The innovation race on geological carbon removal: who is best placed to lead?

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Policy report

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Contents

List of abbreviations

AFOLU	Agriculture, forestry and other land use
AMCs	Advanced market commitments
AR6	Sixth Assessment Report
BECC	Bioenergy with carbon capture
BECCS	Bioenergy with carbon capture and storage
BEIS	(former) Department for Business, Energy and Industrial Strategy (UK)
BiCRS	Biomass carbon removal and storage
CCC	Climate Change Committee
CCfD	Carbon contracts for difference
CCS	Carbon capture and storage
CCTP	Carbon Capture Technologies Program
CCUS	Carbon capture, usage and storage
CDR	Carbon dioxide removal
CO_2	Carbon dioxide
CPC	Cooperative Patent Classification
DAC	Direct air capture
DACCS	Direct air carbon capture and storage
DEA	Danish Energy Agency
DESNZ	Department for Energy Security and Net Zero (UK)
DOE	Department of Energy (US)
EOR	Enhanced oil recovery
EPO	European Patent Office
ERW	Enhanced rock weathering
ETS	Emission trading scheme/system
$GtCO_2$	Gigatonnes of carbon dioxide
IEA	International Energy Agency
IP	Intellectual property
IPC	International Patent Classification
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
IStraX	Industrial Strategy Index
LULUCF	Land use, land use change and forestry
mCDR	Marine carbon dioxide removal
$MtCO_2e$	Million tonnes of carbon dioxide equivalent
Mtpa CO_2	Million tonnes per annum of carbon dioxide
PATSTAT Global	Worldwide Patent Statistical Database
PV	Photovoltaic
R&D	Research and development
RD&D	Research, development and demonstration
RD&I	Research, development and innovation
RTA	Revealed technological advantage
TRL	Technology readiness level
VCM	Voluntary carbon market

Summary

Headline points

- While the US has been home to substantial patenting and deployment of relevant technologies to date, many European countries — such as France, Germany, the UK and the Netherlands — appear to be well specialised in geological carbon dioxide removal (CDR) innovation. However, different countries demonstrate innovative strengths relevant for geological CDR in different ways, with opportunities available for them all in the innovation race ahead.
- Countries that innovate in clean technologies more generally also generate large numbers of geological CDR innovations, but it is a largely different set of countries that are the most *specialised* in geological CDR innovation.
- Countries' innovative strengths in geological CDR revealed in our analysis appear strongly tied to these countries' previous efforts in other related fields, such as oil and gas, petrochemicals and conventional energy production from biomass.
- Early public investment in geological CDR innovation could unlock large returns through cost reductions and growing knowledge spillovers for other innovations.
- Availability of policy support will influence where investments in geological CDR innovation and supply chains take place, giving those countries with support an advantage to tap into the growing global CDR market.

Recommendations for policymakers looking at geological CDR as a potential industrial opportunity in their country

- Policy support for geological CDR — which is an indispensable tool for global net zero — should be designed and allocated in a way that does not deter and instead complements vigorous emissions reduction efforts.
- Relevant existing capabilities in other sectors such as oil and gas that are transferable into geological CDR should be recognised and capitalised on to build competitive domestic supply chains around related technologies.
- A policy mix designed to maximise growth opportunities from geological CDR should tailor support to the different maturity levels of the different technologies involved, considering direct innovation support for earlier-stage technologies alongside market-based mechanisms such as emissions trading schemes to support more established technologies.
- Policy support for geological CDR should exist within a comprehensive and coordinated national decarbonisation strategy, capturing complementarities with other areas such as carbon capture, usage and storage (CCUS).

Recommendations for UK policymakers

- Policy should be designed explicitly to retain more of the follow-on economic value from geological CDR innovation — in which the UK demonstrates notable strengths, especially in direct air capture (DAC) — maximising domestic jobs and supply chain opportunities from this growing industry.
- The UK's industrial strategy for clean technologies and the forthcoming Greenhouse Gas Removal Review should nurture the country's comparative advantages in geological CDR, and invest in necessary infrastructure and skills, given the country's relatively high innovative specialism — especially in DAC — as well as its geological and policy strengths.

Alongside rapidly reducing new emissions, existing and future carbon dioxide (CO_2) will need to be removed from the atmosphere to meet global climate goals. Scaling up carbon dioxide removal (CDR) is a critical challenge, but it could also represent a significant opportunity for the countries that innovate and build competitive supply chains of relevant technologies. The global market for CDR could be large, with various non-peer review estimates agreeing that it will be worth over US$40 billion by 2030 and over US$300 billion by 2050.

This report analyses innovation activity, drawing on data on global patenting between 2000 and 2020, relevant for two CDR technologies: bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS) (referred to collectively as geological CDR hereafter). These methods have been chosen because they are the most durable; most supplier revenues from CDR are expected to come from these two methods and public policy has so far predominantly also focused here (though a broader mix of methods is needed to support climate goals). Countries that have innovative strengths relevant for BECCS and DACCS — including transferable strengths from other sectors — could be attractive locations for early investments in relevant supply chains, enabling them to capture associated economic benefits.

While not all innovation is patented and innovation is a complex process of which patents can only capture the beginning (i.e. many patents do not go on to become a product or a service), information on patenting is still the best internationally available data to shed light on countries' innovation-focused activities and allow comparative analyses. Furthermore, the latest complete year in the patent data available to us is 2020, and the period between then and the time of writing has seen significant progress and change in the CDR space. This analysis remains relevant nevertheless, given our objective is to capture countries' innovative activities relevant for, but not necessarily explicitly about, geological CDR. In other words, a country's historical efforts to build innovative capabilities in other areas that are now transferable to geological CDR (which our analysis is good at capturing) will be highly relevant for that country's prospects of leading in this field.

Our key takeaways from this analysis are summarised below.

1. While the US has been home to substantial patenting and deployment of relevant technologies to date, many European countries — such as France, Germany, the UK and the Netherlands — appear to be well specialised in geological CDR innovation. However, different countries demonstrate innovative strengths relevant for geological CDR in different ways, with opportunities available for them all in the innovation race ahead.

We use different metrics based on patenting activity to evaluate countries' innovative strengths in geological CDR. Namely, for each country, we calculate its number of innovations, its revealed technological advantage (RTA) (used as a proxy for innovative specialism), and our estimate for its returns to an additional unit of public investment in innovation for bioenergy with carbon capture (BECC) and for direct air capture (DAC). Carbon storage, the final stage of the process for both BECCS and DACCS, is looked at separately and the number of patents found is too small to conduct meaningful comparative analysis.

We find that despite some overlap, different sets of countries perform highly on each metric across BECC and DAC. The US is notable for featuring in strong positions on several metrics across both technologies. France, Germany, the Netherlands and the UK also perform well, particularly on DAC. Other countries where there is evidence of innovative strength are well-spread geographically, located across the Americas, Europe, the Middle East and East Asia. Different countries are good at different parts of the BECC and DAC value chains. For example, Saudi Arabia and Russia are highly specialised in the capture stage of BECC, whereas the UK, France and India are highly specialised in the capture/separation stage of DAC.

Table S1. Summary of results across different metrics of innovative strength in BECC and DAC

	BECC				DAC			
	Global rank			Home to facilities? (existing or planned)	Global rank			Home to facilities? (existing or planned)
	No. of innova-tions	Innovative specialism (RTA)	Estimated domestic returns		No. of innova-tions	Innovative specialism (RTA)	Estimated domestic returns	
Belgium		5						
Brazil		2		Y				
Canada	10		8	Y	10	7	10	Y
China	4		3		4		1	
Denmark		3		Y				
France	5	9		Y	5	2	8	Y
Germany	3		9		2	5	6	
India	9	8	10		9	1	9	
Japan	2		7		3		4	
Netherlands	7	6			8	4	5	
Russia		4	5					
Saudi Arabia		1	6					
South Korea	6		1		7		2	Y
Spain		7						
Taiwan			2					
UK	8	10		Y	6	3	7	Y
US	1		4	Y	1	6	3	Y

Notes: Countries/jurisdictions which appear in the top 10 for at least one metric for either BECC or DAC are included. The colour coding is by the global rank of countries/jurisdictions on each metric, where the darkest shade represents the top spot. There are only seven countries that have a positive RTA for DAC, so only these are displayed. The 'Home to facilities?' column indicates whether the given country/jurisdiction is home to any readily operational or planned facilities of the respective technology, with underpinning lists of facilities provided in the Appendix. Empty cells mean that the given country/jurisdiction has no facilities we have been able to identify ('Home to facilities?' column) or that it does not feature in the global top 10 for that metric ('Global rank' columns).

2. Countries that innovate in clean technologies more generally also generate large numbers of geological CDR innovations, but it is a largely different set of countries that are the most *specialised* in geological CDR innovation.

The US is by far the largest innovator in both BECC and DAC, followed by Japan, Germany and China in both instances (though in a different order). These countries produce large numbers of clean technology patents more generally. Looking at broader trends, the number of global innovations in geological CDR has rapidly increased from 2000 to the early 2010s, followed by a decreasing trend after 2012. This is similar to the trend in global patenting of various other clean technologies, possible drivers of which include changes in energy prices and climate-related regulations. Around 90% of geological CDR innovations between 2000 and 2020 relate to BECC. DAC constitutes a much smaller proportion, where carbon storage is an even smaller category.

Turning to innovative specialism (measured by RTA), Saudi Arabia takes the top spot in BECC, followed by Brazil, Denmark and Russia. None are top innovators in terms of patent quantity. For DAC, there are only seven countries in total that demonstrate overall innovative specialism (only 10 countries have enough innovations to enter our analysis). India takes the top spot followed by four countries in Europe (France, the UK, the Netherlands and Germany). Four countries — India, France, the UK and the Netherlands — feature among the most specialised countries for both BECC and DAC.

3. Countries' innovative strengths in geological CDR revealed in our analysis appear strongly tied to these countries' previous efforts in other related fields, such as oil and gas, petrochemicals and conventional energy production from biomass.

Innovations included in our analysis are relevant for but are not necessarily explicitly about BECCS and DACCS. There are likely to be opportunities available for countries that can translate their relevant innovative strengths in other fields into explicit capability in geological CDR.

Some of our results reflect countries' innovative activities in CCUS more broadly, while innovations originally generated for use in the oil and gas sector also represent strong crossovers with BECCS and DACCS. Indeed, oil and gas companies are responsible for substantial portions of innovation relevant for geological CDR in many countries we have analysed, including China, India, Saudi Arabia, the UK and the US.

