawatt hour |
| n.e.s. | Not elsewhere specified |
| NIC | National Infrastructure Commission |
| Net-zero | The atmospheric state where the overall greenhouse gas emissions produced are balanced by greenhouse gases taken out of the atmosphere to result in the net amount being zero |
| ONS | Office for National Statistics |
| OPEX | Operating expenses |
| R&D | Research and development |
| RD&D | Research, development and demonstration |
| $tCO_2$ | Tonne of carbon dioxide |
| T&S | Transport and storage [parts of the CCUS infrastructure] |
| UKRI | UK Research and Innovation |

# Key messages

- **Carbon capture usage and storage (CCUS) needs to be deployed urgently in the United Kingdom and across the world to bring the global amount of greenhouse gas emissions to net-zero. The UK has a mix of comparative advantages in CCUS that it can commercialise.**
- **The potential contribution of CCUS to sustainable growth in the UK is high,** especially considering the long-term preservation of jobs – potentially up to 53,000 by 2030 – in energy-intensive industries, and benefits from emerging UK CCUS supply chains tapping into export markets.
- **The more aligned CCUS deployment can be with net-zero over this decade, the higher the potential for job creation.** Construction activities will be the main driver of jobs in the short to medium run, which has the potential to contribute to the UK's economic recovery. Estimates suggest up to 31,000 jobs could be created by 2030.
- **Looking at existing export capabilities for CCUS-related products overall, the UK is in a position of slight disadvantage compared with some of its peers, such as Germany and the United States.** However, because countries' specialisms vary by product and no single country has yet established dominance over the market across the product portfolio, plentiful opportunity remains for the UK.
- **A significant number of CCUS-related products that the UK already exports competitively or could do so in the future are in the measuring, monitoring and verification instrument category.** These products will be the backbone of any commercial framework for CCUS as they are needed to put a value on carbon dioxide and to enable the governance and integrity of associated trade activities.
- **The UK demonstrates a comparative advantage in CCUS *innovation* that exceeds its comparative advantage in other broad categories of 'clean' technology.**
- **Evidence points to there being a levelling-up opportunity from CCUS if support is directed strategically to address the unequal distribution of innovative performance across the country.**
    - Areas in the South East, as well as the industrial heartlands in the North East and North West of England, are strongly placed to act as CCUS R&D hubs. Some parts of the South East appear to be capitalising on synergies between oil and gas and CCUS innovation already.
    - There is little CCUS innovation in other parts of the UK generally, though there might be particular opportunities to capture in regions such as North Eastern and Eastern Scotland that innovate extensively in oil and gas but not yet in CCUS.
- **Compared with the top CCUS-innovating countries, the UK has particular strengths in some technologies that are 'adjacent' to CCUS**, including those relating to physical or chemical separation, liquefaction and solidification of gases. These patterns suggest there are potential sources of indirect comparative advantage of relevance for CCUS in the UK.
- **While the returns to public investment in CCUS R&D between 2000 and 2015 were not as great as in other more established areas of clean technology, there has since been a step change in CCUS** in the UK and around the world, which justifies strengthening investment in innovation.
- **The UK cannot afford any further policy failure or delays deterring investment in CCUS,** given the urgency of net-zero, and because investor confidence is already fragile due to past experience, including the cancellation of two major competitions.

## High-level recommendations

- **A consistent, long-term policy, institutional and regulatory framework, underpinned by multi-year funding, is needed** to improve coordination across stakeholders at the national and local levels on the entire portfolio of net-zero solutions and technologies, including CCUS.
- **The Government should make up for years of stalled progress** by taking a holistic approach, addressing barriers to CCUS investment and capitalising on the UK's comparative advantages across the five interrelated types of capital needed for sustainable and inclusive growth: infrastructure/physical capital, knowledge capital/innovation, human, natural and social capital.

# Summary


## Seizing opportunities from the CCUS value chain can be part of an economy-wide, net-zero-aligned growth path in the UK

The UK has responded to the climate emergency facing the world with an economy-wide target to reach net-zero emissions by 2050. The current decade is critical to ensure coordinated investments in infrastructure, innovation and skills reorient the UK economy towards a net-zero-aligned growth path. **As a technological solution for addressing some of the most challenging emissions, CCUS needs to be deployed urgently in the UK and globally,** which implies a rapid growth trajectory for the demand for CCUS-related technologies, products and services.

**The Government's current stated ambition is to capture 10 million tonnes of carbon dioxide ($MtCO_2$) a year by 2030. To meet net-zero, this needs to be ramped up significantly.** There are projects already in early development stages across the UK that together could deliver double that capacity in the 2020s.

An inconsistent policy environment, including two failed major demonstration competitions, has been the primary setback against CCUS development in the UK to date. **Now is the time to make up for years of stalled progress in deploying this essential technology. What's more, fast, strategic action can unlock growth opportunities along the way.** Focus should be on areas where the UK has or can build comparative advantage, crucially by capitalising on its existing capabilities in the oil and gas sector, to deliver significant emissions abatement while generating export opportunities and wider economic benefits from CCUS.

*CCUS as an enabler of sustainable growth can:*

1. **Create net-zero aligned jobs.** Jobs can start emerging in the short term from the construction of CCUS projects with the potential to feed into a net-zero-aligned recovery. If government ambitions come to fruition, there will be two carbon capture clusters constructed by the mid-2020s and a further two clusters by 2030 in the UK, the locations of which will be determined with the cluster sequencing programme. Many jobs thus will be concentrated in the UK's industrial heartlands, which have long been a focus for regional development policies. CCUS can also help to avoid potential job losses from the restructuring of the economy under net-zero as it is a sector demanding skills similar to those currently found in some of the high-emitting industries.

2. **Unlock export opportunities from the supply chain.** Ambitious climate targets coming from around the world imply that demand for CCUS-related products and services will rapidly increase globally as well as in the UK. The UK is not primarily a production-based economy; nevertheless, early action to develop manufacturing capability of CCUS-related products could create significant export opportunities given the immature state of the market for these, in turn supporting jobs into the long term. Arguably, the UK is in a stronger position to capture export opportunities from CCUS-related services than from products, given it currently successfully exports relevant expertise in related industries, notably in the oil and gas sector. A considerable amount of known capacity for geological storage of $CO_2$ in Europe lies in the UK too, unlocking an opportunity to export 'storage as a service'.

3. **Enable net-zero-aligned industrial growth.** In the presence of strong competition, low-cost decarbonisation is crucial for the continuation of existing UK industries and the many jobs that they support. CCUS can act as a 'bridge' for addressing industrial emissions quickly where renewables-based solutions either do not yet exist or are prohibitively expensive. This is crucial for the continued flow of much-needed profits for these industries to fund their own transition to fully renewable solutions in the longer term. CCUS is an enabler of low-cost, low-carbon hydrogen and electricity production, which can replace fossil fuel use in industry. For some industries, CCUS is currently the only technically feasible way to abate process emissions.

4. **Deliver negative emissions, which is essential for net-zero in the UK and globally.** The two main engineered ways of removing $CO_2$ from the atmosphere, bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS), share a technological foundation with CCUS. Both are currently prohibitively expensive, therefore CCUS investments made today are crucial for bringing costs down through shared infrastructure, economies of scale and learning by doing. $CO_2$ removal technologies need to be up and running in the UK by 2030 and will continue to play an essential role even beyond 2050. Removal technologies can abate residual emissions in hard-to-abate sectors, unlock a least-cost pathway to net-zero and create economic benefits from the export of negative emissions. But even purely from a cost perspective in a potential future of very high demand for negative emissions, the focus on removals should be to complement, not to replace, greenhouse gas mitigation.

## Jobs in the UK from the CCUS value chain

Job creation opportunities lie along the highly complex and fragmented value chain for CCUS. Overall, the ex-ante studies reviewed for this report suggest that CCUS investments can generate significant gross value added (GVA) benefits and a substantial number of jobs in the short, medium and long terms. Studies that explicitly quantify these aspects suggest **more jobs will lie in the construction than in the operation phase of CCUS projects, and that potentially higher economic benefits both in terms of jobs and GVA will come from export rather than domestic markets.** According to Energy Innovation Needs Assessment analysis commissioned by the Department for Business, Energy & Industrial Strategy (BEIS), CCUS as an export industry could create almost 50,000 direct jobs for the UK in 2050 (Vivid Economics, 2019b).

*Job retention*

As well as creating new jobs, **CCUS is crucial for helping retain existing jobs in energy-intensive industries.** Estimates of job retention in the UK through CCUS vary; examples include: between 35% and 70% of existing manufacturing jobs supported and safeguarded in the Tees Valley; 60% of direct jobs retained in the iron and steel industry by 2060 in the East Coast region; and up to 53,000 jobs protected by 2030 in the UK's refineries, steel and cement industries, and parts of the chemicals sector.

*Annual job creation during construction*

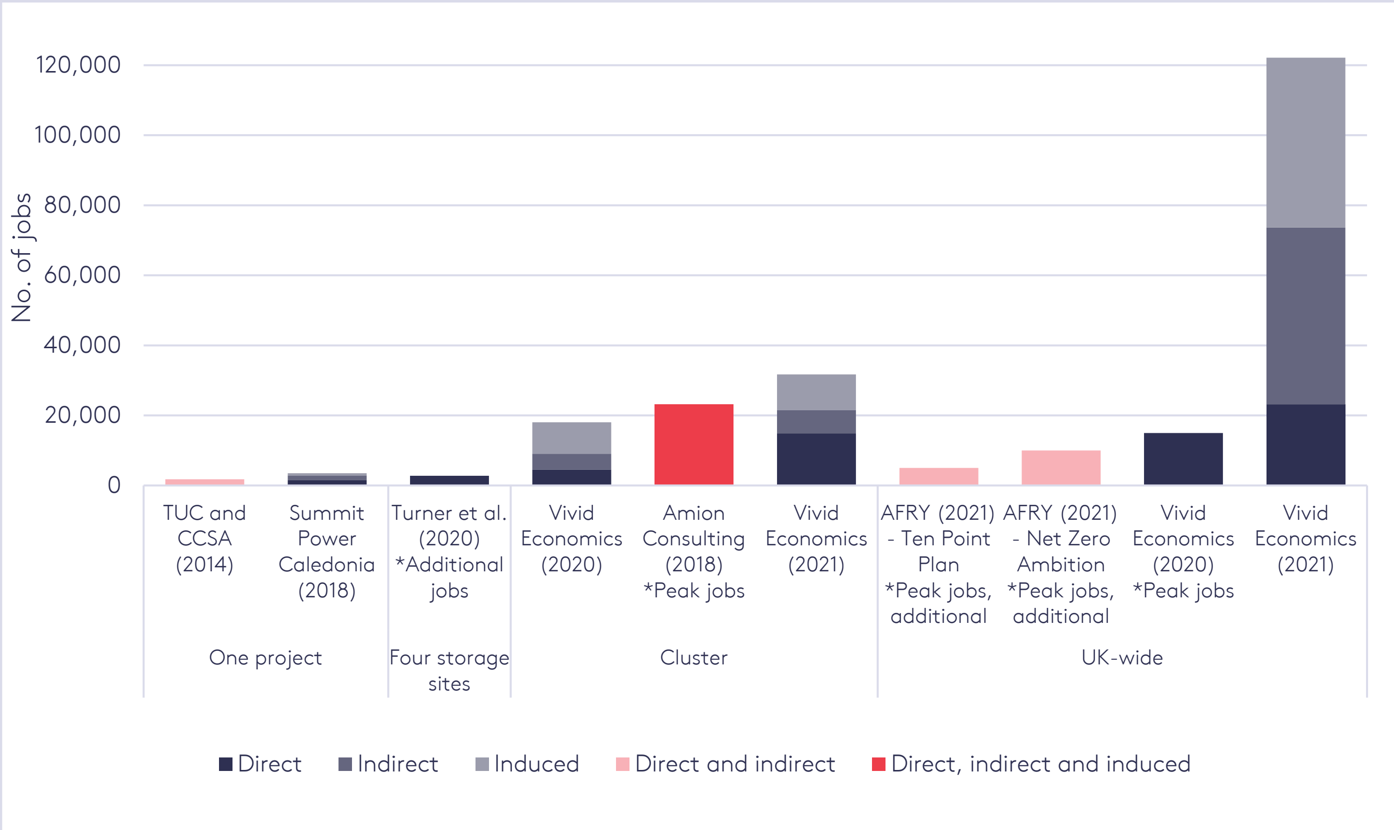
Figure S1 below presents estimates from a set of ex-ante studies that consider the annual average number of jobs created from CCUS during construction. While comparison across studies is not like-for-like given the different scopes, there is a broadly positive relationship with regard to the number of *direct* jobs and the level of CCUS deployment (rising from one project to UK-wide). Where the studies break down the numbers, they show that indirect jobs are responsible for up to 40% of all jobs created, emphasising the size of the opportunity from UK-based CCUS supply chains even when considering demand from domestic deployment only. Notably, AFRY (2021) compares economic impacts of a scenario consistent with the Climate Change Committee's recommended pathway to net-zero with one in which CCUS deployment is limited to the Government's current ambition stated in its *Ten Point Plan for a Green Industrial Revolution* and find that employment benefits up to 2030 are roughly halved in the latter scenario.

*Cumulative jobs to 2030 and beyond*

Multiple estimates of the cumulative jobs created from UK-wide deployment of CCUS by 2030 cluster between 22,000 and 31,000 jobs; this is unsurprising given the studies in scope consider unambiguous deployment scenarios informed by announcements by the various industrial clusters that are designed to be consistent with the UK's climate targets. Estimates of jobs created by 2030 reflect a 'construction boom' in CCUS expected over this decade.

Studies that look beyond 2030 are mixed in terms of both the number and type of jobs they consider, making comparisons challenging. However, **there is considerable agreement that cumulatively, over 40,000 jobs will emerge from the UK-wide deployment of CCUS by or before 2050.**

Figure S1. Annual average jobs from CCUS in the UK during construction – estimates by study




*Source: Authors. See Appendix A for the data and assumptions underlying the figure as well as detail on the CCUS deployment scenarios analysed in each study.*

### *Just transition and levelling-up considerations in job creation*

For CCUS to contribute to a just workforce transition under net-zero, policies need to account for not only the number but also the place-related and social dimensions of the jobs created. Having the skills in place locally will be a prerequisite for retaining economic value from CCUS investments within regions, contributing towards the 'levelling-up' agenda. **The extent of skills transfer from other industries into CCUS will be a crucial determinant of local skills availability.** While most studies that quantify job creation take a top-down approach to translate a given level of CCUS investment into a certain number of jobs, evidence on the supply of skills to fill this demand is limited, especially when it comes to the actual scope for skills transfer at the local level.

Careful consideration must be given to who might be in need of the new jobs that will arise from CCUS. For sustained positive social outcomes, created jobs need to be good quality, offering adequate wages, full-time employment and to be permanent rather than temporary. **CCUS demonstrates good potential to create quality jobs but a more nuanced understanding of the nature of jobs across the CCUS workforce is required to realise this potential.** Diversity of the CCUS workforce must also be considered.

## The UK's productive strengths in CCUS

### *Technological complexity and potential for spillovers*

Our analysis sheds light on the UK's current and future potential competitiveness around CCUS value chains by looking at global trade data. Firstly, we observe that CCUS-related products tend to be somewhat higher in complexity relative to the universe of all traded products. This suggests that on average, CCUS-related products tend to be more technologically sophisticated, requiring more knowledge-intensive skills and capabilities for their production. These products are also likely to have greater opportunities for knowledge spillovers into other areas.

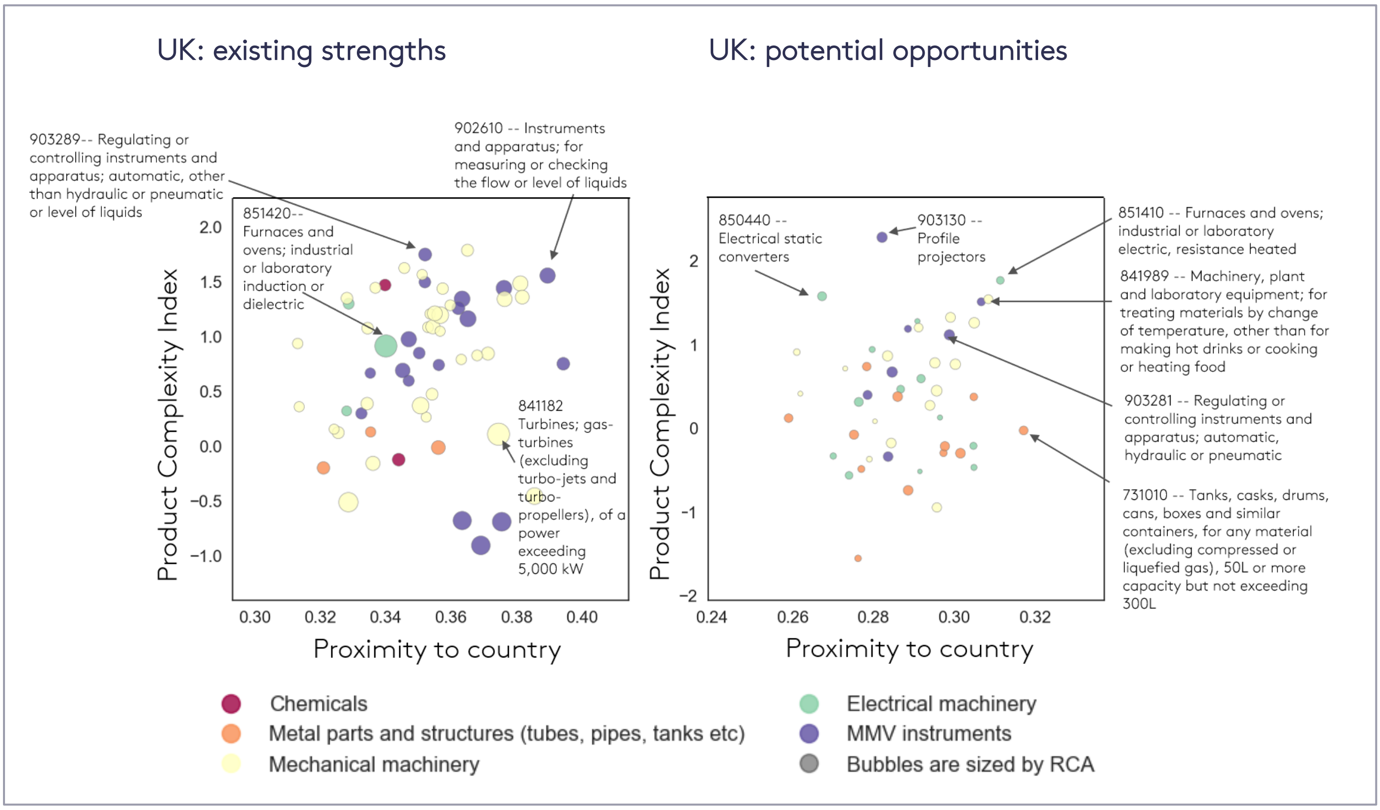
*Share and comparative advantage in products*

The UK's export share in CCUS-related product categories tends to be low (around or below 5%) and declined over the period 1995–2019. The US and Germany historically have been dominant in CCUS-related exports but increasingly are being overtaken by China. This partly reflects China's dominance in global manufacturing exports more generally.

Nevertheless, **the UK has revealed comparative advantage (RCA) in some key CCUS-related products, and a mix of strengths and opportunities, especially in mechanical machinery and measuring, monitoring and verification (MMV) instruments** (see Figure S2). RCA is defined as a given product's share in a country's exports, divided by the product's share in global trade volume.

The UK has comparative advantage in very few products categorised as metal parts and structures or electrical machinery. There are several export opportunities that are both proximate to the UK's existing export capabilities and high in product complexity. It is likely to be easier for the UK to develop competitiveness in these areas and they could also add more value to the UK economy in terms of technological upgrading and knowledge spillovers.

Figure S2. Existing strengths and potential opportunities in CCUS for the UK



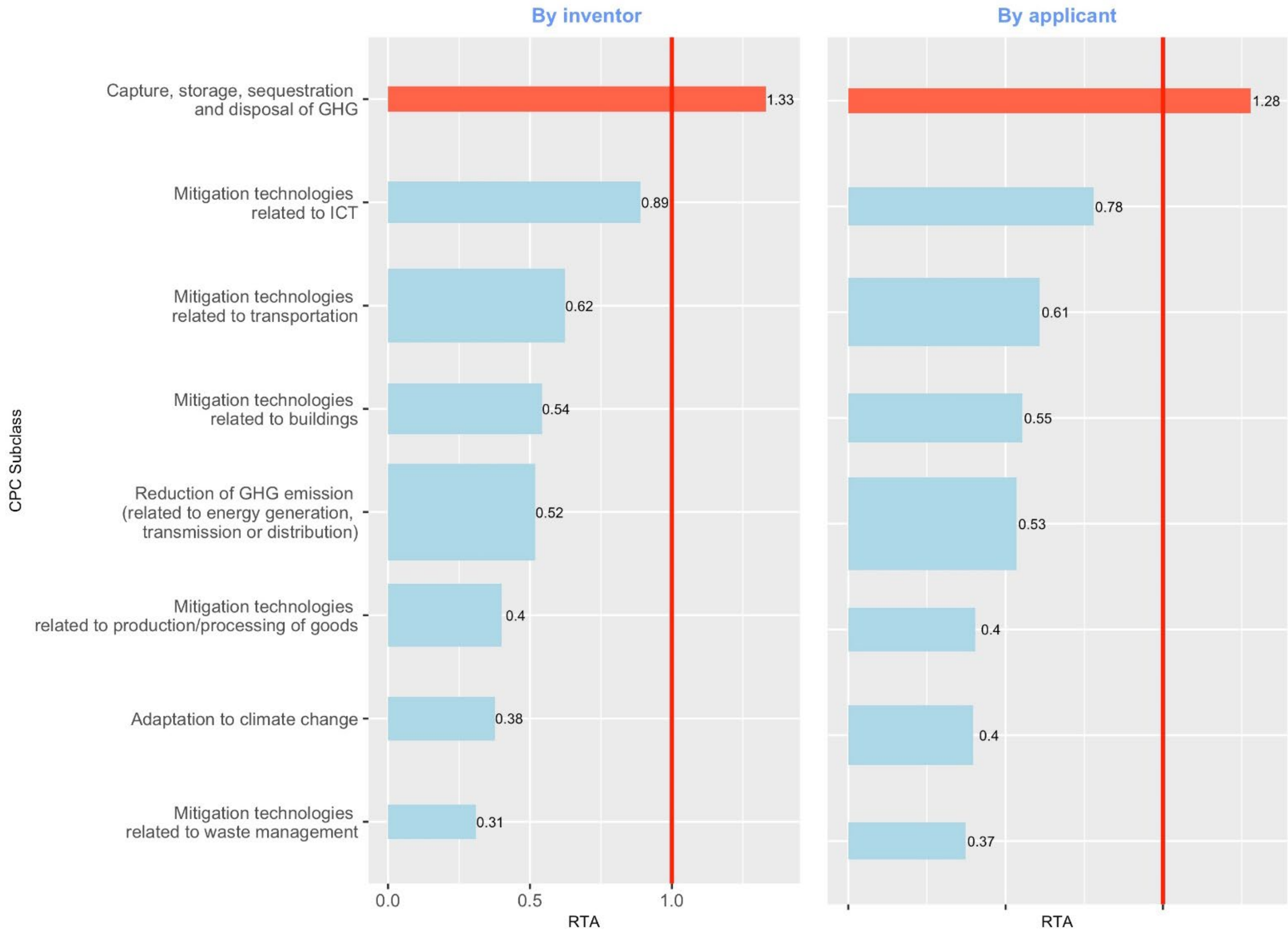

## The UK's innovative strengths in CCUS

A more forward-looking indicator of the UK's comparative advantage in CCUS is its innovative capability. While tracking innovation can give an indication of the areas in which the UK might enjoy future advantage, the extent of this will be contingent on how much of the production and trade activity related to a patent is retained within the UK supply chain.

Our analysis of CCUS-related patenting shows global CCUS innovation has been growing rapidly over the last 20 years but experienced a decline following the financial crisis (in common with clean technologies more generally). **Just 4% of global CCUS patent applicants over the period 2000–2015 were made in the UK but the country demonstrates a comparative advantage in this area** – which also exceeds other broad categories of 'clean' innovation (see Figure S3). However, previous analyses have shown that the UK exhibits strong comparative advantage in specific technologies within these broad categories of 'clean' innovation, including wind and ocean energy.

We measure comparative advantage in innovation by comparing the share of a country's patents in a particular technology field relative to the global share of patents in that field, termed 'revealed technological advantage' (RTA). Our further analysis provides evidence for potential economic returns from public R&D investments in CCUS.

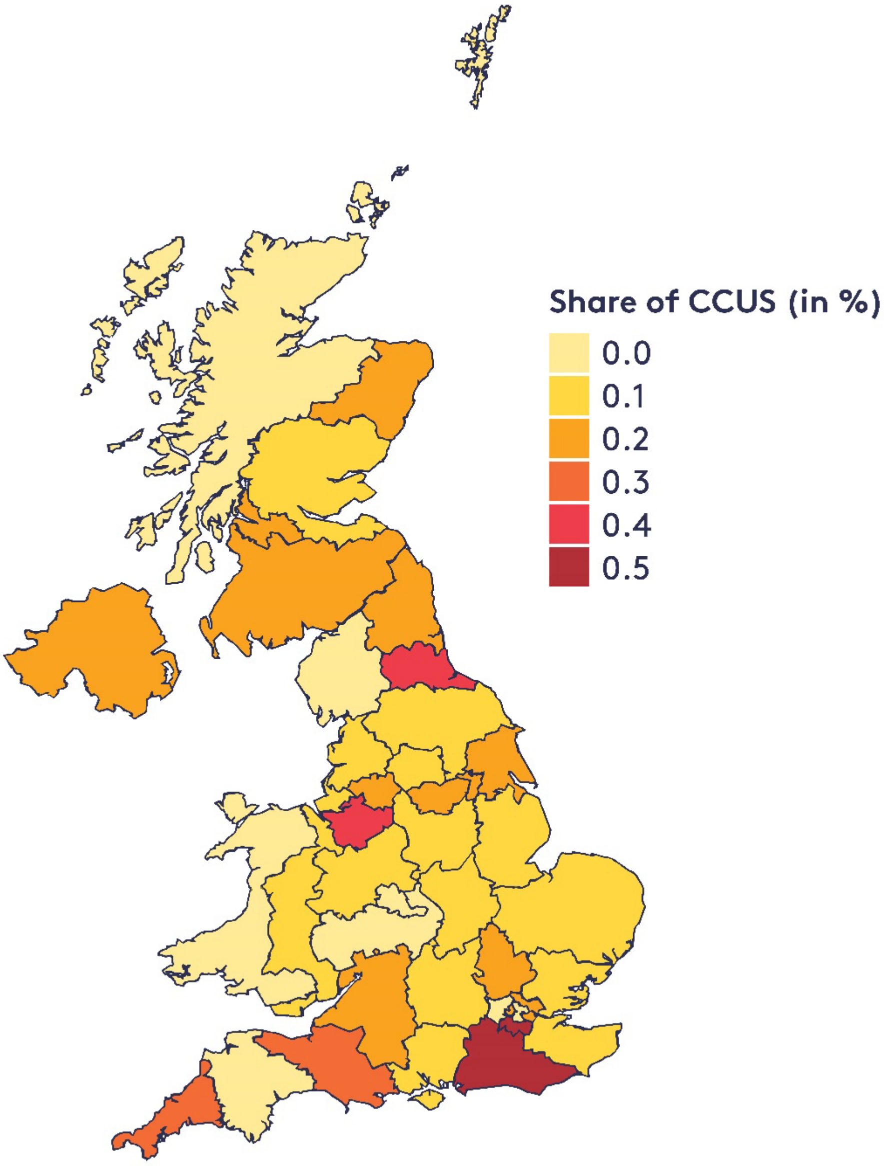
Figure S3. Revealed technological advantage (RTA) of the UK in CCUS compared with other broad clean technology categories, 2000–15




*Notes: The length of each bar on the horizontal axis shows the RTA; the width of each bar on the vertical axis reflects the number of patent families in each category. 'Applicant' refers to the legal owner of the invention, which might be an individual, business, university or other entity. An 'inventor' is an individual who has contributed to the invention. CPC = Cooperative Patent Classification. GHG = greenhouse gas. ICT = information and communication technologies.*
*Source: Authors' estimates based on PATSTAT – 2018 Spring Edition.*

**Looking at patenting at a regional level (Figure S4), we find a relatively high share of CCUS-related innovation activity in the South East of England.** Industrial areas in the North East and North West also appear to have a relatively high share of CCUS-related patents compared with other regions. Regional dimensions and transferability of R&D capability require further attention to ensure CCUS-driven growth is regionally balanced. In the context of uneven economic performance across the country, it is important to understand where technological strengths are located, and the extent to which different parts of the UK could be well positioned to act as R&D hubs for CCUS in the coming years. While CCUS has the potential to contribute to future growth and employment in the UK's industrial heartlands, the extent to which this is the case will depend on where new knowledge is generated, patterns of knowledge spillovers, the structure of supply chains and the skills base.

Figure S4. Share of CCUS innovation out of total innovation in the UK, 2000–15 (share of patents at NUTS2 regional level)




*Source: Authors' estimates based on PATSTAT – 2018 Spring Edition*

**A positive correlation between CCUS innovation and areas that have traditionally patented more intensively in oil and gas extraction technologies is also shown by our analysis.** This suggests that places that have specialised in these technologies might be well-placed to benefit from the transition to CCUS. Regions such as North Eastern and Eastern Scotland have a large share of innovation in oil and gas extraction but quite a low share in CCUS-related technology, whereas inner London and parts of South East England including Surrey, East and West Sussex display a large share of patenting in oil and gas extraction as well as CCUS-related technologies.

Finally, we conduct preliminary analysis on innovation in technologies that appear to be 'adjacent' to CCUS technologies, to shed light on potential sources of indirect comparative advantage and knowledge spillovers for CCUS innovation. We find that patents that are classified as CCUS are also often classified under some other related technology classes, in particular, 'physical or chemical processes of separation' and 'liquefaction, solidification or separation of gases by pressure and cold treatment'. Turning to RTA, we find evidence that suggests the UK could capitalise on its strengths in these CCUS-adjacent technologies to improve its position as a global leader in CCUS innovation. The UK ranks fourth by inventor and fifth by applicant when it comes to innovation in technologies adjacent to CCUS (within a list of 15 countries with the highest RTA in CCUS-related technologies) – higher compared with its position as eighth in the world as both applicant and inventor for its RTA in technologies directly related to CCUS.

A crucial consideration when interpreting our innovation-related findings is the lag inherent to the data we rely on. The patent data underpinning this section is for the period 2000–15. However, **the UK has seen a significant step change in the CCUS landscape since the net-zero target was signed into law in 2019.** This, combined with the tangible CCUS opportunity emerging from the industrial decarbonisation agenda focused on clusters, has translated into significant interest from project developers and supply chain companies in the UK to develop capacity and innovate in CCUS. This renewed context for CCUS is not captured by the latest patent data available to us.

## Recommendations for sustainable growth from CCUS in the UK

Recent policy frameworks and funding committed to CCUS have set a clear deployment pathway for initial CCUS projects in the UK but more needs to be done to stimulate investment at the required scale and pace. In light of our analyses of the data on economic impacts, trade and innovation relating to CCUS, and the current barriers to CCUS development that we identify, we present a set of policy recommendations. Our recommendations span national and local levels, and relate to the investments across infrastructure, innovation, human, natural and social capital that are required for sustainable and inclusive growth.

Policy risk operates across these five types of capital and therefore needs to be carefully managed at an overarching level to avoid policy failures that can deter investment, as occurred following the cancellation of the two CCUS competitions in the UK. Creating and sustaining investor confidence will come down to a consistent, long-term policy, institutional and regulatory framework. This framework will need to help reduce uncertainty, and improve coordination across policymakers, industry and other stakeholders at the national and local levels on the entire portfolio of net-zero solutions and technologies, including CCUS. The Government's forthcoming Net Zero Strategy is a major opportunity to set this framework.

### 1. Infrastructure/physical capital

Capital investment requirements for CCUS are high, but there is currently no meaningful economic value attached to emissions reductions to drive these investments in the UK. The lack of economic incentive for investment is especially true for CCUS applications in the industrial sector and greenhouse gas removals where there are no apparent revenue streams. In contrast, BECCS for power can tap into revenues from the sale of low-carbon electricity, although even that on its own would hardly create the appetite to develop transport and storage infrastructure. The absence of CCUS business models proven by experience in the UK adds to the investment finance challenge. Although the business models proposed by BEIS are being designed with close industry consultation, no bankable commercial structure or risk allocation has yet been agreed for any commercial-scale CCUS project in the UK. The business models are also yet to be backed by a long-term funding framework.

*Recommendations*

1.1. Finalise CCUS business models as an immediate priority, underpinned by long-term funding to support deployment in the 2020s, and with a coordinated approach across interrelated energy systems including hydrogen and greenhouse gas removal technologies, to unlock opportunities from infrastructure and knowledge sharing.

Action leads: *Department for Business, Energy and Industrial Strategy (BEIS) and HM Treasury*

1.2. Link CCUS investment with a robust, net-zero-aligned carbon price, starting with:

- A long-term signal on the future of the UK Emissions Trading Scheme, including how it will interact with or incorporate incentives for investment in negative emissions technologies.
- Detail on any complementary measures that will be used to safeguard competitiveness of UK industry in the presence of a strong carbon price, without compromising on the incentive for deep and fast decarbonisation.

- Detail on complementary measures that will be used to create consumer demand for low-carbon products.

Action lead: *BEIS, in close consultation with HM Treasury*

1.3. Leverage the role of the UK Infrastructure Bank to create the conditions to crowd much-needed private sector investment into CCUS while ensuring support for CCUS is not at the expense of necessary investment in other net-zero-enabling technologies.

Action leads: *UK Infrastructure Bank and HM Treasury*

1.4. Develop CCUS as part of a holistic infrastructure programme considering infrastructure that will be shared across various technologies (e.g. greenhouse gas removal) as well as complementary assets (e.g. broadband) required for the overall net-zero-aligned growth of regions.

Action lead: *HM Treasury, in close consultation with local government, and by extension communities, across the UK*

## 2. Knowledge capital and innovation

The limited deployment of CCUS in the UK and globally means many of the associated supply chains do not yet exist. In addition, the UK is starting on the back foot compared with some of its peers when it comes to exporting CCUS-related products. This is in the context of a history of inconsistent policy support for CCUS in the UK, including the late-stage cancellation of two major competitions due to cost concerns. Given that the commercial certainty needed to incentivise industry to invest in CCUS supply chain capacity is still limited, there is a risk that the UK could miss the limited window to establish comparative advantage and capture export opportunities, including those that lie in utilising productive and innovative capabilities from existing supply chains like oil and gas.

Currently, the UK's innovative capabilities in CCUS are located unevenly across the country, which could have implications for regional growth patterns. Some areas, such as North Eastern and Eastern Scotland, that innovate extensively in oil and gas but not yet in CCUS might be missing a particular opportunity that they could unlock from transferable R&D capabilities. Another challenge is around the path dependencies that characterise innovation systems. The substantial uncertainties that surround technologies for CCUS, hydrogen and greenhouse gas removals individually and in combination make it difficult to account for the path dependencies in policies and investment decisions made today, implying a risk that the eventual outcome may be sub-optimal.

*Recommendations*

2.1. Draw on diverse economic evidence to align domestic CCUS supply chain ambitions with a proper understanding of the UK's comparative advantage in production, services and innovation, with early coordination between CCUS project developers and supply chain companies, and considering an outcome-based approach that brings in international supply chains where necessary.

Action leads: *BEIS and Department for International Trade (DIT), in close consultation with businesses*

2.2. Ensure that support for innovation in net-zero-enabling technologies, including CCUS, is ambitious, considering enhanced R&D tax credits where applicable, and that it is channelled in a way that addresses regional disparities as well as the current gaps in thinking across path-dependent innovation systems, to improve coherence especially between the development and deployment of CCUS, hydrogen and greenhouse gas removal technologies.

Action leads: *BEIS and UK Research and Innovation (UKRI)*

2.3. Explicitly link domestic CCUS policy with the ambitions to play an international leadership role on climate action, especially in the context of COP26, considering further collaboration in R&D.

Action lead: *COP26 Team within the Cabinet Office, in close consultation with a range of other government departments including BEIS, Foreign and Commonwealth and Development Office (FCDO), and DIT*

2.4. Inform industrial and innovation strategy at national and local levels by creating a robust evidence base on what works that draws upon enhanced collaboration and co-creation between higher education institutions and industry as well as lessons shared across projects by capitalising on the cluster sequencing agenda.

Action leads: *BEIS, Department for Education (DfE) and UKRI, in close consultation with local government, businesses and education institutions*

## 3. Human capital

The overall disruption from CCUS to the current workforce within the engineering construction industry is not expected to be major, but there will be potential upskilling requirements on the operational side as well as training needs on the specifics of CCUS for technical workers. Even where skills are abundant, for instance in commercial and financial services, the strategic planning to channel the required workforce into CCUS needs to happen now.

Although many analyses have focused on quantifying job creation from CCUS, evidence is limited on the skills that will need to underpin these jobs. Neither the extent of transferability from existing sectors nor the 'place' dimensions of matching the demand for CCUS skills with the supply are yet fully understood. Furthermore, while CCUS is recognised as a potential enabler of just workforce transitions for workers in industries subject to decline as part of the net-zero transition, there are currently limited processes in place for actively managing these transitions.

*Recommendations*

3.1. Complement CCUS investments with a special emphasis on skills as part of a holistic, proactive net-zero skills programme, designing targeted re- and upskilling for those displaced in the COVID-19 crisis and who will be displaced by ongoing structural change towards net-zero, using human capital tax credits to incentivise firms to play an enhanced role in the programme.

Action leads: *BEIS, DfE and Department for Work and Pensions (DWP), in close consultation with local government*

3.2. Ensure collaboration across departments on the net-zero skills agenda, including skills required for the successful delivery of CCUS, and embedding necessary frameworks in overarching policies underway, such as the Skills and Post-16 Education Bill.

Action lead: *Cross-government*

3.3. Ensure joint effort between government, industry and education providers to take a place-based approach to map and quantify the existing skills base that is transferable into CCUS, identify skills gaps, and develop education/training curricula accordingly.

Action leads: *BEIS, DfE and DWP, in close consultation with local government, businesses and education institutions*

## 4. Natural capital

There are several issues related to natural capital. Given the absence of commercial CCUS applications in the UK, CCUS and especially large-scale storage of $CO_2$ underground raises new issues of liability and risk. The potential risk of large losses, especially in the case of accident and/or $CO_2$ leakage, not only raises the cost of capital but can also deter investment altogether.

Furthermore, there is a high level of path dependence and interactions regarding the development and deployment of the various net-zero technologies but limited evidence to suggest the required amount of joined-up thinking exists in the current policy landscape. This may undermine the ultimate ability of policies to minimise disruption to natural ecosystems while leading the economy to decarbonise.

Finally, despite its net climate benefits, CCUS requires large amounts of energy and in poorly designed systems may lead to the depletion of natural resources and other negative environmental impacts. Failure to consider the impacts of applications over the relevant lifecycle, including potential perverse indirect effects, may undermine the climate benefit of CCUS.

*Recommendations*

4.1. Ensure environmental regulation and legislation keep pace with developments in CCUS in an agile way, and that the drive to support faster deployment does not compromise on environmental scrutiny.

Action leads: *BEIS, Department for Environment, Food & Rural Affairs (Defra) and the Oil & Gas Authority*

4.2. Take a holistic view of all energy systems to minimise environmental disruption from investments in CCUS and related economies at both the national and local levels, respecting local ecosystems and natural resource constraints.

Action leads: *BEIS, Defra and the Oil & Gas Authority, in close consultation with local government*

## 5. Social capital

A comprehensive programme to establish awareness and social acceptability of CCUS in the wider population is currently lacking in the UK. There is limited public awareness of CCUS and it is often viewed as a fossil fuel technology that competes with renewable energy for public and private investment. This implies a gap in effective communication, since in reality investments in CCUS and renewable energy can be mutually reinforcing rather than competing.

Another likely reason for opposition is the perceived risk of accidental leakage from storage sites. This is especially important as a CCUS public dialogue showed public support for CCUS was conditional, above all, on safety. Lack of timely investment in social capital around CCUS would also pose a threat to the long-term sustainability of the CCUS workforce if the sector fails to establish itself as an attractive place to work for future generations. It would also undermine the Government's ability to absorb any social tensions that might arise if policy support for CCUS leads to an increase in the cost to consumers.