4. Early public investment in geological CDR innovation could unlock large returns through cost reductions and growing knowledge spillovers for other innovations.

To date, likely owing to the technologies' nascency, our estimates of the domestic returns to additional public investments in geological CDR innovation (calculated using the Industrial Strategy Index [IStraX] methodology) are lower than our equivalent estimates of the average returns from broader clean technology innovation.[1]

As geological CDR technologies mature, related innovation is likely to require less public support while generating greater knowledge spillovers for other innovations, resulting in greater returns. This is an incentive for early public investment in, and demand side policies for, geological CDR innovation. The past decade is evidence of how policies supportive of research into, and development and deployment of, early-stage clean technologies can drive remarkable cost reductions.

Estimated returns to date vary across different countries/jurisdictions. South Korea has the greatest estimated domestic returns per unit of additional public investment it makes in BECC innovation, followed by Taiwan, China, the US, Russia and Saudi Arabia. Of these, the US and Saudi Arabia generate especially large estimated spillovers for the rest of the world from these investments. On the other hand, South Korea and China seem to have retained over half of their estimated returns domestically, with relatively small spillover elsewhere.

The greatest estimated domestic returns per unit of additional public investment in DAC lie in China and South Korea. This is helped by the ability of these countries to retain a high proportion (over 40%) of their overall estimated returns domestically. This contrasts with the rest of the countries/jurisdictions analysed, such as the US, Japan and the Netherlands, which have generated higher overall estimated returns but retained much smaller portions domestically.

5. Availability of policy support will influence where investments in geological CDR innovation and supply chains take place, giving those countries an advantage to tap into the growing global CDR market.

Despite current uncertainty about its continuation, the US has long had the most established policy framework surrounding geological CDR technologies, with the 45Q tax credit incentivising geological storage of carbon in the country since 2008. The country also has the infrastructure in

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[1] The IStraX is based on a model of the innovation process, which is fitted to global data on patenting and valuations of companies undertaking innovation. Resulting estimates reflect the economic value of an innovation in a given field calculated as the difference between the expected increase in total value (private value as well as external values from knowledge spillovers) generated by that innovation and the expected cost of the subsidy, scaled by the expected cost of the subsidy.

place for CO_2 transport and storage (an advantage that most other countries do not have) and is home to the largest number of facilities (existing and planned) for both BECCS and DACCS. However, current policy uncertainty regarding the development of US geological CDR could be an opportunity for other countries to forge ahead in the geological CDR race.

The UK, for example, has potential to be a leading player with its abundant geological storage capacity, relatively low-carbon electricity supply, maturing policy frameworks, and a transferable skills base from a long-standing oil and gas industry. It is also among the most specialised innovator countries for both technologies, with a particularly strong position in Europe. Its performance in DAC stands out especially, while it faces more competition in BECC.

The availability of policy support — alongside other factors such as the availability of low-cost clean electricity and heat, availability and price of biomass, and access to CO_2 transport and storage infrastructure — will continue to influence where investments in geological CDR and related supply chains take place. As BECCS and DACCS can share CO_2 transport and storage infrastructure with point source CCUS applications, BECCS and DACCS development will also be helped by wider CCUS support.

Given the nascency of BECCS and DACCS and the dynamic nature of emerging CDR markets, opportunities will be available for both existing and new players that manage to create supportive policy environments to attract ambitious investment. As countries race to capture growth opportunities from geological CDR, it will be important to ensure investments in this field only complement, not replace, investment in other essential solutions for achieving global net zero.

1. Introduction

Scaling up carbon dioxide removal (CDR) is necessary for meeting global climate targets. Doing so is a critical challenge, but it could also represent a significant opportunity for the countries that innovate and build competitive supply chains of relevant technologies. This report analyses innovation activity in CDR, drawing on data on global patenting between 2000 and 2020 relevant for two key technologies: bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS).

What is carbon dioxide removal and why do we need it?

Alongside rapidly reducing greenhouse gas emissions, carbon dioxide (CO_2) will need to be removed from the atmosphere to meet global climate goals. This is now 'unavoidable' according to the Sixth Assessment Report (AR6) — the latest comprehensive assessment of climate science — by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2023). Over the near-term, this necessitates a significant scaling of removals of CO_2 from the atmosphere, either by enhancing natural carbon sinks or by developing novel carbon dioxide removal (CDR) technologies. Indeed, recent estimates suggest the current CDR gap — the difference between the quantity of CDR in scenarios that meet the Paris Agreement temperature goal and the amount of CDR in national proposals — ranges from 0.9 to 2.8 gigatonnes of carbon dioxide ($GtCO_2$) per year in 2030 and from 0.4 to 5.4 $GtCO_2$ per year in 2050 (Smith et al., 2024).[2]

Carbon dioxide removal as an economic opportunity

While CDR is now an indispensable component of modelled global climate change mitigation pathways, support for CDR in public policy is still nascent. With policymakers increasingly placing economic growth at the centre of discussions on ambitious climate policy, demonstrating that investing in CDR can be growth-inducing may convince policymakers of the benefits of greater public support for the sector. Investing in CDR can help drive growth in a country, mainly in two ways. Firstly, having domestic CDR capacity would allow a range of otherwise difficult-to-abate sectors in the country to operate in a way that is aligned with net zero, thereby allowing them (and in turn, all the other sectors that rely on them) to grow. As such, CDR is a tool that can help countries to retain and build economic competitiveness in a decarbonising world.

Secondly, countries which develop the capabilities and supply chains to create competitive products and services relevant for CDR can tap into growing global markets for these products and services as mitigation efforts advance around the world. Indeed, 143 countries that represent 76% of global emissions and 78% of global gross domestic product (GDP) have net zero targets in place at the time of writing (Net Zero Tracker, 2025), implying strong demand growth for CDR products and services over the years ahead.

Renewed interest in industrial strategy is at the centre of national efforts to build capabilities in growing net zero-aligned markets. Consequently, many advanced economies are developing more ambitious industrial policies to tap into growing markets for clean technologies, requiring the identification of areas where they have current or potential relative strengths (Serin et al., 2024). Successful industrial strategies around CDR will combine supply-side support — such as subsidies and tax incentives for supply chains — with mechanisms that drive demand pull for the relevant technologies and services. Formally integrating removals into their decarbonisation pathways can help jurisdictions in achieving the latter objective.

Although there is limited academic literature on the size of the future economic opportunity from CDR, recent grey literature suggests it could be large, with most future value lying in two

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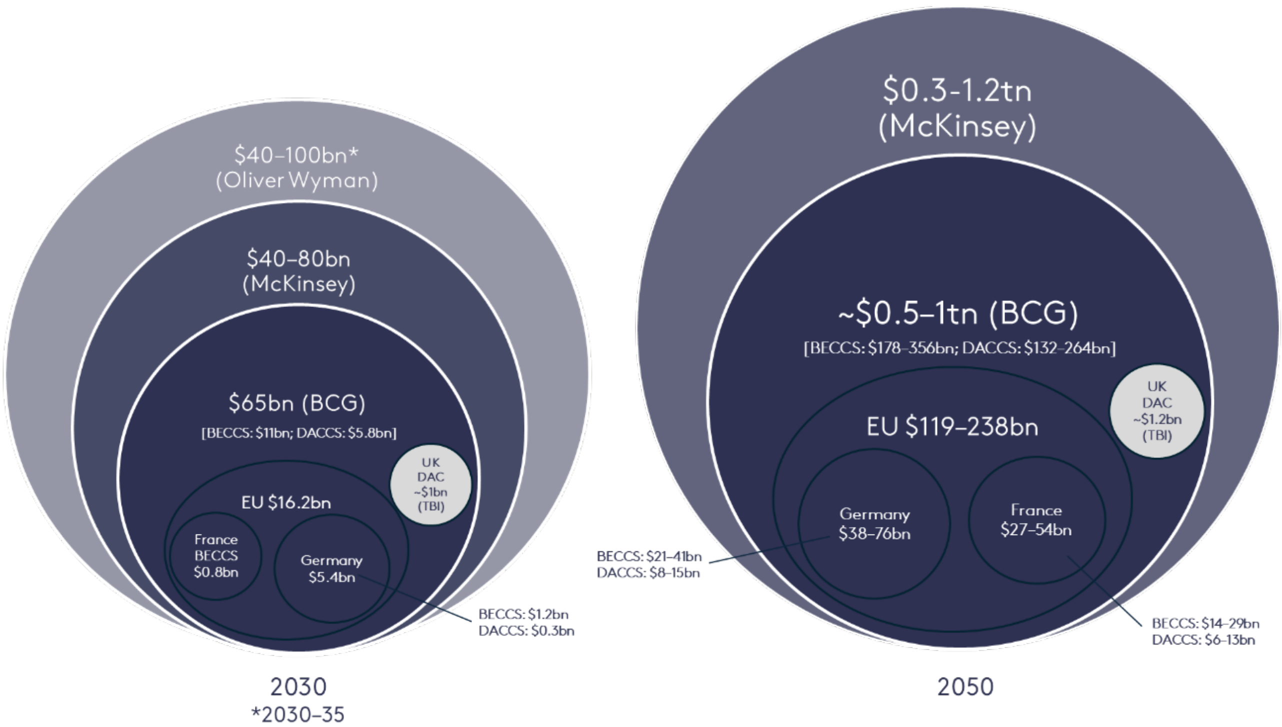
[2] For context, the UK's territorial greenhouse gas footprint in 2023 was approximately 0.4 $GtCO_2$ (DESNZ, 2025a).

methods: BECCS and DACCS. Some upper-bound estimates suggest the global market for CDR could reach US$100 billion a year between 2030 and 2035 (Oliver Wyman, 2024) (from US$2.7 billion in 2023), and up to US$1.2 trillion by 2050 (McKinsey & Company, 2023) (various estimates are summarised in Figure 1.1.). The arithmetic here is simple: expected CDR volume multiplied by marginal price. Using the IPCC's assumed volume of 5 gigatonnes of CDR/year and an average cost of US$200/tonne, a trillion dollars is reached easily.

Of this potential market by 2050, suppliers are estimated to capture between US$840 and US$960 billion,[3] with BECCS and DACCS together accounting for over 70% of supplier revenues[4] (McKinsey & Company, 2023). This is broadly consistent with analysis from Boston Consulting Group (BCG) which indicates that 61% of 2050 supplier revenues would accrue to these two methods combined (BCG, 2025). More modest estimates of the global annual market value for DAC suggest this could reach almost £60 billion (~US$75 billion) by 2050 (Tony Blair Institute, 2025). Interestingly, in calculating the estimates cited in Figure 1.1., most country-specific studies assume their focus country can capture 5% of the global market.

Figure 1.1. Estimates of the size of the global CDR market and market size captured by stated jurisdictions in US$ per annum in 2030 (left) and 2050 (right)



Notes: Estimates include all CDR methods, unless otherwise stated. White-bordered circles are estimates of the global market size while black-bordered circles are estimates of the market size captured by the stated jurisdictions. Estimates stated within circles of the same colour come from the same source, stated in parentheses in the outermost circle of that colour. The UK estimates (indicated by light grey circles) come from a different source compared to the darker circles they sit within. Estimates are in 2023 prices (or assumed to be, where not specified in the source), and currency conversions are based on the average EUR–USD and GBP–USD conversion rates for the year 2023 (based on the European Central Bank [2025] and ONS [2025], respectively). Circle sizes are rough illustrations and not proportional to the exact values.
Source: Authors' collation of estimates from BCG (2024; 2025), McKinsey & Company (2023), Oliver Wyman (2024) and Tony Blair Institute (2025). For illustration only; figures from different sources may not be directly comparable due to methodological differences.

3 The rest is estimated to be captured by traders, financiers, validation and credit actors and advisory providers.

4 With the rest shared between biochar, forestry, cropland and grassland, blue carbon and other technology-based removals.

These numbers will inevitably be used to drive expectations about future demand and entice public and private investment into CDR, but there is a need to scrutinise and validate industry estimates. Realising this potential is far more challenging than the maths. For example, the total amount spent on all durable CDR methods to date is US$6.2 billion (CDR.fyi, 2025a). For the 2030–35 estimates of market size (from Oliver Wyman) to be achieved, this requires scaling current spending by 6.5 times for the lower bound estimate and 16 times for the upper bound. Given that on average from 2019 to 2025 the market only grew at US$1billion per year (ibid.), a significant scale-up is required for these estimates to be achieved. A full assessment of market estimates is out of scope for this analysis, and it is a gap in the peer-reviewed literature that needs filling.

Jurisdictions such as the EU and the UK have developed policy positions which recognise the ways that CDR can benefit their economies. For example, the EU's recently launched Competitiveness Compass acknowledges the role of permanent[5] CDR within an overall agenda to protect and promote the Union's industrial competitiveness. Similarly, in the UK, the Government is committed to supporting the deployment of engineered[6] CDR, both to deliver on future domestic carbon budgets and to position the UK as a global leader in this sector (DESNZ, 2024).

At the same time, early frontrunners in the emerging CDR economy may be squandering their competitive edge. The US, for example, has seen rapid growth to date in inventions and demonstration plants for CDR (notably for BECCS and DACCS [Nemet et al., 2024]) and has benefited from CDR-specific research, development and innovation (RD&I) programmes. In contrast, although the EU has several mechanisms that have funded CDR, non are dedicated specifically to CDR RD&I (Carbon Gap, 2025). Beyond the R&D and demonstration phase, the US is also a leader in the commercialisation of many novel CDR methods, supplying the biggest volumes (tonnes sold) of DACCS (due in large part to the Inflation Reduction Act and 45Q tax credit), enhanced rock weathering (ERW), biomass carbon removal and storage (BiCRS) and marine carbon dioxide removal (mCDR) (CDR.fyi, 2025b).

However, the recent change in administration in the US, the subsequent dismantling of government agencies and departments, and potential revocation of generous subsidies for CDR (Volcovici, 2025) may spur companies to redirect investments to less capricious policy environments. With the right understanding of the policies that can support CDR in the face of various market failures and uncertainties, other jurisdictions and countries can capitalise. This analysis attempts to identify which jurisdictions are best placed to capture a share of the global economic opportunity from geological CDR by capitalising on their innovative capabilities.

The focus on geological CDR

The focus of this report is limited to BECCS and DACCS, hereafter collectively referred to as geological CDR.[7] Here, the term geological refers to the way carbon is stored in BECCS and DACCS applications, while the capture method of carbon is biological or chemical.

Although a wider range of CDR methods is emerging, with other examples including biochar and enhanced rock weathering, most of the future economic potential from CDR is estimated to lie within geological CDR methods and public policy has so far predominantly focused on these methods, inferring higher political salience. This is evident in both modelled pathways and CDR-

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[5] Typically refers to CDR that stores carbon in the geosphere with durations greater than 10,000 years. This is often used interchangeably with 'engineered' removals.

[6] The UK defines 'engineered removals' as measures which remove CO_2 from the atmosphere to be permanently stored. This definition typically includes BECCS, DACCS, biochar and enhanced rock weathering.

[7] Geological CDR takes concentrated CO_2 streams chemically or biologically captured (either directly from the air, or from processes where biomass is converted into fuels or directly burned to generate energy) and injects them into geological formations such as depleted oil and gas fields, saline aquifers or reactive mineral deposits underground. Various processes then act to sequester the CO_2 in these formations, including physical trapping by impermeable rocks, dissolving of the CO_2 in water, and eventual mineralisation. The predominant technologies are BECCS and DACCS.

specific policies and targets. The UK and the EU, for example, anticipate geological CDR to play a central role in modelled pathways. By 2050, the UK's Seventh Carbon Budget advice developed by the Climate Change Committee (CCC) suggests engineered CDR will counterbalance around 36 million tonnes of carbon dioxide equivalent ($MtCO_2e$) of greenhouse gas emissions, with removals from BECCS and DACCS accounting for 70% and 22% of that total, respectively (CCC, 2025). The European Commission 2040 Impact Assessment modelling estimates even bigger EU demand for CDR in 2050, reaching around 120 $MtCO_2e$, with BECCS and DACCS accounting for nearly all of this with a roughly equal split between them (European Commission, 2024).

That said, future deployment projections are in a dynamic phase of iteration and are highly uncertain. Changes in modelling and accounting assumptions can dramatically alter modelled future outcomes. For example, due to improved LULUCF (land use, land use change and forestry) inventory modelling and lower projected economy-wide residual emissions, the approximate 36 $MtCO_2e$ of engineered removal in 2050 included in the CCC's Seventh Carbon Budget (CCC, 2025) advice for the UK is down from 58 $MtCO_2e$ in their Sixth Carbon Budget advice from five years ago (CCC, 2020). Conversely, owing to different assumptions about carbon capture and storage (CCS) deployment (rather than assumptions about LULUCF in the case of the UK), a recent report by the European Scientific Advisory Board on Climate Change more than doubles previous estimates of future CDR demand provided by the European Commission 2040 Impact Assessment. It is important to note that methodologies for calculating economic value of CDR (e.g. those summarised in Figure 1.1.) reflect assumptions about future demand. If future demand is uncertain, so are estimates of future economic value calculated at the national or international level, or attributed to specific removal methods, which may easily be revised up or down.

When it comes to CDR-specific policies and targets, the predominant focus on geological CDR is evident in policy discourses. In the UK, BECCS and DACCS are the main (but not sole) CDR technologies under consideration for inclusion in its domestic compliance carbon market (i.e. the UK Emission Trading Scheme [ETS]) and within explicit deployment targets (e.g. the UK's ambition to deploy at least 5 $MtCO_2$/year of engineered removals by 2030, potentially scaling to 23 $MtCO_2$/year by 2035, with BECCS and DACCS expected to account for the vast majority).[8] Furthermore, in the US, specific DACCS demonstration support programmes have been created (e.g. the US DAC hubs); in Sweden reverse government auctions for BECCS have been established; and Japan's carbon market (i.e. GX-ETS) now accepts removal credits from BECCS and DACCS (as well as coastal blue carbon) (Chen, 2024).

Due to their larger project size, BECCS and DACCS also make up a sizeable share of the financial support available for R&D into CDR overall (Minx et al., 2024). These trends contrast with the current state and trajectory of the voluntary carbon removal market, which has so far shown broader interest in removals from biochar and agriculture, forestry and other land use (AFOLU) approaches.

As countries advance their public policy programmes around geological CDR, there is also an opportunity to incentivise deployment while making the use case explicit. Reserving the use of CDR to only compensate for emissions from hard-to-abate sectors should be a priority. New evidence suggests that the use of CDR to compensate for emissions from easier-to-decarbonise sectors such as electricity would leave less capacity available to compensate for hard-to-abate emissions, increasing system-wide costs of net zero or rendering such goals impossible to achieve (Shindell and Rogelj, 2025). However, such usage contrasts with current demand which predominantly comes from easier-to-decarbonise sources that should not be long-term sources of demand (Burke and Fankhauser, 2023). Examples include large corporations like TikTok, Meta,

[8] These quantities may be revised subject to the outcome of the Independent Review of Greenhouse Gas Removals commissioned by the Secretary of State for Energy Security and Net Zero. The Review was announced in March 2025 and is expected to conclude in October 2025 (DESNZ, 2025b).

Microsoft and Shopify which have invested in CDR technologies in recent years (Mittal, 2025; Burke and Fankhauser, 2023).

Moreover, the durability of CDR is critical for achieving the Paris Agreement, where geological CDR is needed to counterbalance fossil emissions (Brunner et al., 2024). Indeed, robust net zero strategies require that any continued generation of fossil CO_2 must be balanced by geological CO_2 sequestration or equally permanent disposal (Allen et al., 2022), a concept known as 'Geological Net Zero'.

Background and objectives

This report is a partnership between the CO_2RE Hub at the Smith School of Enterprise and the Environment at the University of Oxford and the Grantham Research Institute, the Centre for Economic Performance (CEP), the Programme on Innovation and Diffusion (POID) and the Productive & Inclusive Net Zero (PRINZ) programme at the London School of Economics and Political Science (LSE). It builds on a series of reports on sustainable growth opportunities for the UK by the listed four centres and programmes at LSE. These reports previously provided high-level analyses on the UK's strengths relevant for capturing sustainable growth opportunities across a range of clean technologies (e.g. see Curran et al. [2022] and Serin et al. [2024]), as well as granular analyses on specific technologies including zero emission passenger vehicles (Unsworth et al., 2020), carbon capture, usage and storage (CCUS) (Serin et al., 2021) and tidal stream energy (Serin et al., 2023).