*Recommendations*

5.1. Create an awareness and information programme to ensure social acceptability of CCUS, using a positive but realistic narrative that positions CCUS within the wider portfolio of essential net-zero technologies, while emphasising the role of CCUS as an enabler of just workforce transitions towards net-zero.

Action leads: *BEIS, DfE and Department for Digital, Culture, Media & Sport (DCMS)*

5.2. Rebuild pride and sense of community within regions around a shared purpose for clean growth that includes CCUS, in particular through participatory decision-making processes at a local level, to ensure community buy-in and just outcomes.

Action leads: *BEIS, in close consultation with local government, and by extension communities, across the UK*

# 1. Introduction: context, purpose and approach

## The importance of CCUS to reaching net-zero

Limiting global temperature rise to around 1.5°C above pre-industrial levels to limit the worst impacts of climate change implies net-zero emissions of carbon dioxide ($CO_2$) by 2050 (IPCC, 2018). Investments made in this decade in infrastructure, innovation and complementary assets will either create lock-in to high emissions or enable reorientation towards a net-zero-aligned growth path.

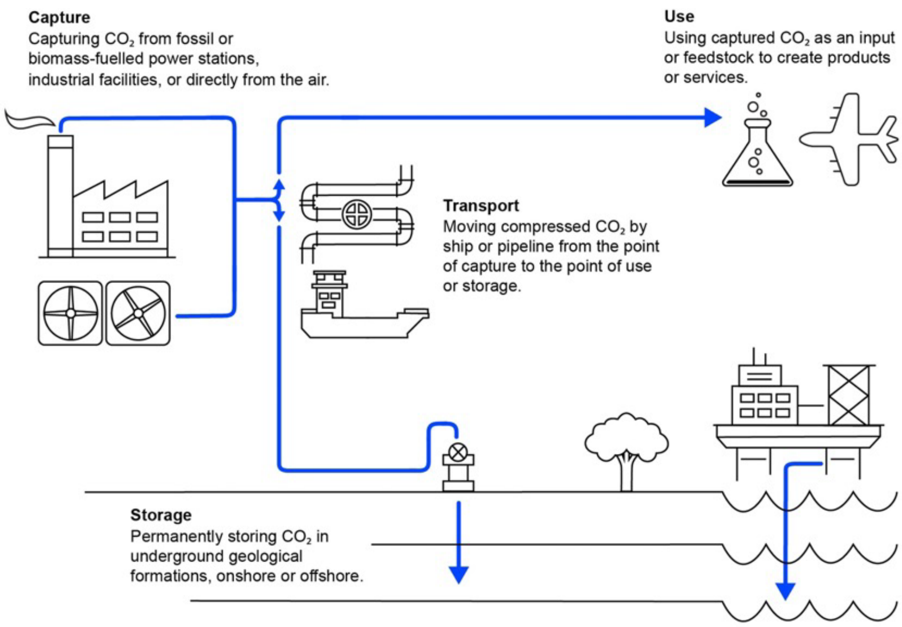
**The use of carbon capture, usage and storage (CCUS) is key for enabling a net-zero-aligned growth path, given its role in decarbonising hard-to-abate industries such as steel and cement, producing low-carbon hydrogen and delivering negative emissions.** As such, the International Energy Agency (IEA) has concluded that reaching net-zero globally will be virtually impossible without CCUS (IEA, 2020). In its recent *Net-Zero by 2050* Roadmap the IEA recommends that 10 heavy industrial plants should be equipped with carbon capture technology every month from 2030 onwards (IEA, 2021b). Progress in the energy sector to date does not reflect this level of activity and there is a need to urgently ramp up investment in CCUS research, development, demonstration and deployment over this decade globally.

**To meet its own net-zero target, the UK will have to deploy CCUS.** In this study we take a pragmatic look at CCUS to make actionable recommendations for the UK government to be able to maximise economic opportunities and wider societal co-benefits while building CCUS as a sector in its own right.

## What is CCUS?

**CCUS covers a suite of technologies.** These include those that enable the capture of $CO_2$ from large point sources, including power generation or industrial facilities that involve the combustion of either fossil fuels or biomass, as well as facilities such as cement plants that release $CO_2$ as a direct by-product of industrial processes (IEA, 2020). The $CO_2$ can also be captured directly from the atmosphere. Captured $CO_2$ is then compressed and transported by pipeline, ship, rail or road to a destination where it is injected into deep geological formations (e.g. depleted oil and gas reservoirs), which trap the $CO_2$ for permanent storage. The captured $CO_2$ can also be used in a range of industrial applications (described further on p15 below).

**Figure 1.1.** Schematic of the carbon capture, usage and storage process




*Source: International Energy Agency (2020) All rights reserved. https://iea.blob.core.windows.net/assets/181b48b4-323f-454d-96fb-0bb1889d96a9/CCUS_in_clean_energy_transitions.pdf*

## CCUS: a necessity for the UK, despite uncertainty

**There is now wide acknowledgement that CCUS is a necessity rather than an option for the UK for the country to meet its legally binding target of net-zero greenhouse gas emissions by 2050** (CCC, 2019). This follows years of stalled progress, primarily due to 'turbulent' policy support (BEIS Committee, 2019), including the cancellation of two major competitions at a late stage. The Government has now made CCUS one of the key pillars of its agenda to 'level up' across the regions and its plans to revitalise the UK economy in line with net-zero in the wake of the COVID-19 pandemic (HM Government, 2020a). Consequently, the Energy White Paper of December 2020 confirmed £1 billion of government investment to facilitate the deployment of CCUS in four industrial clusters, all to be operational by 2030 (HM Government, 2020b).

**Net-zero requires far greater urgency in CCUS deployment than the Government's current stated ambition to capture 10 million tonnes (Mt) of $CO_2$ a year by 2030** (HM Government, 2020a, 2020b), as illustrated in the Climate Change Committee's *2021 Progress Report to Parliament* (CCC, 2021). There are already projects in early development stage across the UK amounting to more than double the 10 Mt capture capacity planned to become operational in the 2020s (Global CCS Institute, 2020). The policy framework will need to support these projects to come to fruition in order to deliver a cost-effective pathway to net-zero while unlocking wider economic benefits from CCUS, including a sustainable, inclusive and resilient economic recovery from COVID-19 and redefining the UK's role in the post-Brexit world. This needs to be the decade that government support is channelled into areas along the CCUS value chain that can deliver significant emissions abatement while generating export opportunities for the UK in related technologies, products or services where the country has, or can build comparative advantage – and where global demand is growing.

**CCUS can be used for multiple purposes, from decarbonising industry to mitigate new emissions, to removing existing $CO_2$ from the atmosphere.** There are other solutions to these problems too, such as fuel switching and nature-based solutions, which means the ultimate level of CCUS that will be deployed is uncertain. This uncertainty is illustrated in the vastly different CCUS deployment scenarios found in various models of the UK's pathway to meeting net-zero, for instance by the National Grid (2020) and the CCC (2020b). Notably, the amount of $CO_2$ captured in 2050 ranges from less than 80 to 180 Mt across the different CCC scenarios for meeting net-zero. Nevertheless, there is now a firm commitment to deploy an initial set of CCUS projects in the UK that will lay down the shared $CO_2$ infrastructure, creating different options for the amount and sources of $CO_2$ that may use it in the future.

## Our approach

We have assessed:

- National and local economic opportunities from CCUS in the UK – both direct and indirect via supply chains
- Potential employment and implications for skills needs
- Transferability of existing strengths and capabilities from other sectors
- Barriers and enablers of growth, and implications for both national and local policy.

This study builds on a series of reports on sustainable growth for the LSE Growth Commission and mirrors the approach of a previous report in the series on the possibilities for sustainable growth in the UK's passenger vehicles sector (Unsworth, Valero et al., 2020). Focusing on CCUS as the next sector for examination was a choice informed by other work in the series, including the report by Rydge et al. (2018) which identified CCS as a technology area with significant innovation spillovers, and a report by Unsworth, Andres et al. (2020), which pointed to the job creation potential from investments in CCUS and hydrogen in the order of tens of thousands, spread across the UK's regions.

The report does not attempt to 'pick winners' between the different applications of CCUS (see above) or to compare CCUS with other emissions reduction and/or removal solutions. Instead, the report aims to identify areas of opportunity for a sector for which we know there is an unambiguous commitment by government to expansion.

### A note on carbon 'usage'

Usage (or utilisation) refers to using the captured $CO_2$ to produce commercially marketable products (Bassi et al., 2015). $CO_2$ usage does not necessarily reduce emissions or deliver a net climate benefit, once indirect and other effects have been accounted for (Hepburn et al., 2019). For instance, one of the most well-known forms of $CO_2$ usage is enhanced oil recovery, which can utilise and store $CO_2$ at scale, but it may not yield any net climate benefit and may even be detrimental when the usage of the oil extracted from the process is considered (ibid.). Enhanced oil recovery is not currently being considered by projects in the UK.

Other forms of $CO_2$ usage are less developed and include the use of flue gases for the cultivation of algae (used, for example, as biofuels); $CO_2$ carbonation for the production of plastics, petrochemicals or construction material via the remediation of waste; and the storage of carbon as biochar (Bassi et al., 2015). These have potential to offer climate benefits where the application is scalable, uses low-carbon energy and displaces a product with higher lifecycle emissions (IEA, 2019). Assessing the climate impact of $CO_2$ usage on a lifecycle basis is crucial, considering the end use and the source of the $CO_2$ to begin with. For instance, using $CO_2$ captured from a fossil fuel origin will impact the overall carbon 'budget' in the atmosphere differently from using $CO_2$ captured directly from the air.

Even if we only consider areas of $CO_2$ usage that offer a net climate benefit, the amount of $CO_2$ that needs to be captured when looking at CCUS to deliver emissions reduction and removal requires the main focus, at least in the short term, to be on dedicated permanent storage. For instance, Alberici et al. (2017) estimate the demand for $CO_2$ in the UK from a selected set of usage applications at around 113–624 $ktCO_2$/year by 2030, which is very small in comparison with the 22 $MtCO_2$/year captured and stored in 2030 which the CCC recommends for the delivery of net-zero (CCC, 2021). At the global level, the IEA concludes similarly that $CO_2$ usage is a complement, not an alternative, to $CO_2$ storage for large-scale emissions reductions, noting that the size of the market for $CO_2$ usage will likely remain relatively small in the short term and is highly uncertain further into the future (IEA, 2019).

This study recognises $CO_2$ usage as an important area for further investigation as part of the CCUS value chain. However, given that our focus on CCUS is driven first and foremost by the need to get to net-zero, we do not explicitly discuss or analyse the scope for $CO_2$ usage. It is important to note that the report contains several references to *carbon capture and storage* (CCS) without the usage aspect. These are all linked to external references whose underlying studies choose to exclude 'usage' from their terminology, a choice that we respect.

### A note on lifecycle emissions

Throughout the report we discuss the opportunity for the UK from the sale of products and services towards CCUS projects to be deployed domestically and around the world. The UK already has an increasingly low-carbon electricity supply and is a leader on ambitious climate targets which, where delivered, will further decarbonise the energy supply underpinning the UK's manufacturing industries. Therefore, the production of CCUS equipment in the UK is likely to be lower carbon than in most other countries. However, the analyses we present in this report take an economic view of the UK's comparative advantages across the CCUS supply chain without an assessment of the emissions embedded in the delivery of the associated products and services. Although comparative advantage will increasingly depend on the carbon content of a supply chain in a decarbonising world, an explicit assessment of environmental impacts of the CCUS supply chain on a lifecycle basis is required to complement the analysis we present in this report and to ensure genuine climate benefits from the delivery of CCUS projects.

**Report structure**

- Section 2 reviews the overall case for focusing on CCUS to drive sustainable growth in the UK.
- Section 3 conceptualises the products and services in the CCUS value chain and sets out evidence from a range of forward-looking analyses on the economy-wide opportunity from CCUS, with a particular focus on jobs.
- Sections 4 and 5 present new analyses that shed light on the economic opportunity from CCUS by identifying the UK's international competitiveness around CCUS technologies, through analysing data relating to global trade and patents.
- Section 6 evaluates the barriers inhibiting sustainable growth from CCUS in the UK across five types of capital needed for sustainable and inclusive growth.
- Section 7 first assesses the adequacy of the current CCUS policy landscape for addressing the barriers identified in the previous section and then presents policy recommendations to help fill the gaps that we identify.
- Section 8 concludes.
- The Appendices provide further detail and assumptions underlying the discussion in Section 2; the methodology for and further data emerging from the global trade data analysis in Section 4; and supplementary plots emerging from the patent data analysis in Section 5.

# 2. Why focus on CCUS for sustainable growth in the UK?

**An inconsistent policy environment for CCUS in the UK has kept the technology 'stuck' in a pre-commercial state to date** (Element Energy and Vivid Economics, 2018). The two major demonstration competitions abandoned at a late stage are the most apparent examples of unsuccessful policies undermining the UK's CCUS sector. The first of these was cancelled four years after its launch in 2007, due to costs exceeding the £1bn budget agreed in the 2010 Spending Review (BEIS Committee, 2019). A second £1bn competition was launched in 2012 but cancelled in 2015, due to concerns about the future costs for consumers (ibid.).

**Net-zero has changed the context for CCUS in the UK entirely, making the deployment of the technology virtually inevitable.** Now is the time to make up for years of stalled progress in deploying this essential technology and fast strategic action can unlock growth opportunities along the way.

**We identify four main ways** that CCUS can represent a sustainable growth opportunity for the UK:

1. To create net-zero-aligned jobs
2. To capitalise on supply chain opportunities
3. To enable sustainable industrial growth
4. To create negative emissions.

### Creating net-zero-aligned jobs in the UK from CCUS

**Labour-intensive and hence job-creating investments in regions across the UK are a particularly urgent priority,** not least following the job displacement impacts of the COVID-19 pandemic, which have tended to hit the lowest-paid the hardest, and the Government's pre-articulated goal of 'levelling up' across regions. CCUS presents potential for delivering a material number of net-zero-aligned jobs in the short run (Unsworth, Andres et al., 2020). Related construction projects are recognised as being capable of delivering jobs at speed. According to government plans, two carbon capture clusters will be constructed by the mid-2020s and a further two clusters by 2030 in the UK (HM Government, 2020a), the locations of which will be determined with the cluster sequencing programme. Industry has already showed ambition to go further, with five major industrial clusters in the Humber, Teesside, Scotland, the North West and Wales looking to deploy CCUS as part of their decarbonisation plans (UKRI, 2021).

**CCUS jobs will, by nature, be concentrated in industrial heartlands that have long been a focus for regional development policies, or in places whose incomes depend primarily on oil and gas activities,** where there is a need for major economic restructuring in line with net-zero. The silver lining is the strong relevance for CCUS of the skills in some of these industries that are set to decline, skills that could be transferred with minor upskilling (Element Energy, 2020). The UK therefore could create a natural destination for these workers who might otherwise be at risk of job loss, while capitalising on existing capabilities to develop competitive CCUS supply chains.

**Investments in CCS and hydrogen infrastructure could also help at a regional level to mitigate labour market displacements due to COVID-19** (Jung and Murphy, (2020). For instance, the number of jobs created from these investments could roughly match the number of jobs lost in real estate in England, those lost in public administration in Scotland and those lost in education in Wales. Despite slight improvements, in June 2021 the employment rate in the UK was still 1.5 percentage points lower than before the pandemic (ONS, 2021), and 1.9 million staff were still furloughed at the end of that month (HMRC, 2021).

## Supply chain opportunities and the UK's existing capabilities for CCUS

CCUS is in its early stages globally, with very limited commercial application other than for enhanced oil recovery (Global CCS Institute, 2020). However, given strengthened climate targets all around the world and the recognition of the necessity for CCUS to achieve these, momentum for CCUS has been growing, with plans for more than 30 new facilities announced since 2017 (IEA, 2020). If all these projects were to proceed, global $CO_2$ capture capacity would more than triple, to around 130 Mt/year (ibid.). In the UK, the Government commitment is to capture and store 10 $MtCO_2$/year by 2030 but, as previously mentioned, this falls short of the 22 $MtCO_2$/year in 2030 recommended by the Climate Change Committee (CCC, 2021). The demand for CCUS-related products and services thus needs to increase rapidly both in the UK and globally.

The ambition to build competitive UK CCUS supply chains to seize commercial opportunities both domestically and abroad has already been articulated by the Government itself (BEIS, 2021f) and internalised by industry (BEIS, 2021b). This will involve building new supply chains but also diversifying some existing ones that offer a high level of transferability, particularly from the UK's long-established oil and gas sector.

**The UK is not primarily a production-based economy but early action to develop manufacturing capability of CCUS-related products could create significant export opportunities**, given the immature state of the market for these. While labour intensity varies by product, focusing on the competitive production and further innovation of related components and technologies could also support jobs into the long term. A typical argument when deploying emerging technologies would be to wait for other countries to act as 'first movers' and make the necessary initial investments to bring product costs down, including through innovation and economies of scale. This argument applies less to the UK context for CCUS, where deployment is driven by annual climate targets, which means moving late is unlikely to realise cost savings, as other measures would need to be deployed in the interim (AFRY, 2021).

**Arguably, the UK is in a stronger position to capture export opportunities from CCUS-related services than it is from products**, given that it currently successfully exports its expertise in engineering, procurement, construction and project management in related industries, notably in the oil and gas sector (Vivid Economics, 2019b). The UK can also use its expertise in regulatory innovation to unlock opportunities to export consultancy and specialist services on CCUS regulation (NIC, 2021).

**Furthermore, a considerable amount of known capacity for geological storage of $CO_2$ in Europe lies in the UK** (Global CCS Institute, 2020), presenting an opportunity to export 'storage as a service'. This would involve $CO_2$ produced elsewhere being shipped and permanently stored within the UK, which could be a particularly attractive offer for European countries that do not have storage potential (Vivid Economics, 2020). The opportunity to export storage as a service is discussed extensively by Vivid Economics (2019b, 2020) and Element Energy (2019). Summit Power (2017) assesses the counter scenario of relying on exporting UK $CO_2$ to third countries against domestic storage and finds strong downsides in doing so.

## CCUS as an enabler of sustainable industrial growth – process emissions, hydrogen and electrification

Turning to domestic deployment, CCUS can be an enabler of net-zero-aligned growth for the UK's high-emitting industries. The cost of achieving the original 2050 target in the Climate Change Act – an 80% reduction in greenhouse gas emissions relative to 1990 levels – without deploying any CCS was estimated to be at least 2% of GDP higher than achieving it with CCS by 2050 (Clarke, 2016). In the presence of strong competition, low-cost decarbonisation is crucial for the continuation of existing UK industries and the many jobs that they support, as £77,000 could be lost in GVA per employee made redundant in energy-intensive industries (TUC, 2012).

**The three most significant methods of reducing emissions from the UK's manufacturing and construction sectors in 2050, as identified by the Climate Change Committee, are the use of hydrogen, electrification and CCS** (CCC, 2020a). CCS in this context refers to applications where carbon is captured directly from industrial process, and these applications make up 3 $MtCO_2$ of the overall Government target to capture and store 10 $MtCO_2$ per year by 2030 (HM Government, 2021). For certain industries, such as those that involve non-combustion processes (e.g. cement production), CCUS is the only deep decarbonisation option available.

**CCUS also feeds into the other two major sources of industrial emissions abatement, as it can enable the production of both hydrogen and electricity in a low-cost, low-carbon manner.** CCUS-based production of hydrogen (i.e. 'blue hydrogen') is currently much cheaper than renewables-based production via electrolysis (i.e. 'green hydrogen') (IRENA, 2020) and the UK has a fleet of gas-based power plants with a long lifetime ahead of them which will become incompatible with net-zero in the absence of abatement measures. In that sense, CCUS can act as a 'bridge' for addressing industrial emissions quickly where renewables-based solutions either do not yet exist or are prohibitively expensive. This would enable the continued flow of much-needed profits for these industries to fund their own transition to fully renewable solutions in the longer term.

**CCUS can enable a reliable, low-carbon supply of hydrogen at scale, which will be critical to paving the way for fuel-switching in industry early on.** This in turn can make the introduction of green hydrogen more accessible than it would be without the shared infrastructure, learning by doing and regulatory structures that can be established with an early switch to blue hydrogen. Low-carbon hydrogen also has a role in decarbonising transport and heat more widely, in particular as an alternative to electrification, although there is no broad consensus on the best route to follow in the long term (CCUS Cost Challenge Taskforce, 2018). Hydrogen can be used to fuel hard-to-decarbonise parts of the transport sector, such as heavy goods vehicles and shipping, and replace natural gas in the existing gas grid for domestic heating if appropriate modifications are made to infrastructure and appliances.

**Alongside existing industries, the commitment to deploy CCUS in the industrial heartlands could enable new manufacturing supply chains and attract inward investment.** For instance, a recent deal with Drax has led the Japanese engineering company Mitsubishi to pledge to moving its CCS operations to the UK, with the possibility of producing its carbon capturing solvent in the UK as well (Armitage, 2021). Furthermore, while the EU's hydrogen strategy explicitly prioritises green hydrogen, with a target to install at least 40 GW of electrolyser capacity by 2030 (European Commission, 2020), the UK's 5 GW target of low-carbon hydrogen production capacity by 2030 supports a mix of both blue and green hydrogen (HM Government, 2020b). A favourable policy environment could allow the UK to develop comparative advantage in blue hydrogen and unlock export opportunities if the cost of electrolysis remains high.

## CCUS for negative emissions – BECCS and DACCS

**The evidence on the need for greenhouse gas removal (GGR) technologies to constrain global warming within acceptable limits is growing** and was recently articulated in the UK by the Energy Transitions Commission (ETC, 2021) and the National Infrastructure Commission (NIC, 2021).

**Two main engineered ways of removing $CO_2$ from the atmosphere are bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS), which both share a technological foundation with CCUS.** While DACCS allows the capture of $CO_2$ directly from the atmosphere, BECCS can result in $CO_2$ removal on a *net* basis where the biomass is sustainably sourced and the $CO_2$ produced during the conversion of biomass to energy is captured and permanently stored. BECCS can include a variety of biomass feedstocks (e.g. wood, energy crops, organic wastes), methods of energy conversion (e.g. combustion, fermentation) and types of energy produced (e.g. power, heat, hydrogen). In the CCC's Balanced Net Zero pathway, power and hydrogen production make up the two largest BECCS applications by volume in 2050 (CCC, 2020b).

**Given BECCS and DACCS are currently prohibitively expensive, CCUS investments made today are crucial for bringing down costs** through creating shared $CO_2$ transport and storage infrastructure, as well as through economies of scale and learning by doing. This is particularly important for DACCS, which is currently by far the most expensive $CO_2$ capture application (IEA, 2021a).

**The NIC (2021) recommends that the first engineered GGR plants in the UK should be up and running no later than 2030**, delivering 5–10 $MtCO_2$-e of removals a year. Looking further into the future, half or more of the $CO_2$ captured in 2050 relates to GGR technologies in most CCC scenarios for meeting net-zero, including the Balanced Net Zero Pathway. The need for GGR at scale will likely continue beyond 2050 in line with the many IPCC scenarios that suggest more emissions will need to be removed than are emitted globally in the long term (NIC, 2021 based on IPCC, 2005, 2018).

**GGR is key for unlocking a least-cost pathway to net-zero.** A recent study estimated that achieving the net-zero target without BECCS would cost the UK an additional £15 billion, or £17 a year for every household, by 2050 (Baringa Partners LLP, 2021). Furthermore, given its large storage capacity, the UK has the potential to export negative emissions achieved through GGR technologies. Establishing the required $CO_2$ transport and storage infrastructure early on is important for establishing a comparative edge in a future international market for GGR, contingent on the UK being able to deliver more removals than it needs (NIC, 2021).

**The focus on GGR should be to complement, not replace, greenhouse gas mitigation, however** (ETC, 2021). GGR can offset some technologically or economically hard-to-abate emissions (e.g. from aviation, marine transport and agriculture) but even purely from a cost perspective in a potential future of very high demand for offsets, neither the UK nor the world as a whole will be able to entirely offset their way to net-zero emissions.

# 3. The economy-wide opportunity from CCUS

## What does the CCUS value chain look like?

CCUS is a suite of technologies that link to a shared infrastructure. While the products and services that feed into CCUS installations may therefore differ on a case-by-case basis, there are key examples that we can consider as part of the CCUS value chain, some of which are presented in Table 3.1. The UK can unlock opportunities to stimulate jobs, regional growth and wider societal co-benefits by capitalising on its productive and innovative capabilities across the CCUS value chain.

Table 3.1. Key products and services along the CCUS value chain

| Category | Source of $CO_2$ | | | | $CO_2$ capture | $CO_2$ transport | $CO_2$ storage/end use | |
|---|---|---|---|---|---|---|---|---|
| $CO_2$ process | $CO_2$ released from burning fuels in industrial processes or power generation | $CO_2$ released as a direct by-product of industrial processes | $CO_2$ released from hydrogen production e.g. via steam or autothermal reforming | Existing $CO_2$ in the atmosphere | $CO_2$ captured, separated and compressed | $CO_2$ transported to storage or usage location | $CO_2$ injected and permanently stored in underground formations | $CO_2$ used as an input for industrial processes (out of scope) |
| Examples of associated products | Various industrial, power generation or hydrogen production equipment for process (out of scope) | | | n/a | Specialty solvents<br>Flue gas desulphurisation equipment<br>Air separation and compression equipment | Steel pipes<br>Steel frames<br>$CO_2$ shipping vessels<br>Surface storage equipment (for non-pipeline options) | Injection rigs<br>Post-closure MMV instruments<br>Pressure management equipment | Various equipment for feeding $CO_2$ into industrial processes (out of scope) |
| Examples of associated services | Various services relating to industrial, power generation or hydrogen production process (out of scope) | | | n/a | EPCm<br>Installation and construction<br>O&M<br>Legal, professional and financial services | EPCm<br>Installation and construction<br>O&M<br>Legal, professional and financial services | Exploration and appraisal<br>EPCm<br>O&M<br>Legal, professional and financial services | Various services relating to $CO_2$ usage (out of scope) |

*Notes: EPCm = Engineering, procurement, and construction management. O&M = Operation and management. MMV = Measuring, monitoring, and verification.*
*Source: Authors. Examples adapted from the EINA CCUS sub-theme (Vivid Economics, 2019b).*

## Review of the evidence base on future economic opportunity

Given the nascent nature of the CCUS sector, there is very limited ex-post evidence with which to assess the job creation potential and the wider economic impacts of related investments. For this reason, ex-ante economic impact assessments, as well as other analyses that can provide an indication of economic potential, can help inform policy.

Table 3.2 summarises forward-looking studies that assess the economic impact from CCUS investments in three industrial clusters that have been given the green light to further develop their projects in the latest competition under the Industrial Decarbonisation Challenge (UKRI, 2021). While these three studies have been selected to show potential economic benefits from CCUS in various regions of the UK, our discussion draws on a more extensive review of 15 forward-looking studies (including the three presented here) that consider potential benefits under a broader range of modelled scenarios. A summary of the findings from, as well as detail on, the scenarios and methodologies employed in each of these studies is provided in **Appendix A.** The scenario assumptions, methodologies and timelines considered vary considerably across these studies, which makes direct comparisons of economic impacts challenging.

Table 3.2. Summary of selected ex-ante studies on economic benefits of CCUS investments in the UK

| Authors | CCUS sectors covered | Activity detail | Deploy-ment scope | GVA and timeframe | No. of jobs and timeframe |
|---|---|---|---|---|---|
| *Vivid Economics (2021)* | Power, BECCS, Industry, Hydrogen production, $CO_2$ T&S | Deployment and operation of CCS and hydrogen technologies in the Humber industrial cluster (to be up and running by 2031), including two Drax BECCS units of 0.66 GW each, deployed as a staggered pair in 2027–28 | Cluster – Humber | Annual avg GVA added during construction (2024–31): £1,113m direct; £421m indirect; £544m induced; £2,078m total<br>Peak at 2027: £1,783m direct; £564m indirect; £753m induced; £3,100m total | Annual avg jobs during construction (2024–31): 14,900 direct; 6,649 indirect; 10,185 induced; 31,733 total<br>Peak at 2027: 24,203 direct; 9,518 indirect; 14,092 induced; 47,813 total |
| *Vivid Economics (2020)* | Power, BECCS, Industry, Hydrogen production, $CO_2$ T&S | Deployment and operation of full-chain CCUS projects. Benefits quantified separately for three markets: the Net Zero Teesside (NZT) project; the UK domestic market; and the global export market | Cluster – Teesside | Direct GVA benefits: £370m annually (2024–28)<br>Indirect and induced GVA benefits:<br>During construction (2024–28): £750m annually<br>During operation (2030–50): £600m annually | Direct jobs:<br>During construction (2024–28): 4,500 annually<br>During operation (2030–50): 900 annually<br>Indirect and induced jobs:<br>During construction (2024–28): 13,500 annually (approx. 4,500 indirect and 9,000 induced)<br>During operation (2030–50): up to 9,500 annually |
| *Amion Consulting (2018)* | Hydrogen production, $CO_2$ T&S | Design, deployment and operation of a regional hydrogen economy (including CCS) across the North West, to 2050. | Cluster – North West | GVA gains from the HyNet NW project – cumulative up to 2050 (£m): 11,144 direct; 14,812 indirect and induced; 25,956 total (annual avg: £811m; peak year gains: £2bn)<br>GVA gains from the HyNet NW project AND inward investment - cumulative up to 2050 (£m): 30,540 (annual avg: £954m) | Employment from the HyNet NW project – cumulative up to 2050 (total employment years): 110,394 direct; 178,983 indirect and induced; 289,377 total (annual avg: 9,043 jobs; peak: 23,167 jobs)<br>Employment from the HyNet NW project AND inward investment – cumulative up to 2050 (total employment years): 360,273 (annual avg: 11,259 jobs) |

*Notes: T&S = transport and storage. 'Power' as a CCUS sector in the UK typically refers to gas-based power generation with CCS, unless otherwise specified. In this table 'power' does not cover cases where CCUS is indirectly used for power: e.g. if a study is based on hydrogen-fuelled power where hydrogen is produced via a CCUS-based method, this would be categorised as 'hydrogen production', not 'power'.*
*Further details on the considered studies, including the scenarios and methodologies that underlie their respective results, can be found in Appendix A.*
*Source: Authors. Certain assumptions and simplifications have been made to categorise studies in an attempt to facilitate comparisons across estimated economic impacts; any errors in the interpretations of the studies are the authors' alone.*

### *Limited information in some areas and the need to address 'additionality'*

The collection of all 15 ex-ante studies we present in Appendix A is not intended to reflect an exhaustive review, nor does it evaluate the strength of the evidence, though there are areas where information is noticeably limited. In particular, further work could focus on a consistent definition of the distinction drawn between 'direct', 'indirect' and 'induced' jobs from CCUS, and a breakdown of CCUS jobs created by development stages (e.g. planning, construction, O&M). It is also important to further detail 'additionality' of the quantified impacts, given that the growth of the CCUS sector will involve diversifying some existing supply chains, as previously discussed.

Despite recognition that some of the estimated economic impact may not be additional but rather displace existing activity, only two of the reviewed studies specify the jobs they quantify as additional. Turner et al. (2020) quantify additionality using a computable general equilibrium model, allowing analysis of interdependencies across all sectors of the UK economy, arriving at an estimate of 1,700–3,850 additional jobs per year resulting from Government spend on the development of $CO_2$ transport and storage infrastructure over a six-year period. On the other hand, AFRY (2021) compares its modelled scenarios including CCUS with a baseline case without CCUS to infer additional impact and estimates up to 10,000 new jobs by 2025 in a net-zero-aligned CCUS deployment scenario. In general, there should also be a proactive approach to creating an ex-post evidence base on the economic impacts of CCUS investments through robust monitoring and evaluation, starting with initial projects to inform future policy.

*Estimates for gross value added, jobs and support to existing industry*

**Overall, the ex-ante studies reviewed in this report suggest that CCUS investments can generate significant GVA benefits and a substantial number of jobs in both the short and the long term,** with quantitative estimates stretching out to 2060. Studies that explicitly quantify these aspects suggest more job generation will lie in the construction than in the operation phase of CCUS projects, and potentially higher economic benefits from both jobs and GVA coming from export markets than from domestic markets. According to EINA analysis commissioned by BEIS, CCUS as an export industry could create almost 50,000 direct jobs for the UK in 2050 (Vivid Economics, 2019b).

**Alongside the creation of new jobs within the CCUS sector, CCUS is crucial to helping retain existing energy-intensive industry jobs.** Few studies have attempted to quantify this impact. One example, by Vivid Economics (2020), suggests availability of CCUS could support and safeguard between 35% and 70% of existing manufacturing jobs in the Tees Valley. Summit Power (2017) also estimates the degree to which direct jobs could be retained with CCUS solutions available, compared with potential losses that would occur without a solution to reduce their $CO_2$ emissions. For example, in the iron and steel industry, they suggest 60% of direct jobs could be retained by 2060 through CCUS investments on the East Coast. However, since total employment impacts depend overwhelmingly on how the aggregate labour market works, not the employment multipliers for individual projects, a more macro-level understanding of job retention through CCUS would be beneficial. Looking at the overall economy, AFRY (2021) assesses that CCUS will be crucial to protect up to 53,000 jobs by 2030 that lie in industrial sectors where CCUS currently provides the only technologically feasible option to decarbonise: refineries, steel, cement and parts of the chemicals sector.

## CCUS jobs in the short, medium and long run

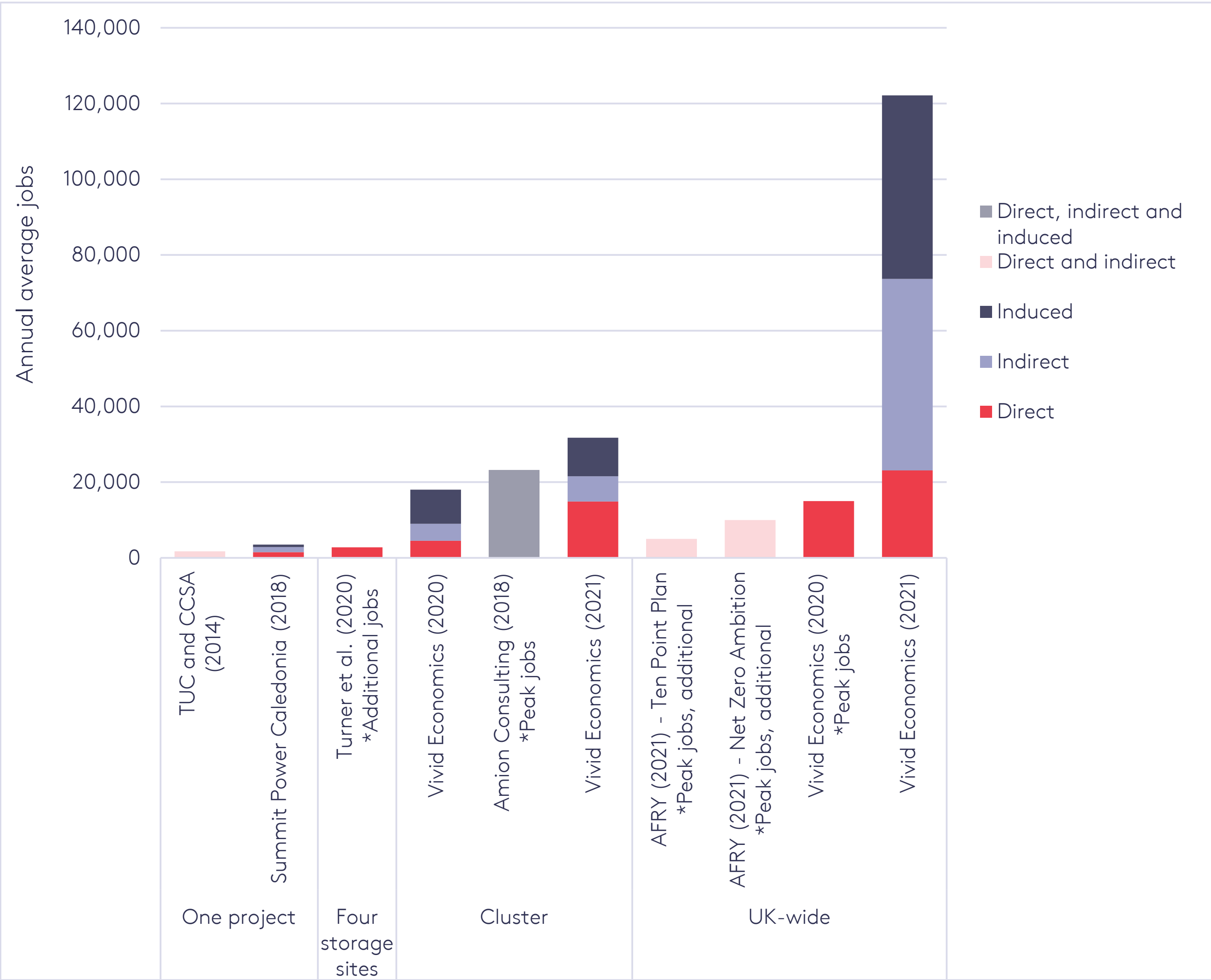
While short-run jobs from CCUS will typically relate to the construction of capture, transport and storage infrastructure, medium- to long-run employment will be driven by continued construction and operation of infrastructure as well as UK production of, and R&D related to, equipment for the capture, transportation, storage and usage of the $CO_2$. Because of the strong relationship between CCUS and potential hydrogen economies, the development of CCUS will also help create jobs in the construction and operation of hydrogen production facilities as well as the UK production of, and R&D related to, equipment for the production, transmission, storage and usage of hydrogen (but this is out of scope of our review).

**In Figure 3.1 we present estimates from a sub-set of ex-ante studies presented in Appendix A that explicitly consider the annual average number of jobs created during construction, or provide a peak number of annual jobs that occur in a period of high capital expenditure.** Study scopes vary across four different levels of CCUS deployment: a single project, four $CO_2$ storage sites, four industrial clusters and UK-wide. Except for Turner et al. (2020), who consider only the construction of transport and storage infrastructure, deployment scenarios cover the full chain of CCUS, including installation of capture technologies at emission sources as well as transport and storage infrastructure. The studies also differ in the scope of the types of jobs they consider; where made available, we provide a breakdown between direct, indirect and induced jobs.

**While comparison across studies is not like-for-like given the different scopes, there is a broadly positive relationship between the number of *direct* jobs and the level of CCUS deployment** – rising from one project to UK-wide. Vivid Economics (2021) defines 'direct jobs' as jobs supported from direct project expenditure, 'indirect jobs' as those supported from spending in the wider supply chain, and 'induced jobs' as those supported from spending in the local economy by employees (e.g. an on-site technician purchasing coffee from a local shop). Across the studies covered in Figure 3.1, where broken down, indirect jobs are responsible for up to 40% of all jobs created, emphasising the size of the opportunity from UK-based CCUS supply chains even when considering demand from domestic deployment only.

The smallest estimate in the figure is 1,750 jobs (reported as an average of provided range, 1,000–2,500), created from a single power plant CCS installation, and the largest estimate is of over 120,000 jobs created when considering UK-wide deployment, 23,000 of which are direct jobs. Notably, AFRY (2021) compares economic impacts of a scenario consistent with the CCC's recommended pathway to net-zero with one where CCUS deployment is limited to the Government's current ambition stated in the *Ten Point Plan for a Green Industrial Revolution*. AFRY finds that employment benefits up to 2030 are roughly halved in the *Ten Point Plan*'s scenario.