While the previous reports in the series assessed growth opportunities purely through a UK lens, this study takes a global view and tries to identify the countries where the greatest opportunities from geological CDR lie. The study still includes a section that zooms in on the results with a UK view, to maintain comparability of insights with previous work in the series and to be able to inform ongoing development of UK policy in this area.

Existing literature examining the economic opportunity from CDR has either focused on ex-ante national and international market projections (as outlined in the previous discussions) or ex-ante estimations of job creation potential (Rhodium Group, 2025). This body of literature has also tended to focus on singular jurisdictions, with limited international comparisons. These are valid approaches and useful to policymakers. However, while they make the case that CDR is a theoretical growth opportunity, they do not evaluate actual performance or shed light on a country or jurisdiction's ability to tap into that opportunity through comparative analysis against its competitors. By using ex-post analysis of patent data, we attempt to fill this important knowledge gap.

Where analysis of patenting activity relating to geological CDR exists (e.g. Minx et al., 2024; Kang et al., 2022), this is limited to the historical evolution and distribution of CDR inventions across geographies and methods. The novelty of this analysis is that it examines two further metrics relating to patenting in geological CDR which can shed light on the economic opportunities available to countries from investing and innovating in this field. These are:

- Revealed technological advantage
- Estimated economic returns to additional public investment in innovation.

The study also analyses patenting activity, not just for geological CDR as an aggregate category, but also for specific stages of the BECCS and DACCS value chains (e.g. carbon capture, energy conversion, regeneration). This detailed analysis of geological CDR patenting was made possible by the development of a novel dataset by Feng (2025, forthcoming). Further detail on the construction of the dataset is provided in the next section.

2. Approach and methodology

What is the relevance of patent analysis?

Patents are a key measure of innovation output and they can help identify countries' areas of innovative strength where future economic value is likely to be generated (Curran et al., 2022). Indeed, literature demonstrates a positive link between patents and subsequent firm-level performance and industry-level growth and productivity, particularly when patent quality is accounted for (see Hall et al., 2005; and Kogan et al., 2017). The relative strengths of countries which we identify using patents data should point out where knowledge bases relevant for CDR technologies are located around the world, which could be attractive locations for investment in relevant value chains.

While not all innovation is patented and innovation is a complex process of which patents can only capture the beginning (i.e. many patents do not go on to become a product or a service), patents are still the best internationally available data that can shed light on countries' innovation-focused activities. Indeed, data on patents are commonly used by researchers to make comparative analyses of innovation patterns. These data are available internationally over time and organised under detailed technological classifications. It is true that patents do not capture all innovation activity, with advancements in the services sector especially less likely to be patented. However, the transition to a clean economy will inevitably require further innovation of physical equipment, for which patents data provide good coverage (as is the case for CDR equipment).

Source database and construction of dataset

This analysis has been enabled by a new dataset constructed by Feng (2025, forthcoming) to identify patents relevant for geological CDR that are either not classified under, or not easily isolated within, the Y02C class of the Cooperative Patent Classification (CPC) system. Y02C looks at patents associated with 'Capture, storage, sequestration or disposal of greenhouse gases (GHG)' but does not comprehensively cover all technological developments relevant across the BECCS and DACCS value chains or break down into sufficiently granular sub-classes to describe the different types of technological developments it covers.

The new dataset we use for analysis was constructed by conducting a keyword search (detailed below) on the 2023 Spring edition of the Worldwide Patent Statistical Database (PATSTAT Global) published by the European Patent Office (EPO). PATSTAT Global contains information on patent applications filed with patent authorities in various countries/jurisdictions. We consider patent applications filed between 2000 and 2020, where the latter is the latest complete year available to us to extract.[9]

Our analysis of patent data focuses on patent 'families': sets of patents, utility models, and other legal instruments that refer to the same invention. The analysis is restricted to patent families consisting of more than one application; this is used as a proxy for patents of higher quality (see related discussion under limitations at the end of the current section).[10] We refer to these as 'multi-application innovations' (or simply, 'innovations') in subsequent discussions. We identify

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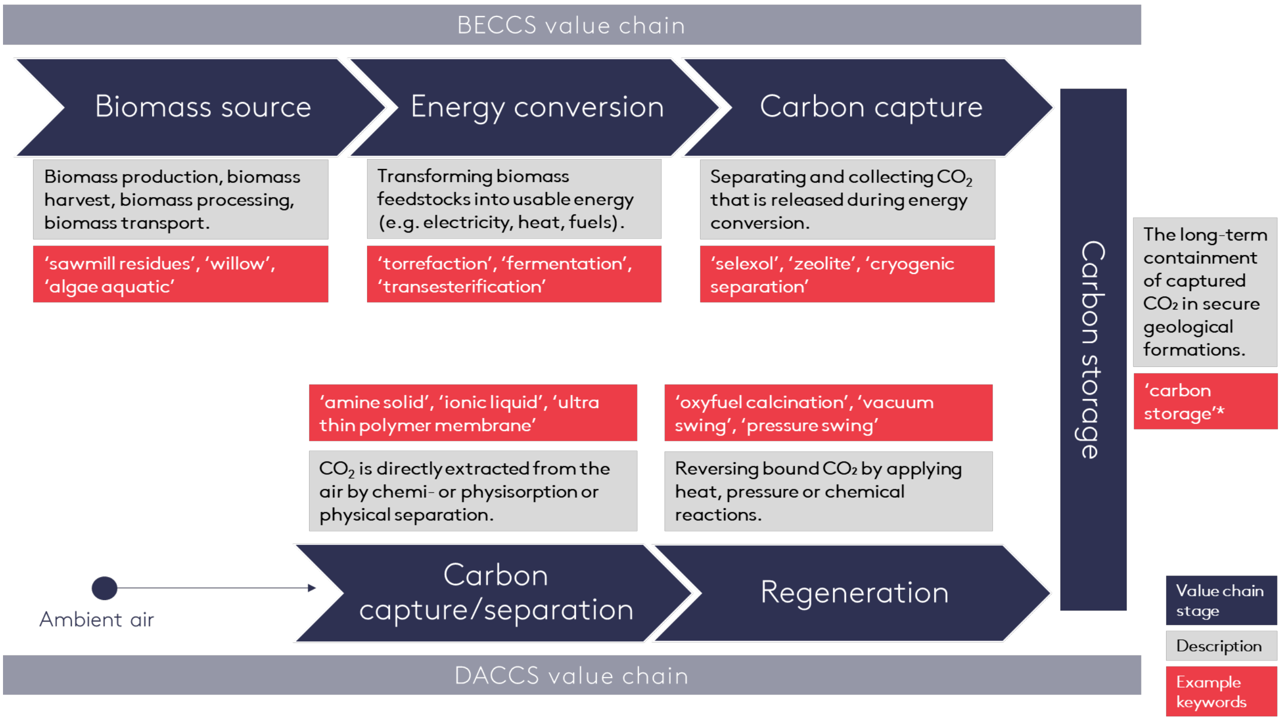
[9] This is because patent data get recorded with lags, with each PATSTAT edition having complete data up to a few years before it. We observed inconsistencies in completeness of recorded data across different countries beyond 2020, leading us to conclude this is the latest complete year available in the edition we work with. While not available to us, the latest PATSTAT published at the time of writing is the 2024 Autumn edition. This could theoretically contain a year or so more of data beyond what we have been able to analyse.

[10] Our estimates of returns to additional public investments in innovation (i.e. the Industrial Strategy Index [IStraX], explained on page 18), however, is based on all patent families, and not just those with more than one patent application. This follows the methodology in Guillard et al. (2023).

the country/jurisdiction of origin for patent families by mapping them to the current country/jurisdiction of residence of the corresponding inventors.[11]

To construct our dataset of geological CDR patents drawing on PATSTAT Global, firstly, the technological components across the value chains of BECCS and DACCS were systematically identified. Each value chain was then analysed to derive a set of keywords corresponding to the technologies involved at each stage, based on existing literature. This enabled a structured approach for examining innovation activity across value chains. A keyword-based search was employed to retrieve patents *relevant* to each stage, ensuring comprehensive coverage of technological developments. Examples of keywords used to capture patents aligned with specific value chain components include 'wood chips', 'fermentation', 'liquid amine sorbent' and 'oxyfuel calcination'. The word 'relevant' should be emphasised here, as the innovations captured represent capabilities relevant for geological CDR, but they may have originally been developed for use in other fields. In other words, our approach captures not just explicit geological CDR innovation but also innovations from other fields which have functions transferable into geological CDR.

Figure 2.1. Description of BECCS and DACCS value chain stages and corresponding keywords used for dataset construction



*Notes: *Due to the limited number of patents directly related to carbon storage, the keywords used to capture innovations in this stage of the value chain have been kept relatively high-level instead of using highly specific technical terms.*
Source: Authors' analysis

The retrieved dataset underwent a multi-step refinement process to enhance its relevance. An initial screening of patent titles and abstracts was conducted to exclude unrelated entries. Further refinement involved screening remaining patents and excluding those that fell outside the

[11] See Annex 1 in Curran et al. (2022) for further detail on our approach to assigning patent families to geographical locations.

combined scope of a selected set of CPC system[12] codes, ensuring alignment with predefined technological classifications identified as being relevant for BECCS and DACCS value chains.[13]

Focusing on patent families which contain at least one patent that satisfies the selection and screening criteria, we have achieved a dataset containing around 84,000 patent families (of which around 25,000 are multi-application patent families), providing a structured foundation for assessing technological advancements relevant for BECCS and DACCS. Each patent family within the final dataset is associated with at least one of the three value chain stages within bioenergy with carbon capture (BECC) (biomass source, energy conversion, capture), or with one of the two value chain stages within direct air capture (DAC) (capture/separation, regeneration), or with carbon storage (the final value chain stage involved in both BECCS and DACCS).[14] The relationship between these value chain stages is visualised in Figure 2.1, provided together with brief descriptions and several examples of the keywords used to capture innovations relevant for each stage.