**Figure 3.1.** Annual average jobs from CCUS in the UK during construction (estimates by study)

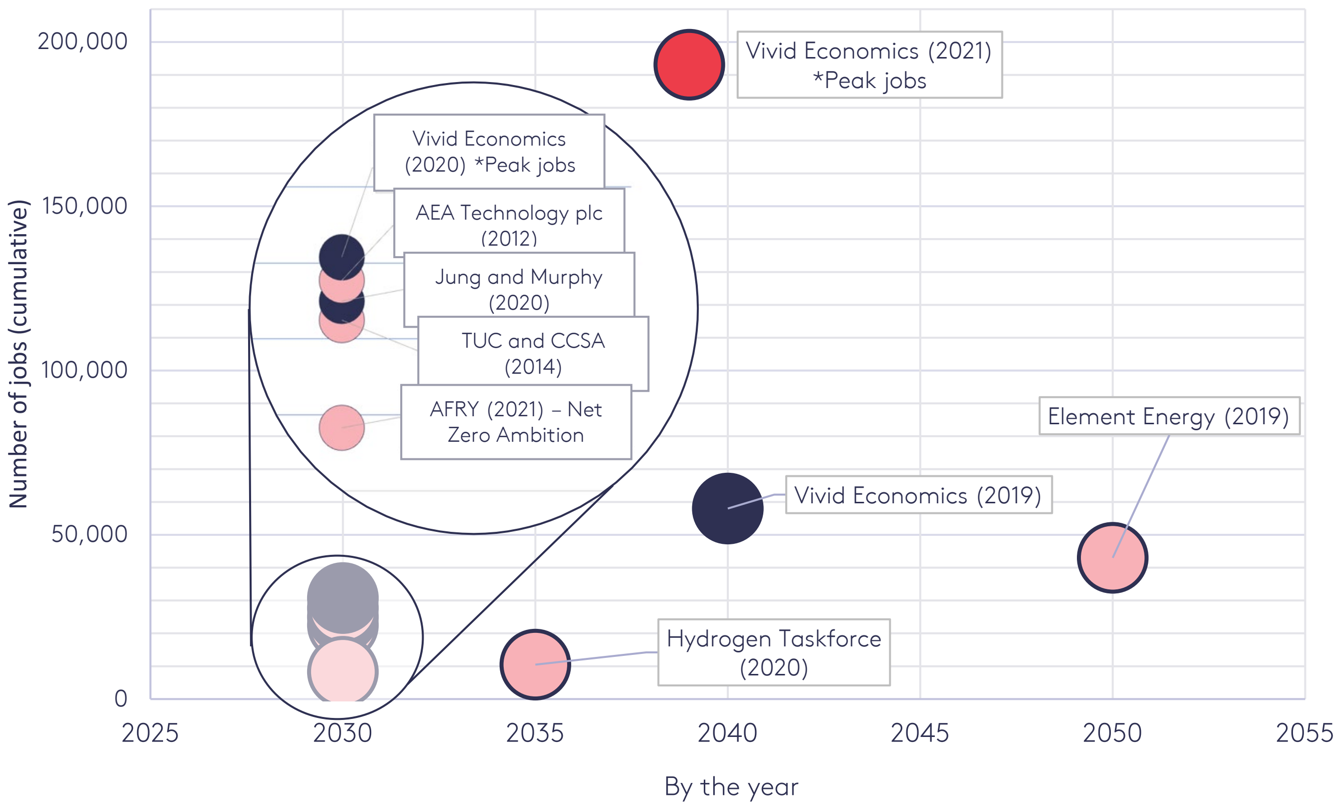



*Note: 'Direct jobs' are jobs supported from direct project expenditure; 'indirect jobs' are those supported from spending in the wider supply chain, and 'induced jobs' are those supported from spending in the local economy by employees (Vivid Economics, 2021).*
*Source: Authors. See Appendix A for the data and assumptions underlying the figure as well as detail on the CCUS deployment scenarios analysed in each study.*

**Figure 3.2 brings together estimates from another sub-set of ex-ante studies presented in Appendix A: of cumulative jobs created from UK-wide deployment of CCUS.** We observe that multiple estimates by 2030 cluster between 22,000 and 31,000 jobs; this is unsurprising given these studies consider unambiguous deployment scenarios informed by announcements by the various industrial clusters and are designed to be consistent with the UK's climate targets. AFRY (2021) presents the lowest estimate by 2030 at 8,300 jobs, but as previously discussed, this is an estimate specifically of additional jobs.

**Taken together, the studies broadly suggest that thousands of jobs will be created by 2030, reflecting a 'construction boom' expected over this decade.** Studies that look beyond 2030 are mixed in terms of both the number and type of jobs they consider, making comparisons challenging. However, there is considerable agreement that over 40,000 jobs will cumulatively emerge from the UK-wide deployment of CCUS by or before 2050.

**Figure 3.2.** Cumulative jobs from UK-wide CCUS deployment (estimates by study, years by study horizon)




*Note: Bubble colours reflect the extent the studies consider direct, indirect and induced impacts. Dark blue corresponds to direct jobs only; pink corresponds to direct and indirect jobs; red corresponds to direct, indirect and induced jobs [see previous definitions].*
*Source: Authors*

## Just transition and regional jobs

**The energy sector needs to recruit for 400,000 jobs between now and 2050 to get the UK to net-zero,** according to an estimate by National Grid (2020). Meanwhile, many workers currently employed in high-emitting industries are at risk of displacement as their industries reorient or decline subject to the structural changes from the net-zero transition. Based on historical examples, it is possible for governments to create the institutional setting to stimulate transitions from declining industries towards low-polluting energy sectors if there is the political will (Fouquet, 2016). Given its strong potential to create net-zero-aligned jobs in the short, medium and long run, CCUS could serve as an enabler of just – or fair – workforce transitions if supportive policy is put in place.

Our review in this section so far has demonstrated the job creation potential from CCUS in terms of numbers. However, in the context of a just workforce transition, **the place-related and social dimensions of the jobs created are as important as the number of jobs created, if not more so.**

*Place-based considerations*

The place dimensions depend on the nature of the jobs. **While most construction and operation jobs are inherently local, jobs from CCUS in the longer term may be less place-dependent when activities tip towards business support and trade.** Having the skills in place locally will be the prerequisite for retaining economic value from CCUS investments within regions.

While most studies that quantify job creation (see Appendix A) take a top-down approach to translate a given level of CCUS investment into a certain number of jobs, **evidence on the supply of skills to fill this demand is limited, especially at the local level.** Without making an explicit link to actual local skills availability and instead using assumptions on local supply chain expenditure as a proportion of total spend, Summit Power Caledonia (2018) and Amion Consulting (2018) quantify job creation in Scotland and in the North West, respectively, as opposed to most other studies that only estimate an overall figure for the UK. Vivid Economics conducts a more granular assessment to understand how jobs demand can be matched with the local supply of CCUS skills, for Teesside and the Humber cluster (Vivid Economics, 2020, 2021). For instance, it identifies that the Humber has a skills gap partly driven by its lower proportion of school leavers achieving higher National Vocational Qualifications compared with Great Britain as a whole (ibid.).

**The extent of skills transfer from other industries into CCUS will be a crucial determinant of local skills availability and needs more research.** Most ex-ante studies in our review include a qualitative discussion on this. TUC and CCSA (2014) point to an 'abundance' of the engineering skills required for CCUS in the UK, primarily resulting from long-standing experience in the oil and gas, energy supply and process industries. However, the actual scope for skills transfer needs to be investigated further, building on the work by Element Energy (2020). Mapping and quantifying the scope for skills transfer at a local level can help build a bottom-up understanding of skills availability for CCUS in the UK as a whole, enabling strategic decisions around investment in skills. It is also informative to look at case studies of companies successfully transferring their skills base as they diversify into different sectors: for instance, Sembmarine Ltd, which went from building offshore oil rigs to offshore wind substations, or Tekmar, which used its lifting and mechanical services expertise in the oil and gas sector to start work on subsea cables (Muttitt et al., 2019).

*Social considerations*

**The Government recognises CCUS as being among the priority areas for investment to level up the country** (HM Government, 2020a) but further work is needed to enable this in practice. Careful consideration must be given to who might need the new jobs that will arise from CCUS. In the wider net-zero context, Robins et al. (2020) demonstrate that the 10 most deprived constituencies in the UK, where thousands of workers are exposed to the risks of the transition, are also constituencies that would benefit from the new jobs and industries associated with the transition. The Great Plains Institute (2021) explicitly links job creation elsewhere in the world from proposed CCUS retrofits on hydrogen production facilities with supporting local communities that are classified as 'at risk' or 'distressed', where factors such as income, employment turnover, housing vacancy, and education level are considered.

**For sustained positive social outcomes, created jobs need to be of good quality.** Quality of a job typically is determined by criteria including adequate wages, full-time employment and permanency (Bays and Hanna, 2021). According to Vivid Economics (2019a) analysis, CCUS ranks above both the UK average and many other energy sectors in terms of GVA per worker, which is used as an indication of the potential quality of jobs created. Furthermore, the Carbon Capture and Storage Association finds that more than half of total expenditure in CCUS assets is in the operational rather than the construction phase, pointing to potential to sustain jobs in the long term from the ongoing operation of these assets (CCSA, 2021). Realising this potential requires a nuanced and detailed understanding of the nature of jobs across the CCUS workforce.

**It will be necessary to ensure that job creation from CCUS investments does not follow pre-existing gender-related trends in the UK workforce that leave women at a disadvantage** (Unsworth, Andres et al., 2020). CCUS-related education and skills programmes will need to be designed being mindful of this, and made available and accessible for people from different backgrounds and circumstances in order to realise the Government's ambitions on the inclusivity and diversity of the CCUS workforce (BEIS, 2021f). Steps that need to be taken to ensure a diverse net-zero workforce overall are discussed extensively by the Green Jobs Taskforce (2021).

# 4. Analysing global trade data to identify opportunities for the UK across the CCUS value chain

## Analysing trade data and its contribution to growth policy

**An important question for policymakers concerned with industrial or growth policy is how to best target investments and design policies to promote competitiveness in key sectors.** It can be challenging to identify a country's existing comparative advantage in particular industries relative to other countries, and even more difficult to determine new markets or technologies into which a country might be able to successfully break in the future.

Evidence from the economic geography literature has shown that countries and regions more easily develop new competitive advantages in products and sectors that are similar to those they already produce competitively (Hidalgo et al., 2007a; Neffke et al., 2011). In other words, **industrial development involves a degree of path dependence.** Moreover, producing and exporting technologically sophisticated products is associated with greater economic prosperity and growth (Hidalgo et al., 2007a, 2007b; Hausmann et al., 2007).

*Overview of methodology*

To identify the UK's current competitiveness and future competitiveness potential in key CCUS technologies, we apply work by Hidalgo et al. (2007a) and Mealy and Teytelboym (2020) to a set of 107 traded products (defined in the Harmonised System[1]) identified as relevant to CCUS. We draw our list of CCUS-related products from three sources: the Green Transition Navigator (Andres and Mealy, 2021), the Energy Innovation Needs Assessment CCUS sub-theme and Saudi Arabia's submission to the World Trade Organization (WTO) negotiations on environmental goods (Doha Round).[2] We benchmark the UK against a number of key competitors:[3] China, France, Germany, Japan, Norway and the United States. There are several CCUS-related products that are high in product complexity (a proxy for technological sophistication) and could add significant value to the UK's economy. Demand for these products is likely to rise in the coming years as more countries deploy CCUS technologies.

Measures calculated through this analysis are based on country-level trade data from CEPII's BACI database, 2021 version (CEPII, 2021). Following the methodology developed by Hidalgo et al. (2007a), we first calculate **'revealed comparative advantage' (RCA)**. RCA is defined as the product's share in the country's exports, divided by the product's share in global trade volume. On average (if all countries were identical in their productive capabilities) we would expect this to equal 1. If it is greater than 1 we infer that the country has revealed comparative advantage as it exports more than its fair share of the product. If RCA is less than 1 the country does not export the product competitively. To ensure our analysis is not skewed by short-term fluctuations in trade, we calculate this measure on the basis of five-year rolling averages in annual trade values, starting in 1995–99 and ending in 2015–19.

We then calculate measures of product-to-product and product-to-country proximity. Product-to-product proximity is the probability that a country has RCA>1 in product *p* if it has RCA>1 in product *q*. Product-to-country proximity is calculated as the average product-to-product proximity between product *p* and all the products the country currently exports competitively. Countries that have higher

[1] The Harmonised System (HS) is a multipurpose international product nomenclature developed by the World Customs Organization that comprises more than 5,000 commodity groups, each identified by a six digit code, arranged in a legal and logical structure and supported by well-defined rules to achieve uniform classification. Refer to the WCO website for further details.

[2] See Appendix B for further information on each source and how we merge them to arrive at our list of 107 products.

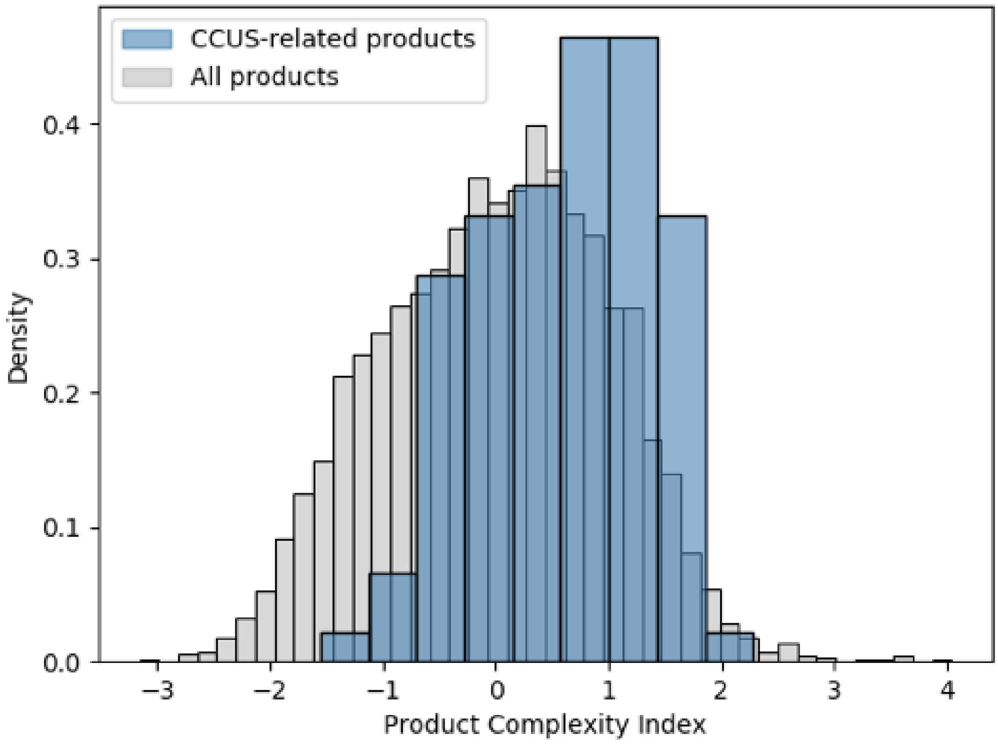
[3] We define our list of key competitors by combining the US, Germany, China and Japan, which are the countries that the Energy Innovation Needs Assessment CCUS sub-theme (Vivid Economics, 2019b) identifies as key CCUS competitors for the UK, with France and Norway, which were mentioned in discussions we held with CCUS stakeholders during the development of this report as plausible countries against which to benchmark, due to current or potential future similarities in their strategic approach to CCUS.

product-to-country proximity to particular products in which they are not yet competitive have been shown to be more likely to develop competitiveness in them in the future (Hidalgo et al., 2007a).

Finally, the **Product Complexity Index (PCI)** ranks products based on the similarity of the countries that export them. Products that are high in PCI tend to be exported by countries with high economic complexity. PCI is used as a proxy for technological sophistication and is located in denser areas of the product space, meaning it opens up a greater number of other (complex) diversification paths.

**Figure 4.1 plots the distribution of PCI for all traded products (grey) against that of those that are classified as CCUS-related (blue). It shows that CCUS-related products tend to be somewhat higher in complexity, with a mean PCI of 0.59** (as compared with 0 for the universe of all traded products). This suggests that on average, CCUS-related products tend to be more technologically sophisticated, requiring more knowledge-intensive skills and capabilities for their production. These products are also likely to have greater opportunities for knowledge spillovers into other areas.

Figure 4.1. Distribution of Product Complexity Index (PCI) of CCUS-related products relative to all traded products

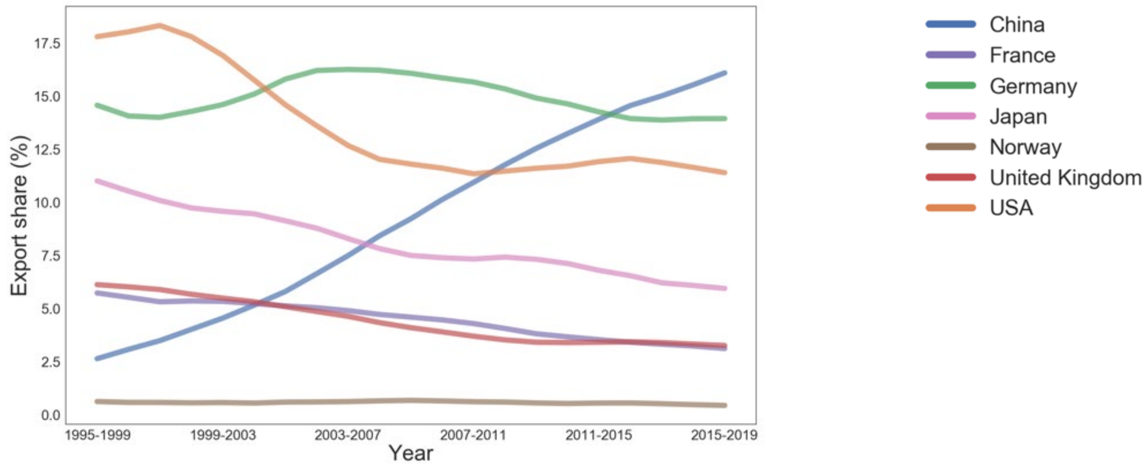



*Source: Authors (this applies to all figures in this section)*

### The UK's export share in CCUS-related products compared with its key competitors

Figure 4.2 shows trends in country-level shares of global exports of CCUS-related products for the UK, China, France, Germany, Japan, Norway and the US. **It shows that the UK's share in global trade tends to be quite low (around or below 5%) and has declined over time.** The US and Germany were historically dominant in exporting CCUS-related products but at the end of the period increasingly were being overtaken by China. This partly reflects China's dominance in global manufacturing exports more generally; however, an analysis of China's strengths and opportunities specifically in CCUS does show high RCA and proximity to existing capabilities for many CCUS-related products (see Appendix B).

Figure 4.2. Trend of country-level export shares in CCUS-related products, 1995–99 to 2015–19




We also disaggregate the 107 CCUS-related products into five categories based on their Harmonised System classifications at the two-digit level (see Appendix B). The plots from this analysis are presented in Appendix B and show that China's dominance in CCUS-related trade is primarily driven by electrical machinery and metal parts and structures. China's export shares in CCUS-related chemicals, mechanical machinery, and measuring, monitoring and verification (MMV) instruments have also been increasing, but remain below those of the US and Germany at present.

## The UK's revealed comparative advantage (RCA) in CCUS products compared with its key competitors

The following analysis focuses on a list of seven products that we define as our 'core' list, as these appear in all three sources from which we draw our list of CCUS-related products (see Appendix B). These products are listed below, along with their six-digit HS classification codes:

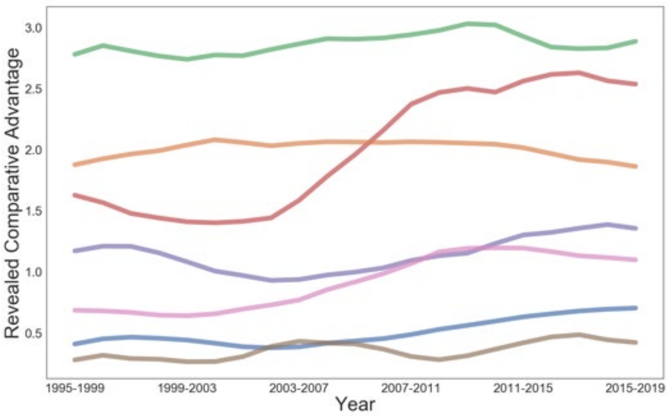
1. **HS902620:** Instruments and apparatus; for measuring or checking pressure
2. **HS902690:** Instruments and apparatus; parts and accessories for those measuring or checking the flow, level, pressure or other variables of liquids or gases (excluding those of heading no. 9014, 9015, 9028 or 9032)
3. **HS842139:** Machinery; for filtering or purifying gases, other than intake air filters for internal combustion engines
4. **HS842199:** Machinery; parts for filtering or purifying liquids or gases
5. **HS841480:** Pumps and compressors; for air, vacuum or gas, not elsewhere specified in heading no. 8414
6. **HS841490:** Pumps and compressors; parts, of air or vacuum pumps, air or other gas compressors and fans, ventilating or recycling hoods incorporating a fan
7. **HS901580:** Surveying equipment; articles not elsewhere specified in heading no. 9015, including hydrographic, oceanographic, hydrological, meteorological or geophysical instruments and appliances (excluding compasses).

**The product-level plots show trends in RCA, rather than shares in absolute trade volume (Figure 4.3).** This takes into account how much the country exports of a product in proportion to its overall exports, whereas shares in global trade (as above) do not consider the size of a country's overall economy or manufacturing sector.

**The UK's RCA is above 1 for all seven 'core' products, and many show a relatively constant trend over the years.** RCA has increased for a few products, in particular instruments and apparatus for measuring or checking pressure, while for some other products the UK has started falling behind, for instance in pumps and compressors parts.

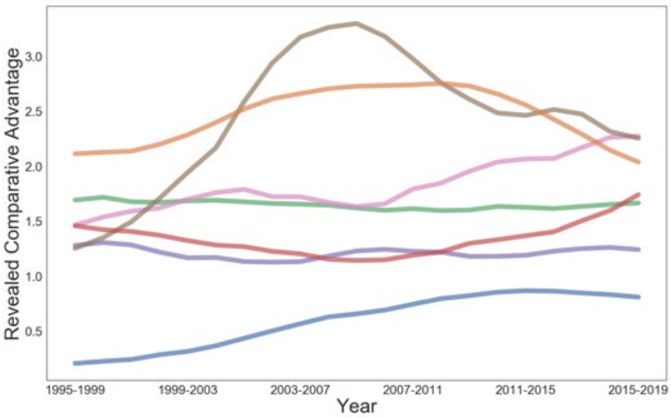
Figure 4.3. Trends in revealed comparative advantage (RCA) in CCUS-related core products, in the UK and six of its key competitors, 1995–99 to 2015–19


Instruments and apparatus for measuring or checking pressure (HS902620)




The UK increased its RCA in instruments and apparatus for measuring or checking pressure over the study period and overtook the US in terms of RCA around 2004–08. RCA stayed fairly static for Germany and the US. Japan and France also had a competitive advantage in this product during the period, unlike China and Norway, for whom RCA was below 1 throughout.

Instruments and apparatus; parts and accessories for those measuring or checking the flow, level, pressure, etc.[4] (HS902690)

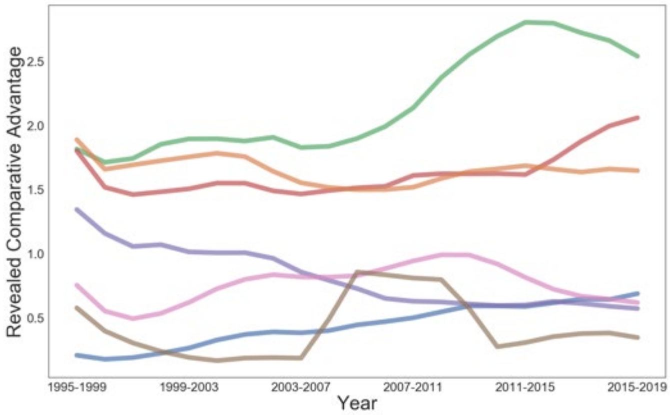



Norway had significant RCA in this product in the early 2000s, but its RCA has declined somewhat since its peak. However, this product category remains an important export for Norway, with RCA>2. The US's comparative advantage also declined since its peak around 2008–12, but remained high at the end of the period. Japan and the UK have increased their RCA in recent years, while Germany and France do export this product competitively, but without a clear trend in either direction. China does not yet have a competitive advantage but increased its RCA in the product over the study period.

[4] Or other variables of liquids or gases (excluding those of heading no.s 9014, 9015, 9028 and 9032).

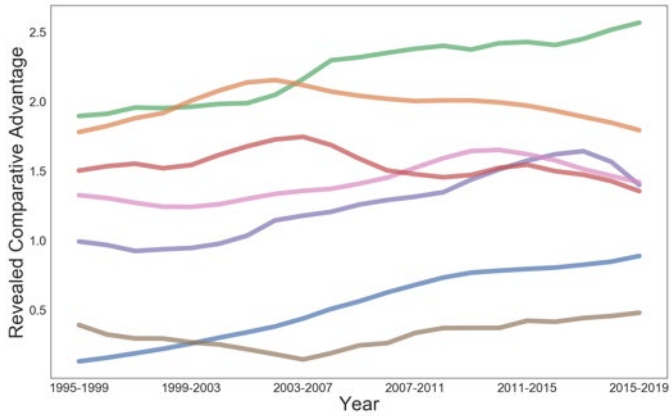
Figure 4.3. (cont.)


### Machinery; for filtering or purifying gases[5] (HS842139)



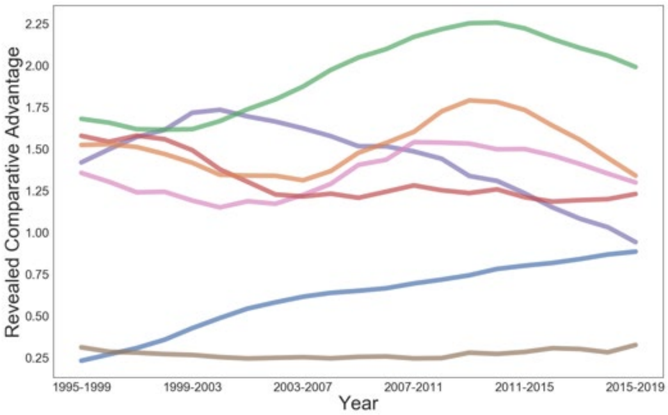

Machinery for filtering or purifying gases is a very important export for Germany, though its RCA dipped slightly in recent years compared with its peak in 2011–15. It also became increasingly important for the UK, over the study period, at the end of which it had an RCA of about 2 in the product. China's RCA has seen an increasing trend but remained below 1 in 2019, while the US maintained its RCA of slightly above 1.5 for most of the period.

### Machinery; parts for filtering or purifying liquids or gases (HS842199)



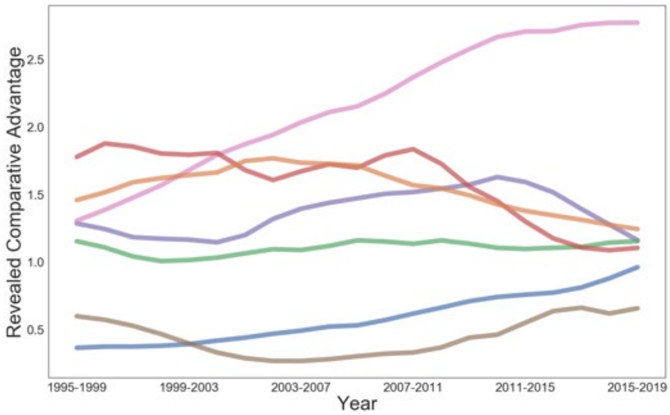

The UK had a competitive advantage in machinery – parts for filtering or purifying liquids or gases by 2019; however, its RCA started to decline from around 2003–07. The product was becoming an increasingly important export for Germany, which had an RCA of about 2.5 by 2019. China did not have a competitive advantage by the end of the period, but its RCA has been increasing monotonically.

### Pumps and compressors[6] (HS841480)




Germany, the US, Japan and the UK export pumps and compressors competitively, but RCA declined in Germany, the US and Japan over the period, while remaining fairly steady in the UK from about 2002–06. France's RCA declined from around 2000 and fell below 1 by the end of the period. China and Norway do not yet export this product competitively, but China's RCA has been steadily increasing.

### Pumps and compressors parts[7] (HS841490)




Japan significantly increased its RCA in this product over the study period. For the UK, revealed comparative advantage declined from around 2007–11, but was still above 1 in 2019, indicating that the UK was exporting more than its fair share of parts of pumps and compressors. China and Norway increased their RCA but were still below 1 for most of the period.

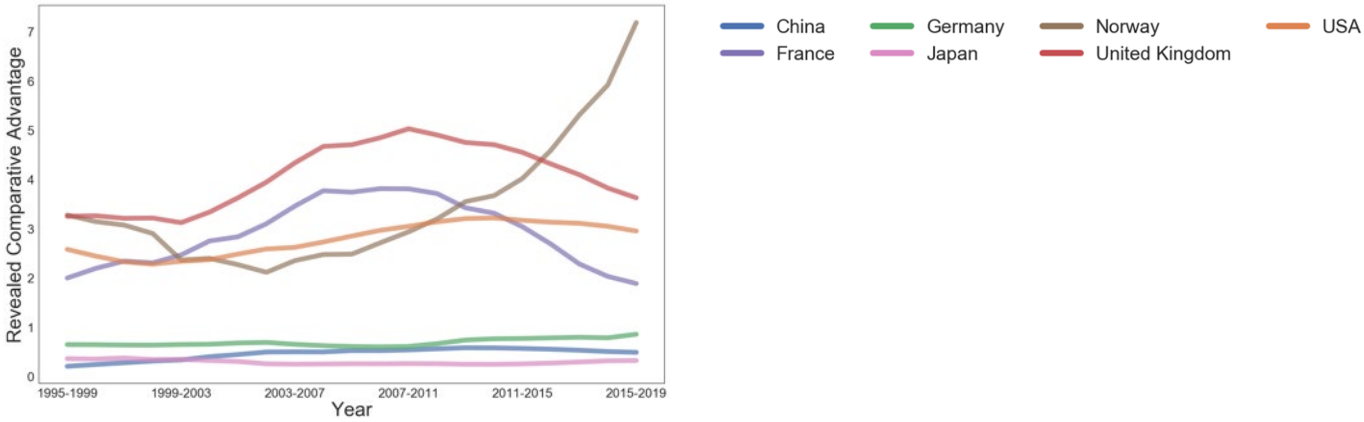
[5] Other than intake air filters for internal combustion engines.

[6] For air, vacuum or gas, not elsewhere specified in heading no. 8414.

[7] Of air or vacuum pumps, air or other gas compressors and fans, ventilating or recycling hoods incorporating a fan.

Figure 4.3. (cont.)

Surveying equipment[8] (HS901580)




Norway's RCA in surveying equipment increased drastically from about 2–3 to 7 over the period, suggesting that it is a highly significant export for Norway and its importance was still on the upward trajectory in 2019. The UK also had comparatively high RCA in this product, but there was a drop from about 5 in 2007–11 to below 4 in 2015–19. However, it remained a very important export at the end of the period. France's RCA also declined towards the end. Germany, Japan and China did not export surveying equipment competitively at any point during the period.

## Country-level strengths and opportunities

**Figure 4.4 below maps the UK's strengths and opportunities in CCUS-related products against their proximity to the UK's existing capabilities on the X axis, and their Product Complexity Index (PCI) on the Y axis.** These values are calculated based on average trade values for 2015–19, the most recent time period in our panel dataset. In the left-hand panel, we show some of the CCUS-related products in which the UK was competitive at the end of the period. In the right-hand panel, we show CCUS-related products that the UK does not competitively export at the moment but potentially could do in the future (such products can be considered to be potential opportunities for the UK).

**There is a mixture of strengths and opportunities, especially in mechanical machinery and MMV instruments.** MMV instruments[9] are relevant across $CO_2$ capture, transport and storage processes and have an inherent role for enabling commercial frameworks for CCUS, as treating $CO_2$ as a financial asset will only be possible through accurately tracking and measuring associated flows.

**There are very few products categorised as metal parts and structures or electrical machinery in which the UK has comparative advantage.** The plot highlights some specific products for illustrative purposes: high complexity strengths include, for example, product HS 902610 – Instruments and apparatus for measuring or checking the flow or level of liquids. High complexity opportunities include HS 903130 – profile projectors and HS 851410 – furnaces and ovens. These two products provide an example of a trade-off between product complexity and ease of transitioning: profile projectors are higher in PCI, but furnaces and ovens are more similar to the UK's existing capabilities, implying a higher probability of developing a competitive advantage in the future. Appendix B provides the RCA, PCI and country-to-product proximity measures for all 107 CCUS-related products underlying this analysis for the UK.

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8 Articles not elsewhere specified in heading no. 9015, including hydrographic, oceanographic, hydrological, meteorological or geophysical instruments and appliances (excluding compasses).

9 Examples include oceanographic surveying equipment; thermometers and hydrometers; instruments for measuring or checking the flow or level of gases/liquids; gas and liquid supply meters; hydraulic regulating and controlling instruments.

**There are a number of export opportunities that are both proximate to the UK's existing export capabilities and high in product complexity.** It is likely to be easier for the UK to develop competitiveness in these areas and they could also add more value to the UK economy in terms of technological upgrading and knowledge spillovers.

**Figure 4.4.** Existing strengths and potential opportunities in CCUS for the UK

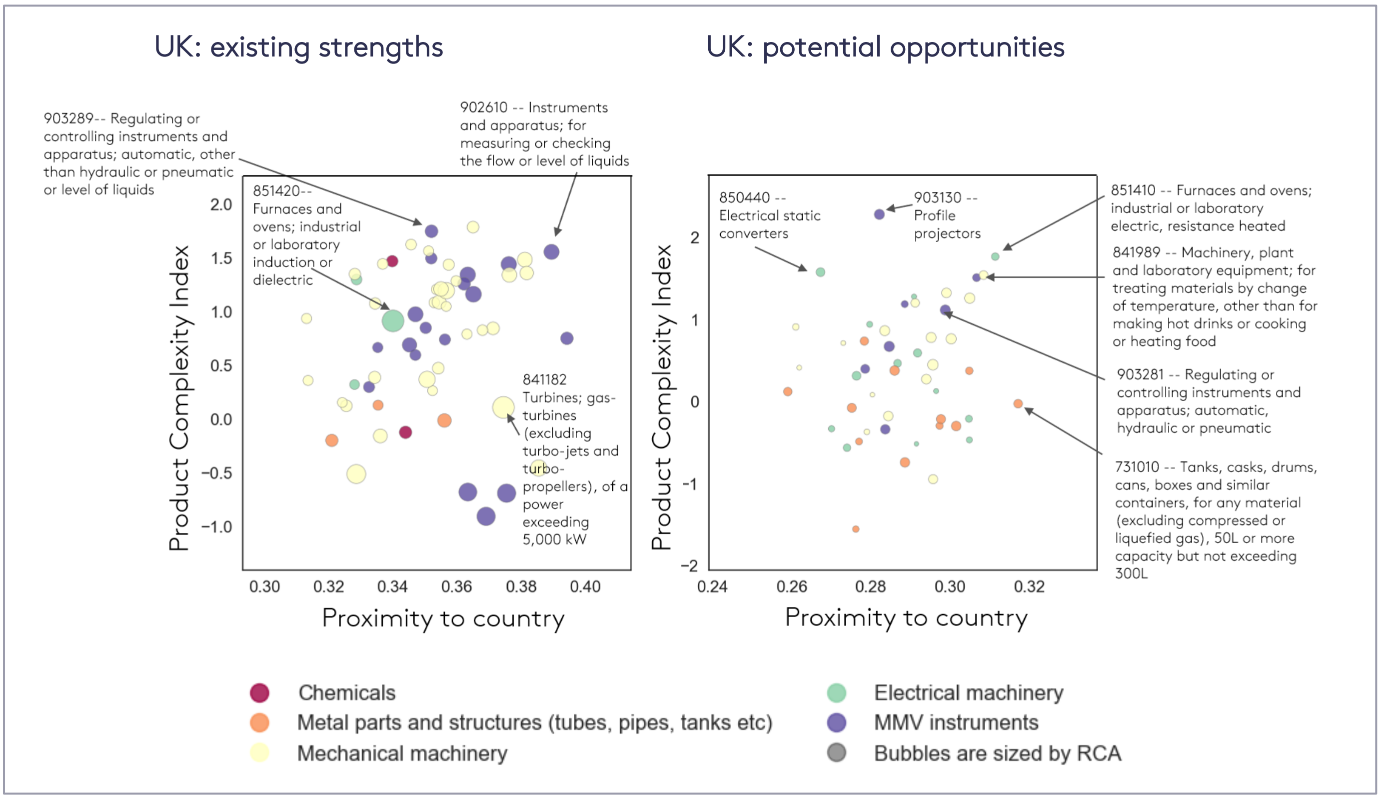
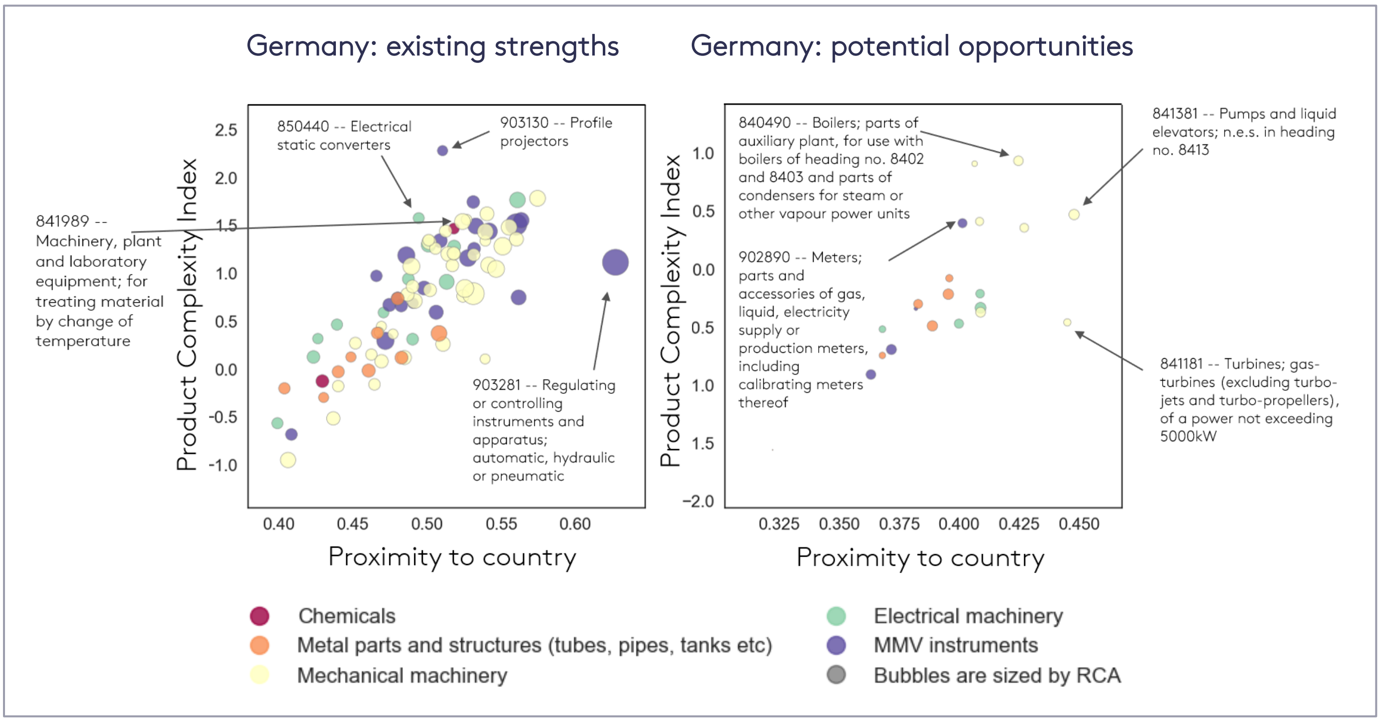



**Figure 4.5 shows the same plot but for Germany. It shows that compared with the UK, Germany is competitive in many more CCUS technologies**. Proximity, which indicates ease of developing future comparative advantage, for both strengths and opportunities is higher for Germany than for the UK. Moreover, the positive correlation between proximity and PCI is much clearer and more pronounced, which indicates that Germany's productive capabilities particularly lie in the production of very complex CCUS products.

Further insights could be provided by looking at this type of analysis in combination with evidence on the wider commercial, environmental and social context. For instance, the CCUS sub-theme of the Energy Innovation Needs Assessment highlighted Germany's strong manufacturing capability especially of large turbines, making it a key competitor to the UK in the trade of CCUS-related goods; however, it pointed to a different area of potential opportunity for the UK in exporting 'storage as a service', because public opposition to $CO_2$ storage might lead to a storage bottleneck in Germany (Vivid Economics, 2019b).

**Appendix B** visualises strengths and opportunities in the other countries included in the analysis. It shows that the UK's proximity to CCUS technologies is, on average, higher than Norway's and Japan's, but smaller than France's, Germany's, the US' and China's proximity. This suggests **the UK is at a slight disadvantage compared with some of its peers on seizing future CCUS opportunities.**

Figure 4.5. Existing strengths and new opportunities in CCUS for Germany




## Interpretation of results

**Measures of proximity and complexity are not intended to serve as deterministic policy advice.** Proximity is a useful indicator of countries' tendencies to develop comparative advantage in a product in the future. This does not necessarily imply that 'further away' products and sectors are not worth pursuing as part of an industrial strategy; however, doing so may take more time and policy effort, and involve a greater risk of failure. Exporting products that are more technologically sophisticated is associated with greater prosperity and growth, implying an additional trade-off between the ease of transitioning and developing competitive advantages in more complex products in those countries in which there is no positive correlation between proximity and complexity.

**Bringing this type of high-level insight into the UK's comparative advantages with firm-level understanding of strengths and hands-on industry experience would further inform decision-making.** For instance, CCSA (2021) identified an instance where the UK supply chain available to the engineering, procurement and construction (EPC) contractor was very weak for post-combustion $CO_2$ removal plant (fabricated vessels, exchangers and so on) and machinery (pumps, compressors, etc.).

**Policymakers will need to give consideration to factors that will affect the competitiveness of the UK CCUS supply chain beyond productive capability in itself.** Ability to scale is a critical factor in achieving cost reductions. Only with certainty around a consistent pipeline of projects will the industry have the incentive to invest in developing a supply chain at scale. Starting with a strong domestic market is important, given that countries tend to export goods for which they have significant domestic markets (Krugman, 1980). Scaling up the domestic market for CCUS is possible via interventions downstream, such as new standards and certification to drive demand for low-carbon industrial products (CCUS Cost Challenge Taskforce, 2018).

**In terms of the opportunity from global markets, free trade agreements can play a role to build demand for UK-sourced CCUS products and services,** as recognised in the BEIS supply chain roadmap for CCUS (BEIS, 2021f).

# 5. Analysing patent data to identify opportunities for the UK across the CCUS value chain

## Analysing patent data and its contribution to policymaking

In the previous section we considered trade data that reflect the UK's productive capability of and comparative advantage in existing CCUS-related products. Based on the products the UK already produces and trades, we saw the UK is at a slight disadvantage compared with some of its peers. **We now turn to a more forward-looking indicator of the UK's comparative advantage in CCUS: innovative capability.** While tracking innovation can give an indication of the areas in which the UK might enjoy future advantage, the extent of this will be contingent on how much of the production and trade activity related to a patent is retained within the UK supply chain.

**Investments in 'clean' innovation and its diffusion are key to shaping a strong and sustainable recovery from the COVID-19 crisis** (Martin et al., 2020; Stern and Valero, 2021). Where countries have relative strengths in particular technological areas, investments in related innovation are likely to create opportunities for growth in new or growing global markets, and associated gains in productivity and resource efficiency. We are already seeing evidence of increasing returns to scale in the discovery and production of clean technologies (Ekins and Zenghelis, 2021), for example via the dramatic declines observed in the costs of renewable energy, battery storage and electric vehicles.

**Nevertheless, a number of market failures and path dependencies in innovation systems justify coordinated policy action to move economies onto a clean growth path at the pace required** (Aghion et al., 2014; Stern and Valero, 2021). The existence of knowledge spillovers, whereby the innovator is unlikely to be able to capture all the financial returns from associated R&D investments, is a key justification for support for innovation in general. And empirical evidence suggests that knowledge spillovers in clean technologies (as measured using forward citations in patents related to energy production and transport) tend to be higher than those generated by their dirty counterparts (Dechezleprêtre et al., 2017). This suggests that there is an enhanced case for public support or incentives in such areas, even from a purely growth perspective.

**However, policy decisions regarding areas to support, and the form that such support should take, can be particularly challenging in areas such as CCUS, where technologies are at a relatively early stage.** According to the International Energy Agency's new net-zero emissions 'roadmap' to 2050, "almost half the [emissions] reductions come from technologies that are currently at the demonstration or prototype stage" (IEA, 2021b). In the case of CCUS, this share is 55 per cent.

**Tracking innovation activity can give an indication of the areas in which the UK might enjoy future advantage. In this section, we set out an analysis of CCUS-related patenting,** which sheds light on the UK's international comparative advantage in and potential economic returns from innovation in this area – and where innovation activity is occurring across the country. We also examine innovation in technologies that appear to be 'adjacent' to CCUS technologies to understand where sources of indirect comparative advantage relevant for CCUS innovation might lie.

## Trends and patterns in CCUS innovation

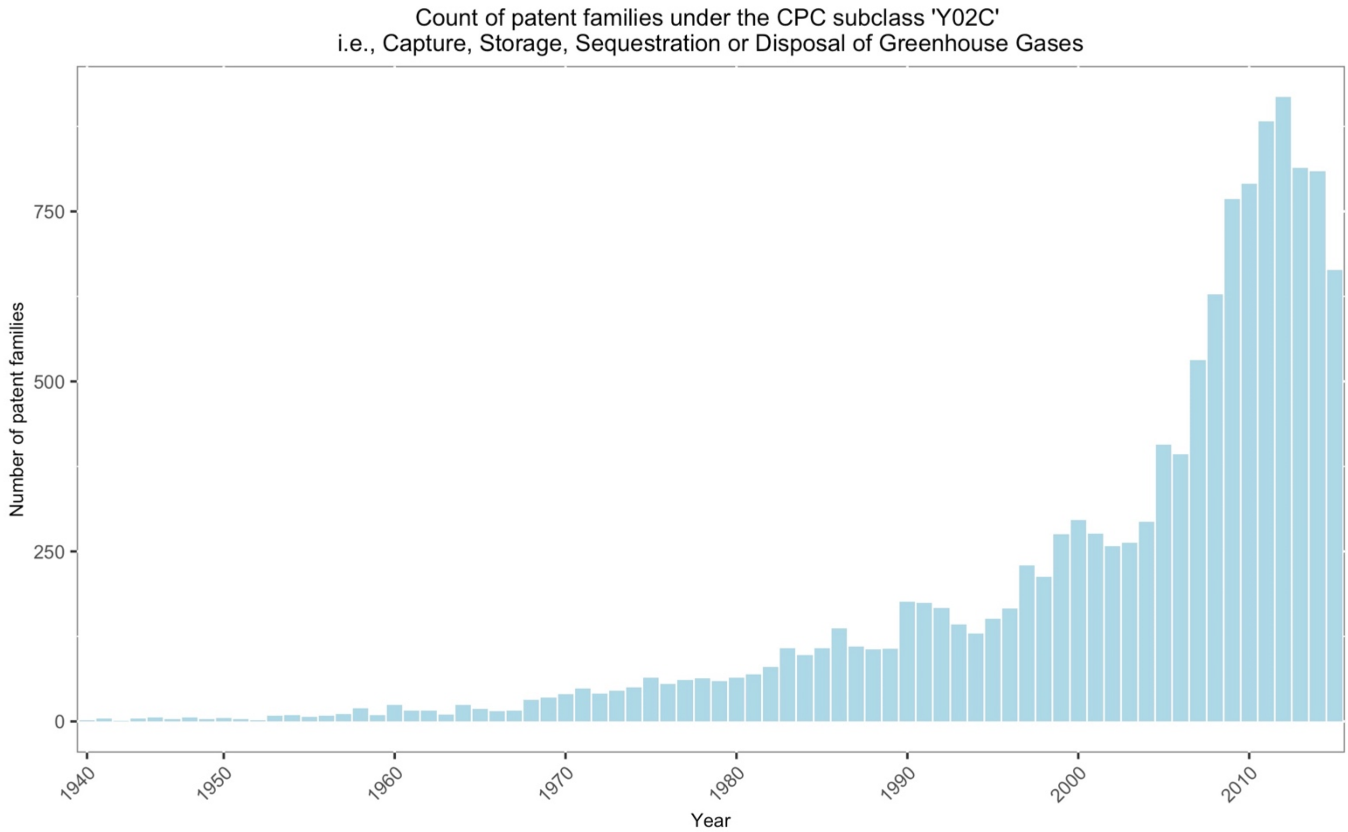
A body of empirical work has analysed 'clean' innovation using patents. While not all innovation is patented, the advantages of this approach include the fact that patent data is available across countries, over time and with detailed technology classifications that enable researchers to identify technologies that are relevant for climate change mitigation and adaptation. More specifically, **the Cooperative Patent Classification[10] system for categorising patents in different technology 'classes'**

[10] Patents are categorised under different classification systems by a patent authority according to the technical fields they pertain to. Cooperative Patent Classification (CPC) is one such system which includes an additional section for emerging cross-sectional technologies (including technologies related to climate change mitigation). The CPC classification system arranges subject matter into hierarchical arrays. The highest level is the Section, which can be divided into Classes. Each class is further divided into subclasses, which can be broken down into groups (main and sub-groups).

**includes a specific class ('Y02') related to climate change mitigation technologies.** Within this class, a subset of technologies relates to the Capture, Storage, Sequestration or Disposal of Greenhouse Gases ('Y02C'). This is the category (subclass) that represents what we refer to as being 'CCUS-related' and on which our analysis of CCUS innovation is based. Overall, we find that **there have been nearly 13,000 CCUS-related patents globally, representing less than 1 per cent of cumulative patents in clean technologies.**

**Figure 5.1 shows how global patenting in CCUS-related technologies has evolved over time.**[11] In common with clean technologies more generally, there is evidence of a decline in patenting in CCUS-related technologies after the global financial crisis (Popp et al., 2020).

**Figure 5.1.** The evolution of CCUS-related patenting over time (1940–2015)



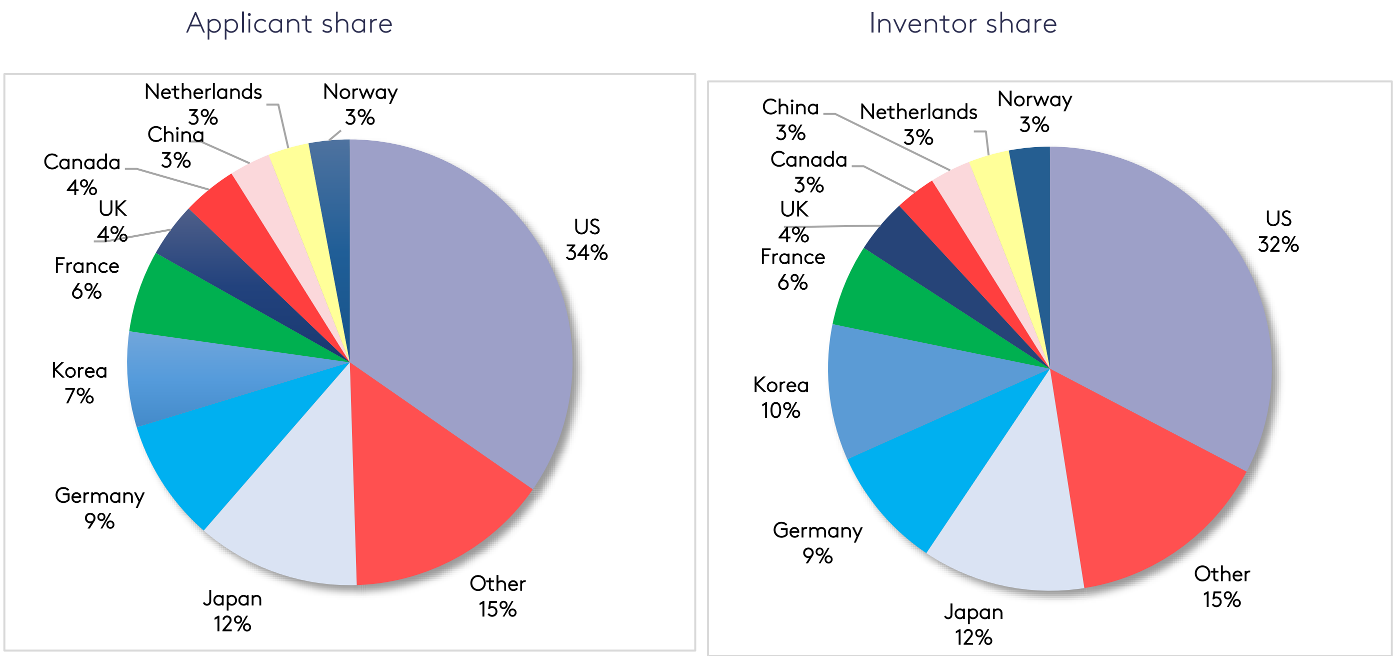

*Note: Count of patent 'families', by the earliest year that the earliest patent application was filed within each family, that have at least one classification under the Y02C subclass.*
*Source: Authors' estimates based on PATSTAT – 2018 Spring Edition.*

Focusing on the most recent period for which we have data, from 2000 to 2015, **Figure 5.2 below shows how CCUS-related patenting is distributed across countries. This is set out along two measures: one is based on the location of 'inventors'** – which can be thought of as the source of knowledge, and **the other is based on the source of 'applicants'** – which reflects the entity that made the patent application and hence is more likely to be the location where the invention is commercialised (in many cases these will coincide).

This analysis reveals that in absolute terms, the United States dominates with 35% of CCUS applicants, and the UK ranks sixth, with 4% of CCUS applicants. However, Norway, South Korea and the Netherlands stand out when we normalise by population (Figure 5.3).

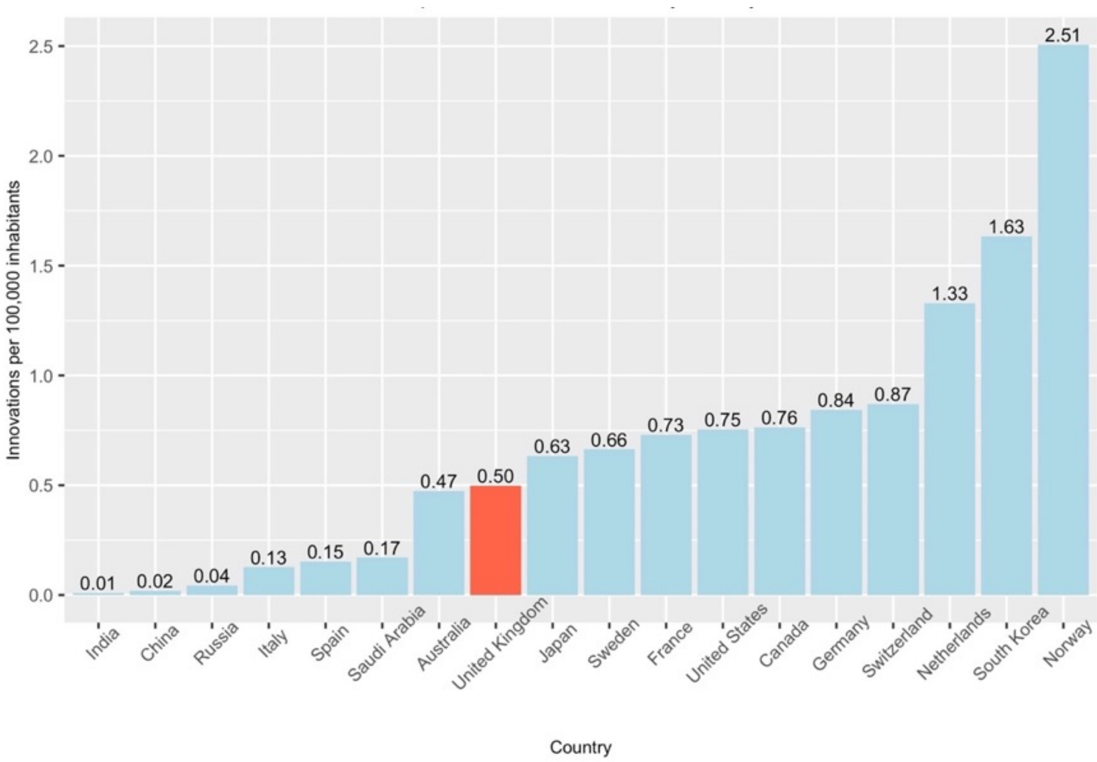
11 Although we rely on patent applications and application dates, these are only recorded in the public patent databases once the patent application has been fully processed, which can take several years, hence there is a time lag of three to four years. In the 2018 version of PATSTAT, which we are using, 2015 is the last usable year. See p43 for a discussion of the implications of the time lag in the patent data.

**Figure 5.2.** Share of applicants/inventors by country for CCUS-related patent families, 2000–15




*Note: Shares of applicants/inventors that have at least one patent classification under the Y02C subclass. Data are for 2000–15.*
*Source: Authors' estimates based on PATSTAT – 2018 Spring Edition.*

**Figure 5.3.** CCUS-related patents per 100,000 inhabitants by country, 2000–15




*Note: CCUS-related patent families (by country of inventor), normalised by population. Data are for 2000–15.*
*Source: Authors' estimates based on PATSTAT – 2018 Spring Edition. Population data are sourced from World Bank, Total Population for the year 2015.*

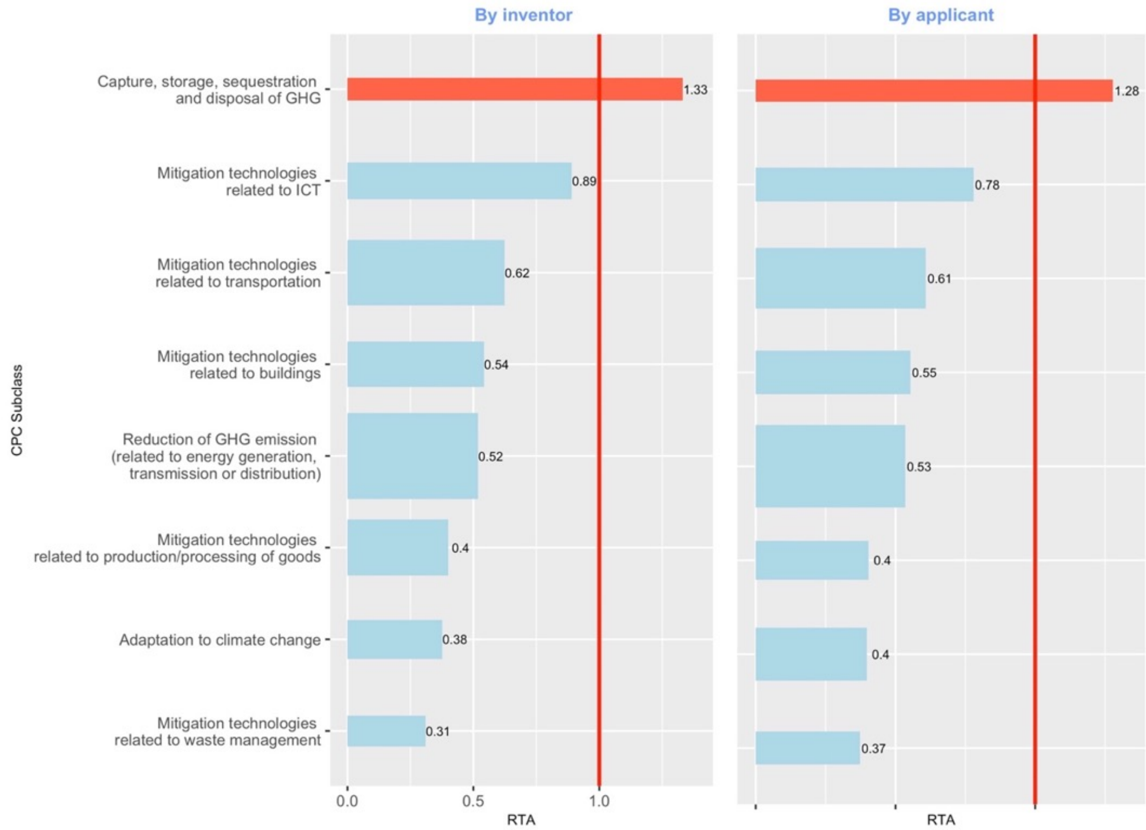
## Revealed technological advantage

We employ a concept related to revealed comparative advantage in trade data to patenting data. **A country's revealed technological advantage (RTA) is defined as the share of that country's patents in a particular technology field relative to the global share of patents in that field.** This gives an indication of the relative specialisation of a given country in different categories of technology.

- An RTA of 1 would indicate that the UK's share of innovations in the category is aligned with the global average.
- An RTA above 1 suggests that the UK specialises in that particular area.

The UK's RTA compared with the rest of the world in CCUS technologies over the period 2000 to 2015 is shown in Figure C1 in the Appendix.

Figure 5.4. Revealed technological advantage (RTA) of the UK in CCUS-related compared with other broad clean technology categories, 2000–15




The length of each bar on the horizontal axis shows the RTA; the width of each bar on the vertical axis reflects the number of patent families in each category.

*Notes: CPC = Cooperative Patent Classification. GHG = greenhouse gas. ICT = information and communication technologies.*
*Source: Authors' estimates based on PATSTAT – 2018 Spring Edition.*

**Interestingly, CCUS is the only broad category within 'clean' technologies where the UK does exhibit an overall RTA.** It is important to note that each of these categories contains many more detailed technologies and in previous reports we have highlighted a number of specific technologies for which the UK does have comparative strengths, including ocean and wind energy technologies within 'clean energy' (Martin et al., 2020) and connected and autonomous vehicle technologies within 'clean cars' (Unsworth, Valero et al., 2020). Figure C2 in the Appendix shows the RTA of the UK in CCUS-related sub-categories.

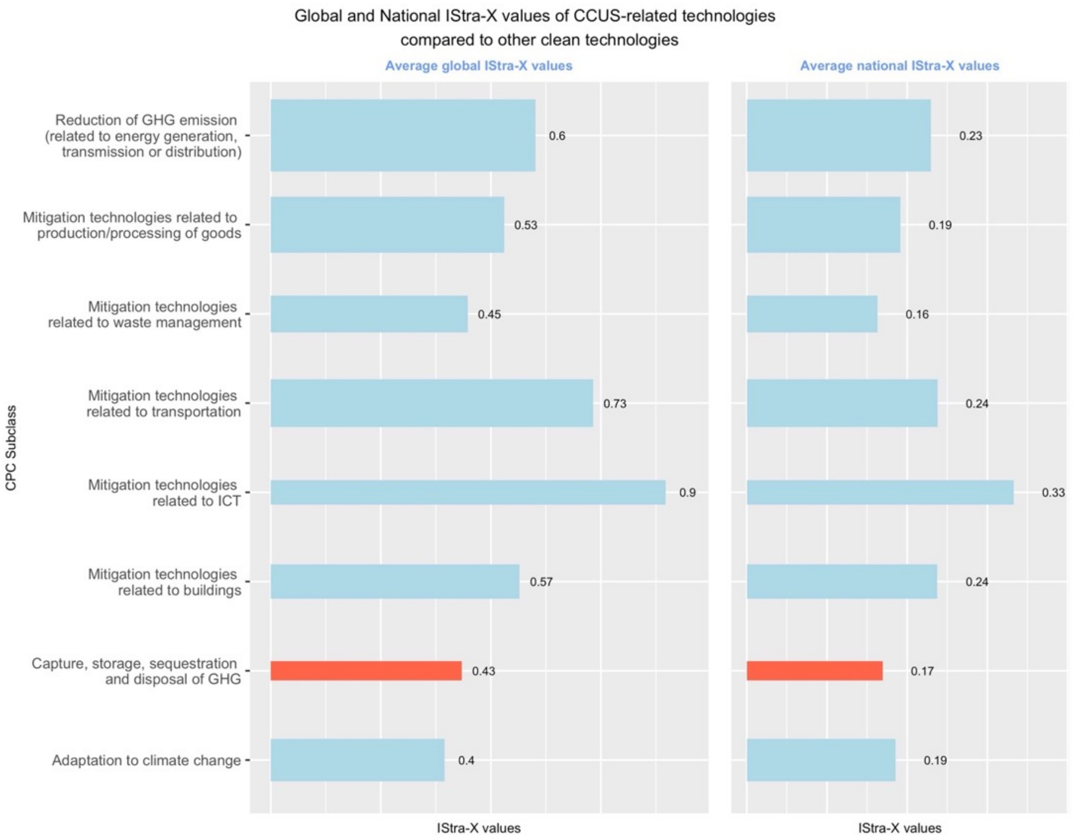
## Estimating the national economic returns to CCUS innovation

**The RTA gives an indication that the UK has to date been relatively specialised in CCUS-related technologies, but it does not give an indication of the economic value that can be generated in the UK by innovations in that field.** Nor does it take into account the variation in knowledge spillovers that different technologies generate, or variation in the ability of governments to promote further innovation in specific areas. **The 'IStra-X' industrial strategy index methodology provides a framework to take these issues into account.** Developed by Guillard et al. (2021), it allows for the computation of the national economic return on potential government R&D subsidies to different technology areas. This is based on a model of the innovation process, which is fitted to global data on patenting and valuations of companies undertaking innovation. It also takes account of the possibility that innovators in different areas might vary in their responsiveness to government R&D support.

It is important to note that the estimated economic return does not include the value of other important but hard to quantify externalities associated with favouring some technological fields over others, such as the widespread benefits of reducing global warming. Instead, this analysis can be informative for maximising the economic benefits of industrial policies for clean technologies or sectors. In other words, **the analysis helps to identify an industrial strategy that may result in a 'win-win' scenario of future growth and reducing carbon emissions.**

Earlier analyses have shown that spillovers from CCS, at both the global and national level, are higher than those from dirty or grey energy (Rydge et al., 2018). Here we provide up-to-date estimates that compare the economic returns to innovation in CCUS. **Figure 5.5 shows both the global and UK national returns from UK innovations across broad clean technology groupings, and highlights CCUS.**

Figure 5.5. Global and UK returns to public R&D investments across technologies, 2000–15




The length of each bar on the horizontal axis shows the IStra-X value*. The depth of each bar on the vertical axis reflects the number of patents in each category.

**IStra-X values reflect the difference between the expected increase in total value (private returns as well as external values from knowledge spillovers) generated by innovations in a field and the expected cost of the subsidy, scaled by the expected cost of the subsidy.*

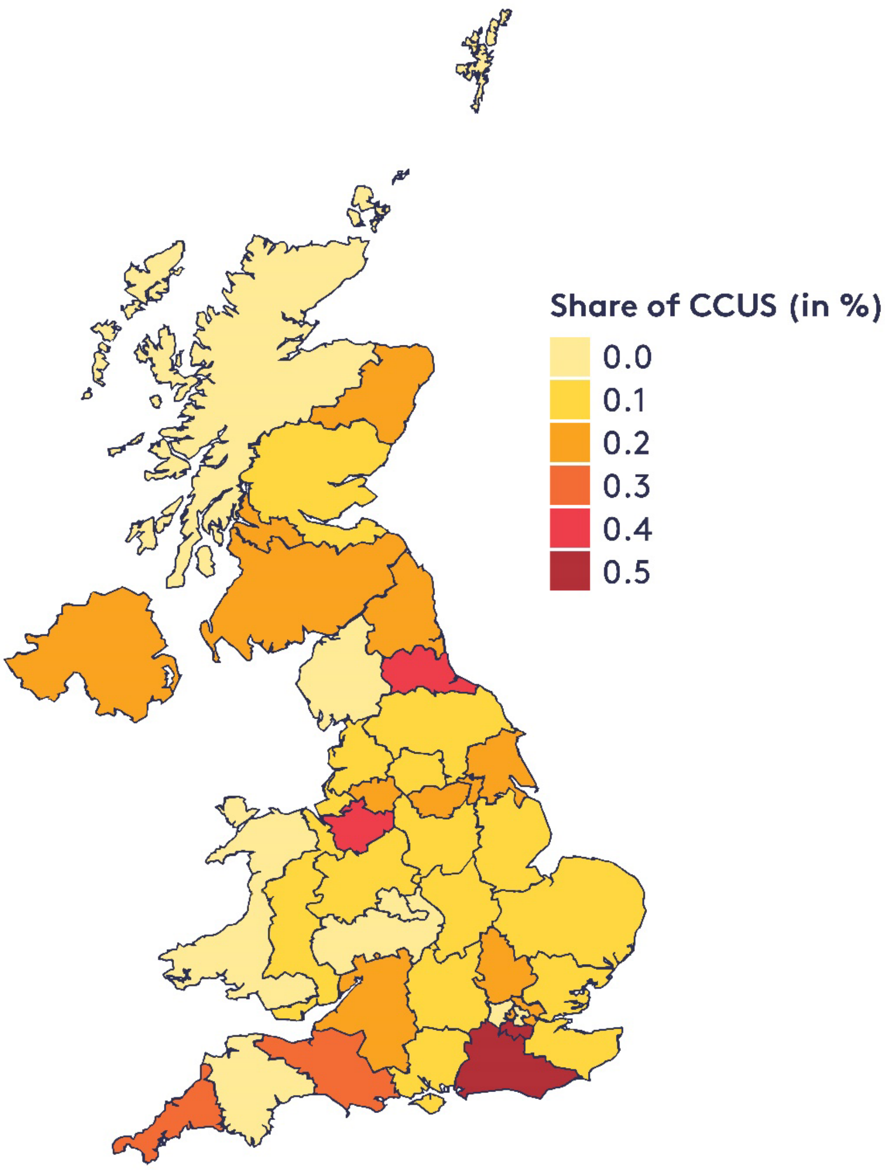
*Notes: The figure reports average returns to public R&D subsidies by technology area. The calculations account for direct and indirect knowledge spillovers occurring globally (left) and in the UK (right), variations in private R&D returns, variation in R&D costs and differences in the responsiveness to subsidies between different technology areas. This is based on the 'IStra-X' indicator (Guillard et al., 2021).*
*Source: Authors' estimates based on PATSTAT – 2018 Spring Edition.*

**The overall pattern shown in Figure 5.5 is similar globally and nationally, perhaps reflecting the fact that CCUS-related technologies are at an early stage,** and the returns are not as great as in other more established areas such as mitigation technologies relating to buildings or, in particular, mitigation technologies related to ICT. **Figure C3** in the Appendix disaggregates returns to public R&D investments for specific CCUS-related technologies and shows that at both the global and national levels, there is not much variation across the specific technologies in terms of economic returns.

**This is an emerging methodology, and there are other benefits and costs that may not be captured,** for example innovations that are not patented (particularly relevant in the service sector), or patents that are not perceived by the stock market to deliver value at the point of filing. Moreover, it may be that market valuations underlying our methodology are clearer in more distinct areas of innovation (e.g. pharmaceuticals) than in incremental advances in interrelated technologies for which the full market potential is not yet understood. Nonetheless, the methodology provides new insights into the possible global and UK returns across CCUS and other types of clean innovation.

### The geographical distribution of CCUS innovation

Figure 5.6. Share of CCUS innovation out of total innovation in the UK, 2000–15 (share of patents at NUTS2 level)




*Source: Authors' estimates based on PATSTAT – 2018 Spring Edition.*

Another key advantage in the analysis of patent data is the fact that patents contain information on the location of the innovators – both within and across countries.

The preceding analysis suggests that at the national level the UK has some relative strength in CCUS-related technologies, but in the context of uneven economic performance across the country it is important to understand where such strengths are located, and the extent to which different parts of the UK could be well positioned to act as R&D hubs for CCUS in the coming years. While CCUS has the potential to contribute to future growth and employment in the UK's industrial heartlands, the extent to which this is the case will depend on where new knowledge is generated, the structure of supply chains and the skills base.

**Figure 5.6 above plots the regional share of CCUS-related patents across NUTS2[12] regions of the UK.** The relatively high share in the South East of England relates to companies such as BOC Ltd. and BP Alternative Energy International as well as a number of individual inventors. Industrial areas in the North East and North West of England also appear to have a relatively high share of CCUS-related patents compared with other regions.

## Shedding light on transferable strengths in oil and gas

**The UK's existing oil and gas pipelines provide an infrastructure advantage to be leveraged in the roll-out of CCUS;** the industry also provides relevant skills. Given the UK's experience in the oil and gas, energy supply and process industries, a pre-existing supply of the relevant engineering skills should exist (TUC and CCSA, 2014).

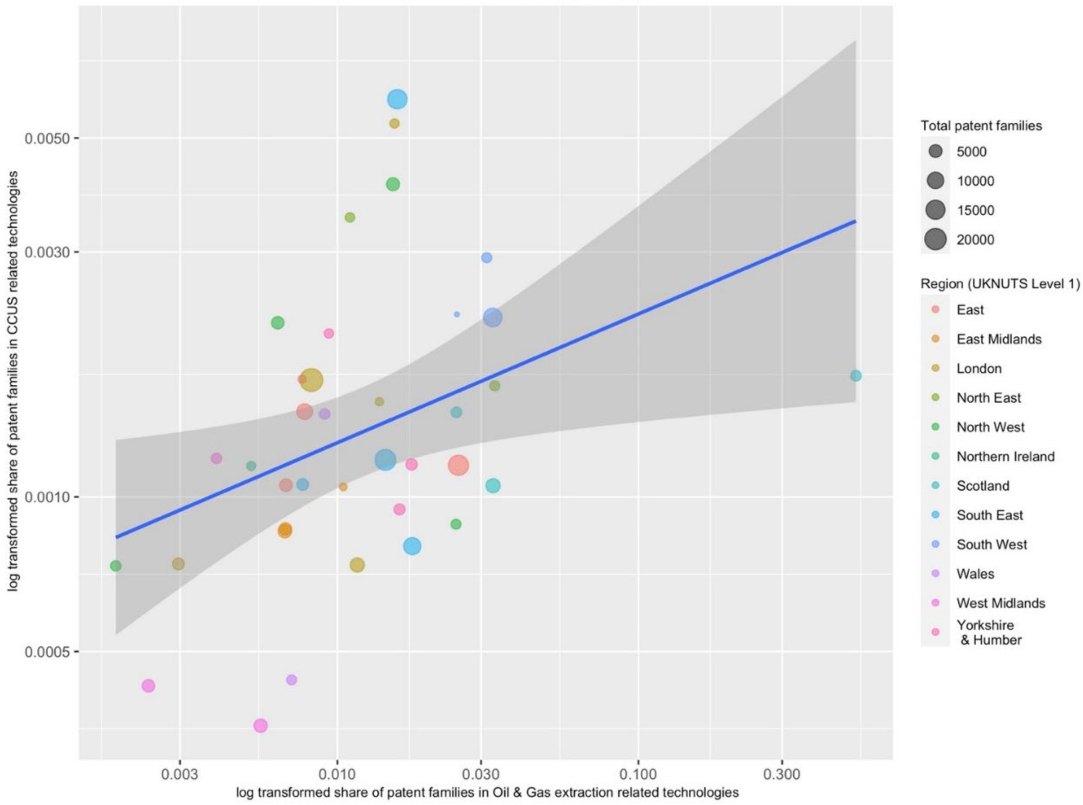
**There is some positive correlation between the location of CCUS innovation and areas that have traditionally patented intensively in oil and gas extraction technologies,** according to our analysis of patenting data (Figure 5.7, next page). This analysis suggests that places that have specialised in oil and gas extraction might be well-placed to benefit from the transition to CCUS. As yet, the pattern is uneven: regions such as North Eastern and Eastern Scotland have a large share of innovation in oil and gas extraction but quite a low share in CCUS-related technology, whereas inner London and parts of South East England including Surrey, East and West Sussex display a large share of patenting in oil and gas extraction as well as CCUS-related technologies.

**We have conducted similar analysis at the organisation level to understand if specific firms that patent in oil and gas technologies also appear to be more likely to innovate in CCUS** (illustrated in Appendix Figure C4). There are 5,571 applicants and 24,194 inventors that patent in either CCUS-related or oil and gas extraction technologies. Out of the 5,571 applicants, 4,983 applicants (89%) patent exclusively in oil and gas extraction technologies and 414 applicants (7%) patent exclusively in CCUS-related technologies. Only 174 applicants (3%) patent in both CCUS and oil and gas extraction.

There is less overlap at the inventor level than at the applicant level, which is to be expected since applicants are businesses or organisations that might have different R&D teams working on different areas. Out of a total of 24,194 inventors that patent in either CCUS-related or oil and gas extraction technologies, 23,014 inventors patent exclusively in oil and gas extraction and 990 inventors patent exclusively in CCUS-related technologies. Only 190 inventors patent in both CCUS and oil and gas extraction, equating to approximately 0.7% of total inventors that patent in either CCUS or oil and gas.

[12] "The NUTS classification (Nomenclature of territorial units for statistics) is a hierarchical system for dividing up the economic territory of the EU and the UK"; NUTS 2 regions are "basic regions for the application of regional policies" (Eurostat).

**Figure 5.7.** CCUS innovation versus oil and gas innovation in the UK, 2000–15




*Notes: The chart plots the log transformed share of CCUS-related patent families to all patent families against the log transformed share of patent families in oil and gas extraction technologies to all patent families, at the NUTS2 level. A simple linear regression returns a coefficient of 0.25 with a standard error of 0.10 at $p < 0.05$.*[13]
*Colour coding in the legend groups the NUTS2 level regions into NUTS1 regions.*
*Source: Authors' estimates based on PATSTAT – 2018 Spring Edition.*

## Future opportunities for CCUS innovation from adjacent technologies

Building further on the analysis above, we explore other technology areas in which patenting activities co-occur with those in CCUS-related technologies. We observe that out of approximately 13,000 patent families classified under the subclass related to CCUS i.e., *Y02C*, around 60% (approx. 7,700) are also classified under the CPC subclass *B01D*, which pertains to 'physical or chemical processes of separation'. Approximately 7% of CCUS-related patent families are also classified under the subclass *F25J*, which pertains to '*liquefaction, solidification or separation of gases by pressure and cold treatment*' (see Figure C5 in the Appendix).

The first of these (B01D) is a large technology subclass including over 280,000 patents, and the overlap with CCUS is small (only 3% of B01D patents are also CCUS). In contrast, the second class (F25J) is much smaller, with around 11,000 patents, and a larger share (8%) being classified also as CCUS (see Figure C6 in the Appendix[14]).

This is a preliminary step to identify opportunities for innovation offered by technology areas that are relevant for CCUS-related technologies. Competencies and resources employed within such 'CCUS-adjacent' technologies could be utilised to pursue CCUS-related targets not only in innovation but also in industrial applications.

We also calculate the RTA for the CCUS-adjacent technologies (i.e., top 20 CPC subclasses based on the frequency of co-occurrence with the CCUS-related subclass – Y02C). Figure C7 in the Appendix shows the RTA in CCUS-adjacent technologies for countries with the highest RTA in CCUS-related

[13] A 1% increase in share of oil and gas patents is associated with a 0.25 % increase in CCUS-related patents.
[14] The Appendix also provides further details on the CPC subclasses mentioned in Figures C5 and C6.

technologies. Comparing Figures C1 and C7 demonstrates that the UK performs relatively better in CCUS-adjacent technologies than it does in directly CCUS-related technologies. While the UK has the eighth highest RTA in the world in CCUS-related technologies as both applicant and inventor, it ranks fourth as inventor and fifth as applicant (within a list of 15 countries with the highest RTA in CCUS-related technologies) when it comes to innovation in CCUS-adjacent technologies. This suggests that the UK could further capitalise on its strengths in these CCUS-adjacent technologies to improve its position as a global leader in CCUS innovation.

## Interpretation of results

**The UK accounts for just 4% of global CCUS patenting over the period 2000–15 but demonstrates a comparative advantage in this area**, we find – an advantage that also exceeds other broad categories of 'clean' innovation (though as we note, previous analyses have shown that the UK exhibits strong comparative advantage in specific technologies within these broader categories, including wind and ocean energy). Looking at patenting at a regional level, we find a relatively high share of innovators especially in the South East of England, and a positive correlation between patenting in CCUS and patenting in oil and gas. Regional dimensions and transferability of R&D capability require further attention to understand the role of support for CCUS in the broader 'levelling up' agenda.

Technological breakthroughs can achieve significant cost reductions (for example, see the novel power cycle developed by Net Power, 2021) and may change the shape of supply chains (CCSA, 2021). The most useful point at which to capture supply chain value from a new technology is at its first commercial demonstration which, if successful, would undoubtedly boost the supply chain's export potential (ibid.). Historically, the policy framework for CCUS in the UK has not been conducive to maximise the opportunity from R&D in CCUS, given the damage to supply chain confidence from the two CCUS competitions cancelled due to concerns around technology costs (see Section 6). With recognition that deployment itself at scale is the main driver of cost reduction, **the focus of early CCUS deployment has changed from being on a few large end-to-end applications to industrial clusters consisting of many large and small emitters of varying needs.** This has fundamentally changed the opportunity for CCUS innovation, as one patent can benefit, and be monetised in, many different applications across the UK rather than acting as a bespoke solution for one or two large projects.