Key concepts underpinning the analysis

Revealed technological advantage (RTA)

A country/jurisdiction is said to have RTA in a technology field for a given period if the field's share of the country/jurisdiction's total patenting is larger than the field's share of total global patenting over that period. We estimate RTA values of countries based on the number of multi-application innovations (of the given country/jurisdiction and the global total) between 2000 and 2020.[15] We adjust RTA values so that they lie between –1 and +1,[16] whereby numbers greater than zero indicate that the given country/jurisdiction has innovative specialism in that field. Accordingly, RTA is used interchangeably with the phrase 'innovative specialism' in subsequent discussions.

For BECC, we calculate the RTA only for countries/jurisdictions which have recorded a minimum of 200 multi-application innovations in the field between 2000 and 2020. For DAC, we set this threshold at 50 multi-application innovations, recognising that DAC is an area of smaller overall quantity of innovation than BECC globally.[17] This approach is to ensure our results only reflect countries/jurisdictions which can be considered substantive innovators in the respective fields.[18]

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12 PATSTAT classifies patents according to the Cooperative Patent Classification system (CPC). The CPC is a result of a joint effort between the United States Patent and Trademark Office (USPTO) and the EPO. Its objective is to harmonise the European Classification system (ECLA) and the United States Patent Classification (USPC) while being compliant with the International Patent Classification system (IPC). The CPC classifies patents at a granular level across a wide range of technological fields. A patent can have more than one CPC classification if the innovation is pertinent in more than one technological context.

13 Various CPC codes were selected for this screening exercise, drawing on previous literature, to represent key technologies along the BECCS and DACCS value chains. Selected CPC codes included, but were not limited to, Y02C. For example, further CPC codes were drawn from Kessler and Sperling (2016) for biomass source; from US DOE, EERE and BETO (2021) for bioenergy conversion; and from Kang et al. (2021) for carbon capture and storage. The complete CPC code list that was used is available in Feng (2025, forthcoming).

14 Theoretically, a patent family can be assigned to more than one value chain stage if the underpinning innovation is relevant in more than one technological context. However, there are no instances of this observed in practice.

15 While this is the case for the majority of the analyses, in some Appendix charts we calculate RTA values of countries for five-yearly intervals between 2000 and 2020. Figure 3.10. is another exception, which focuses on the period 1980–2018.

16 As the ratio of a technology area's share of the country/jurisdiction's total patenting to the area's share of total global patenting, RTA can normally take any value between zero and infinity. We transform these raw RTA values so that they lie between –1 and +1 using the following formula: (RTAraw –1)/(RTAraw +1), where RTAraw refers to the untransformed RTA calculated as described.

17 Globally, our data records around 22,500 multi-application innovations for BECC, and 2,500 multi-application innovations for DAC between 2000 and 2020.

18 It should be emphasised that the thresholds only impact what we present, and not the underlying RTA calculations. Namely, the 'total global patenting' component contained in the denominator for RTA calculations takes into account multi-application innovations in all countries/jurisdictions, not just those generated by countries/jurisdictions that meet the thresholds we set.

Estimated returns to additional public investments in innovation (IStraX)

This is calculated based on the Industrial Strategy Index (IStraX) methodology developed by Guillard et al. (2023) (detailed further in the Appendix).[19] The IStraX provides a framework to estimate the economic return on potential government R&D subsidies to different technology fields, while taking into account variation in the private returns on innovation in different sectors, as well as direct and indirect knowledge spillovers to other firms (as measured through citations in patents). It also takes account of the possibility that innovators in different areas might vary in their responsiveness to government R&D support.

The IStraX is based on a model of the innovation process, which is fitted to global data on patenting and valuations of companies undertaking innovation. The resulting IStraX values reflect the economic value of an innovation in a given technology field calculated as the difference between the expected increase in total value (private value as well as external values from knowledge spillovers) generated by that innovation and the expected cost of the subsidy, scaled by the expected cost of the subsidy. Put another way, when a subsidy induces a firm to innovate more than would be profitable without the subsidy, the net estimated economic value of that newly profitable innovation is our IStraX value. The IStraX values are expressed asrates of return, that is, as a percentage of the one additional unit of R&D subsidy originally invested.

For each technology field, the overall IStraX (estimated 'global' returns) can be disaggregated into returns that are realised within the inventor's home country/jurisdiction (estimated 'domestic' returns), and those that are realised in the rest of the world (estimated 'outside-country/ jurisdiction' returns). For example, suppose that a country has a global IStraX of 80% and a domestic IStraX of 30% for BECC. This indicates that a £1 additional R&D subsidy for BECC in this country generates an estimated total value of £1.80 globally. £0.80 of this is the estimated global return, which is the estimated value beyond the original £1 subsidy recovered, and £0.30 of that £0.80 is retained within the country (estimated domestic return). A higher IStraX therefore represents greater estimated returns to government R&D subsidies.

We estimate IStraX for innovations occurring between 2009 and 2018, as this the most recent 10-year period for which IStraX calculations are available. We choose to focus on this more recent 10-year period (as opposed to the overall period since 2000) so that our results can be more closely indicative of current returns to public investments in geological CDR innovation, particularly given that this is a nascent field.

In presenting our IStraX results, we again limit our scope to countries/jurisdictions that meet the same thresholds for the number of multi-application innovations as described above for RTA. We note that the IStraX itself is estimated based on *all* innovations between 2009 and 2018 for which an IStraX calculation is available (following the approach of Guillard et al. [2023]), whereas the thresholds we impose (which determine which countries/jurisdictions we present results for) are based on multi-application innovations between 2000 and 2020.

The number of innovations depicted in the rest of the report always represents multi-application innovations between 2000 and 2020. Our methodology allows us to report on numbers of innovations at the level of value chain stages within BECC and DAC (e.g. capture, energy conversion), as well as in carbon storage. However, we do not estimate RTA and IStraX at the level of value chain stages, since numbers of innovations at this level of disaggregation are too small to yield reliable and meaningful estimates.

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[19] We estimate IStraX values using the 2021 Autumn version of PATSTAT, whereas numbers of innovations and RTA calculations are based on the 2023 Spring version of PATSTAT. For further detail on the IStraX methodology, see Guillard et al. (2023).

Limitations and areas for further research

Covered time period

One major limitation of our analysis is that we are only able to capture innovation activity up to the end of 2020, which is the latest complete year of data available to us to extract. That means the significant momentum in geological CDR innovation in more recent years will not be visible, likely missing insights about countries which have only recently become active in the BECCS and DACCS space, such as Kenya and Canada. Our analysis remains relevant nevertheless, given our objective is to capture countries' innovative activities relevant for, not just those explicitly about, geological CDR. In other words, a country's historical efforts to build innovative capabilities in other areas which are now transferable into geological CDR (which our analysis is good at capturing) will be highly relevant for that country's prospects of leading the innovation race in this field. Grey literature — such as industry and trade group reports (e.g. from the DAC Coalition) — can also help fill some of this knowledge gap, providing more up-to-date insights and anecdotal evidence on country activities relating to CDR in the last five years. We draw on such complementary literature where possible.

Patent quality

The quality of patents is highly heterogeneous and ideally, we would like to focus only on high-quality patents in our analysis. One way to do this would be to use patent citations as a measure of the quality of each patent. In the literature, it is also common to specifically focus on triadic patent families: these are a subset of patent families for which applications for the same invention were filed in the EPO (European Patent Office), USPTO (United States Patent and Trademark Office), and JPO (Japan Patent Office). However, given the small overall pool of patents available in the context of geological CDR, we focus on multi-application patent families as a proxy for patent quality, as opposed to one of these stricter approaches. Multi-application patent families are those patent families for which more than one application was filed. We assume that these are more likely to represent economically or technologically significant innovations than single-application patent families (which we filter out). This is because applicants will typically pursue broader protection by filing more than one application (across jurisdictions, and/or within the same jurisdiction using different legal instruments) for inventions with greater expected value.

Coverage of different innovator types

Our patent analysis understates the role of start-ups and small firms in the innovation ecosystem. One reason for this is that our filtering method for patents (focusing on multi-application patents only) may exclude start-ups. Patents have very different roles in start-ups compared to established firms. Patents in incumbents have a strong legal value in that they can be part of large patent portfolios used to maintain a monopoly in key markets. Start-ups, meanwhile, tend to use patents as a signal to investors that their inventions are a worthwhile investment and do not often have the resources to defend their portfolios. We can observe from Orbis Intellectual Property (IP) data that anecdotally, larger companies have larger patent families and are more involved in litigation than start-ups. Since we filter our data to patent families with more than one application, start-ups appear far less in our data. As a broader point, many key start-ups in this space were founded in the 2010s, meaning they are only present in the latter half of our analysis period and do not account for many captured innovations. There has been even greater momentum in more recent years. The International Energy Agency (IEA, 2025) shows that the number of start-ups founded in the CDR space has increased from just under 30 in 2019 to over 140 in 2024. Given their importance for technological innovation and capturing associated growth opportunities, future work could focus on comparing countries on their conduciveness for start-up activity in this space by drawing on qualitative evidence and other datasets such as the DAC Coalition's Mega DAC database.