*Considering the time lag in the patent data*

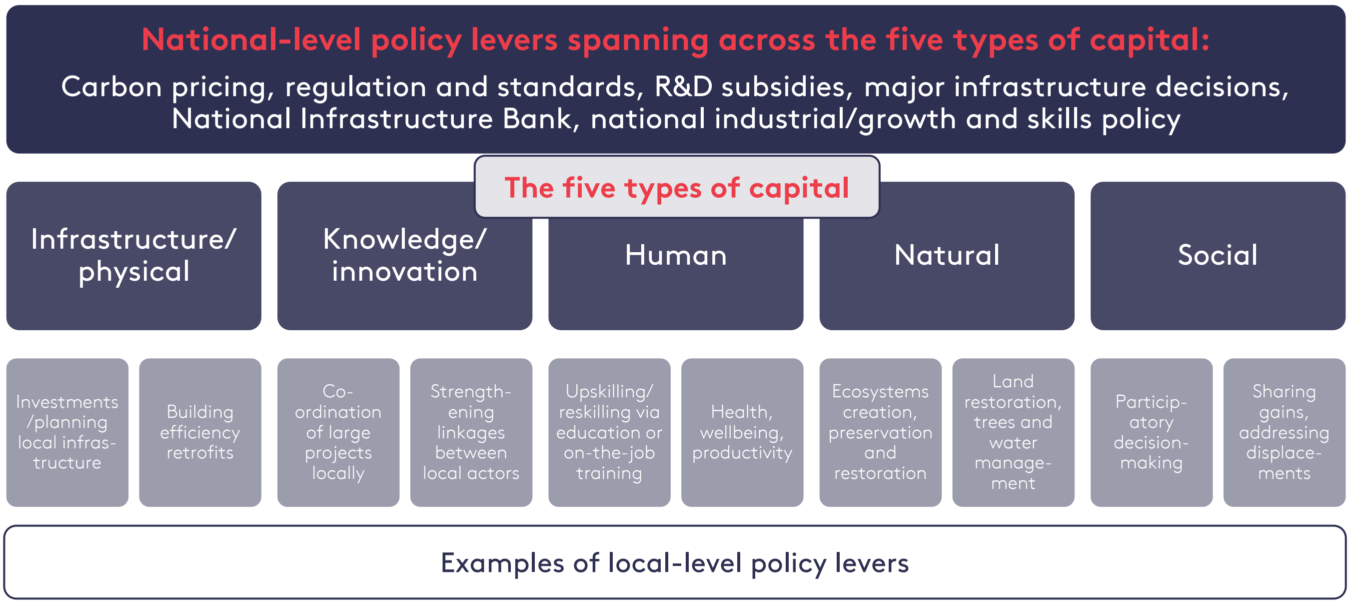
A crucial consideration when interpreting the findings we have described in this section is the lag inherent to the data we rely on. The patent data underpinning this section is for the period 2000–15. However, the UK has seen a significant step change in the CCUS landscape since the net-zero target was signed into law in 2019, accelerated further by the Government's messaging, starting from the *Ten Point Plan for a Green Industrial Revolution* in November 2020, that CCUS will be a central pillar of the economic recovery from COVID-19. This, combined with the tangible CCUS opportunity emerging from the cluster decarbonisation agenda, has translated into significant interest from project developers and supply chain companies in the UK to develop capacity and innovate in CCUS. While it is important to understand the technological foundation that is the UK's starting point, the analysis in this section does not capture the latest context from the last 18–24 months; rather, it reflects a period characterised by the UK's former 2050 target of an 80% emissions reduction on 1990 levels and the run-up to the cancellation of the £1bn CCUS competition in 2015.

# 6. Barriers to driving sustainable growth from CCUS in the UK

## Assessing the barriers inhibiting CCUS growth and their policy implications

In this section we summarise the barriers inhibiting CCUS growth in the UK across five interrelated types of capital set out in a framework developed by Stern et al. (2020): infrastructure/physical capital, knowledge capital/innovation, human, natural and social capital – see Figure 6.1. Our assessment of the barriers is informed by the literature and a stakeholder roundtable held during the development of this report, and it feeds into our policy recommendations presented in the next section.

Figure 6.1. Five types of capital needed for sustainable and inclusive growth, with examples of general policy levers at national and local levels




While we frame our discussion in this section under *barriers* inhibiting CCUS growth, the barriers need to be thought of in conjunction with risks, given the interdependencies between them. **Crucially, policy risk operates across the five types of capital when it comes to a major infrastructure programme like CCUS development.** Policy risk occurs when unexpected changes to government regulations and policies change the investment environment (Micale et al., 2013). This has been the primary reason for the stalled progress in CCUS development in the UK to date. According to investigations by the National Audit Office, cancellations of both CCUS competitions in the UK were linked to a lack of early cross-departmental coordination, which led to budgetary disagreements later (BEIS Committee, 2019). This shows how failure to successfully implement a policy lever intended to address a barrier to investment can have long-term, difficult-to-reverse impacts on investor confidence, in turn creating a barrier in itself to investment.

## Barriers around the five types of capital needed for sustainable and inclusive growth

*Infrastructure and physical capital*

**Capital investment requirements for CCUS are high, but there is currently no meaningful economic value attached to emissions reductions to drive these investments in the UK.** While the UK Emissions Trading Scheme (ETS) imposes a market price on carbon, this alone is currently insufficient to justify investment in CCUS. Carbon allowances in the UK ETS started trading high, at £50 per tonne of $CO_2$ (Sheppard and Hodgson, 2021), but the levelised cost of even just the capture of $CO_2$ (excluding transport and storage) likely exceeds this for some of the most essential CCUS applications, including in power generation, cement, and iron and steel (IEA, 2021a).

**The lack of economic incentive for investment is especially true for CCUS applications in the industrial sector, where there is no apparent revenue stream.** In contrast, BECCS for power can tap into revenues from the sale of low-carbon electricity, although even that on its own would hardly create the appetite to develop transport and storage infrastructure. Furthermore, many manufacturing industries are exposed to international trade, meaning CCUS costs cannot be passed onto consumers easily, given competitiveness impacts, unless a carbon border adjustment is implemented (see Section 7) (Bassi et al., 2015). Direct public funding to overcome high upfront costs, such as through the CCUS Infrastructure Fund, is therefore crucial to enable initial projects, but private investment is required for continued growth once the technology reaches commercial maturity (Carey, 2020).

**The absence of CCUS business models proven by experience in the UK adds to the investment finance challenge.** Although the business models proposed by the Department for Business, Energy & Industrial Strategy (BEIS) are being designed with close industry consultation, no bankable commercial structure or risk allocation has yet been agreed for any commercial-scale CCUS project in the UK (CCUS Cost Challenge Taskforce, 2018). The business models have also yet to be backed by a long-term funding framework like the Levy Framework, which provided both funding visibility and consumer protection for renewables a decade ago (AFRY, 2021). In the absence of confidence in funding being available in the long term to match the current deployment targets, there will be limited incentive to invest in the CCUS industry and supply chain (ibid.). There are also UK-specific uncertainties and challenges that will inevitably impact the investment environment for CCUS, including the shape of the economic recovery from COVID-19, change due to Brexit, and challenges due to regional disparities in productivity and skills.

**Arguably, a more complex question surrounds the attachment of economic value to DACCS and greenhouse gas removals more widely.** It is uncertain that the UK ETS is a suitable framework for doing this, since unlike CCUS applications for emissions reduction, which allow payments under an ETS to be avoided, emissions removals do not operate against a counterfactual emissions cost. Engineered removals are likely to cost between £100 and £400 per tonne of $CO_2$ removed, and therefore are currently much more expensive than most other ways to decarbonise (NIC, 2021).

*Knowledge capital and innovation*

CCUS technologies are not new but their application explicitly for emissions reduction is at an early developmental stage. **The limited deployment of CCUS in the UK and globally means many of the associated supply chains do not yet exist and the UK is starting on the backfoot** compared with some of its peers when it comes to exporting CCUS-related products. Until 2020, the Government's stated ambition to deploy CCUS was preconditioned on "costs coming down sufficiently", which came under fire from CCUS stakeholders for a lack of specificity (BEIS Select Committee, 2019), in turn creating uncertainty for investors. The lack of specificity has undermined not only domestic deployment but also the private sector's confidence to invest in technology and capability that could have given UK supply chains a competitive edge early on.

**Given that the commercial certainty to incentivise industry to invest in CCUS supply chain capacity is still limited, there is a risk that the UK could miss the limited window to establish comparative advantage and capture export opportunities.** There are examples of this from other sectors. For instance, despite being a world leader in installed offshore wind capacity (GWEC, 2020), the UK largely missed the opportunity during early deployment to develop substantial domestic intellectual property, technology and capability, meaning supply chain benefits have been largely retained within the non-UK businesses that have led the process (Whitmarsh et al., 2019).

Our analysis has shown that the UK's innovative performance in CCUS is uneven across the country, implying that there might be regional disparities in the way future economic returns from new supply chain opportunities are distributed. Some areas, such as North Eastern and Eastern Scotland, that innovate extensively in oil and gas but not yet in CCUS might be missing a particular opportunity since capabilities in oil and gas, in theory, are highly transferable into CCUS. The UK's comparative advantage will also depend on the potential scope for technological breakthroughs, for instance on

$CO_2$ capture rates. However, the path and cost to commercialisation for these innovations are highly uncertain, especially where targeted R&D is insufficient or absent. The case for innovation support for CCUS is strong but due to the immaturity of the sector there might be a concern that the returns from investment in R&D could be lost to other countries if the supply chains and skills are not in place to retain economic value.

**Another challenge is around the path dependencies that characterise innovation systems.** CCUS, hydrogen and greenhouse gas removal technologies cannot be thought of separately from each other as they share technological and infrastructure-related synergies that open up opportunities for co-location, as well as knowledge, skills and capability transfer. The substantial uncertainties that surround these technologies individually and in combination make it difficult to account for the path dependencies in policies and investment decisions made today, implying a risk that the eventual outcome may be sub-optimal.

*Human capital*

**In the absence of proactive thinking and policies, the UK may face shortages in the skills required to develop CCUS.** Element Energy (2020) evaluates that carbon capture technologies deployed in industry or for power generation use processes similar to those in the chemical industry, while the transport and storage of the carbon resemble typical oil and gas installations. It suggests, therefore, that the overall disruption to the current workforce within the engineering construction industry will not be major, but highlights potential upskilling requirements on the operational side as well as training needs on the specifics of CCUS for technical workers. Even where skills are abundant, for instance in commercial and financial services, the strategic planning to channel the required workforce into CCUS needs to happen now. In a survey of UK energy professionals, for whom CCUS was among the most cited destinations for those expecting to move to another field within the energy industry as a result of net-zero, half of the respondents cited barriers to their personal development, including the lack of appropriate training courses available (Energy Institute, 2021).

Although many analyses have focused on quantifying job creation from CCUS (see Section 3), evidence is limited on the skills that will need to underpin these jobs (Green Jobs Taskforce, 2021). Neither the extent of transferability from existing sectors nor the 'place' dimensions of matching the demand for CCUS skills with the supply are fully understood. Furthermore, **while CCUS is recognised as a potential enabler of just workforce transitions for workers in industries subject to decline as part of the net-zero transition, there are limited processes in place for managing these transitions in a just way.** This transition management needs to include the workers in decisions about their own future while making the necessary re- and upskilling opportunities available.

*Natural capital*

Given the absence of commercial applications in the UK, CCUS and especially large-scale storage of $CO_2$ underground raises new issues of liability and risk. The potential risk of large losses, especially in the case of accident and/or $CO_2$ leakage, not only raises the cost of capital but can also deter investment altogether (Bassi et al., 2015). Ultimately, neither insurers nor storage operators will be able to bear unlimited liabilities and some form of government guarantee will be required where risks are essentially uninsurable (ibid.).

There is a high level of path dependence and interaction between the development and deployment of the various net-zero technologies but limited evidence to suggest the required amount of joined-up thinking exists in the current policy landscape (see also Section 7). For example, BEIS is leading work on business models for CCUS, hydrogen and GGR, but for the most part is looking at each of these separately, with different teams working to their own timelines. **This may undermine the ultimate ability of policies to minimise disruption to natural ecosystems while leading the economy to decarbonise.**

**Despite its net climate benefits, CCUS requires large amounts of energy and in poorly designed systems may lead to depletion of natural resources and other negative environmental impacts** (Singh et al., 2012). For instance, incorrect handling of chemicals used in the capture process could lead to soil and water pollution, and the large amounts of water required to grow biomass for BECCS could place stress on the surrounding environment. Failure to consider impacts of applications over the relevant lifecycle, including potential perverse indirect effects, may also undermine the climate benefit of CCUS in the first place (NIC, 2021). For example, if not carefully managed, land-use change resulting from BECCS could lead to a net increase in atmospheric $CO_2$ (Hepburn et al., 2019). Blue hydrogen presents an especially complex challenge from a lifecycle perspective as its climate benefit relative to alternatives like electrification or green hydrogen may be highly dependent on the local context and on emissions upstream (e.g. fugitive methane) as well as downstream (Howarth and Jacobson, 2021).

*Social capital*

Social acceptability is a challenge that is easily underestimated but must be addressed, especially for the success of technologies like CCUS which involve construction of large-scale infrastructure that might face local opposition. For instance, opposition from the public and the media against carbon storage, in some cases igniting voter protests, has impacted the pace of CCUS development in Germany (Wettengel, 2020).

**In the UK, a comprehensive programme to establish awareness and social acceptability of CCUS in the wider population is currently lacking.** In March 2021, almost 70% of the UK public either had never heard of CCUS, or did not really know what it was, despite being aware of it (BEIS, 2021a). CCUS is also often viewed as a fossil fuel technology that competes with renewable energy for public and private investment (IEA, 2020). This implies a gap in effective communication since in reality, investments in CCUS and renewable energy can be mutually reinforcing rather than competing. Another likely reason for opposition is the perceived risk of accidental leakage from storage sites.

**There has been important progress in gathering an in-depth understanding of the public's attitude towards CCUS, however**. Wickett-Whyte et al. (2021) recently led a public dialogue on CCUS, from which key insights included: support for CCUS is conditional, above all, on safety; there is more support for the idea of CCUS being deployed nationally than locally; and cost is a major concern, with participants wanting CCUS costs to be weighed against the emissions reduction it can deliver (ibid.). Such insights into people's attitudes on CCUS and their underlying reasoning now need to be translated into a well-planned programme to ensure social acceptability. Climate Assembly UK (2020) also recently covered CCUS for power, GGR and hydrogen in a wider discussion with members of the public on climate action.

Lack of timely investment in social capital around CCUS would pose a threat to the long-term sustainability of the CCUS workforce if the sector fails to establish itself as an attractive place in which to work for future generations. It would also undermine the Government's ability to absorb any social tensions that might arise if policy support for CCUS leads to an increase to the cost to consumers.

# 7. Policy recommendations for driving sustainable growth from CCUS in the UK

## Analysis of the current policy landscape around CCUS

The UK has seen a range of policy frameworks relating to CCUS developed or redesigned in recent years and the number of announcements has increased rapidly since CCUS was made a centrepiece of the COVID-19 recovery package (HM Government, 2020a). While the *Ten Point Plan for a Green Industrial Revolution*, *Energy White Paper* and *Industrial Decarbonisation Strategy* position CCUS as a strategic priority within the wider government agenda for meeting net-zero and levelling up across the UK, BEIS has also produced several CCUS-specific publications designed to lead industry in concrete terms in this overall direction, such as those under the Business Models and Cluster Sequencing programmes.

The case for direct support for early projects and the need to coordinate and underwrite the development of industrial hubs with shared $CO_2$ infrastructure has been made strongly by the International Energy Agency (2020). By focusing early efforts on the deployment of CCUS in major industrial clusters, the UK is well-positioned to unlock economies of scale and to transfer lessons learned across clusters developed in parallel and into the future.

**In Table 7.1 below, we summarise some of the key policy frameworks relating to CCUS, with an indicative assessment of their potential to address the barriers inhibiting CCUS growth identified in the previous section under each type of capital needed for sustainable and inclusive growth.** This is an attempt to assess the potential of each policy framework within its own remit, rather than against each other, given their different scopes and objectives. We look at direct and explicit links articulated between the policy frameworks and each type of capital, and use our own judgment to qualitatively assess the potential of that link to address the related barriers. We assess the potential of a policy framework separately for each type of capital but recognise that the effects are in fact highly interrelated.

**Our indicative assessment shows that while significant policy progress has been made to address barriers relating to infrastructure and physical capital as well as knowledge capital and innovation, measures to address barriers relating to human, natural and social capital are lagging behind.**

Table 7.1. Summary of key CCUS-related policy frameworks recently announced in the UK

*I/PC = infrastructure/physical capital; KC&I = knowledge capital and innovation; HC = human capital; NC = natural capital; SC = social capital

| | | | Potential to address barriers relating to types of capital* | | | | |
|---|---|---|---|---|---|---|---|
| **Policy framework** | **Description** | **Type of incentive** | **I/PC** | **KC&I** | **HC** | **NC** | **SC** |
| Industrial Decarbonisation Challenge (IDC) | £170m (from 2019–2024, funded initially from the Industrial Strategy Challenge Fund) delivered by UK Research and Innovation (UKRI) to support three workstreams: rollout of the decarbonisation of industrial clusters, development of industrial cluster decarbonisation roadmaps and the Industrial Decarbonisation Research and Innovation Centre (IDRIC) | Demonstration funding | Amber = strong potential | | Red = weak potential | | |
| Net Zero Innovation Portfolio, including CCUS Innovation competition 2.0 | £200m per year (total of £1bn from 2021–2026) to build on the projects funded as part of the Energy Innovation Programme (2016–2021) to support innovative technologies across key areas of industrial decarbonisation, including hydrogen, CCUS, bioenergy and GGR technologies | Demonstration funding | | | | | |
| CCUS Infrastructure Fund | £100m per year (total of £1bn from 2021–2030) to support the development of CCUS business models and contribute to the capital costs primarily of transport and storage infrastructure and early industrial capture projects | Deployment and infrastructure funding | | | | | |
| Clean Steel Fund | £250m fund (in development as of July 2021) to support the steel industry's transition to lower carbon production processes, including through energy efficiency, renewable energy, CCUS and hydrogen | Deployment and infrastructure funding | | | | | |
| Industrial Energy Transformation Fund | £315m fund in total from 2020 until at least 2024 to help businesses with high energy use, including energy-intensive industries, to invest in energy efficiency and low-carbon technologies including CCUS to reduce emissions and energy bills | Deployment and infrastructure funding | | | | | |
| CCUS Business Models | Development of commercial frameworks for business models that apply to $CO_2$ transport and storage, power and industrial carbon capture | Revenue mechanism | | | | | |

| | | | Potential to address barriers relating to types of capital* | | | | |
|---|---|---|---|---|---|---|---|
| Policy framework | Description | Type of incentive | I/PC | KC&I | HC | NC | SC |
| CCUS Cluster Sequencing | A two-phase approach to allocate CCUS programme support in line with government ambition timelines, allowing certainty around a pipeline of projects, where Phase-1 clusters are to be chosen based on suitability to deploy in the mid-2020s | Support allocation framework | | | | | |
| CCUS supply chains roadmap | Roadmap setting out how government and industry can work together towards a strong, industrialised UK CCUS supply chain, covering four cross-cutting activities: supply chain mapping, capability development, skills and innovation, and finance and trade | Sector deal/roadmap | | | | | |
| North Sea Transition Deal | Sector deal between government and the offshore oil and gas industry to work together to deliver the skills, innovation and new infrastructure required to align the sector with net-zero, including ambitious domestic supply chain targets | Sector deal/roadmap | | | | | |
| Hydrogen Strategy | Strategy for delivering the Government ambition for 5 GW of low-carbon hydrogen production capacity by the 2030s, committing to a 'twin track' approach supporting both electrolytic and CCUS-enabled hydrogen, with recognition of the need to co-develop CCUS and hydrogen policy to ensure optimum outcomes in both areas | Sector deal/roadmap | | | | | |
| UK Emissions Trading Scheme | A 'cap and trade' emissions trading scheme that covers energy-intensive industries (eligible for a volume of free allowances), power generation and aviation to incentivise sector decarbonisation through a long-term carbon price signal (the cap to be aligned with net-zero by 2024) | Carbon pricing | | | | | |
| UK Infrastructure Bank | New, government-owned, operationally independent policy bank providing £22bn of infrastructure finance with a core objective to help tackle climate change and support local growth | Project finance | | | | | |
| Green Jobs Taskforce | Group of experts tasked to set the direction for the job market as the UK transitions to a high-skill, net-zero economy | Advisory taskforce | | | | | |

*Source: Descriptions of policy frameworks collated from Industrial Decarbonisation Strategy (HM Government, 2021), Garvey and Taylor (2020) and respective BEIS pages on gov.uk. Indicative evaluation of the potential of each policy framework to address barriers based on authors' analysis.*

## Policy recommendations around the five types of capital needed for sustainable and inclusive growth

Below we provide specific recommendations spanning the national and local levels across the five types of capital needed for sustainable and inclusive growth. As previously discussed, policy risk operates across the five types of capital. The recommendations derive from our assessment of policy gaps combined with insights from our analyses of the data on economic impacts, trade and innovation relating to CCUS, as set out in the previous sections of this report.

Tentativeness of Government commitments to deep decarbonisation investments can exacerbate technological and commercial risks around CCUS in both perceived and real terms (Element Energy and Vivid Economics, 2018). Against the backdrop of two failed competitions, long-term certainty is key to create and sustain investor confidence.

**Therefore, at an overarching level, the primary objective of any policy agenda surrounding CCUS should be to create a consistent, long-term policy, institutional and regulatory framework that improves coordination across stakeholders at the national and local levels.**

Achieving the required long-term framework will come down to shifting the focus of the dialogue from cost to value, which can help overcome short-termism or myopia in policy (Element Energy and Vivid Economics, 2018).

We identify *action leads* for each recommendation to facilitate implementation but note that this does not imply the responsibility to carry out the action lies solely with the named lead(s). In fact, the primary objective of action leads should be to better coordinate and share responsibilities with relevant parties across national and local government. We also provide relevant lessons from other countries and sectors in a series of boxes.

### 1. Infrastructure/physical capital

1.1. **Finalise CCUS business models as an immediate priority, underpinned by a long-term funding envelope to support deployment in the 2020s, and with a coordinated approach across interrelated energy systems, including hydrogen and greenhouse gas removal technologies, to unlock opportunities from infrastructure and knowledge-sharing**

Action leads: *Department for Business, Energy & Industrial Strategy (BEIS) and HM Treasury*

First and foremost, there needs to be a sufficient economic incentive attached to reducing $CO_2$ emissions to drive investments in CCUS. This economic incentive could come in the form of a carbon price, an investable policy-driven instrument (e.g. tax credits), a market mechanism, or regulation (see Appendix D for a selected list of specific instruments included under each category). The economic incentive could also be designed to differentiate between CCUS applications in different sectors and be tailored to the stage of technological development. Government intervention is especially critical for first-of-a-kind projects, where high risk perceptions make market mechanisms on their own unlikely to secure access to suitable finance for investment (Bassi et al., 2015).

#### Lessons from the 45Q tax credits in the United States

In the United States, the expansion of a tax credit known as Section 45Q alongside the California Low Carbon Fuel Standard (LCFS) and other complementary plans has stimulated many new CCUS investment plans (IEA, 2020). The 45Q tax credit was expanded in 2018 to provide a credit of up to US$50/t for $CO_2$ that is permanently stored and up to US$35/t for $CO_2$ used in enhanced oil recovery or other beneficial uses, for 12 years from the start of project operation. On the other hand, the California LCSF allows transport fuels whose lifecycle emissions have been reduced through CCUS to become eligible for additional tax credits – these credits were trading at more than US$190/t$CO_2$ in Q3 2020 (ibid.). The Global CCS Institute (2020) identifies 45Q tax credits as a financial driver for all the 14 CCS facilities and storage hubs currently under development in the US, where the California LCFS features as a driver in five of those.

BEIS has been developing business models defining revenue mechanisms, complemented with operational subsidies where necessary, tailored to applications in different parts of the CCUS chain. For instance, while a contract-based model has been designed for industrial carbon capture, a 'user pays' revenue model was seen as appropriate for transport and storage operators (BEIS, 2021d). This work demonstrates essential progress to provide revenue certainty to stimulate private sector investment in CCUS that will cascade through to local content requirements and the development of competitive UK CCUS supply chains. However, the business models now need to be backed with a long-term funding framework to establish investor confidence for driving projects and supply chains. Drawing on the lessons found in similarities between the state of CCUS now and that of offshore wind a decade ago, AFRY (2021) emphasises that funding within this framework should increase over time to signal continual, rather than stop-start, procurement. It is also crucial to enhance coordination of investments across interrelated energy systems to capitalise on economic benefits from shared infrastructure and knowledge. In particular, a joined-up approach and better alignment of timelines between CCUS, hydrogen and GGR business models will be key.

1.2. Link CCUS investment with a robust, net-zero-aligned carbon price, starting with:

- A long-term signal on the future of the UK ETS, including how it will interact with or incorporate incentives for investment in negative emissions technologies
- Detail on complementary measures that will be used to safeguard competitiveness of UK industry in the presence of a strong carbon price, without compromising on the incentive for deep and fast decarbonisation
- Detail on complementary measures that will be used to create consumer demand for low-carbon products

Action lead: *BEIS, in close consultation with HM Treasury*

As the market for CCUS matures and reaches a 'tipping point', the need for government intervention to support deployment should decrease, opening the way for technology-neutral measures such as carbon pricing to replace targeted subsidies needed for initial projects (IEA, 2020). Accurately assessing this 'tipping point' is crucial. Evidence from the history of the UK gas industry suggests decisions at key branching points may be different under market- and government-led transitions, which lead to path dependencies, affecting later decisions (Arapostathis et al., 2013). Therefore, tipping the balance too early from government-led to market-led mechanisms carries the risk of creating sub-optimal path dependencies, ultimately hindering CCUS development.

### Lessons from the Porthos project, Netherlands

Contracts-for-difference (CfD) mechanisms can help to bridge the gap between project costs and a market price, enabling a managed transition from a government- to a market-led approach. For instance, the Dutch government recently granted around €2 billion in the form of a CfD for the Porthos project, which is planned to store around 2.5 Mt$CO_2$ captured per year from industry in the North Sea (Lewis, 2021). The 15-year contract will see government subsidies covering the differential between the carbon price under the European Union ETS and actual project costs for CCUS, with the required subsidies expected to decrease as the carbon price under the EU ETS increases (ibid.). Although the reference price (the level from which the government 'tops up' to the agreed strike price per t$CO_2$ abated) in the CfD element of the industrial carbon capture business model developed by BEIS will be linked to the newly launched UK ETS and not the EU ETS (BEIS, 2021b), lessons from the Porthos project could be highly applicable in the UK, given the similar market and challenges involved here (Element Energy, 2018).

Carbon pricing is a necessary tool to level the playing field between high- and low-carbon technologies and to stimulate private investment (Bassi et al., 2015). However, as set out in the previous section, the current carbon price under the UK ETS of around £50/t$CO_2$ is insufficient to stimulate investment in CCUS on its own. Research by Burke et al. (2019) suggests complete decarbonisation in the UK implies a carbon price rising steadily towards £160/t$CO_2$ (with a range of 125–300/t$CO_2$) by 2050 – a level required to incentivise investments in negative emissions technology at the scale required for meeting net-zero. The price incentive for negative emissions may need to be treated separately from incentives for other CCUS applications to stimulate and sustain innovation as well as to avoid substitution between emissions mitigation and removal. For instance, a public procurement scheme (see ibid.) may be a more appropriate framework for incentivising negative emissions than the UK ETS.

The design of the carbon price also needs to address competitiveness impacts for UK businesses trading internationally, and mitigate the risk of carbon leakage; possible measures such as a Carbon Border Adjustment Mechanism are discussed in detail by the Energy Systems Catapult (Sturge, 2020). Free allowances under the UK ETS also play an important role in preserving the competitiveness of the UK's energy-intensive industries. Treatment of free allowances under the Industrial Carbon Capture business model should be kept under close review as the sector matures and clarity around the position that will be taken in future contracts should be provided in a timely manner as promised (BEIS, 2021b).

Finally, the carbon price imposed on industry needs to be passed on, in a fair way, to end-consumers in order to shift demand to lower-carbon products, in turn driving CCUS deployment. Public procurement and product standards are also crucial tools for creating the 'pull' for low-carbon products from the demand side. These levers have all been discussed in the Industrial Decarbonisation Strategy and further detail on timelines and implementation is now required.

### Lessons from Norway's carbon tax

Most commercial applications of CCUS worldwide take their financial motivation from enhanced oil recovery. To date, Norway is the only country where an explicit carbon price has supported investment in CCUS (IEA, 2020). The two projects, Sleipner and Snøhvit, were subject to a $CO_2$ tax on offshore oil and gas production introduced in 1991, creating the technical and commercial need to separate the $CO_2$ from the extracted natural gas before it could be sold. The IEA also highlights several supporting factors that fed into the viability of the projects, including strong subsurface expertise and knowledge within the developing company, Equinor, favourable geology, relatively high product margins, and a lack of alternative abatement options.

### 1.3. Leverage the role of the UK Infrastructure Bank to create the conditions to crowd much-needed private sector investment into CCUS while ensuring support for CCUS is not at the expense of necessary investment in other net-zero-enabling technologies

Action leads*: UK Infrastructure Bank and HM Treasury*

The recently launched UK Infrastructure Bank can play a large role in financing CCUS projects in the absence of proven business models and carry the technology to commercialisation. Investments made in an initial set of projects, led by the public sector, will be unlikely to catalyse a longer-term increase in these kinds of investments if they do not effectively leverage private investment by demonstrating a path for the private sector to follow (Unsworth, Andres et al., 2020). NIC (2021) suggests that the UK Infrastructure Bank could support CCUS by addressing the lack of long-term finance and liquidity, and by absorbing some of the risks around technology and construction through provision of equity – similarly to how the Green Investment Bank supported the offshore wind sector. (See box, next page.)

### 1.4. Develop CCUS as part of a holistic infrastructure programme considering infrastructure that will be shared across various technologies (e.g. GGR) as well as complementary assets (e.g. broadband) required for the overall net-zero-aligned growth of regions

Action lead: *HM Treasury, in close consultation with local government, and by extension communities, across the UK*

The Government needs to align national and local planning around the development of a holistic portfolio of net-zero-enabling infrastructure, including CCUS. Thinking holistically is important for decarbonisation in a cost-efficient manner and to enable net-zero to begin with, given that the ability of an individual to choose the 'clean' option depends on complementary infrastructure or systems being in place, e.g. charging infrastructure in relation to electric vehicles (Stern and Valero, 2021). A coherent and strategic development of infrastructure that allows net-zero-aligned growth in regions will depend on a constructive collaboration between public and private actors. Specifically for CCUS, because the private sector would have little incentive to invest in infrastructure that is beyond its needs, clarity around the Government's role, crucially through the Transport and Storage business model (BEIS, 2021c), can ensure that the infrastructure built today can accommodate future larger flows of $CO_2$ from multiple sources.

### Lessons from national investment banks in other countries

Muttitt et al. (2019) detail three examples where public sector finance directly or through a national investment bank has supported clean energy sectors by establishing the required confidence in the market to drive large-scale private investments.

The first example is **Denmark**, where the success of the wind power sector is attributed to a mandated 30% state investment in each windfarm between 1980 and 1990, which gave the industry the boost it needed to set up. [See next box for more on windfarms.]

Secondly, in **Germany** the public bank KfW dedicated €15bn to co-finance renewable energy projects in 2015 and 2016 alone.

Finally, in 2016 **Canada** committed CA$21.9bn over 11 years, including through the Canadian Infrastructure Bank, to support green infrastructure and clean energy.

## 2. Knowledge capital and innovation

### 2.1. Draw on diverse economic evidence to align domestic CCUS supply chain ambitions with a proper understanding of the UK's comparative advantage in production, services and innovation, with early coordination between CCUS project developers and supply chain companies, and considering an outcome-based approach that brings in international supply chains where necessary

Action leads: *BEIS and Department for International Trade (DIT), in close consultation with businesses*

Domestic CCUS deployment and supply chain ambitions need to be aligned with collaboration early on between key actors. The Supply Chain Excellence programme[15] led by the Carbon Capture and Storage Association (CCSA) is a crucial starting point. This needs to be supported by policy frameworks that draw on economic evidence around the UK's current and potential future competitiveness in CCUS products and services. Analyses similar to that which we have presented in Section 4, using global trade data, could be highly informative in that respect. Building comparative advantage by capitalising on the evidence base is key for retaining economic benefits from investments in CCUS and unlocking export opportunities that can sustain jobs in the long term. Furthermore, collaboration is required not only within CCUS but across the entire net-zero supply chain to maximise knowledge sharing and spillovers.

[15] The Supply Chain Excellence programme is a four-phase collaborative programme commissioned by the CCUS Council aiming to develop excellence across the UK supply chain for CCUS. Findings from Phase 2 of the project focusing on opportunity identification developed with input from sector experts from almost 50 organisations were published in July 2021. Subsequent phases of the project will focus on the development of long-term supply chain strategies and ensuring these are embedded and sustained among all stakeholders.

### Lessons from government support for wind power supply chains in various countries

Muttitt et al. (2019) gather different approaches from around the world of governments supporting domestic supply chains for wind installations. For instance, **Denmark**'s early state support for windfarm manufacturers in the 1970s and 1980s gave its wind industry 'first mover advantage' globally, including over the UK (based on research by Kyle Smith at the University of Edinburgh).

In **Taiwan**, the government mandated 'fully localised' wind turbine towers for projects for construction in 2021, leading to commitments from Vestas, Swancore and others, and many contracts for local manufacturers.

**France** requires companies bidding to install renewable energy generation to demonstrate manufacturers' commitment to invest in and operate local factories, and investment in economically deprived regions is favoured. This industrial planning has led to commitments to build assembly facilities in various coastal towns for associated windfarms.

The ability of the UK's CCUS supply chain to compete in a global market and capture export opportunities can be strengthened by robust standards underpinning the products and services it provides. Standards establish an agreed way of doing things and therefore are crucial to developing trust among customers in novel, complex technologies like CCUS, in turn driving investment, widespread adoption and further innovation (BEIS et al., 2021). Standardisation can pave the way for CCUS supply chain companies to focus their efforts on manufacturing large volumes of the same components designed to industry best practice, in turn driving costs down, rather than on developing bespoke solutions for individual CCUS projects (CCSA, 2021). The 'Fit for CCUS' programme being developed by BEIS (BEIS, 2021f) could be the starting point for standardisation in the UK CCUS supply chain as a collaborative effort between the Government and the industry, allowing companies to demonstrate and gain competitive edge in international markets.

**2.2. Ensure that support for innovation in net-zero-enabling technologies including CCUS is ambitious, considering enhanced R&D tax credits where applicable, and that it is channelled in a way that addresses regional disparities as well as the current gaps in thinking across path-dependent innovation systems, to improve coherence especially between the development and deployment of CCUS, hydrogen and greenhouse gas removal technologies**

Action leads: *BEIS and UK Research and Innovation (UKRI)*

There is an immediate need to ramp up innovation in CCUS so that key applications are commercially available in the coming decades, for instance in cement production (IEA, 2020). In the presence of large-scale uncertainties, a holistic approach will be needed across path-dependent innovation systems to link technological developments with investments in infrastructure, skills and supply chains. This will require timely and often multidisciplinary research to inform CCUS policies in 'real time' and enable CCUS development at the scale and pace required. It will also be necessary to consider regional patterns in CCUS innovation and spillovers, and their implications for the 'levelling-up' agenda.

The infrastructure-first approach to CCUS that the UK is taking with a focus on industrial clusters creates the frameworks for learning by doing and economies of scale. Lessons from these projects will be crucial for an accelerated path to commercialisation for urgently needed innovations. Government support to the demonstration of CCUS innovations, such as through the Net Zero Innovation Portfolio, will need to continue, as the industry on its own will likely take a conservative approach on technology readiness. Furthermore, adequate support will need to be available throughout the innovation cycle, carrying technologies from low technological readiness levels all the way to demonstration and commercial deployment, avoiding a potential gap in the middle. Overall, allocation of innovation support should draw on evidence of economic returns that could be created from government R&D subsidies in CCUS technologies (see our analysis using the 'Istra-X' industrial strategy index methodology in Section 5).

2.3. Explicitly link domestic CCUS policy with the ambitions to play an international leadership role on climate action, especially in the context of COP26, considering further collaboration in R&D

Action lead: *COP26 Team within the Cabinet Office, in close consultation with a range of other government departments including BEIS, Foreign, Commonwealth and Development Office (FCDO), and DIT*

Being the innovative 'first mover' might present challenges but it can also be an opportunity if lessons are shared internationally, unlocking mutually reinforcing pathways and spillovers between innovations around the world. As the host of COP26, the UK has articulated an ambition to leverage CCUS expertise to demonstrate international climate leadership. Sharing lessons from domestic R&D while being responsive to concerns around intellectual property could help build the explicit link that is currently missing between domestic CCUS policy and the UK's international climate leadership ambitions. While facilitating stronger climate policies elsewhere is an objective in itself to enable global net-zero, it would also lead to increased global commitment to CCUS, potentially increasing the export opportunity and wider economic benefits from CCUS for the UK.

2.4. Inform industrial and innovation strategy at the national and local levels by creating a robust evidence base on what works that draws on enhanced collaboration and co-creation between higher education institutions and industry as well as lessons shared across projects by capitalising on the cluster sequencing agenda

Action leads: *BEIS, Department for Education (DfE) and UKRI, in close consultation with local government, businesses and education institutions*

Enabling shared learning and innovation is key for reducing technology costs and maximising the economic benefits from CCUS for the UK. This necessitates a solid basis for collaboration between the Government, industry and higher education institutions, encouraging the showcasing of technologies, examples of best practice, knowledge sharing and communication between stakeholders, and taking stock of spillovers from technology developments (Bassi et al., 2015).

Industrial clusters create a favourable space, shielded from mainstream market conditions for CCUS innovation, by offering unique advantages around infrastructure re-use, proximity to offshore storage, relatively low capture costs (due to high purity $CO_2$) and a diverse skills base (Mander, 2021). While the cluster sequencing framework instates confidence in the Government's commitment to deploy CCUS, all industrial clusters will ultimately need to decarbonise and the incentives made available to first movers should not be at the expense of continued CCUS development. Therefore, the sequenced approach to supporting CCUS deployment should create a framework for lesson sharing and continuous improvement from one project to the next, rather than a source of uncertainty for CCUS developers and their associated supply chains at future 'phases' and 'tracks' of the framework. Establishing competitive CCUS supply chains in the UK will depend on the Government's ability to provide investors the certainty around a pipeline of CCUS projects, avoiding potential boom and bust effects.

### Lessons from learning by doing in the United States and Canada

IEA (2020) presents evidence that experience with building and operating CCUS facilities has already driven improvements in associated technologies and cost reductions, pointing to the potential for further improvements through increased research, development and demonstration (RD&D) and growing practical experience. For instance, the capture costs at the Petra Nova coal-fired power plant in Houston, Texas are 35% lower than at the Boundary Dam facility in Canada, which was built just a few years earlier. And a detailed feasibility study for retrofitting the Shand coal-fired power station in Canada with CCUS suggested that cost reductions of around 70% for capital and operating expenditures (CAPEX and OPEX) are possible, relative to the Boundary Dam project. Similarly, the Quest CCS project, also in Canada, has identified that its CAPEX would be 20% to 25% lower if the plant were to be built again today.

## 3. Human capital

3.1. Complement CCUS investments with a special emphasis on skills as part of a holistic, proactive net-zero skills programme, designing targeted re- and upskilling for those displaced in the COVID-19 crisis and who will be displaced by ongoing structural change towards net-zero, using human capital tax credits to incentivise firms to play an enhanced role in the programme

Action leads: *BEIS, DfE and Department for Work and Pensions (DWP), in close consultation with local government*

The UK needs a comprehensive, consistent and long-term policy framework around skills for net-zero that includes skills for the development of CCUS. Following disruptions in policy support and investment, the nuclear industry may now be on the verge of a workforce shortage (Element Energy, 2020). This reiterates the importance of a long-term policy that works holistically across infrastructure, technology and skills. Ensuring skills are in place to deliver net-zero needs to be a collaborative effort between the Government, industry and all other stakeholders of the economy; therefore, it is important for the Government to explore and implement policy measures such as tax credits that can unlock private alongside public investment in human capital. This also needs to be a continuous effort, to accommodate changing workforce patterns as the net-zero transition gains pace (Green Jobs Taskforce, 2021).

### Lessons from the transition of Cottam coal-fired power station workers into the nuclear sector

The Accelerated Experience and Learning Programme (AELP) led by the Engineering Construction Industry Training Board is a retraining programme aimed at 'sector jumpers' (ECITB, 2020). It was used successfully to move 20 EDF Energy staff working in the operation of the now-closed Cottam coal-fired power station into roles within its nuclear fleet. EDF Energy proactively engaged with affected workers to understand their individual aspirations and needs. As part of the AELP many of the technical skills and behaviours required in the nuclear sector were identified as being comparable with those working in the coal station, including a similar safety and security culture as well as the turbines and control room. The AELP recognised and built on the existing skills of the workers from Cottam to provide a path to becoming a 'suitably, qualified and experienced person' in 12 rather than 18 months.

3.2. Ensure collaboration across departments on the net-zero skills agenda, including skills required for the successful delivery of CCUS, and embedding necessary frameworks in overarching policies underway, such as the Skills and Post-16 Education Bill

Action lead: *Cross-government*

Cross-departmental collaboration is required to establish a proactive, strategic investment programme in net-zero skills. This is reflected in the recommendation by the Green Jobs Taskforce (2021) for the Government to establish a UK-wide body with national representation to monitor, drive and report on progress on the delivery of good quality green jobs and skills. This was given the necessity of coherence across different departments and different sectors of the green economy around the workforce transition. Furthermore, it is important to use periodical policy reviews and overarching policy changes underway, such as the Skills and Post-16 Education Bill (UK Parliament, 2021), to embed and continuously improve much-needed frameworks and public funds to stimulate investment in net-zero skills.

3.3. Ensure joint effort between government, industry and education providers to take a place-based approach to map and quantify existing skills base transferable into CCUS, identify skills gaps, and develop education/training curricula accordingly

Action leads: *BEIS, DfE and DWP, in close consultation with local government, businesses and education institutions*

The skills programme needs to be designed with a focus on place at its core so that the economic benefits and jobs from CCUS deployment and supply chains can be retained locally but also spill over to the rest of the country. All levels of government, industry and the education sector should work in close collaboration to identify current and likely future skills gaps and design appropriate curricula at all levels of the learning cycle, from schools to adult skills programmes, to fill these gaps. Input from the Carbon Capture and Storage Association, the Engineering Construction Industry Training Board (ECITB) – and notably its Connected Competence programme – as well as the Government's Green Jobs Taskforce will be critical in this process. An important responsibility will also fall on 'local transition bodies' to understand the changes needed in their areas and enable the development of place-based skills strategies (Green Jobs Taskforce, 2021).

## 4. Natural capital

### 4.1. Ensure environmental regulation and legislation keep pace with developments in CCUS in an agile way, and that the drive to support faster deployment does not compromise on environmental scrutiny

Action leads: *BEIS, Department for Environment, Food & Rural Affairs (Defra) and the Oil & Gas Authority (OGA)*

Stringent but agile regulation and legislation need to be introduced early on and to evolve based on lessons from initial projects. Liabilities especially around $CO_2$ storage and potential leakage need to be carefully defined as a priority to enable initial projects in a timely manner and to create the right conditions for future investment while helping build public trust. The development of innovative insurance instruments, coupled with risk-sharing between private operators and the Government, will help mitigate some of the business risks of CCUS (Bassi et al., 2015). BEIS's May 2021 update to the Transport and Storage business model signals a firm direction on how risks relating to long-term $CO_2$ storage will be shared between the operator and the Government (BEIS, 2021c). However, the thinking around the role of liability and risk sharing in the subsurface between government and industry still needs to be finalised to help instate efficient private sector investment. In that respect, lessons from the context of nuclear waste where liabilities are not limited in size can be informative.

### 4.2. Take a holistic view of all energy systems to minimise environmental disruption from investments in CCUS and related economies at both the national and local levels, respecting local ecosystems and natural resource constraints

Action leads: *BEIS, Defra and the OGA, in close consultation with local government*

In the presence of large-scale uncertainties, it will be necessary to support deployment across all net-zero-enabling technologies while respecting local ecosystems and natural resource constraints. Interdependencies, especially between CCUS, hydrogen and GGR technologies, need to be considered where strategic measures – for example, separate targets for emissions reduction and negative emissions (McLaren et al., 2019) – may be required to ensure genuine climate benefit. Climate and other environmental impacts also need to be thought of on a lifecycle basis, compared with a plausible baseline or counterfactual. Calculating direct impacts in one place and at one time is of little use if indirect effects create emissions somewhere else, or later (Hepburn et al., 2019). This is a particular concern for BECCS, as its climate benefits depend on how the biomass is supplied.

## 5. Social capital

### 5.1. Create an awareness and information programme to ensure social acceptability of CCUS, using a positive but realistic narrative that positions CCUS within the wider portfolio of essential net-zero technologies, while emphasising the role of CCUS as an enabler of just workforce transitions towards net-zero

Action leads: *BEIS, Department for Education and the Department for Digital, Culture, Media & Sport (DCMS)*

There is a need to raise basic awareness of CCUS as a first step (Whitmarsh and Xenias, 2017), being clear on the purpose of deploying it in the UK with an explicit link to net-zero, and addressing certain misconceptions around its association with fossil fuels. The recent public dialogue on CCUS emphasised the importance of delivering information in a way that is transparent, easy to understand, accommodating the needs of different audiences, and from trusted messengers perceived as having no vested interest (Wickett-Whyte et al., 2021). Arts and cultural activities like the CCS exhibition at the Science Museum (2021) could make a helpful contribution to public awareness.

At the local level, it is key to promote the opportunities that lie in CCUS while also being realistic about the challenges and risks involved. Gough and Mander (2019) emphasise framing as a critical factor in how society responds to CCUS technologies and there is evidence to suggest that discussing CCUS paired with bioenergy for achieving negative emissions may reduce local opposition (for example, see Wallquist et al., 2012).

A study by Cox et al. (2021) indicates that public trust relating to one technology may have knock-on impacts elsewhere. They suggest that perceptions of $CO_2$ removal technologies have been negatively impacted by risk perceptions and recent policy decisions surrounding shale gas and fracking, reporting on concerns raised by research participants along the lines of "but they told us it was safe!" This shows the importance of a holistic public narrative from the start on the entire portfolio of net-zero solutions and technologies, including CCUS. Historical experience, such as events following the 1952 Big Smog in London, also suggests that the public's awareness of the impacts of environmental problems influences the demand for change (Fouquet, 2016). Therefore, the social acceptability of CCUS will benefit from a continued robust government narrative on the necessity of net-zero itself to begin with.

### 5.2. Rebuild pride and sense of community within regions around a shared purpose for clean growth that includes CCUS, in particular through participatory decision-making processes at a local level, to ensure community buy-in and just outcomes

Action leads: *BEIS in close consultation with local government, and by extension communities, across the UK*

At a local level, people who will be involved and impacted by the deployment of CCUS need to be made part of the key decisions and gathered around a shared purpose towards net-zero. Two-way engagement with people at a local level, in which their concerns are taken seriously and acted on, will be crucial for building the social licence to operate for CCUS as well as for a host of other much-needed technologies (Cox, 2021). Insights from the public dialogue on CCUS reiterate this need: participants wanted there to be inclusive and meaningful engagement with local communities directly impacted by CCUS, with information on risks as well as benefits clearly communicated, and people's views listened to (Wickett-Whyte et al., 2021). Furthermore, intangible factors such as regional pride were reflected in people's reactions to CCUS: seeing a clear link between CCUS projects and local jobs led to more positive views (ibid.).

#### Lessons from public opinions on nuclear energy in the United States

Bisconti (2016) evaluates the results from public opinion polls on nuclear energy conducted in the US, which suggest two important lessons that can inform policies around social acceptability. Firstly, there is evidence to suggest public support grows in line with feeling informed about nuclear energy. Secondly, living near nuclear power plants is shown to correlate positively with public support. While 67% of the American public favour the use of nuclear energy as one way to provide electricity, the support increases to 83% among people living within a 10-mile radius of any nuclear power plant (excluding households with any member working at the plant). Even for a technology that is characterised by higher material risks to safety than CCUS, solid public support is possible when economic and social benefits are visible at a local level.

# 8. Conclusions

CCUS is an essential tool for meeting net-zero, both in the UK and globally. The UK has seen a step change in the commitment to deploy CCUS since the net-zero target was signed into law in 2019. Industry has already put forward an ambitious portfolio of CCUS projects to be deployed in the 2020s, which in combination exceed the Government's currently stated ambition to capture 10 $MtCO_2$ per year by 2030. The Government needs to recognise the industry's appetite to deliver, step up its ambition and support these projects to fruition with a policy framework that truly reflects the urgency of CCUS delivery that is inherent to its own net-zero target. There is evidence that suggests more ambitious action early on can increase the jobs and wider economic benefits from the CCUS sector, with potential to contribute towards a net-zero aligned recovery from COVID-19 and to levelling up across the UK.

This report has highlighted the UK's comparative advantages in productive and innovative capability within the CCUS supply chain. A strategic approach to developing the capacity of the supply chain by capitalising on these capabilities and with coordination between the Government, project developers, supply chain companies and other stakeholders can secure and enhance export opportunities for the UK, in turn supporting jobs and sustainable growth into the future. Seeing where the UK's existing strengths and capabilities for CCUS are concentrated suggests that sustainable growth opportunities from the sector can help reduce regional disparities. The puzzle pieces are in place for the industrial heartlands to lead on CCUS – but government needs to spur investment.

Investment in the UK in a CCUS supply chain depends first and foremost on there being certainty on a credible pipeline of domestic projects. Consistent messaging since the *Ten Point Plan for a Green Industrial Revolution*, as well as specific frameworks under CCUS business models and cluster sequencing, have made clear that CCUS is a strategic priority within the Government agenda. However, against the backdrop of two major competitions being abandoned at a late stage, establishing investor confidence in CCUS requires longer-term certainty underpinned by a multiyear funding framework. The UK simply cannot afford further similar policy failures and delays given the urgency for net-zero of deploying CCUS.

Our recommendations aim to overcome barriers to CCUS development across five interrelated types of capital needed for sustainable and inclusive growth. Holistic thinking across these types of capital can attract much needed investment into CCUS supply chains and innovation to underpin the target levels of deployment in the short term and drive further ambition in the longer term. Maximising opportunities from a holistic approach requires a consistent, long-term policy, institutional and regulatory framework to improve coordination across stakeholders at the national and local levels on the entire portfolio of net-zero solutions and technologies. The UK government should urgently embed its ambitions for CCUS into this framework, crucially through the upcoming Net Zero Strategy, and in doing so demonstrate globally, ahead of COP26, that it is leading the race to net-zero.

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# Appendix A

## Review of the evidence base on future economic opportunity: summary of results, further detail and assumptions

Table A1. Summary of ex-ante studies on economic benefits of CCUS investments in the UK

| Authors | CCUS sectors covered | Activity detail | Deploy-ment scope | GVA and timeframe | No. of jobs and timeframe |
|---|---|---|---|---|---|
| AFRY (2021) | Power, BECCS, Industry, Hydrogen production, $CO_2$ T&S (DACCS projects potentially covered too, grouped with BECCS) | Deployment and operation of full-chain CCUS under two scenarios reflecting different capture volumes:<br>1. Ten Point Plan (10Mt$CO_2$/year by 2030);<br>2. Net Zero Ambition (22Mt$CO_2$/year).<br>The capture volume to 2030 in each scenario is broken down equally into four broad categories of projects: power with gas, GGRs (covering BECCS and DACCS), hydrogen production and industry. | UK-wide | **Ten Point Plan scenario:** almost £1bn annually from base at its peak in 2025<br>**Net Zero Ambition scenario:** almost £2bn annually from base at its peak in 2025 | **Ten Point Plan scenario:** approx. 5,000 additional jobs at its peak in 2025<br>**Net Zero Ambition scenario:** approx. 10,000 additional jobs at its peak in 2025; 8,300 additional jobs by 2030 (as a sum of sectoral impacts on employment in Exhibit 3.10) |
| *Vivid Econ-omics (2021)* | Power, BECCS, Industry, Hydrogen production, $CO_2$ T&S | Deployment and operation of CCS and hydrogen technologies in the Humber industrial cluster (to be up and running by 2031), including two Drax BECCS units of 0.66 GW each, deployed as a staggered pair in 2027-2028. | Cluster – Humber | **Annual avg GVA added during construction (2024–31):** £1,113m direct; £421m indirect; £544m induced; £2,078m total<br>**Peak at 2027:** £1,783m direct; £564m indirect; £753m induced; £3,100m total | **Annual avg jobs during construction (2024–31):** 14,900 direct; 6,649 indirect; 10,185 induced; 31,733 total<br>**Peak at 2027:** 24,203 direct; 9,518 indirect; 14,092 induced; 47,813 total |
| *Vivid Econ-omics (2021)* | Power, BECCS, Industry, Hydrogen production, $CO_2$ T&S | Deployment and operation of CCS and hydrogen technologies across the UK, comprising four industrial clusters (Humber, Teesside, Scottish Acorn, North West HyNET), amounting to 53.1 Mtpa of $CO_2$ captured and stored by 2031. | UK-wide | **Annual avg GVA added during construction (2024–31):** £1,733m direct; £2,098m indirect; £4,343m induced; £8,174m total<br>**Peak at 2039:** £2,285m direct; £4,104m indirect; £7,479m induced; £13,867m total | **Annual avg jobs during construction (2024–31):** 23,114 direct; 50,584 indirect; 48,457 induced; 122,155 total<br>**Peak at 2039:** 27,738 direct; 81,915 indirect; 83,446 induced; 193,098 total |
| *Hydrogen Taskforce (2020)* | Hydrogen production | Deployment and operation of UK-wide blue hydrogen production (autothermal reforming with CCS). | UK-wide | **Cumulative to 2035:** £2,759bn (from blue hydrogen production) | **Cumulative to 2035:** 10,482 (from blue hydrogen production) |

| Authors | CCUS sectors covered | Activity detail | Deploy-ment scope | GVA and timeframe | No. of jobs and timeframe |
|---|---|---|---|---|---|
| *Turner et al. (2020)* | $CO_2$ T&S | Design and deployment of $CO_2$ T&S infrastructure in four pre-identified sites across the UK continental shelf (does not include $CO_2$ capture or the operation of T&S assets installed) | Four storage sites | Cumulative GDP gain of £0.2m per £m spent.<br><br>GDP during construction:<br>2021: £125m; 2022–25: £63-73m; 2026: £38m | 1,700–3,850 additional jobs required per year.<br><br>Jobs during construction:<br>2021: 3,850; 2022–25: 2,250- 2,670; 2026: 1,700 |
| *Jung and Murphy (2020)* | Unspecified – assume all | Development of hydrogen and CCS infrastructure and supply chain over the next decade. | UK-wide | N/A | 25,000 direct jobs up to 2030 |
| *Vivid Econ-omics (2020)* | Power, BECCS, Industry, Hydrogen production, $CO_2$ T&S | Deployment and operation of full-chain CCUS projects – benefits quantified separately for three markets: the Net Zero Teesside (NZT) project; the UK domestic market; and the global export market. | Cluster – Teesside | Direct GVA benefits: £370m annually (2024–28)<br><br>Indirect and induced GVA benefits:<br>During construction (2024–28): £750m annually<br>During operation (2030–50): £600m annually | Direct jobs:<br>During construction (2024–28): 4,500 annually<br>During operation (2030–50): 900 annually<br><br>Indirect and induced jobs:<br>During construction (2024–28): 13,500 annually (approx. 4,500 indirect and 9,000 induced)<br>During operation (2030–50): up to 9,500 annually |
| *Vivid Econ-omics (2020)* | Power, BECCS, Industry, Hydrogen production, $CO_2$ T&S | See previous. | UK-wide | Direct GVA benefits:<br>UK domestic market: £1.6bn annually by 2030<br>Exports market: £1.1bn by 2030; £1.2bn annually by 2040 | Direct jobs:<br>UK domestic market: 18,000 annually by 2030<br>Exports market: 12,500 by 2030; 13,000 annually by 2040 |
| *Element Energy (2019)* | Industry, Hydrogen production, $CO_2$ T&S | Deployment and operation of CCS for industry and hydrogen production from 2020–50. By 2035 three UK industrial clusters have operational hydrogen and CCS infrastructure (first installations operational in 2025), with deployment extending to all six major UK industrial clusters by 2050. | UK-wide | £4bn by 2050 | By 2050: 43,000 (13,700 direct jobs related to the infrastructure deployment, 9,000 jobs in the operation of the newly built facilities, and over 20,000 indirect jobs in the supply chain) |
| *Vivid Econ-omics (2019b)* | Power, Industry, Hydrogen production, $CO_2$ T&S | UK-wide deployment of CCUS by 2050 including 21.5 GW of gas CCUS, 12 Mt of $CO_2$ per annum captured and stored by industry, and 114 Mt of $CO_2$ pa captured from hydrogen production. | UK-wide | From export markets:<br>£4.3bn per annum by 2050 (£2.1bn coming from exports of EPCm services, £1.5bn from exports of innovative solvents and capture technologies)<br>From the domestic market:<br>£850m per annum by 2040 | From export markets:<br>48,000 direct jobs in 2050 (39,400 from industry CCUS projects, 6,000 from $CO_2$ T&S and 3,000 from power CCUS)<br>From the domestic market:<br>nearly 10,000 jobs per annum by 2040 (EPCm services and T&S components each support 2,000 jobs per annum by 2040) |

| Authors | CCUS sectors covered | Activity detail | Deploy-ment scope | GVA and timeframe | No. of jobs and timeframe |
|---|---|---|---|---|---|
| *Summit Power Caledonia (2018)* | Power, $CO_2$ T&S | Design, deployment and operation of the Caledonia Clean Energy Project plant in Scotland. Project base case: gas-fired CCGT with post-combustion $CO_2$ capture and supporting infrastructure. | One project | **During construction (2018–23):** £0.7bn–1.2bn direct, £0.5bn–1.4bn indirect/induced | **During construction (2018–23):** 1,200–1,800 direct, 800–1,900 indirect, 500–800 induced<br><br>**During operation:**<br>**In Scotland:** 300–600 direct (100–150 jobs related to the power/$CO_2$ capture plant), 600–1,000 indirect and induced |
| *Amion Cons-ulting (2018)* | Hydrogen production, $CO_2$ T&S | Design, deployment and operation of a regional hydrogen economy (including CCS) across the North West over a period to 2050. | Cluster – North West | **GVA gains from the HyNet NW project – cumulative up to 2050 (£m):** 11,144 direct; 14,812 indirect and induced; 25,956 total (annual avg: £811m; peak year gains: £2bn)<br><br>**GVA gains from the HyNet NW project AND inward investment – cumulative up to 2050 (£m):** 30,540 (annual avg: £954m) | **Employment from the HyNet NW project – cumulative up to 2050 (total employment years):** 110,394 direct; 178,983 indirect and induced; 289,377 total (annual avg: 9,043 jobs; peak: 23,167 jobs)<br><br>**Employment from the HyNet NW project AND inward investment – cumulative up to 2050 (total employment years):** 360,273 (annual avg: 11,259 jobs) |
| *Summit Power (2017)* | Power, BECCS, Industry, Hydrogen production, $CO_2$ T&S | Deployment (phased schedule from 2020–50) and operation of a CCS network along the UK East Coast (four industrial clusters). Study considers direct investments in CCS as well as the impact through linked economies e.g. power generation, fuel refineries. | Four clusters | **Cumulative to 2032:** £5bn<br>**Cumulative to 2060:** £54bn<br><br>Unlike employment figures, GVA impacts defined solely in terms of discounted totals (not broken down into direct and indirect components) | **Cumulative to 2032:**<br>**From CCS investments:** 7,600 (3,050 direct/4,550 indirect)<br>**From linked economies:** 4,860 (1,810 direct/3,050 indirect)<br>**Overall:** 12,460 (4,860 direct/ 7,600 indirect)<br><br>**Cumulative to 2060:**<br>**From CCS investments:** 47,000 (18,800 direct/28,200 indirect)<br>**From linked economies:** 178,600 (49,150 direct/129,450 indirect)<br>**Overall:** 225,600 (67,950 direct /157,650 indirect) |
| *TUC and CCSA (2014)* | Power | Deployment and operation of up to 20 GW of CCS by 2030, translating to 15–25 installations (report discusses CCS widely but GVA and job estimates based on power sector-specific multipliers) | UK-wide | **Per year by 2030:** £2bn–4bn (depending on the installed capacity of 10 or 20 GW respectively)<br>**UK share in domestic and export markets combined (per year by 2030):** £5bn–9bn<br>**Cumulative by 2030:** £15bn–35bn | 15,000–30,000 by 2030 (depending on the installed capacity of 10 or 20 GW – translating to 15 or 25 installations – respectively)<br><br>**Per installation estimates (new-build plant only):**<br>**During construction (typically 4-6 yrs):** 1,000–2,500<br>**During operation:** 200–300 jobs in O&M and the associated supply chain, of which 40–100 jobs are at the plant itself |

| Authors | CCUS sectors covered | Activity detail | Deploy-ment scope | GVA and timeframe | No. of jobs and timeframe |
|---|---|---|---|---|---|
| *AEA Tech-nology plc (2012)* | Power, $CO_2$ T&S | Design, deployment and operation of the full CCS chain within the power sector (both retrofits and new-build) amounting to 10 GW by 2030. | UK-wide | Investment figures rather than GVA (in 2010 prices)<br>Cumulative market (2021–30): £15.3bn<br>Annual market in 2030: approx. £2.7bn/year<br>Max growth potential of UK supply chain (2021–30): £10.9bn (if the UK were to capture entire UK supply chain) | Total labour required (2021–30): 277,100 job-years<br>Total breaks down into supply chain components as follows (1,000 job-years required): 13.8 for project management; 31.8 for design and engineering; 15.3 for procurement; 114.3 for manufacturing; 75.8 for construction; 20.4 for commissioning; 5.5 for legal and financial |

*Notes: T&S stands for transport and storage. 'Power' as a CCUS sector in the UK typically refers to gas-based power generation with CCS, unless otherwise specified. In this table 'power' as a CCUS sector does not cover cases where CCUS is indirectly used for power. For example, if a study is based on hydrogen-fuelled power where hydrogen is produced via a CCUS-based method, this would be categorised as 'hydrogen production', not 'power'.*

*Source: Authors. Certain assumptions and simplifications have been made to categorise studies in an attempt to facilitate comparisons across estimated economic impacts – any errors in the interpretations of the studies are the authors' alone.*

Table A2. Further detail on ex-ante studies summarised in Table A1 (scenario assumptions and methodologies)

| Report title | Scenario | Key methodology |
|---|---|---|
| *Economic Analysis of UK CCUS: A report to Carbon Capture and Storage Association.* AFRY (2021) | The two scenarios contained in the report differ in terms of their driver categories:<br>1. Ten Point Plan scenario – Investment-driven: delivers on the Government's Ten Point Plan and Energy White Paper commitment to 10 $MtCO_2$/year of CCUS by 2030 in four clusters which is assumed to be underpinned by a defined public investment portfolio<br>2. Net Zero Ambition scenario – Emissions/net-zero target-driven: deployment at the level recommended in the CCC's Sixth Carbon Budget (Balanced Net Zero), deploying 22 $MtCO_2$/year of CCUS by 2030 and then more than tripling capacity through the 2030s. | Input/output (I/O) macroeconomic modelling: Cambridge Econometrics' E3ME macroeconomic model designed for impact analysis through the development of scenarios (previously used in analyses for the Government and the CCC). The model is structured around a standard national accounting framework that breaks the UK's economy into 70 sectors, which are linked together through input-output relationships that determine the structure of supply chains. The input shocks, here mostly changes to investment, operating costs and energy consumption, are entered into the model and the outputs cover a range of standard macroeconomic indicators. The model captures the labour market in a relatively high level of detail, covering labour demand, participation rates and average wage rates. |
| *Capturing Carbon at Drax: Delivering jobs, clean growth and levelling up the Humber.* Vivid Economics (2021) | Investment-driven: Capture of over 30 $MtCO_2$-e per annum of emissions by 2040 in the Humber Cluster in line with a set of defined/planned investments by Drax, Equinor, Immingham VPI and industry partners. | GVA and employment multipliers (for direct benefits): Multiply market share of goods and services relevant to the CCS industry, which will be captured by UK firms, with the CAPEX required to bring this project online. Jobs estimates are the no. of full-time equivalents supported directly through expenditure on CCS based on average salaries per sector from the Office for National Statistics (ONS).<br>I/O macroeconomic modelling (for indirect and induced benefits): Vivid's I/O Impact Investment Model (previously tried and tested for the NZT Project), updated and fully calibrated to the UK and the North East. |
| | Emissions / net-zero target-driven: To 2030, CCUS deployment in line with defined/planned investments at Net Zero Teesside, Zero Carbon Humber, Hynet and Acorn. Beyond 2030, additional CCS capacity assumed to be deployed elsewhere in the UK, to linearly hit the CCC's Further Ambition scenario (net-zero report). | As above. |
| *Economic Impact Assessment: Hydrogen is ready to power the UK's green recovery.* Hydrogen Taskforce (2020) | Market development-driven: project hydrogen demand by 2035 in four end-use sectors – transport, heat, industry and power generation. Estimate required blue hydrogen production installed capacity assuming 80%/20% split between blue and green hydrogen, to meet total demand. | I/O macroeconomic modelling: Create bespoke macroeconomic model to estimate the economic contribution from investing (and maintaining) the necessary hydrogen infrastructure, according to projected demand. Uses ONS Input-Output tables and Supply & Use tables, with demand mapped to each SIC classified industry. |
| *How is Planned Public Investment to Enable CCS Likely to Impact the Wider UK Economy?* Turner et al. (2020) | Investment-driven: defined funding of £1.75bn for the development of four $CO_2$ storage sites (Hamilton, Captain X, Viking A and Bunter 36, as detailed in the Strategic UK CCS Storage Appraisal storage development plans, D10, D12, D13 and D14). | CGE modelling: Use the UKENVI multi-sector computable general equilibrium model of the UK economy (fully specified and detailed in previous peer-reviewed papers) to analyse the development of pre-identified potential $CO_2$ storage sites. |

| Report title | Scenario | Key methodology |
|---|---|---|
| *Transforming the Economy after Covid–19: A clean, fair and resilient recovery.* Jung and Murphy (2020) | N/A | N/A (appears literature review-based) |
| *Net Zero Teesside Economic Benefits.* Vivid Economics (2020) | Emissions/net-zero target-driven: approx. 10 Mtpa of carbon capture by the NZT project by 2030 and 170 Mtpa of carbon capture by the entire UK by 2050. This level of UK-wide deployment is consistent with the Climate Change Committee's Further Ambition scenario (net-zero report, 2019). Global deployment scenario is based on the IEA ETP 2-degree scenario. | GVA and employment multipliers (for direct benefits): Estimate turnover based on CCUS deployment aligned with net zero, determine level of UK content by component (based on UK market share of similar goods and services today), estimate turnover captured by UK firms, estimate GVA and jobs from captured turnover using GVA multipliers and GVA per worker ratios from the ONS Annual Business Survey (ABS) (2019). I/O macroeconomic modelling (for indirect and induced benefits). |
| *Hy-Impact Series Study 1: Hydrogen for economic growth Unlocking jobs and GVA whilst reducing emissions in the UK.* Element Energy (2019) | Emissions/net-zero target-driven: Key model input is the demand for technologies, goods, and services under the form of investment and OPEX to meet a projected volume of $CO_2$ capture needed to decarbonise each of the UK's main six industrial clusters. CCUS uptake scenario in line with two key publications: CCC *2018 Progress Report to Parliament* and *2050 Roadmaps Cross-Sector Summary report* (2015) used in the UK's *Clean Growth Strategy* (2017). | GVA and employment multipliers: Direct jobs calculated based on the relationship between UK gross output and the Labour Intensity for the relevant industries based on the ONS ABS. Indirect jobs calculated based on the number of direct jobs and employment multipliers provided by the UK Input-Output Tables (IOTs). GVA calculated based on the UK gross output, using industry specific multipliers provided by the UK IOTs, following the calculation methodology published by the ONS. |
| *Energy Innovation Needs Assessment – Sub-Theme Report: CCUS.* Vivid Economics (2019b) | Emissions/net-zero target-driven: Domestic CCUS deployment scenario based on ESME modelling (a peer-reviewed whole energy system model that derives cost-optimal energy system pathways to 2050) consistent with an 80% reduction in UK GHG emissions by 2050. Global and regional CCUS markets to 2050 sized based on deployment forecasts which come from the IEA 2-degree scenario. | GVA and employment multipliers: 1) Market to 2050 sized based on deployment and cost estimates; 2) tradability of the markets estimated based on current trade data, where available, and informed by expert judgement; 3) UK's share of the tradable market, estimated based on current trade data, research and expert consultation to calculate UK captured turnover; 4) UK-captured turnover figure multiplied by a GVA/turnover multiplier which most closely resembles the market to obtain GVA; 5) GVA figure is divided by productivity figures for that sector to obtain jobs supported. |
| *Caledonia Clean Energy Project – Feasibility Study Phase 2 Final Report.* Summit Power Caledonia (2018) | Investment-driven: Not explicit in the report but the starting point of the study is the development of a CCS plant with a portfolio of defined investments. | I/O macroeconomic modelling: Not explicit in the report but assumed same as in the previous Summit Power report (2017), calibrated to project-level only. |
| *Potential Economic Impacts of the HyNet North West Project.* Amion Consulting (2018) | Investment-driven: CAPEX and OPEX profiles of the pre-defined project investment defined as the basis of analysis, distinguishing where feasible between design, construction and equipment costs, and establishing the likely sourcing of these activities from within the North West, UK and overseas. | I/O macroeconomic modelling: CAPEX and OPEX investment and expenditure profiles are integrated into the UK IOTs, which are used as the basis for assessing the nature and level of inputs. IOTs provide the basis on which expenditure is allocated between labour and intermediate inputs. Employment numbers based on industry specific wage costs sourced from ONS datasets. |

| Report title | Scenario | Key methodology |
|---|---|---|
| *Clean Air – Clean Industry – Clean Growth: How carbon capture will boost the UK economy.* Summit Power (2017) | **Emissions/net-zero target-driven:** Amount of CCS capacity in line with the UK 2050 emissions reductions targets (at the time of the study this was 80% reduction) and an allocation of this capacity to the East Coast. East Coast capacity further allocated between four CCS sectors located in four clusters (Scotland, Teesside, Humber-Yorkshire and Southeast England), reflecting the outputs and geographical distribution of these sectors. | **I/O macroeconomic modelling:** Outputs: costs of CCS, jobs potential, GVA, balance of trade (BoT), health and wellbeing benefits, and value of avoided $CO_2$ emissions.<br>Inputs: CAPEX, OPEX, operation and performance of the CCS investments, and quantities of $CO_2$ avoided through the assumed economic lifetime. GVA estimated using ONS statistical data 'Output per Job' and applying this to the direct and indirect jobs created and retained by selecting the relevant manufacturing and services subsections. |
| *The Economic Benefits of Carbon Capture and Storage in the UK.* TUC and CCSA (2014) | **Emissions/net-zero target-driven:** Translate CCSA's projection of CCS-installed capacity required in the UK by 2030 to meet UK emissions targets (10–20 GW), into number of CCS plant installations to 2030 (15–25). | **GVA and employment multipliers:** Projected new CCS installations to 2030 multiplied by existing estimates of job generation per plant installation. GVA calculation is based on AEA figures (see report below) for labour input per GW CCS installation (280,000 man years for cumulative 10 GW installation) and using an estimate of the proportion of UK supply chain content in UK CCS projects. |
| *Assessing the Domestic Supply Chain Barriers to the Commercial Deployment of Carbon Capture and Storage Within the Power Sector.* AEA Technology plc (2012) | **Emissions/net-zero target-driven:** Projections of CCS capacity and technology mix in the UK based on the UK's Carbon Plan at the time and was agreed with DECC [the then-Department for Energy and Climate Change]. Cumulative CCS capacities: 2 GW by 2020, 3 GW by 2025, 10 GW by 2030. | **I/O macroeconomic modelling:** Supply chain model constructed in order to quantify CCS market demand, capability of the UK CCS supply chain and corresponding maximum potentials for UK supply chain growth. Model flexible to investigate different deployment levels and technologies. |

*Source: Authors. Certain assumptions and simplifications have been made to categorise studies in an attempt to facilitate comparisons across estimated economic impacts – any errors in the interpretations of the studies are the authors' alone.*

The scenarios and methodologies employed can be grouped into categories, providing a framework for understanding the types of evidence available.

The **scenario categories** identified among this selection of studies can be defined as:

a) **Investment-driven** – by assumptions on benefits triggered by a specific investment envelope
b) **Market development-driven** – by projections of market growth and UK market share
c) **Emissions/net-zero target-driven** – by the assumption that an emissions/net-zero target is met.

The **methodology categories** are defined as:

a) **Computable General Equilibrium (CGE) modelling:** An analytically consistent mathematical representation of an economy, CGE modelling comprises a detailed database of economy-wide data, which captures the interdependencies across all sectors in the economy at a particular point in time, and a set of equations describing model variables. The model is solved computationally, with an equilibrium being characterised by a set of prices and level of production across all sectors, such that demand equals supply for all commodities simultaneously (UKERC, 2014).
b) **Input/output (I/O) macroeconomic modelling:** I/O modelling uses a set of IO accounts for an economy, which identify the monetary linkages between production sectors and between production sectors and consumers of output, to model the economy-wide impact of exogenous final demand disturbances (UKERC, 2014).
c) **Employment multiplier modelling:** This multiplies projected capital or market size by ex-post estimates of labour intensity.

**Table A3.** Data and assumptions underlying Figure 3.1 (annual average jobs from CCUS in the UK during construction)

| Deploy-ment scope | Study | No. of jobs | | | | | Jobs coverage | Assumptions |
|---|---|---|---|---|---|---|---|---|
| | | Direct jobs | Indirect jobs | Induced jobs | Direct + indirect | Total | | |
| One project | TUC and CCSA (2014) | | | | 1,750 | 1,750 | Not specified – assumed direct and indirect due to statement "associated supply chain" | Figures taken directly from report (central figure of provided range) |
| | Summit Power Caledonia (2018) | 1,500 | 1,350 | 650 | | 3,500 | Direct, indirect and induced | Figures taken directly from report (central figures of provided ranges) |
| Four storage sites | Turner et al. (2020) | 2,775 | | | | 2,775 | Direct | Figures taken directly from report (central figure of provided range) |
| Cluster | Vivid Economics (2020) | 4,524 | 4,500 | 9,000 | | 18,024 | Direct, indirect and induced | Figures taken directly from report (high and low scenarios only available for direct jobs) |
| | Amion Consulting (2018) | | | | | 23,167 | Direct, indirect and induced | Peak jobs used – assumed to happen during construction (not directly comparable with other studies) |
| | Vivid Economics (2021) | 14,900 | 6,649 | 10,185 | | 31,734 | Direct, indirect and induced | Figures taken directly from report |
| UK-wide | AFRY (2021) – Ten Point Plan | | | | 5,000 | | Direct and indirect – covers direct expenditure and supply chain impacts | Peak jobs used – approximate figure |
| | AFRY (2021) – Net Zero Ambition | | | | 10,000 | | Direct and indirect – covers direct expenditure and supply chain impacts | Peak jobs used – approximate figure |
| | Vivid Economics (2020) | 15,000 | | | | 15,000 | Direct | Peak jobs used – approximate figure corresponding to CAPEX peak based on chart (domestic market only, OPEX jobs excluded) |
| | Vivid Economics (2021) | 23,114 | 50,584 | 48,457 | | 122,155 | Direct, indirect and induced | Figures taken directly from report |

**Table A4.** Data and assumptions underlying Figure 3.2 (cumulative jobs from UK-wide CCUS deployment)

| Study | No. of jobs | By year? | Jobs coverage | Notes |
|---|---|---|---|---|
| AFRY (2021) – *Net Zero Ambition* | 8,300 | 2030 | Direct and indirect – covers direct expenditure and supply chain impacts | Figures taken directly from report (as a sum of sectoral impacts on employment in Exhibit 3.10) |
| TUC and CCSA (2014) | 22,500 | 2030 | Not specified – assumed direct and indirect due to statement "associated supply chain" | Figures taken directly from report (central as an average of high and low) |
| Jung and Murphy (2020) | 25,000 | 2030 | Direct | Figures taken directly from report |
| AEA Technology plc (2012) | 27,710 | 2030 | Not specified – assumed direct and indirect due to statement "supply chain jobs" | No. of jobs assumed as 10% of job years |
| Vivid Economics (2020) | 30,752 | 2030 | Direct | Peak jobs used (domestic and export markets combined) |
| Hydrogen Taskforce (2020) | 10,482 | 2035 | Direct and indirect | Figures taken directly from report |
| Vivid Economics (2021) | 193,098 | 2039 | Direct, indirect and induced | Peak jobs used |
| Vivid Economics (2019b) | 58,000 | 2040 | Direct | Figures taken directly from report (domestic and export markets combined) |
| Element Energy (2019) | 43,000 | 2050 | Direct and indirect | Figures taken directly from report |

# Appendix B

## Methodology for and further data emerging from the global trade data analysis

### Defining the list of CCUS-related products used in the global trade data analysis

In Section 4, we present our analysis applying work by Hidalgo et al. (2007a) and Mealy and Teytelboym (2020) to a set of 107 traded products identified as relevant to CCUS. These products are defined in the Harmonised System (HS), which is a multipurpose international nomenclature developed by the World Customs Organization for the classification of products, commonly used by participating countries for customs purposes. The HS comprises more than 5,000 products identified by a six-digit code.

The UN Trade Statistics website (UN Comtrade Admin, 2017) provides detail on the HS that is relevant for understanding our methodology laid out further below:

> *The HS comprises approximately 5,300 article/product descriptions that appear as headings and subheadings, arranged in 99 chapters, grouped in 21 sections. The six digits can be broken down into three parts. The first two digits (HS-2) identify the chapter the goods are classified in, e.g. 09 = Coffee, Tea, Maté and Spices. The next two digits (HS-4) identify groupings within that chapter, e.g. 09.02 = Tea, whether or not flavoured. The next two digits (HS-6) are even more specific, e.g. 09.02.10 Green tea (not fermented) ... Up to the HS-6 digit level, all countries classify products in the same way (a few exceptions exist where some countries apply old versions of the HS).*
>
> *The Harmonized System was introduced in 1988 and has been adopted by most of the countries worldwide. It has undergone several changes in the classification of products. These changes are called revisions and entered into force in 1996, 2002, 2007, 2012 and 2017.*

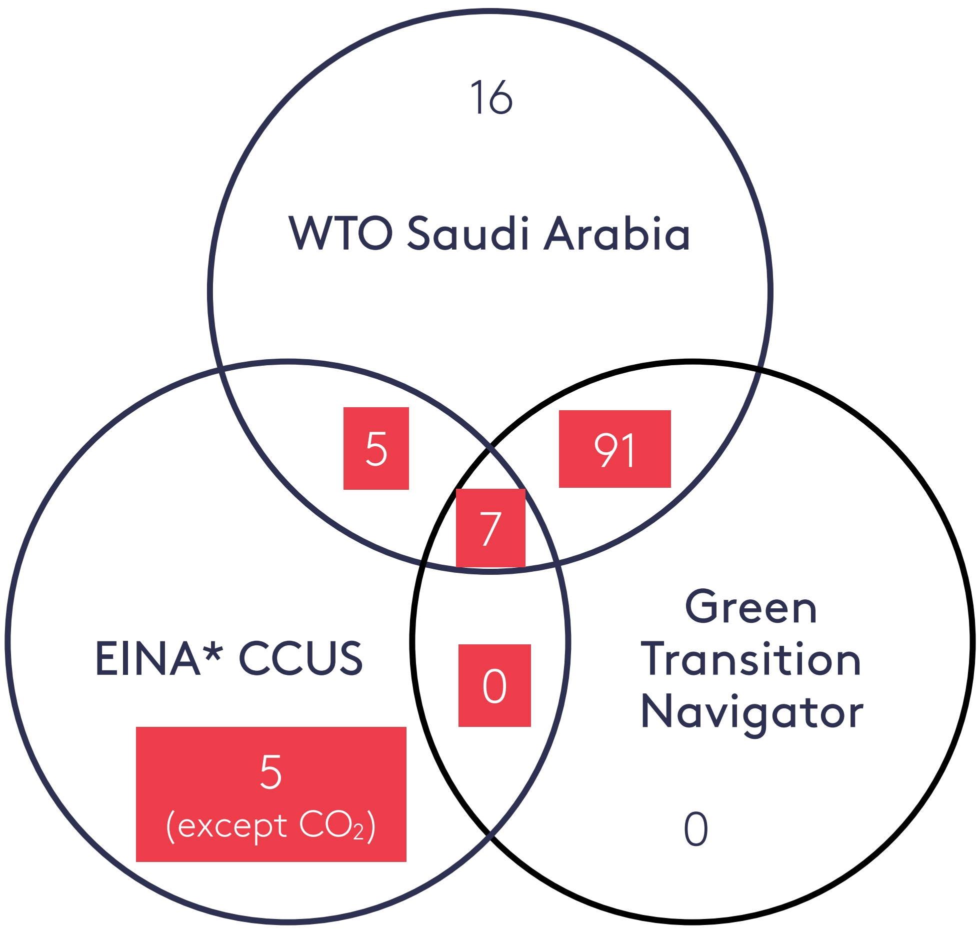
We draw our list of CCUS-related products (provided in the HS six-digit level) from three sources:

- **Green Transition Navigator (GTN) (Andres and Mealy, 2021):** a list of 98 products classified under 'Efficient Consumption of Energy Technologies and Carbon Capture and Storage'
- **Energy Innovation Needs Assessment (EINA) CCUS sub-theme (Vivid Economics, 2019b):** a list of 17 products related to CCUS (used in various combinations for the different pieces of analysis included in the report; details are provided in the footnotes of the report)
- **Saudi Arabia's submission to WTO (Doha round negotiations on environmental goods and services) (Balineau and de Melo, 2011):** a list of 263 products related to CCS

The way we merge the products from the three sources to arrive at our final list of 107 CCUS-related products aims to ensure wide environmental endorsement and validation of CCUS-relatedness of each product while removing any potential conflicts of interest due to trade-driven motivations. For this, we take all products included in at least two of the three lists, plus those unique to the EINA list (except $CO_2$). Our merging logic is illustrated in Figure B1 below, where the boxes highlighted in red demonstrate the final list of 107 products we include in our analysis (despite being in the EINA list, $CO_2$ is excluded from our list). Our reasoning for this merging logic is laid out further below.