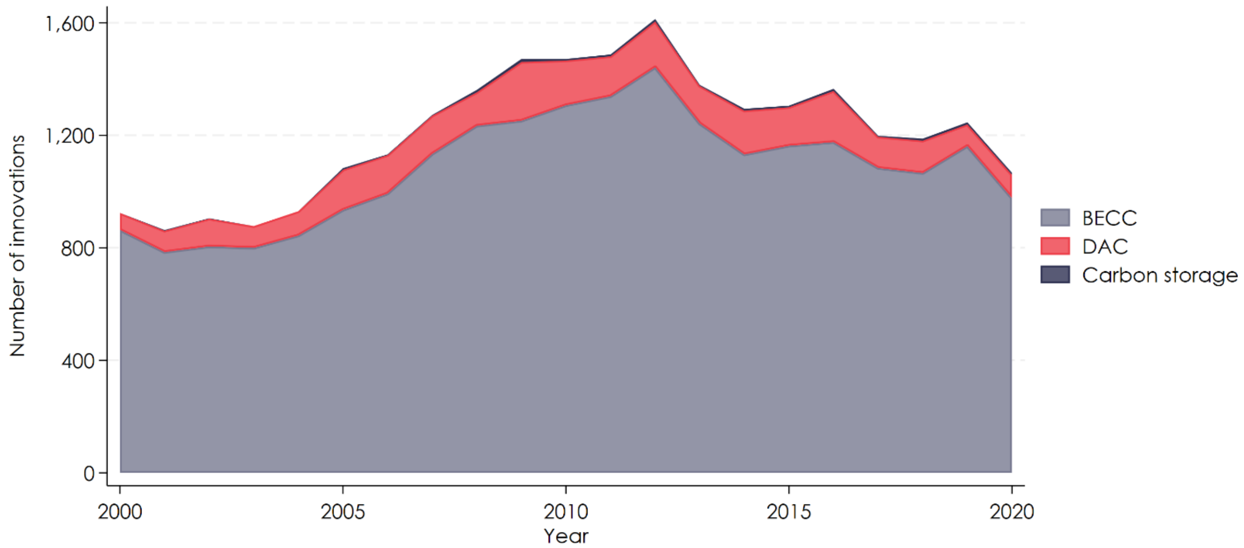
3. Results

Evolution of global innovations in geological CDR

The global number of innovations in geological CDR has increased substantially from the year 2000 to the early 2010s (Figure 3.1.). Indeed, the annual global number of innovations in the field in 2012 was almost double that in the early 2000s. This rapid increase in annual innovations was followed by a decreasing trend after 2012. Using machine learning to track CDR innovations, Minx et al. (2024) observe a similar decline especially in BECCS patenting, suggesting this may potentially be explained by overblown expectations about the technology's large-scale deployment in the 2000s. Such a rise followed by a decline in related patenting with a peak in the early 2010s is also observed for some other clean technologies such as solar photovoltaic (PV), wind, and building energy efficiency (Popp et al., 2022). While the definitive reason is unclear, possible factors discussed in the literature that might have contributed to this decline include falling energy prices, the rise of fracking, changes in climate-related regulations, the possibility of a clean technology 'bubble' and increasing technological maturity for some technologies (ibid.; Probst et al., 2021).

By 2020 (the latest complete year available in our dataset), the global annual number of innovations had dropped to levels last seen in around the mid-2000s, with about 1,000 innovations being recorded annually. This still represents a significant amount of innovation. For comparison, our equivalent analysis on tidal stream energy identified a maximum of 200 innovations being recorded per year over a similar period (Serin et al., 2023).

Figure 3.1. Evolution of the global number of innovations in geological CDR (2000–20)



Notes: The y-axis denotes the global number of multi-application innovations, presented per year between 2000 and 2020 along the x-axis. Innovations are broken into BECC, DAC and carbon storage.
Source: Authors' analysis based on PATSTAT Global 2023 (Spring edition)

Around 90% of geological CDR innovations over this period are related to BECC (biomass source, energy conversion and capture). DAC (capture and regeneration) constitutes a much smaller proportion. Innovation quantities in both BECC and DAC reflect a similar rise and fall over the data period, where the only notable difference is that DAC innovations peak in 2009 — a few years earlier than BECC. Storage, on the other hand, is an even smaller category of innovation. Namely, the maximum number of innovations from BECC in a single year exceeds 1,400 while that number is just over 200 for DAC and only 10 for carbon storage.

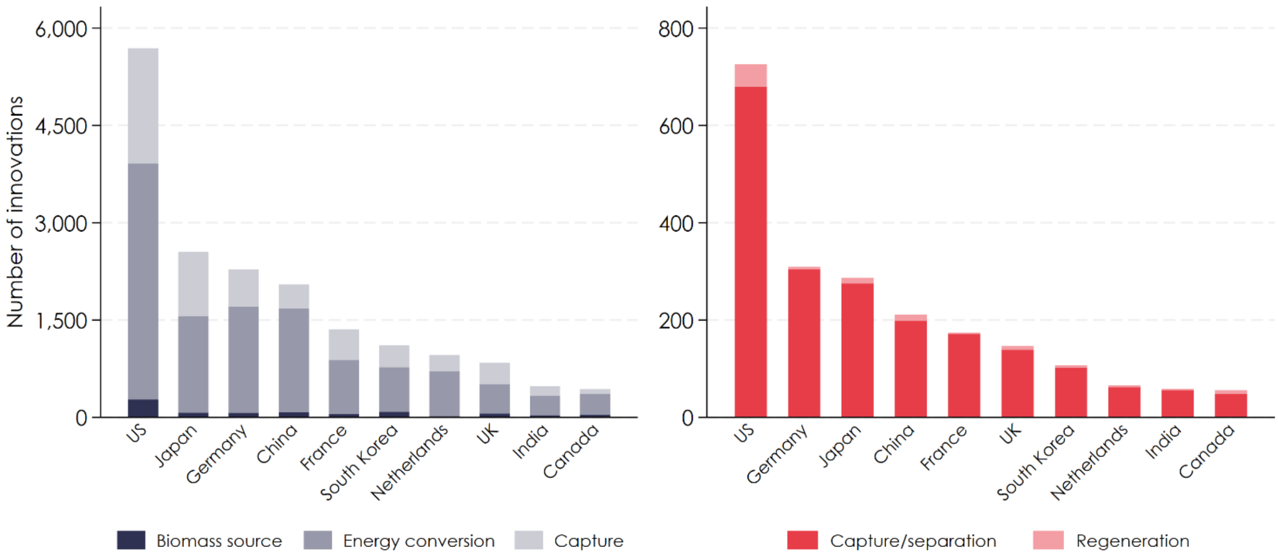
Which countries are innovating the most in geological CDR?

The US has by far the largest number of innovations in both BECC and DAC (Figure 3.2.), accounting for almost 25% of global BECC innovations and almost 28% of global DAC innovations over the data period (see Table A3 in the Appendix). This innovation activity in the country is driven by a range of industries but particularly by oil and gas companies (see Table A4 in the Appendix). While that pattern is also observed in other locations, it is more the case in the US, especially compared to Europe. Our findings are consistent with an earlier study by Kang et al. (2022), which also found that the US has the largest patent quantities in BECCS and DAC over a similar period. In a departure from our study, Kang et al. find China in a more prominent position compared to our analysis, taking second place on patent quantities after the US, but this could be because of differences in the identification of relevant patents since the overall quantity of identified patents in this study is far smaller than ours.

The US is followed by Japan, Germany and China in both instances (though in a different order), each accounting for 8–12% of global innovations in each of the two fields over the data period. These countries are strong innovators of clean technologies more generally, recording some of the largest numbers of clean energy patents between 2000 and 2020 (IEA, 2024b). Interestingly, the US by far exceeds Japan and China when it comes to BECC and DAC patenting but does not take such a clear lead in the broader context of clean energy patenting (in fact, it is surpassed by Japan for the number of clean energy patents between 2000 and 2020) (ibid.). France, South Korea, the Netherlands and the UK also hold a considerable amount of BECC and DAC innovations. Interestingly, the countries that make up the top 10 largest innovators are identical for both BECC and DAC. This likely reflects the fact that these countries are dominant innovators more generally, both for clean and wider technological inventions.

Energy conversion makes up the majority of innovations within BECC for all countries in the top 10. It is followed by capture and then biomass source. Biomass source appears to be a very small area of innovation for most countries. For DAC, capture/separation is a far bigger area of innovation than regeneration for all countries in the top 10.

Figure 3.2. Top 10 countries by total number of innovations (2000–20) — **BECC (left)** and **DAC (right)**



Notes: The y-axis denotes the number of multi-application innovations. Bars are arranged in descending order of number of innovations belonging to each country. Equivalent analysis for carbon storage is presented separately in Figure A11 in the Appendix.
Source: Authors' analysis based on PATSTAT Global 2023 (Spring edition)

Our similar analysis on storage shows that this is a very small area of innovation globally (Figure A11 in the Appendix). The US is the only country that has over 20 multi-application innovations relevant for storage recorded in the 20 years up to 2020. In average terms, that means countries apart from the US have not even recorded one innovation per year in this field over this period. The US is followed by China and South Korea, though none of these countries have enough innovations to be considered substantive innovators in the field.

Next, we look at how the number of innovations of the 10 largest innovators of BECC and DAC we identified above have evolved between 2000 and 2020. For BECC, the number of annual innovations in most countries has at best modestly increased over the period (Figure A1 in the Appendix). One exception is China, which has consistently increased its number of innovations over the years. The US is also notable, experiencing a significant rise followed by a large drop in its annual number of innovations over the period. The trend in the number of global innovations observed in Figure 3.1. appears to largely mirror the trend in the US, given the country is a very large innovator of both BECC and DAC.

The story for DAC is similar, with most countries not seeing a substantial change in their innovation quantities over the years (Figure A2 in the Appendix). However, the overall number of innovations is much lower for DAC, with most countries not exceeding 20 multi-application innovations in a year. The US once again stands out with a similar rise and fall seen in its annual innovation activity. While its peak number of annual innovations approaches 400 for BECC, it is less than 70 for DAC. China has also increased its number of innovations in DAC over the years, though much less strongly compared to BECC.

Which countries are the most specialised in geological CDR innovation?

We now turn to revealed technological advantage (RTA) which is an indicator of a country's innovative specialism in a technology field. We identify the top 10 countries with the highest RTA in each of BECC and DAC,[20] and complement this with our analysis of some additional countries of interest (if not already covered in the top 10). A country of interest for us is one that is home to existing or planned facilities for the respective technology, and/or has a policy programme or ambition to develop it domestically (see Tables A1 and A2 in the Appendix for our full list of countries of interest). We interpret the presence of facilities (existing or planned) in a country as a proxy for domestic demand for relevant technologies. Including these countries within the scope of our analysis allows us to explore any impacts domestic demand may have had on countries' ability to build relevant innovative performance.

The RTA analysis on BECC illustrates European strength in the field, with six countries from the continent featuring in the top 10 (Figure 3.3.). Leadership on innovation quantities for BECC observed in the previous analysis does not translate to high specialism in the field for most countries, with six new countries now taking places in the top 10: Saudi Arabia, Brazil, Denmark, Russia, Belgium and Spain.

Saudi Arabia — responsible for only 1.4% of global BECC innovations — tops the list (see Table A3 in the Appendix).[21] Here, it should be emphasised that RTA reflects the extent of a country's innovative activity in a field relative to its own overall innovation activity and that globally. In other words, this result likely means Saudi Arabia is not a particularly large innovator in other fields, making its focus on innovation relevant for BECC high by its own standards. Saudi Arabia has a high RTA in the energy conversion and capture stages, but not in biomass source, within the BECC value chain (see Figure A14 in the Appendix). It appears to be particularly strong in BECC – Capture, which constitutes 58% of its geological CDR innovations between 2000 and 2020

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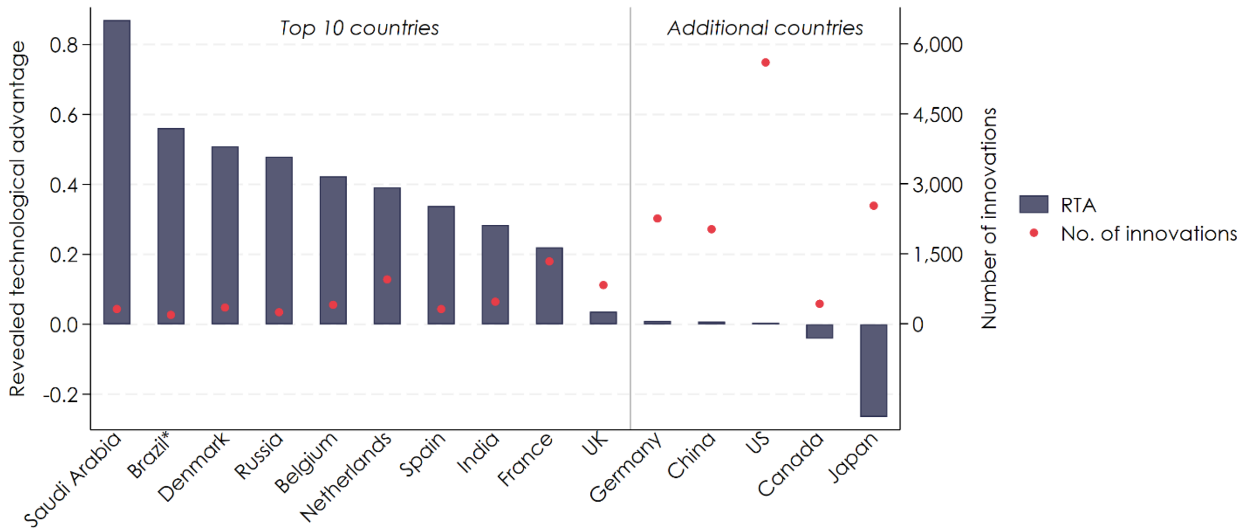
[20] In DAC, there are only 10 countries that have 50 or more multi-application innovations (our minimum threshold to estimate an RTA for DAC), so we provide RTA estimates for all of these countries.

[21] Most countries among those with high RTAs in BECC — including Saudi Arabia — have a fairly stable RTA between 2000 and 2020 (Figure A3 in the Appendix).

(globally, BECC – Capture only constitutes 26% of all geological CDR innovations over the same period). These innovations appear to be largely driven by the oil and gas industry, with Aramco being responsible for a large majority of Saudi Arabia's geological CDR innovations (see Table A5 in the Appendix). There are also several foreign firms operating in Saudi Arabia that account for a material share of Saudi Arabia's innovations in this field.

Russia is a surprising result as we have not been able to identify any domestic projects of BECCS or DACCS, or an explicit policy interest in the technologies, in the country. Russia is particularly specialised in the energy conversion and capture stages within BECC, with an RTA of around 0.5 in both (see Figure A15 in the Appendix). It is slightly less specialised in DAC overall than it is in BECC. Russia's innovation activity appears to be largely driven by foreign firms with Russian inventors, most notably the Ajinomoto Company of Japan (see Table A6 in the Appendix).[22]

Figure 3.3. Revealed technological advantage in BECC (2000–20) — top 10 countries and additional countries of interest



*Notes: The left y-axis indicates RTA values (shown in bars and adjusted to lie between –1 and +1, where positive values indicate innovative specialism). The right y-axis indicates number of multi-application BECC innovations (shown in dots). Countries with fewer than 200 multi-application BECC innovations between 2000 and 2020 are not considered. *The exception to this is Brazil: although Brazil has fewer than 200 multi-application BECC innovations, we include it in our analysis given it is a country of interest, and it has 188 multi-application BECC innovations, which is only slightly lower than the 200 threshold.*
Source: Authors' analysis based on PATSTAT Global 2023 (Spring edition)

Within our countries of interest for BECC (i.e. those that have domestic activities in the field), Brazil, Denmark, the Netherlands, France and the UK are among the top 10 in terms of RTA. The rest of our countries of interest either demonstrate slight or no specialism in the field (Germany, China, the US, Canada, Japan),[23] or do not have enough innovations to be eligible for our RTA calculations (Finland, Hungary, Sweden). It is noteworthy that Germany, China, the US and Japan do not have higher RTAs, as these countries are home to large numbers of innovations in BECC (they are the top four countries in that regard). These countries are known to have large numbers of innovations across different fields, and their low RTAs indicate that they do not have a particular specialism in BECC. In other words, the quantity of innovations they hold in this field, which is nascent, is low by their own standards. For example, the US, which has the highest

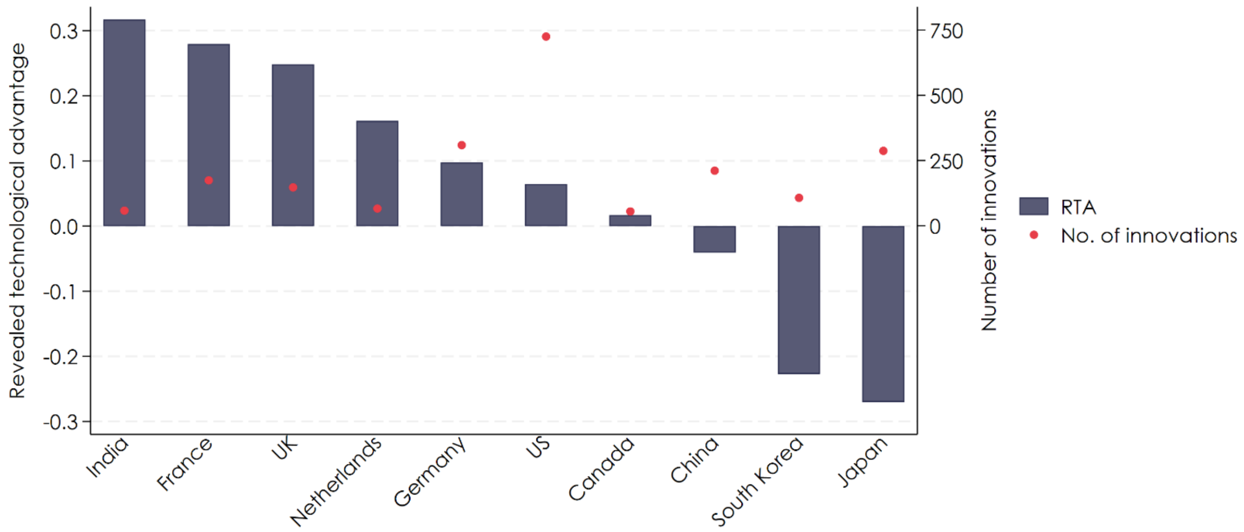
[22] Ajinomoto operates the Ajinomoto-Genetika Research Institute in Russia, which conducts research and development in biotechnology. Some of the intellectual property generated by this institute could be complementary to BECC.

[23] See Figure A4 in the Appendix for the evolution of these countries' RTA values over the data period.

number of innovations in the field, has no meaningful specialism in any stage of the BECC value chain: its RTA in BECC overall is almost 0 (see Figure A13 in the Appendix).

There are only 10 countries that have 50 or more multi-application innovations in DAC (our minimum threshold to estimate RTA). Out of these, seven countries have positive RTA scores, and four of those are in Europe (Figure 3.4.). The remaining three (China, South Korea, and Japan) have negative RTA scores.[24] Of these countries, India has the highest RTA (0.32), driven by its specialism in carbon capture/separation, which constitutes most of its innovations within DAC. India is also strong in biomass source within BECC, in which it has an RTA close to 0.4 (see Figure A16 in the Appendix).

Figure 3.4. Revealed technological advantage in DAC (2000–20) — all analysed countries



Notes: The left y-axis indicates RTA values (shown in bars and adjusted to lie between –1 and +1, where positive values indicate innovative specialism). The right y-axis indicates number of multi-application DAC innovations (shown in dots). Analysis covers all 10 countries with 50 or more multi-application innovations in DAC between 2000 and 2020.
Source: Authors' analysis based on PATSTAT Global 2023 (Spring edition)

Four countries — India, France, the UK and the Netherlands — feature among the most specialised innovators for both BECC and DAC. These four countries also have high numbers of innovations for both BECC and DAC.

Among our countries of interest for DAC (i.e. those that have domestic activities in the field), France, the UK, the US and Canada have positive RTAs; China, Japan and South Korea have negative RTAs; and the remaining seven countries do not have sufficient multi-application innovations to estimate an RTA for.[25] The US has a slightly higher RTA in DAC (0.06, which largely reflects its RTA in capture/separation, where the bulk of its innovations lie) compared to BECC (0), but this is still a relatively low RTA.[26]

The case of Iceland is particularly interesting, as the country is a pioneer of DACCS deployment and is home to the world's only two operational DACCS facilities,[27] but has not recorded any DAC

24 Several countries have experienced substantial fluctuations in their RTA in DAC over the data period (Figure A5 in the Appendix). This is likely explained by the fact that DAC represents a smaller pool of innovations both overall and at the level of individual countries, likely making RTA calculations sensitive even to small changes.

25 See Figure A6 in the Appendix for the evolution of analysed countries' RTA values over the data period, where notable fluctuations are seen.

26 Although the US has a high RTA in regeneration within DAC, the low number of innovations in this stage of the value chain makes the RTA a noisy measure of innovative specialism.

27 Though there are two other operational DAC facilities (i.e. in which the captured CO_2 is used rather than stored) in the US.

innovations in this period. Climeworks — the company behind the DACCS facilities in Iceland — is incorporated in Switzerland. This country does not meet our minimum threshold for inclusion in the analysis either, having recorded fewer than 50 multi-application DAC innovations in this period.

For completeness, we have also analysed countries' specialism in the innovation of carbon storage. However, as previously discussed, there is no country in this field that meets the minimum threshold we would normally apply (50 multi-application innovations between 2000 and 2020) for inclusion in our RTA calculations. In this instance, we have analysed the only three countries which have at least 10 innovations in carbon storage over this period: China, South Korea and the US (see Figures A11 and A12 in the Appendix). Of these, South Korea appears to be the most specialised, followed by China. The US, on the other hand, has a negative RTA in storage over this period.