Before we merge the lists, in cases where the source provides the products in a different revision, we convert them to their HS1988/1992 equivalent based on the Conversion and Correlation Tables provided by the UN (Trade Statistics Branch, n.d.). HS codes of most products at hand remain unchanged through the revisions (i.e. 1:1 correlation) and therefore the conversion does not make any practical difference but there are a small number of cases where a certain code is broken down into multiple classes in a future revision or vice versa. We take an exhaustive approach when making the conversion between revisions whereby if a code in a future revision corresponds to multiple codes in HS1992 (i.e. 1:n correlation), we include any additional corresponding code(s) as well. Therefore, the number of codes we report as being contained in a source might vary slightly from how many codes exist in the source originally.

**Figure B1.** Illustration of our merging logic to arrive at the list of 107 CCUS-related products included in the global trade data analysis

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The Green Transition Navigator (GTN) list is a combination of products found in previous attempts to develop lists of products with environmental benefits – namely by the OECD, WTO and APEC (where the WTO and APEC lists were created specifically for trade negotiation purposes). The specific logic used in the GTN to combine the lists means each product in the GTN list has either been endorsed by many WTO or APEC member countries, or its environmental benefits have been determined by the (rather selective) OECD. Therefore, the products that are in the intersection of the WTO Saudi Arabia and GTN lists carry the advantage of also being in at least one of these lists (OECD, APEC, WTO) that arguably have broader environmental endorsement. However, the GTN list is a combination of products that fall under 'Carbon Capture and Storage' as well as 'Efficient Consumption of Energy Technologies', whereas Saudi Arabia's submission to the WTO is purely in the context of CCS. Focusing on the intersection of the two lists also ensures that only those products from the GTN list that are specific to CCS are kept in the final list to be used in this analysis.

It is important to note our observation that the GTN list did not include any products that were not already in Saudi Arabia's submission to the WTO, and that all products in Saudi Arabia's submission in the context of CCS were in fact also submitted under the 'Efficient Consumption of Energy

Technologies' category during the negotiations – explaining why they were joined up into one category in the GTN in the first place.

Excluding products unique to Saudi Arabia's submission to the WTO ensures wide environmental endorsement of the CCS products at hand, given the strong overlap between CCUS and traditional oil and gas supply chains. This is in the context of the following criticism: "Criticism was also aimed at the Saudi proposal for its inclusion of a large number of 'dual-use' products – particularly those related to natural gas derivatives and natural-gas related technologies. The Saudis however reportedly clarified their submission as a starting basis for discussions and that the products made sense from a 'value-chain' perspective" (ICTSD, 2010).

Keeping all products included in the EINA list (except $CO_2$) regardless of their inclusion in the other two lists is because the EINA makes an assessment from an impartial standpoint (unlike Saudi Arabia's submission, which might naturally carry conflicts of interest) and in the specific context of CCS (as opposed to part of a wider attempt at defining environmental products), meaning it could help capture any dual-use products (i.e. between CCS and oil and gas) that have not made it into a widely accepted classification of green but still relate to CCS. Despite being in the EINA list, $CO_2$ (HS281121) is not included in our final list of 107 products since usage of the captured $CO_2$ is outside the scope of our analysis and importing $CO_2$ for permanent storage is not yet a working concept for us to be analysing associated trade flows.

While our analysis of export shares and country-level strengths and opportunities is based on the full list of 107 products identified as related to CCUS, our analysis of Revealed Comparative Advantage at the product level is for a 'core' list of seven products that exist in all three sources from which we have drawn our CCUS-related products. These seven products are identified by the following six-digit HS codes: 841480; 841490; 842139; 842199; 901580; 902620; 902690.

For the export share analysis, we aggregate the 107 products into five categories based on their HS two-digit code parents. The five categories are provided below with the two-digit HS code parents they each cover. Multiple code parents are grouped together in two cases for simplification purposes.

- **Chemicals:** 'Chemical products n.e.s. [not elsewhere specified]' and 'Plastics and articles thereof'
- **Metal parts and structures (tubes, pipes, tanks, etc.):** 'Iron or steel articles', 'Aluminium and articles thereof', and 'Ships, boats and floating structures' (the latter includes only one code, which is 'Floating or submersible drilling or production platforms')
- **Mechanical machinery:** 'Nuclear reactors, boilers, machinery and mechanical appliances; parts thereof'
- **Electrical machinery:** 'Electrical machinery and equipment and parts thereof; sound recorders and reproducers; television image and sound recorders and reproducers, parts and accessories of such articles'
- **Measuring, monitoring and verification (MMV) instruments:** 'Optical, photographic, cinematographic, measuring, checking, medical or surgical instruments and apparatus; parts and accessories'

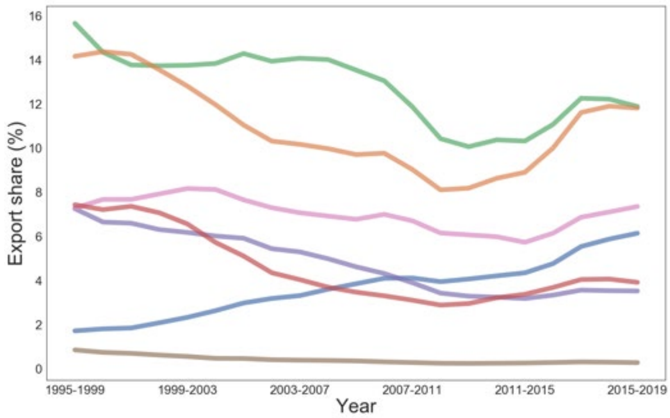
## Trends in country-level export shares in CCUS-related product categories

The following plots show trends from 1995–99 to 2015–19 in country-level shares of global exports for our 107 CCUS-related products, disaggregated to the five product categories detailed above, for the UK, China, France, Germany, Japan, Norway and the US.

**Figure B2.** Trends in country-level export shares in CCUS-related product categories, 1995–99 to 2015–19

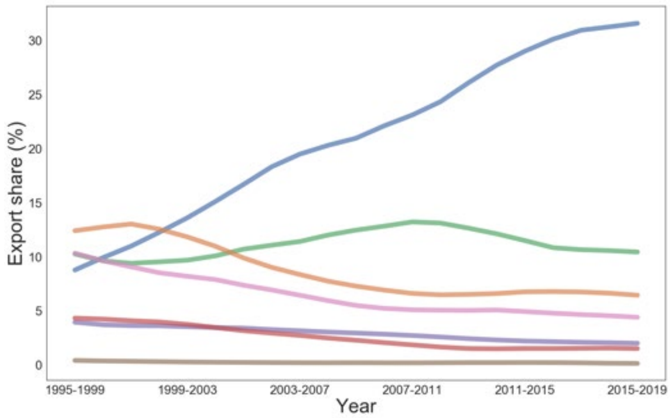
Legend applies to following five plots:


### Chemicals



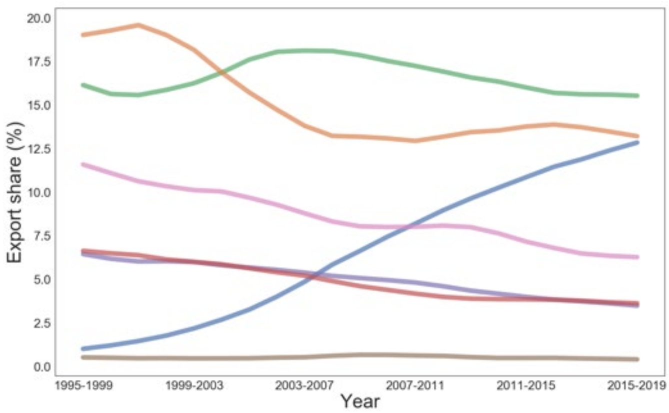

China's share in global exports of CCUS-related chemicals increased slightly from about 2% to 6%, but this increase was much less pronounced than in other categories. Germany and the US dominate; both saw a fluctuating trend in export shares, followed by an upwards trend from 2011–15. The UK's share was low, but increased slightly in recent years after an initial decline.

### Electrical machinery



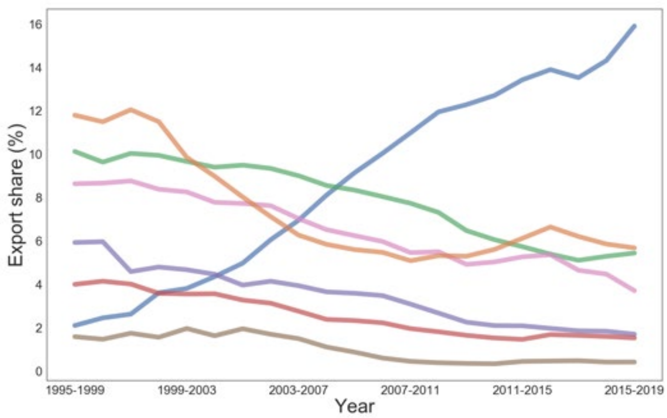

China's share in exports of CCUS-related electrical machinery rose dramatically from about 8% to over 30% through the period. Germany held its share of about 10%, while the US's share declined. The UK was near the bottom and experienced a declining trend.

### Mechanical machinery




Germany maintained a market share of about 16% in CCUS-related mechanical machinery throughout the period, with some degree of fluctuation, while the US lost market share and appeared to be on the verge of being overtaken by China at the end of the period. The UK's export share was near the bottom and declined throughout the study period.

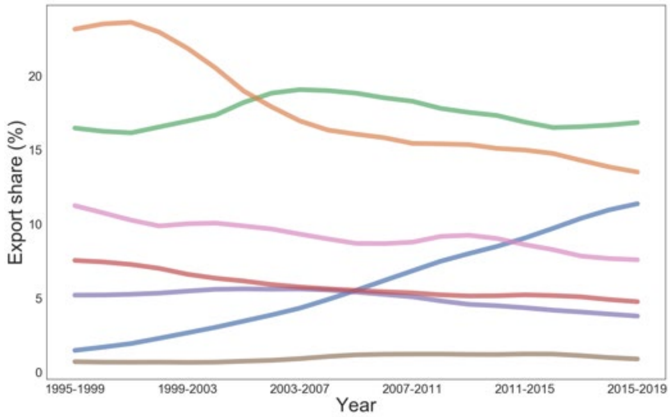
### Metal parts and structures




China's share in exports of CCUS-related metal parts and structures also rose significantly, from 2% to 16%, while it declined for the other countries considered. China clearly dominated in this area. The UK's share was near the bottom.

Figure B2. (cont.)

## Measuring, monitoring and verification (MMV) instruments




The UK's share in global exports of CCUS-related MMV[16] instruments declined from around 7% of global trade to about 5% over the period. China increased its export share from almost 0 to over 10%. Germany and the US remained dominant at the end of the period but seemed to run the risk of being overtaken by China: in particular, Germany's export share fell from over 20% to under 15%.

[16] Components in the MMV category are relevant across $CO_2$ capture, transport and storage processes. Examples include oceanographic surveying equipment; thermometers and hydrometers; instruments for measuring or checking the flow or level of gases/liquids; gas and liquid supply meters; hydraulic regulating or controlling instruments.

## Results underlying Figure 4.5 (Existing strengths and potential opportunities in CCUS for the UK)

Table B1 below provides the list of 107 CCUS-related products we consider in our global trade analysis, alongside their HS descriptions as well as their respective **revealed comparative advantage (RCA)**, **Product Complexity Index (PCI)** and **proximity results** for the UK underlying the strengths/opportunities plot (Figure 4.5) in Section 4 of the report.

Table B1. Existing strengths and potential opportunities in CCUS for the UK

| RCA | PCI | Country-to-product proximity | Category | HS6 | Description |
|---|---|---|---|---|---|
| *Existing strengths* | | | | | |
| **1.674735** | -0.12584 | 0.344003 | Chemicals | 381400 | Solvents and thinners; organic composite solvents and thinners, n.e.s. or included, prepared paint or varnish removers |
| **1.426019** | 1.466726 | 0.339843 | Chemicals | 390940 | Phenolic resins; in primary forms |
| **1.099524** | 0.126517 | 0.335425 | Metal parts and structures (tubes, pipes, tanks, etc.) | 730900 | Reservoirs, tanks, vats and similar containers; for any material (excluding compressed or liquefied gas), of iron or steel, capacity exceeding 300l, whether or not lined or heat insulated |
| **1.620206** | -0.20102 | 0.320984 | Metal parts and structures (tubes, pipes, tanks, etc.) | 731029 | Tanks, casks, drums, boxes and similar containers for any material (excluding compressed or liquefied gas) less than 50l capacity, n.e.s. in item no. 7310.2, of iron or steel |
| **1.981341** | -0.0156 | 0.356124 | Metal parts and structures (tubes, pipes, tanks, etc.) | 761100 | Aluminium; reservoirs, tanks, vats and similar containers, for material (not compressed or liquefied gas), of a capacity over 300l, whether or not lined, not fitted with mechanical/thermal equipment |
| **1.072608** | 0.356367 | 0.313565 | Mechanical machinery | 840410 | Boilers; auxiliary plant, for use with boilers of heading no. 8402 or 8403 (e.g. economisers, super-heaters, soot removers, gas recoverers) |
| **1.110205** | 0.933321 | 0.313107 | Mechanical machinery | 840490 | Boilers; parts of auxiliary plant, for use with boilers of heading no. 8402 and 8403 and parts of condensers for steam or other vapour power units |
| **2.806776** | 0.366454 | 0.350716 | Mechanical machinery | 840510 | Generators; producer gas, water gas, acetylene gas and similar water process gas generators, with or without their purifiers |
| **1.403696** | 1.073057 | 0.334509 | Mechanical machinery | 840999 | Engines; parts for internal combustion piston engines (excluding spark-ignition) |
| **2.052986** | -0.15964 | 0.336137 | Mechanical machinery | 841011 | Turbines; hydraulic turbines and water wheels, of a power not exceeding 1,000kW |
| **1.464906** | 0.120594 | 0.32551 | Mechanical machinery | 841012 | Turbines; hydraulic turbines and water wheels, of a power exceeding 1,000kW but not exceeding 10,000kW |

| RCA | PCI | Country-to-product proximity | Category | HS6 | Description |
|---|---|---|---|---|---|
| 2.834345 | -0.45838 | 0.385577 | Mechanical machinery | 841181 | Turbines; gas-turbines (excluding turbo-jets and turbo-propellers), of a power not exceeding 5,000kW |
| 4.993529 | 0.106026 | 0.374552 | Mechanical machinery | 841182 | Turbines; gas-turbines (excluding turbo-jets and turbo-propellers), of a power exceeding 5,000kW |
| 2.295442 | 1.339154 | 0.376403 | Mechanical machinery | 841199 | Turbines; parts of gas turbines (excluding turbo-jets and turbo-propellers) |
| 1.036173 | 0.261614 | 0.352418 | Mechanical machinery | 841280 | Engines; pneumatic power engines and motors, n.e.s. in heading no. 8412 |
| 1.587672 | 0.38462 | 0.334358 | Mechanical machinery | 841320 | Pumps; hand, fitted or designed to be fitted with a measuring device, for liquids, other than those of item no. 8413.11 or 8413.19 |
| 1.190137 | 1.282557 | 0.359781 | Mechanical machinery | 841350 | Pumps; reciprocating positive displacement pumps, n.e.s. in heading no. 8413, for liquids |
| 1.481491 | 1.783434 | 0.365047 | Mechanical machinery | 841360 | Pumps; rotary positive displacement pumps, n.e.s. in heading no. 8413, for liquids |
| 1.201577 | 1.082059 | 0.352969 | Mechanical machinery | 841370 | Pumps; centrifugal, n.e.s. in heading no. 8413, for liquids |
| 1.455939 | 0.470431 | 0.354211 | Mechanical machinery | 841381 | Pumps and liquid elevators; n.e.s. in heading no. 8413 |
| 1.04773 | 1.04582 | 0.356679 | Mechanical machinery | 841410 | Pumps; vacuum |
| 1.229712 | 1.621348 | 0.34573 | Mechanical machinery | 841480 | Pumps and compressors; for air, vacuum or gas, n.e.s. in heading no. 8414 |
| 1.103455 | 1.561577 | 0.351191 | Mechanical machinery | 841490 | Pumps and compressors; parts, of air or vacuum pumps, air or other gas compressors and fans, ventilating or recycling hoods incorporating a fan |
| 1.099668 | 1.204058 | 0.3536 | Mechanical machinery | 841950 | Heat exchange units; not used for domestic purposes |
| 1.044861 | 0.152097 | 0.324245 | Mechanical machinery | 841960 | Machinery; for liquefying air or gas, not used for domestic purposes |
| 1.113813 | 0.78801 | 0.363145 | Mechanical machinery | 842119 | Centrifuges; n.e.s. in heading no. 8421, including centrifugal dryers (but not clothes-dryers) |
| 1.200478 | 0.824579 | 0.368006 | Mechanical machinery | 842121 | Machinery; for filtering or purifying water |
| 2.335352 | 1.48097 | 0.381238 | Mechanical machinery | 842129 | Machinery; for filtering or purifying liquids, n.e.s. in item no. 8421.2 |
| 2.059823 | 1.086221 | 0.354457 | Mechanical machinery | 842139 | Machinery; for filtering or purifying gases, other than intake air filters for internal combustion engines |
| 1.73244 | 0.841576 | 0.371303 | Mechanical machinery | 842191 | Centrifuges; parts thereof, including parts for centrifugal dryers |

| RCA | PCI | Country-to-product proximity | Category | HS6 | Description |
|---|---|---|---|---|---|
| 1.354315 | 1.434393 | 0.357453 | Mechanical machinery | 842199 | Machinery; parts for filtering or purifying liquids or gases |
| 3.801938 | -0.51454 | 0.328625 | Mechanical machinery | 847420 | Machines; for crushing or grinding earth, stone, ores or other mineral substances |
| 2.855074 | 1.192522 | 0.356717 | Mechanical machinery | 848110 | Valves; pressure reducing, for pipes, boiler shells, tanks, vats or the like |
| 2.280164 | 1.208297 | 0.355047 | Mechanical machinery | 848130 | Valves; check valves, for pipes, boiler shells, tanks, vats or the like |
| 1.956587 | 1.356801 | 0.38181 | Mechanical machinery | 848140 | Valves; safety or relief valves, for pipes, boiler shells, tanks, vats or the like |
| 1.222524 | 1.44156 | 0.336872 | Mechanical machinery | 848180 | Taps, cocks, valves and similar appliances; for pipes, boiler shells, tanks, vats or the like, including thermostatically controlled valves |
| 1.408172 | 1.346681 | 0.328164 | Mechanical machinery | 848190 | Taps, cocks, valves and similar appliances; parts thereof |
| 1.026351 | 0.318312 | 0.328086 | Electrical machinery | 850432 | Transformers; n.e.s. in item no. 8504.2, having a power handling capacity exceeding 1kVA but not exceeding 16kVA |
| 1.218669 | 1.296468 | 0.328708 | Electrical machinery | 850590 | Magnets; electro-magnets, holding devices and parts n.e.s. in heading no. 8505 |
| 5.015328 | 0.910863 | 0.340101 | Electrical machinery | 851420 | Furnaces and ovens; industrial or laboratory induction or dielectric |
| 3.449266 | -0.68199 | 0.363431 | MMV instruments | 901540 | Surveying equipment; photogrammetrical surveying instruments and appliances |
| 3.627922 | -0.69258 | 0.375528 | MMV instruments | 901580 | Surveying equipment; articles n.e.s. in heading no. 9015, including hydrographic, oceanographic, hydrological, meteorological or geophysical instruments and appliances (excluding compasses) |
| 3.604125 | -0.90818 | 0.369133 | MMV instruments | 901590 | Surveying equipment; parts and accessories for articles of heading no. 9015 |
| 1.285004 | 0.593581 | 0.347066 | MMV instruments | 902511 | Thermometers and pyrometers; liquid filled, for direct reading, not combined with other instruments |
| 1.41842 | 0.84619 | 0.350283 | MMV instruments | 902519 | Thermometers and pyrometers; (other than liquid filled, for direct reading), not combined with other instruments |
| 1.347196 | 0.737609 | 0.356273 | MMV instruments | 902580 | Hydrometers and similar floating instruments, barometers, hygrometers, psychrometers, thermometers, pyrometers; recording or not, any combination of these instruments (excluding thermometers and barometers not combined with other instruments) |
| 2.447517 | 1.553004 | 0.38955 | MMV instruments | 902610 | Instruments and apparatus; for measuring or checking the flow or level of liquids |

| RCA | PCI | Country-to-product proximity | Category | HS6 | Description |
|---|---|---|---|---|---|
| **2.535284** | 1.438208 | 0.376215 | MMV instruments | 902620 | Instruments and apparatus; for measuring or checking pressure |
| **2.699994** | 1.159222 | 0.36518 | MMV instruments | 902680 | Instruments and apparatus; for measuring or checking variables of liquids or gases (excluding pressure or the flow and level of liquids and those of heading no. 9014, 9015, 9028 and 9032) |
| **1.741479** | 1.256358 | 0.362243 | MMV instruments | 902690 | Instruments and apparatus; parts and accessories for those measuring or checking the flow, level, pressure or other variables of liquids or gases (excluding those of heading no. 9014, 9015, 9028 or 9032) |
| **1.328185** | 0.295457 | 0.332598 | MMV instruments | 902810 | Meters; gas, supply or production meters, including calibrating meters thereof |
| **1.674791** | 0.748329 | 0.394356 | MMV instruments | 903110 | Machines; for balancing mechanical parts |
| **1.409814** | 1.493625 | 0.352018 | MMV instruments | 903180 | Instruments, appliances and machines; for measuring or checking n.e.s. in chapter 90 |
| **2.557143** | 1.340635 | 0.363401 | MMV instruments | 903190 | Instruments, appliances and machines; parts and accessories for those measuring or checking devices of heading no. 9031 |
| **1.127657** | 0.663141 | 0.335324 | MMV instruments | 903210 | Regulating or controlling instruments and apparatus; automatic type, thermostats |
| **1.7377** | 1.744878 | 0.352089 | MMV instruments | 903289 | Regulating or controlling instruments and apparatus; automatic, other than hydraulic or pneumatic |
| **2.228181** | 0.687325 | 0.345237 | MMV instruments | 903290 | Regulating or controlling instruments and apparatus; automatic, parts and accessories |
| **2.444508** | 0.97276 | 0.347098 | MMV instruments | 903300 | Machines and appliances; instruments or apparatus of chapter 90; parts and accessories n.e.s. in chapter 90 |
| *Potential opportunities* | | | | | |
| **0.453147** | -0.29674 | 0.297378 | Metal parts and structures (tubes, pipes, tanks, etc.) | 730300 | Cast iron; tubes, pipes and hollow profiles |
| **0.717187** | -0.07848 | 0.275185 | Metal parts and structures (tubes, pipes, tanks, etc.) | 730410 | Iron or steel (other than cast iron); seamless, line pipe of a kind used for oil or gas pipelines |
| **0.49546** | 0.373047 | 0.304887 | Metal parts and structures (tubes, pipes, tanks, etc.) | 730431 | Iron or non-alloy steel; cold-drawn or cold-rolled, tubes and pipes of circular cross-section |

| RCA | PCI | Country-to-product proximity | Category | HS6 | Description |
|---|---|---|---|---|---|
| **0.736198** | -0.21608 | 0.297726 | Metal parts and structures (tubes, pipes, tanks, etc.) | 730490 | Iron or steel; tubes, pipes and hollow profiles, seamless, n.e.s. in heading no. 7304 |
| **0.612115** | 0.735751 | 0.278349 | Metal parts and structures (tubes, pipes, tanks, etc.) | 730511 | Iron or steel; line pipe of a kind used for oil or gas pipelines, longitudinally submerged arc welded, external diameter exceeds 406.4mm |
| **0.629033** | 0.119348 | 0.259003 | Metal parts and structures (tubes, pipes, tanks, etc.) | 730512 | Iron or steel; line pipe of a kind used for oil or gas pipelines, longitudinally welded external diameter exceeds 406.4mm |
| **0.417392** | -0.48884 | 0.277011 | Metal parts and structures (tubes, pipes, tanks, etc.) | 730630 | Iron or non-alloy steel; tubes and pipes, welded, of circular cross-section |
| **0.800143** | -0.74338 | 0.28862 | Metal parts and structures (tubes, pipes, tanks, etc.) | 730690 | Iron or steel; tubes, pipes and hollow profiles n.e.s. in heading no. 7306 |
| **0.654474** | -0.02782 | 0.317239 | Metal parts and structures (tubes, pipes, tanks, etc.) | 731010 | Tanks, casks, drums, cans, boxes and similar containers, for any material (excluding compressed or liquefied gas), 50l or more capacity but not exceeding 300l |
| **0.808429** | -0.30017 | 0.301577 | Metal parts and structures (tubes, pipes, tanks, etc.) | 731100 | Containers for compressed or liquefied gas, of iron or steel |
| **0.803415** | 0.376799 | 0.286013 | Metal parts and structures (tubes, pipes, tanks, etc.) | 732490 | Iron or steel; sanitary ware and parts thereof, excluding sinks, wash basins and baths |
| **0.796352** | -0.17793 | 0.284416 | Mechanical machinery | 840219 | Boilers; vapour generating boilers, including hybrid boilers n.e.s. in heading no. 8402 |
| **0.203664** | 0.411292 | 0.261911 | Mechanical machinery | 840290 | Boilers; parts of steam or other vapour generating boilers |
| **0.369519** | 0.908312 | 0.26103 | Mechanical machinery | 840420 | Boilers; condensers, for steam or other vapour power units |
| **0.207973** | 0.711572 | 0.273012 | Mechanical machinery | 840619 | Turbines; steam and other vapour turbines, for other than marine propulsion |
| **0.91101** | 0.762813 | 0.30032 | Mechanical machinery | 840690 | Turbines; parts of steam and other vapour turbines |
| **0.635181** | 1.201508 | 0.291216 | Mechanical machinery | 840991 | Engines; parts, suitable for use solely or principally with spark-ignition internal combustion piston engines (for other than aircraft) |
| **0.186345** | 0.081663 | 0.280386 | Mechanical machinery | 841013 | Turbines; hydraulic turbines and water wheels, of a power exceeding 10,000kW |

| RCA | PCI | Country-to-product proximity | Category | HS6 | Description |
|---|---|---|---|---|---|
| 0.282706 | -0.37117 | 0.278995 | Mechanical machinery | 841090 | Turbines; parts of hydraulic turbines and water wheels, including regulators |
| 0.811575 | 0.271205 | 0.294031 | Mechanical machinery | 841290 | Engines; parts, for engines and motors of heading no. 8412 |
| 0.97305 | 0.44677 | 0.295694 | Mechanical machinery | 841780 | Furnaces and ovens; including incinerators, non-electric, for industrial or laboratory use, n.e.s. in heading no. 8417 |
| 0.893334 | 0.779261 | 0.295256 | Mechanical machinery | 841790 | Furnaces and ovens; parts of non-electric furnaces and ovens (including incinerators), of industrial or laboratory use |
| 0.816468 | 1.323667 | 0.299117 | Mechanical machinery | 841939 | Dryers; for products n.e.s. in heading no. 8419, not used for domestic purposes |
| 0.87845 | 0.862483 | 0.283517 | Mechanical machinery | 841940 | Distilling or rectifying plant; not used for domestic purposes |
| 0.670978 | 1.540864 | 0.30849 | Mechanical machinery | 841989 | Machinery, plant and laboratory equipment; for treating materials by change of temperature, other than for making hot drinks or cooking or heating food |
| 0.926526 | 1.259217 | 0.30499 | Mechanical machinery | 841990 | Machinery, plant and laboratory equipment; parts of equipment for treating materials by a process involving a change of temperature |
| 0.737302 | -0.94848 | 0.295744 | Mechanical machinery | 847439 | Machines; for mixing or kneading mineral substances, excluding concrete mixers and machines for mixing mineral substances with bitumen |
| 0.588914 | 0.590824 | 0.291819 | Electrical machinery | 850300 | Electric motors and generators; parts suitable for use solely or principally with the machines of heading no. 8501 or 8502 |
| 0.674763 | 0.312522 | 0.276381 | Electrical machinery | 850410 | Discharge lamps or tubes; ballasts therefor |
| 0.181767 | -0.51748 | 0.291533 | Electrical machinery | 850421 | Electrical transformers; liquid dielectric, having a power handling capacity not exceeding 650kVA |
| 0.323385 | -0.46952 | 0.304916 | Electrical machinery | 850422 | Electrical transformers; liquid dielectric, having a power handling capacity exceeding 650kVA but not exceeding 10,000kVA |
| 0.347687 | -0.33325 | 0.270054 | Electrical machinery | 850423 | Electrical transformers; liquid dielectric, having a power handling capacity exceeding 10,000kVA |
| 0.494804 | -0.56488 | 0.273968 | Electrical machinery | 850431 | Electrical transformers; n.e.s. in item no. 8504.2, having a power handling capacity not exceeding 1kVA |
| 0.426971 | -0.21176 | 0.304793 | Electrical machinery | 850433 | Transformers; n.e.s. in item no. 8504.2, having a power handling capacity exceeding 16kVA but not exceeding 500kVA |

| RCA | PCI | Country-to-product proximity | Category | HS6 | Description |
|---|---|---|---|---|---|
| **0.229567** | 0.126339 | 0.296511 | Electrical machinery | 850434 | Transformers; n.e.s. in item no. 8504.2, having a power handling capacity exceeding 500kVA |
| **0.678477** | 1.576473 | 0.267287 | Electrical machinery | 850440 | Electrical static converters |
| **0.512007** | 0.464723 | 0.286766 | Electrical machinery | 850490 | Electrical transformers, static converters and inductors; parts thereof |
| **0.23345** | 1.278178 | 0.290919 | Electrical machinery | 850880 | Electro-mechanical tools; (other than drills and saws), for working in the hand, with self-contained electric motor |
| **0.496953** | 1.765814 | 0.311449 | Electrical machinery | 851410 | Furnaces and ovens; industrial or laboratory electric, resistance heated |
| **0.31381** | 0.939857 | 0.279703 | Electrical machinery | 851430 | Furnaces and ovens; industrial or laboratory electric, other than induction dielectric or resistance heated |
| **0.369599** | -1.55703 | 0.2762 | Metal parts and structures (tubes, pipes, tanks etc) | 890520 | Floating or submersible drilling or production platforms |
| **0.423574** | 1.186859 | 0.288571 | MMV instruments | 901530 | Surveying equipment; levels |
| **0.934207** | 0.67025 | 0.284646 | MMV instruments | 902820 | Meters; liquid supply or production meters, including calibrating meters thereof |
| **0.793752** | -0.33994 | 0.283648 | MMV instruments | 902830 | Meters; electricity supply or production meters, including calibrating meters thereof |
| **0.696351** | 0.396177 | 0.278561 | MMV instruments | 902890 | Meters; parts and accessories of gas, liquid, electricity supply or production meters, including calibrating meters thereof |
| **0.903103** | 2.280269 | 0.282157 | MMV instruments | 903130 | Profile projectors |
| **0.558788** | 1.509912 | 0.306734 | MMV instruments | 903220 | Regulating or controlling instruments and apparatus; automatic, manostats |
| **0.899833** | 1.114841 | 0.298827 | MMV instruments | 903281 | Regulating or controlling instruments and apparatus; automatic, hydraulic or pneumatic |

### Strengths and opportunities plots for selected key competitors

Plots for the UK and Germany are included in the main report. We present here the plots for the remaining countries identified as key competitors for the UK: China, France, Japan, Norway and the United States.

- Chemicals
- Metal parts and structures (tubes, pipes, tanks etc)
- Mechanical machinery
- Electrical machinery
- MMV instruments
- Bubbles are sized by RCA

Figure B3. Current strengths and potential opportunities in CCUS for China

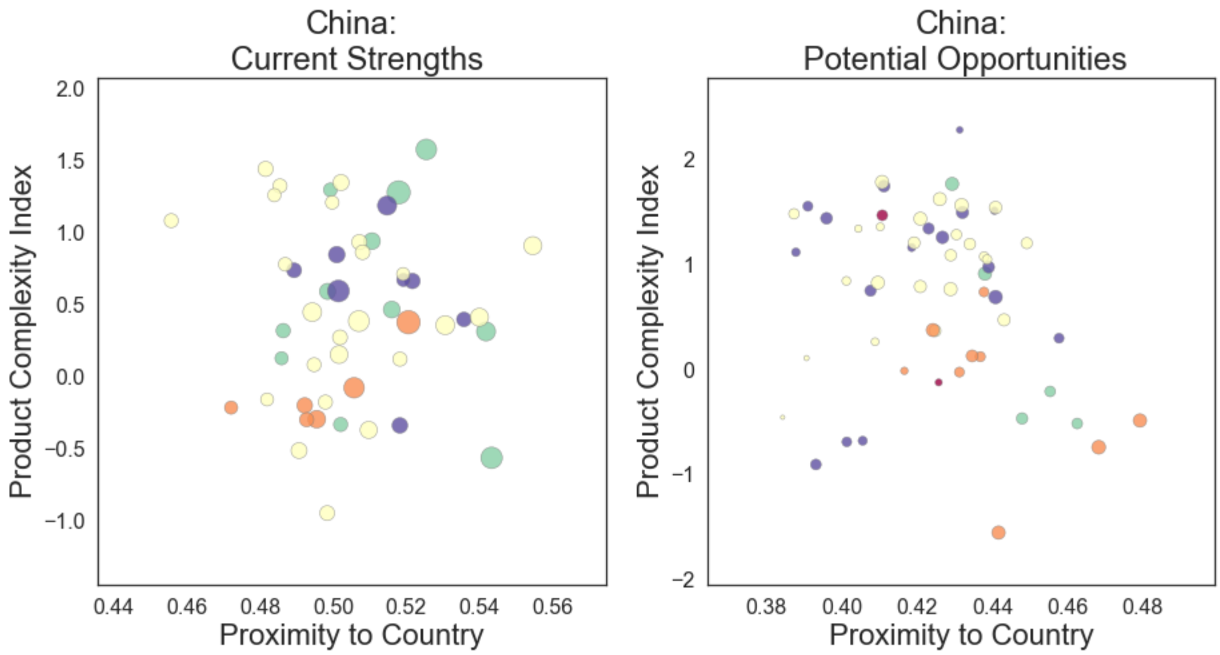



Figure B4. Current strengths and potential opportunities in CCUS for France

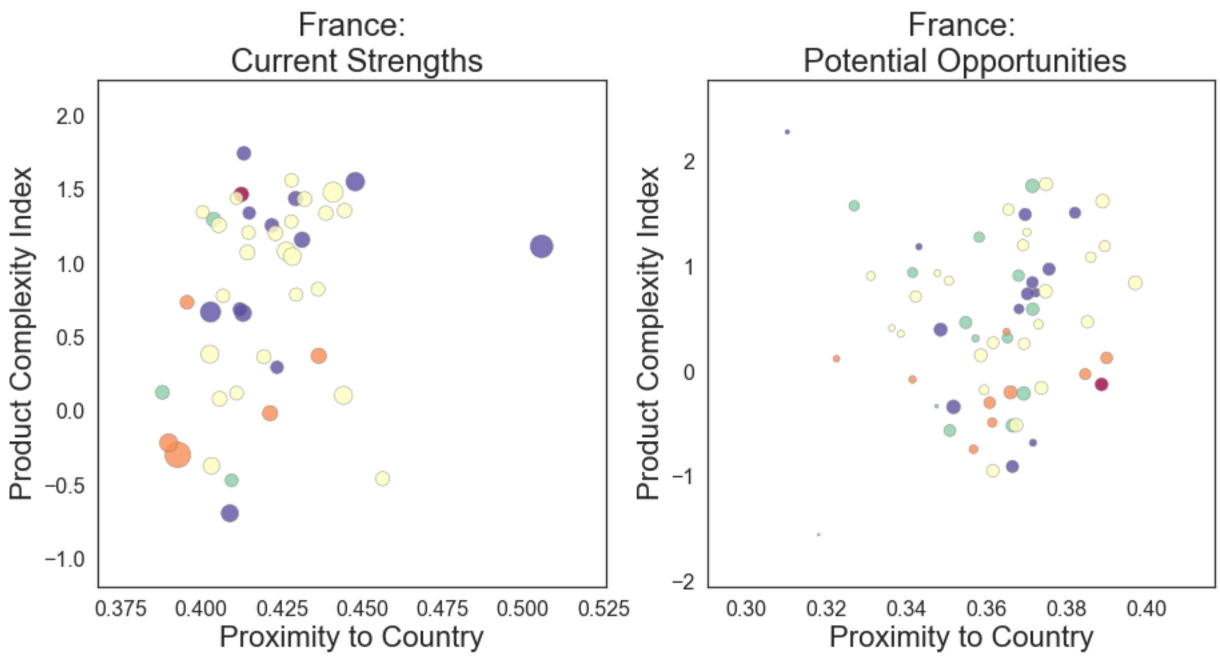



Figure B5. Current strengths and potential opportunities in CCUS for Japan

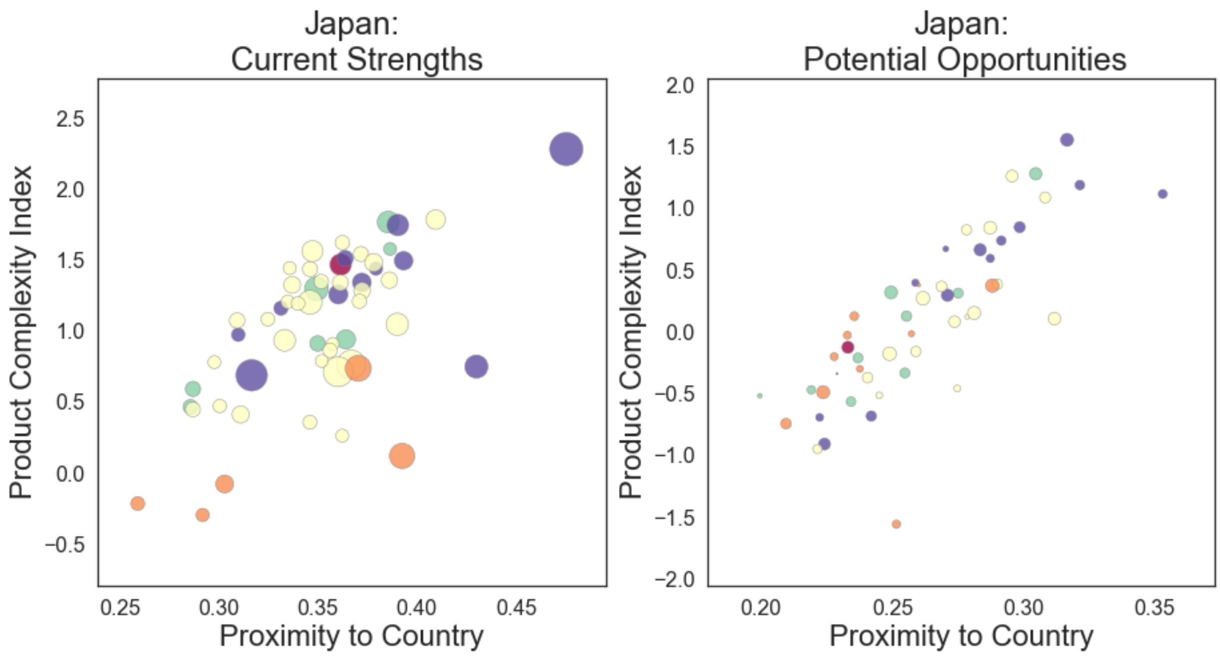
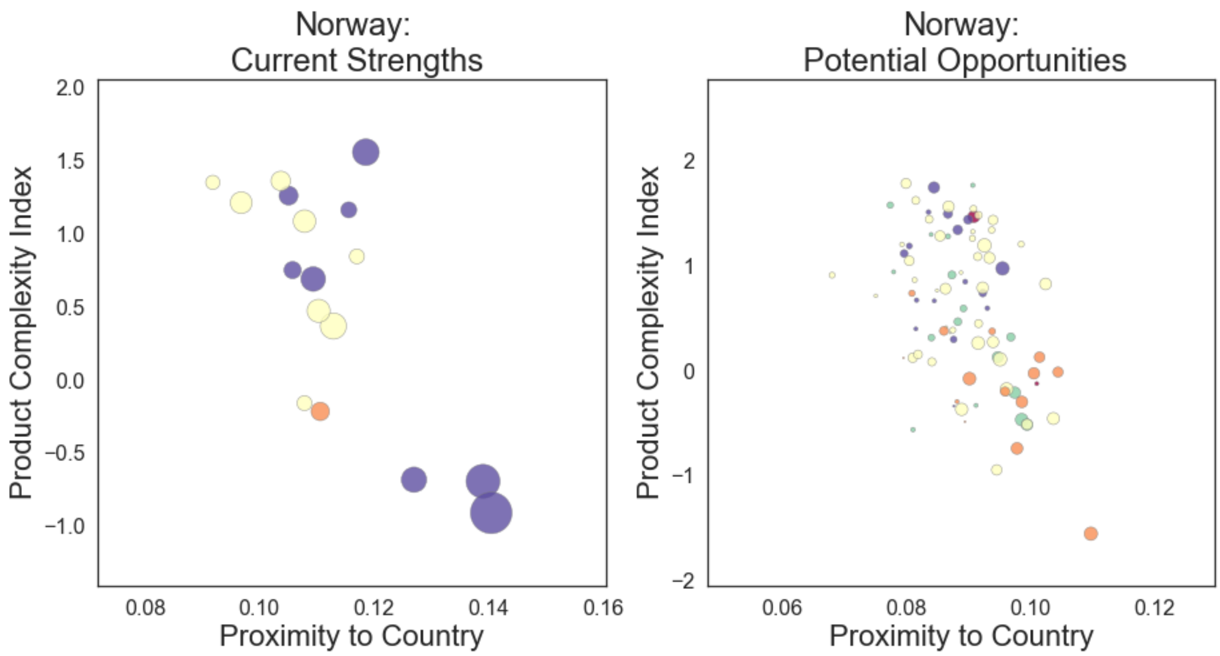



Figure B6. Current strengths and potential opportunities in CCUS for Norway



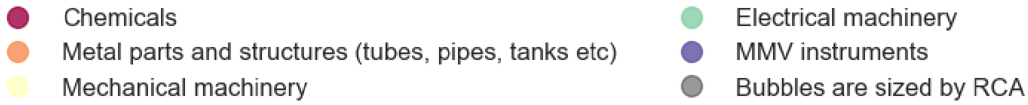
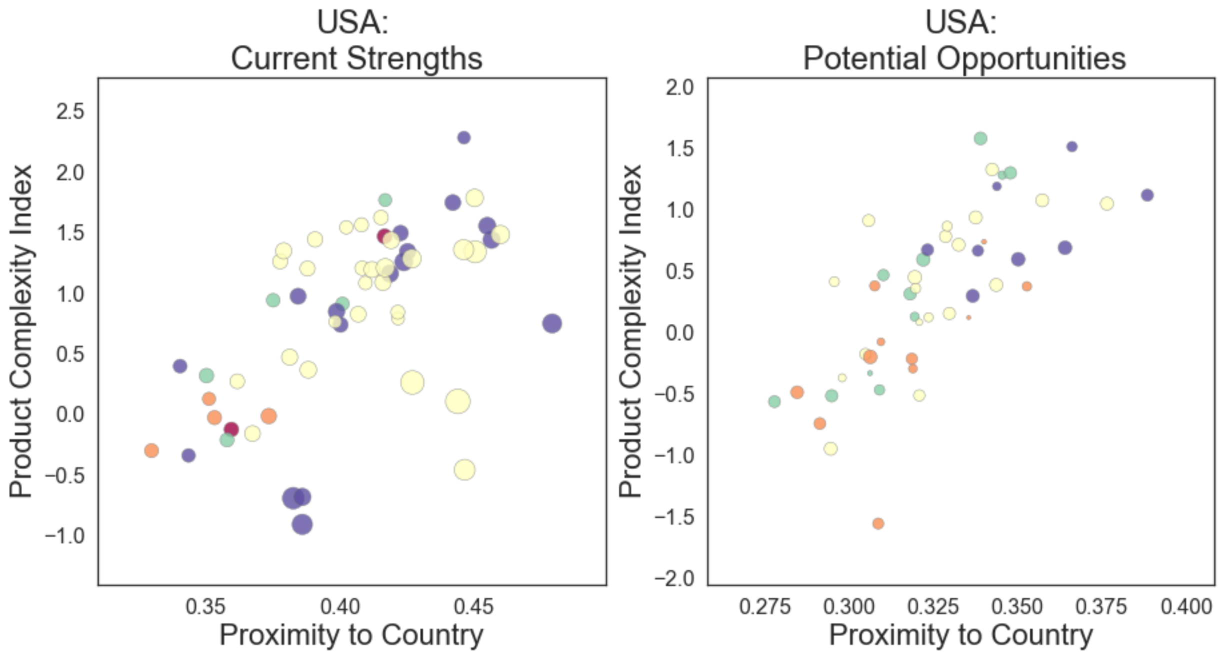


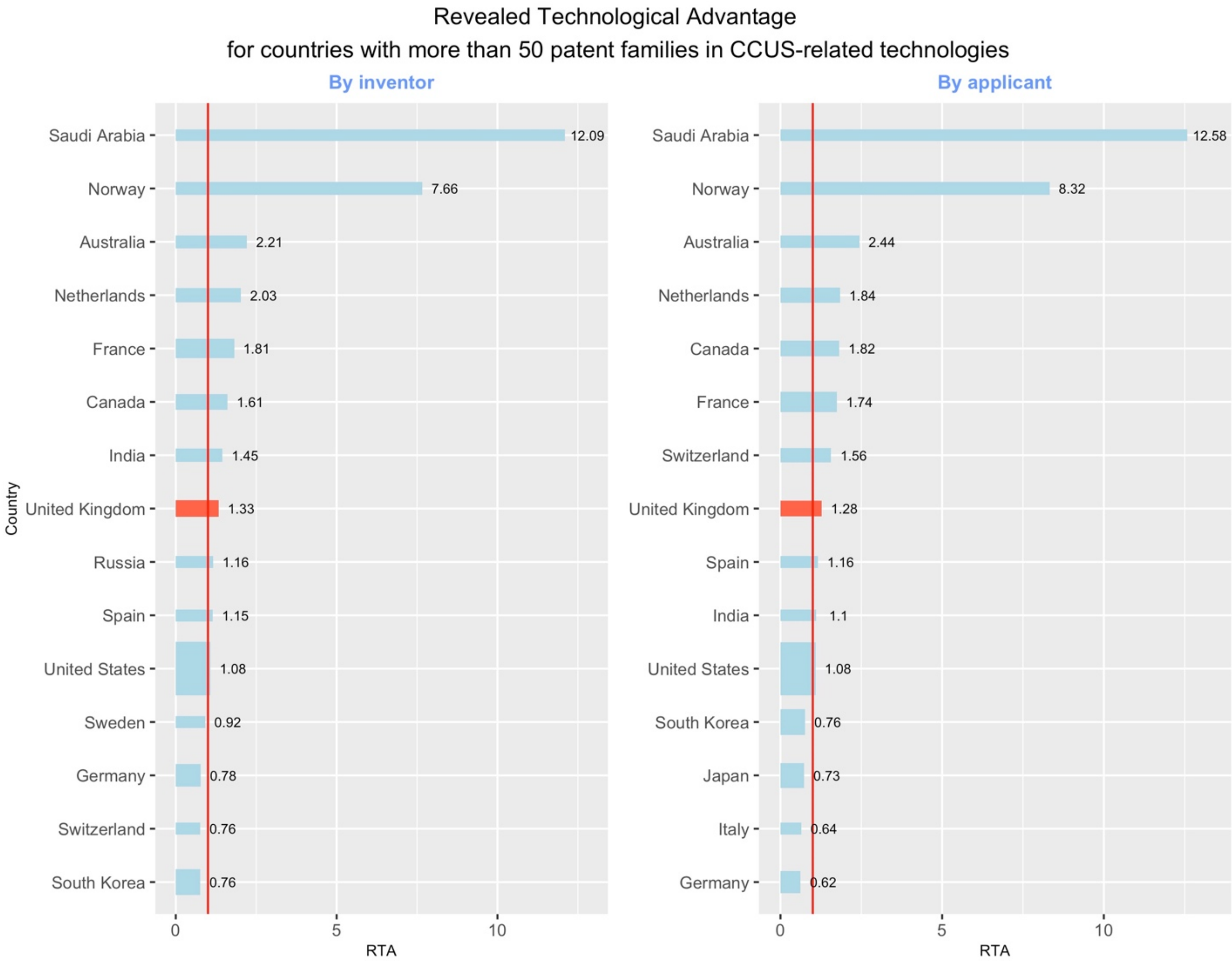

Figure B7. Current strengths and potential opportunities in CCUS for the United States



# Appendix C

## Supplementary plots emerging from patent data analysis

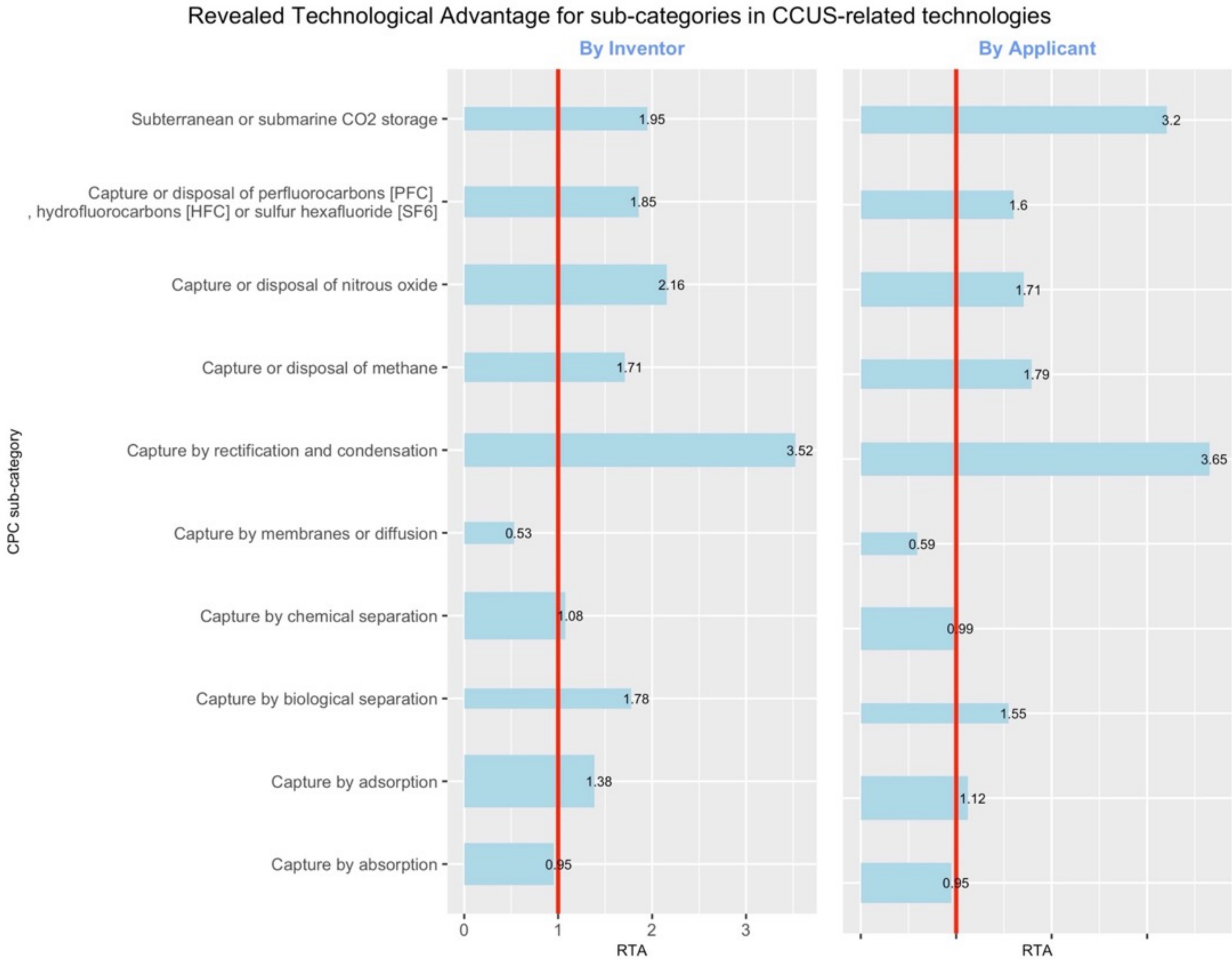
Figure C1. Revealed technological advantage (RTA) of the UK in CCUS-related technologies compared with the rest of the world, 2000–15




*Note: The length of each bar on the horizontal axis shows the RTA; the width of each bar on the vertical axis reflects the number of patents in each category.*

*Source: Authors' estimates based on PATSTAT – 2018 Spring Edition.*

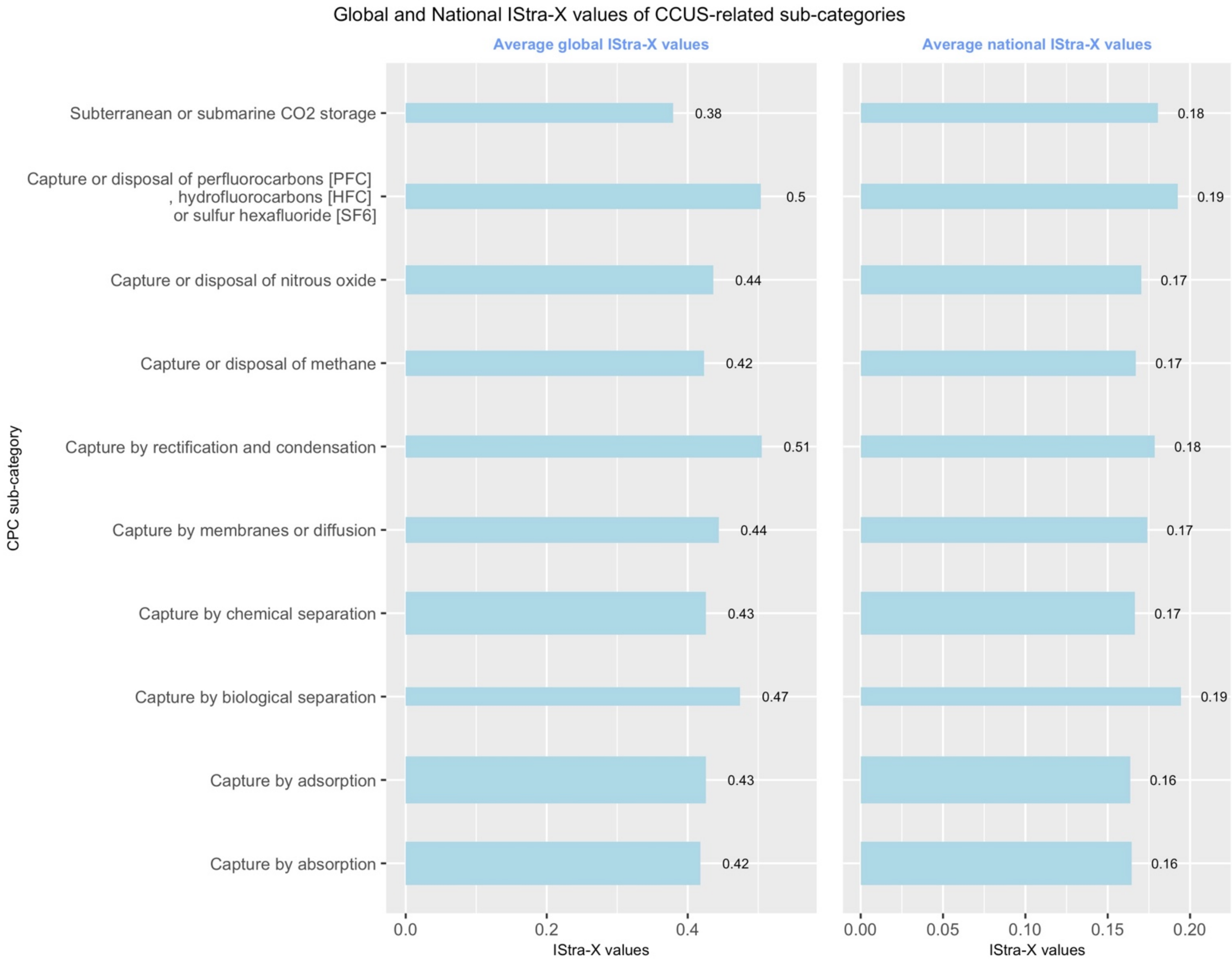
Figure C2. Revealed technological advantage (RTA) of the UK in sub-categories of CCUS, 2000–15




*Note: The length of each bar on the horizontal axis shows the RTA; the width of each bar on the vertical axis reflects the number of patents in each category.*

*Source: Authors' estimates based on PATSTAT – 2018 Spring Edition.*

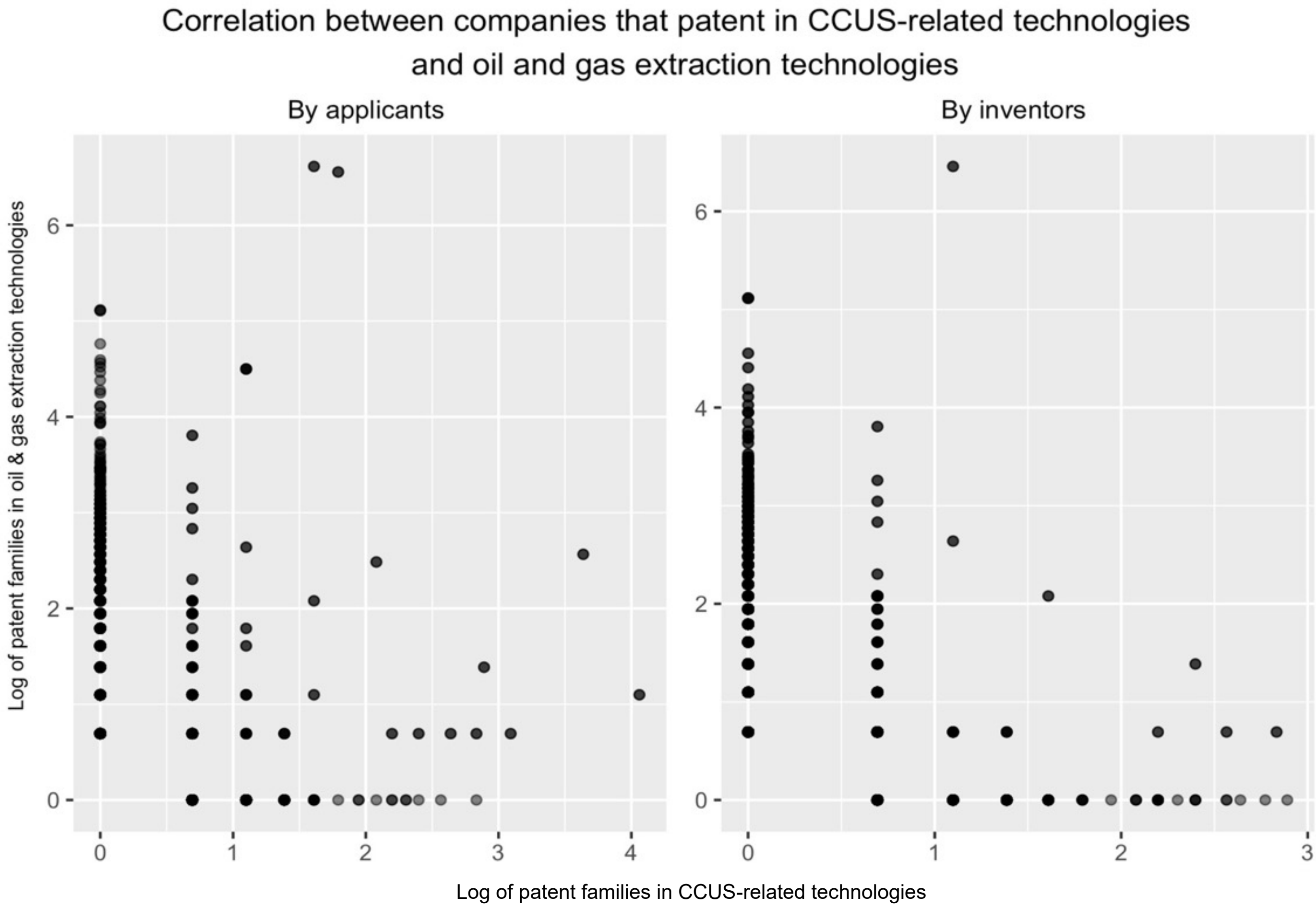
Figure C3. Global and UK returns to public R&D investments across CCUS technologies, 2000–15




*Notes: The figure reports average returns to public R&D subsidies by technology area. The calculations account for direct and indirect knowledge spillovers occurring globally (left) and in the UK (right), variations in private R&D returns, variation in R&D costs and differences in the responsiveness to subsidies between different technology areas. This is based on the 'IStra-X' indicator as developed by Guillard et al. (2021). The length of each bar on the horizontal axis shows the IStra-X value; the depth of each bar on the vertical axis reflects the number of patents in each category.*

*Source: Authors' estimates based on PATSTAT – 2018 Spring Edition.*

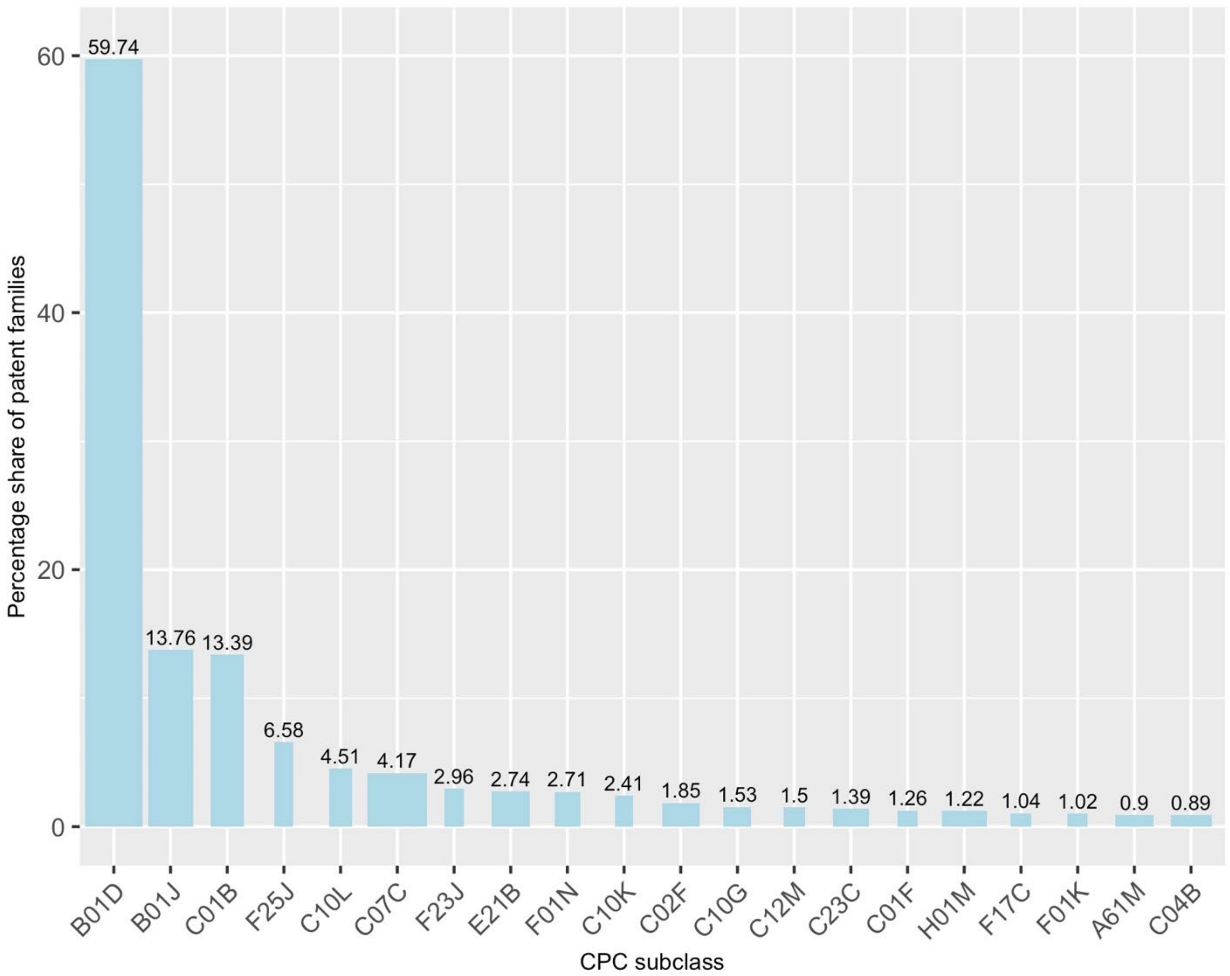
Figure C4. Applicant and inventor-level CCUS versus oil and gas innovation, 2000–15




*Note: The chart plots the log transformed values of patent families in CCUS-related technologies against the log transformed values of patent families in oil and gas extraction technologies, at the applicant and inventor levels respectively. To account for some firms that have 0 patent families, we added 1 to the patent families before the log transformation.*

*Source: Authors' estimates based on PATSTAT – 2018 Spring Edition.*

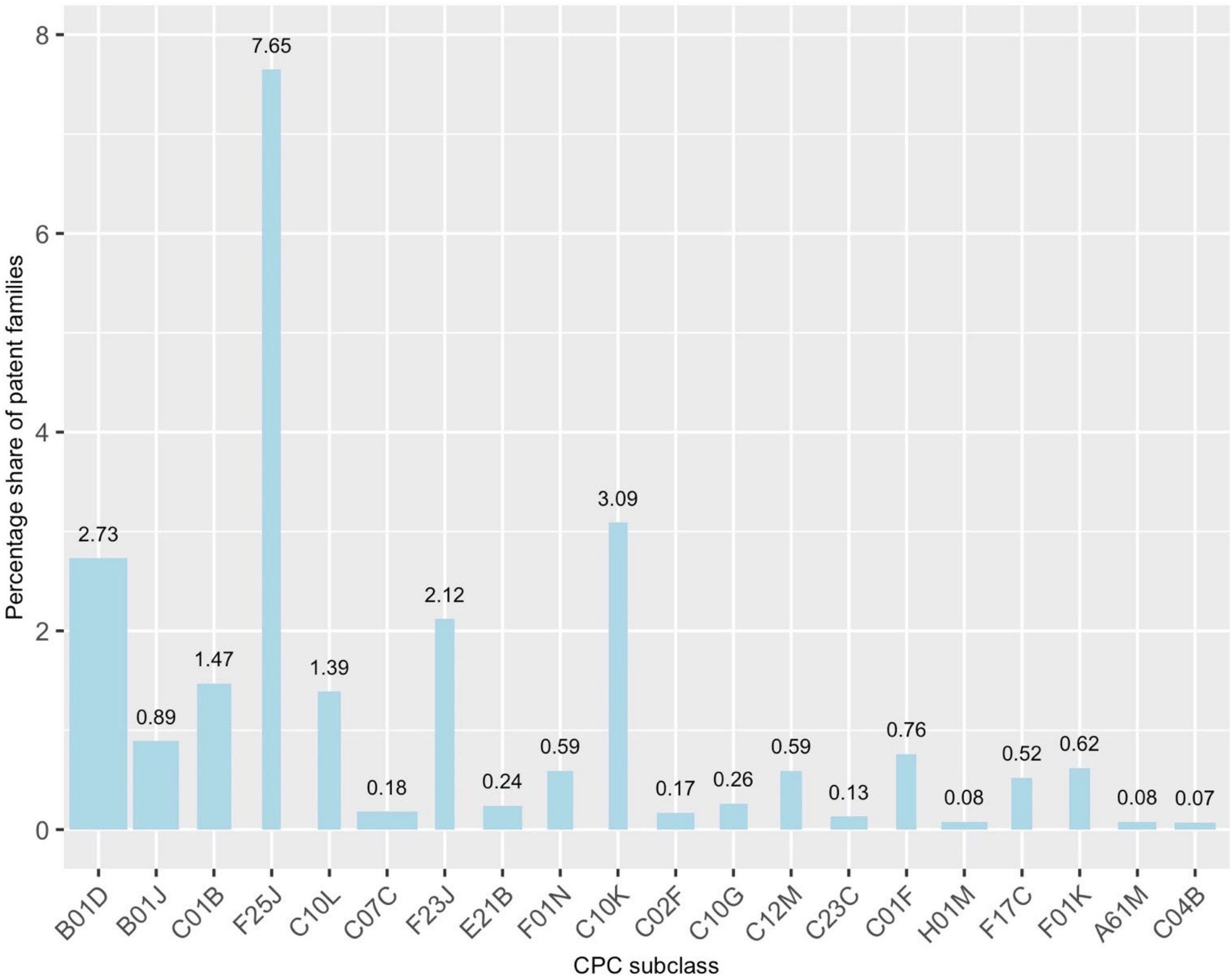
Figure C5. Top CPC subclasses that co-occur with the CCUS-related subclass (Y02C)




*Notes: The figure reports percentage share of patent families in CPC subclass Y02C that are also classified under the CPC subclasses listed on the X-axis. The length of each bar on the vertical axis shows the percentage share of patent families under subclass Y02C that are also classified under the subclass given on the X-axis; the width of each bar on the horizontal axis reflects the number of patent families in each subclass.*

*Source: Authors' estimates based on PATSTAT – 2018 Spring Edition.*

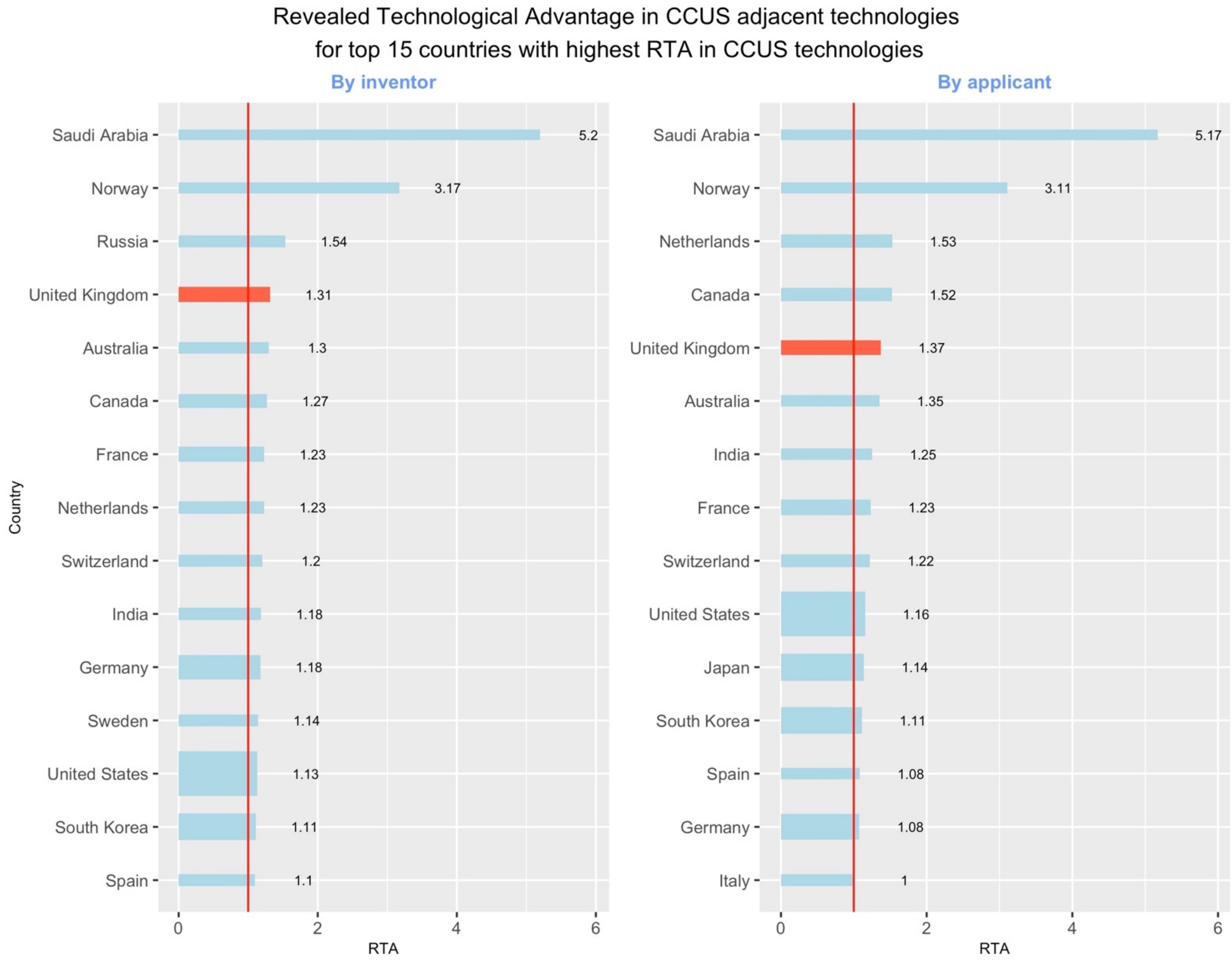
Figure C6. Percentage share of patent families also classified under the CCUS-related subclass (Y02C)




*Notes: The figure reports percentage share of patent families in CPC subclass named on the X-axis that are also classified under the CPC subclass Y02C (i.e., CCUS-related). The length of each bar on the vertical axis shows the percentage share of CCUS-related patent families in the subclass given on X-axis; the width of each bar on the horizontal axis reflects the number of patent families in each subclass.*

*Source: Authors' estimates based on PATSTAT – 2018 Spring Edition.*

**Figure C7.** Revealed technological advantage (RTA) of the UK in CCUS-adjacent technologies compared with other top countries innovating in CCUS, 2000–15




*Note: The length of each bar on the horizontal axis shows the RTA; the width of each bar on the vertical axis reflects the number of patents in each category.*

*Source: Authors' estimates based on PATSTAT – 2018 Spring Edition.*

### Top 20 CPC subclasses that co-occur with the CPC subclass related to CCUS ("Y02C")

The CPC classification system follows the hierarchy outlined below:

CPC Section (e.g., A)

CPC class (e.g., A01)

CPC subclass (e.g., A01C)

CPC group (e.g., A01C 30)

A – HUMAN NECESSITIES

A61 – Medical Or Veterinary Science; Hygiene

A61M – Devices For Introducing Media Into, Or Onto, The Body; Devices For Transducing Body Media Or For Taking Media From The Body ; Devices For Producing Or Ending Sleep Or Stupor

B – PERFORMING OPERATIONS; TRANSPORTING

B01 – Physical Or Chemical Processes Or Apparatus In General

B01D – Separation

B01J – Chemical Or Physical Processes, E.G., Catalysis Or Colloid Chemistry; Their Relevant Apparatus

C - CHEMISTRY; METALLURGY

C01 – Inorganic Chemistry

C01B – Non-Metallic Elements; Compounds Thereof

C01F – Compounds Of The Metals Beryllium, Magnesium, Aluminium, Calcium, Strontium, Barium, Radium, Thorium, Or Of The Rare-Earth Metals

C02 – Treatment Of Water, Waste Water, Sewage, Or Sludge

C02F – Treatment Of Water, Waste Water, Sewage, Or Sludge

C04 – Cements; Concrete; Artificial Stone; Ceramics; Refractories

C04B - Lime, Magnesia; Slag; Cements; Compositions Thereof, E.G., Mortars, Concrete Or Like Building Materials; Artificial Stone; Ceramics; Refractories; Treatment Of Natural Stone

C07 – Organic Chemistry

C07C – Acyclic Or Carbocyclic Compounds

C10 - Petroleum, Gas Or Coke Industries; Technical Gases Containing Carbon Monoxide; Fuels; Lubricants; Peat

C10G - Cracking Hydrocarbon Oils; Production Of Liquid Hydrocarbon Mixtures, E.G., By Destructive Hydrogenation, Oligomerisation, Polymerisation; Recovery Of Hydrocarbon Oils From Oil-Shale, Oil-Sand, Or Gases; Refining Mixtures Mainly Consisting Of Hydrocarbons; Reforming Of Naphtha; Mineral Waxes

C10K - Purifying Or Modifying The Chemical Composition Of Combustible Gases Containing Carbon Monoxide

C10L – Fuels Not Otherwise Provided For; Natural Gas; Synthetic Natural Gas Obtained By Processes Not Covered By Subclasses C10g, C10k; Liquefied Petroleum Gas; Adding

Materials To Fuels Or Fires To Reduce Smoke Or Undesirable Deposits Or To Facilitate Soot Removal; Firelighters

C12 - Biochemistry; Beer; Spirits; Wine; Vinegar; Microbiology; Enzymology; Mutation Or Genetic Engineering

C12M – Apparatus For Enzymology Or Microbiology; {Apparatus For Culturing Microorganisms For Producing Biomass, For Growing Cells Or For Obtaining Fermentation Or Metabolic Products, I.E., Bioreactors Or Fermenters}

C23 – Coating Metallic Material; Coating Material With Metallic Material; Chemical Surface Treatment; Diffusion Treatment Of Metallic Material; Coating By Vacuum Evaporation, By Sputtering, By Ion Implantation Or By Chemical Vapour Deposition, In General; Inhibiting Corrosion Of Metallic Material Or Incrustation In General

C23C – Coating Metallic Material; Coating Material With Metallic Material; Surface Treatment Of Metallic Material By Diffusion Into The Surface, By Chemical Conversion Or Substitution; Coating By Vacuum Evaporation, By Sputtering, By Ion Implantation Or By Chemical Vapour Deposition, In General

E – FIXED CONSTRUCTIONS

E21 – Earth Drilling; Mining

E21B – Earth Drilling, E.G., Deep Drilling; Obtaining Oil, Gas, Water, Soluble Or Meltable Materials Or A Slurry Of Minerals From Wells

F – MECHANICAL ENGINEERING; LIGHTING; HEATING; WEAPONS; BLASTING

F01 – Machines Or Engines In General; Engine Plants In General; Steam Engines

F01K – Steam Engine Plants; Steam Accumulators; Engine Plants Not Otherwise Provided For; Engines Using Special Working Fluids Or Cycles

F01N – Gas-Flow Silencers Or Exhaust Apparatus For Machines Or Engines In General; Gas-Flow Silencers Or Exhaust Apparatus For Internal Combustion Engines

F17 – Storing Or Distributing Gases Or Liquids

F17C - Vessels For Containing Or Storing Compressed, Liquefied Or Solidified Gases; Fixed-Capacity Gas-Holders; Filling Vessels With, Or Discharging From Vessels, Compressed, Liquefied, Or Solidified Gases

F23 – Combustion Apparatus; Combustion Processes

F23J – Removal Or Treatment Of Combustion Products Or Combustion Residues; Flues

F25 – Refrigeration Or Cooling; Combined Heating And Refrigeration Systems; Heat Pump Systems; Manufacture Or Storage Of Ice; Liquefaction Solidification Of Gases

F25J – Liquefaction, Solidification Or Separation Of Gases Or Gaseous (Or Liquefied Gaseous) Mixtures By Pressure And Cold Treatment (Or By Bringing Them Into The Supercritical State)

H – ELECTRICITY

H01 – Basic Electric Elements

H01M – Processes Or Means, e.g. Batteries, For The Direct Conversion Of Chemical Energy Into Electrical Energy

# Appendix D

## Selected policy instruments considered for supporting CCUS development

Provided below is a list of selected policy instruments considered for supporting CCUS development and deployment in the long term (source: IEA, 2020).

Operational subsidies:

- Tax credits based on $CO_2$ captured/stored/used.
- Contracts-for-difference (CfD) mechanisms covering the cost differentials between production costs and a market price.
- Feed-in-tariff mechanisms with long-term contracts with low-carbon electricity producers.

Carbon pricing:

- Carbon taxes which impose a financial penalty on emissions.
- Emissions trading schemes (ETSs) involving a cap on emissions from large stationary sources and trading of emissions certificates.

CCUS-specific market mechanisms:

- Tradeable certificates or obligations. The Oxburgh Review (Oxburgh, 2016) recommended a CCS Obligation System for the UK under which companies supplying fossil fuels would be obliged to prove they have stored (or bought CCS Certificates from others who have stored) $CO_2$ equivalent to a given carbon content of the fuel they have supplied in a given year.
- Carbon storage units based on a verified record of $CO_2$ securely stored, which could be purchased by emitters from those storing carbon.

Regulatory standards and obligations

- Mandates on manufacturers to meet emissions criteria, or oblige firms to purchase a minimum share of products with low lifecycle $CO_2$ emissions.
- Regulated asset base, a model for investment recovery through a regulated product price passed on to consumers.
- Emissions standards establishing limits on unabated $CO_2$ emissions.