Estimated returns to additional public investment in geological CDR innovation

In this section and beyond, we use 'estimated returns' as a shorthand for the estimated rate of return to an additional unit of public investment in innovation in a given field. These values are calculated based on the IStraX methodology (introduced in 'Approach and methodology', with further detail provided in the Appendix). Figure 3.5. demonstrates estimated global returns to a unit of additional public investment in BECC innovation made in each country or jurisdiction on the y-axis (global IStraX), and the percentage of the estimated returns retained in that country or jurisdiction on the x-axis. These are shown for 18 countries or jurisdictions that have 200 or more multi-application innovations in BECC between 2000 and 2020.[28]

Additional public investment in BECC innovation yields the greatest estimated global returns when it is made in Canada (Figure 3.5.). There are several other countries that see similarly high estimated global returns: Saudi Arabia, the US, the Netherlands, Japan, Denmark and India. However, except for the US, these countries retain less than 20% of the estimated global returns domestically, with most of the estimated net value lying elsewhere. On the other hand, South Korea, China and Russia retain the largest proportion of the estimated returns domestically (over 50%), despite generating lower returns overall. Taiwan[29] follows these three countries in terms of retaining estimated returns domestically, keeping around 40% of the net value generated.

Figure 3.6. shows countries and jurisdictions with the greatest estimated returns domestically per unit of additional public investment they make in BECC innovation (domestic IStraX), along with their estimated returns which spill over outside the country or jurisdiction, among countries and jurisdictions that are substantive innovators in BECC (i.e. have 200 or more multi-application innovations). South Korea, Taiwan and China generate the largest estimated returns domestically, and as shown in Figure 3.5., these are also among the top countries and jurisdictions in terms of the percentage of the estimated global returns retained domestically. They are followed by the US in fourth place and Russia in fifth place. These two countries present an interesting contrast: while they retain a similar size of estimated returns domestically, a unit of additional public investment in BECC innovation made in the US generates over four times the estimated spillovers for the rest of the world than that made in Russia. Saudi Arabia — the leading country on innovative specialism in BECC — is in sixth place here and is notable for generating substantial estimated spillovers for the rest of the world. Some other countries with particularly high estimated spillovers for the rest of the world include Japan, Canada, India, the Netherlands and Denmark.[30]

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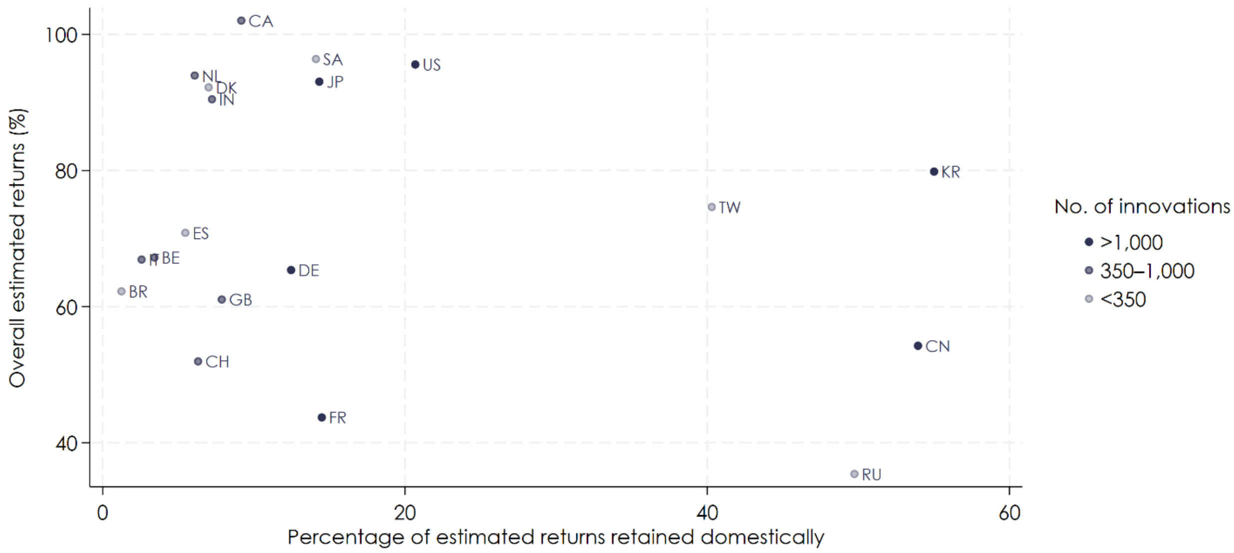
[28] Brazil is included as the 19th country/jurisdiction despite having 188 innovations, given it is a country of interest.

[29] Taiwan has its own patenting office and applications filed with this office do not count towards China's total. In other words, there is no double-counting between Taiwan and China in this analysis.

[30] This can be seen more clearly in Figure A6 in the Appendix which ranks countries by the size of the estimated outside-country returns they generate per unit of additional public investment made in BECC innovation.

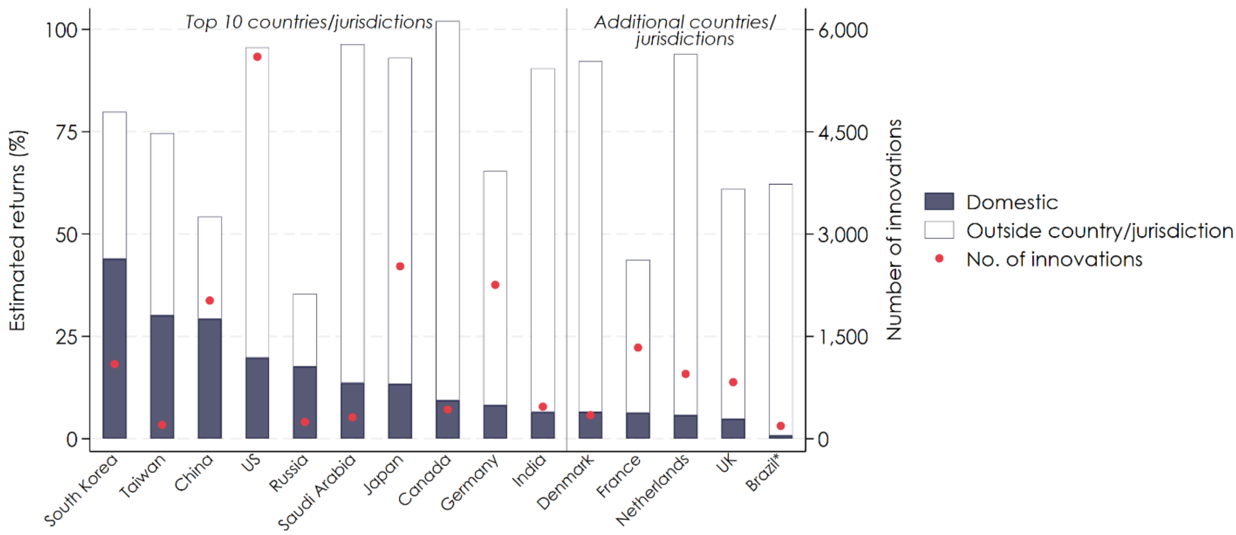
Figure 3.5. Estimated global returns to additional public investments in innovation and percentage retained domestically — BECC (2009–18)



Notes: The y-axis indicates the estimated global returns as a percentage of 1 additional unit of R&D subsidy in BECC in each country/jurisdiction. The x-axis indicates the proportion of these returns that is retained within the country/jurisdiction. The shade of each dot denotes the number of multi-application BECC innovations in that country/jurisdiction between 2000 and 2020. Countries/jurisdictions are identified by their two-letter ISO country codes.

Source: Authors' analysis based on PATSTAT Global 2021 (Autumn edition) and PATSTAT Global 2023 (Spring edition)

Figure 3.6. Estimated global returns (split into domestic and outside-country/jurisdiction returns) to additional public investments in BECC innovation — top 10 countries/jurisdictions by domestic returns, and additional countries/jurisdictions of interest

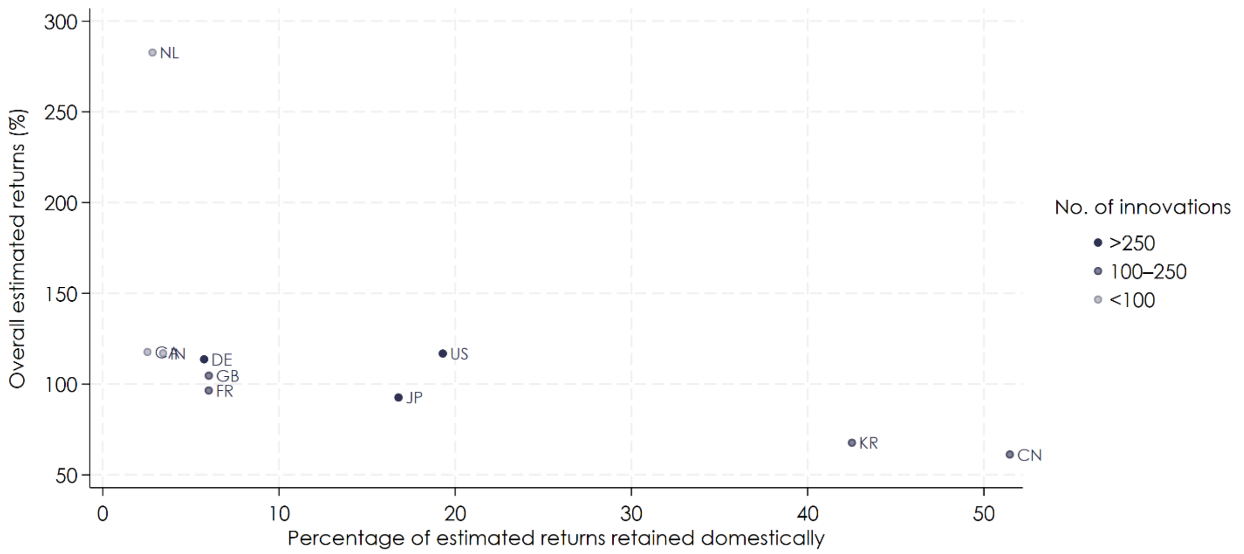


*Notes: The left y-axis indicates the estimated returns as a percentage of 1 additional unit of R&D subsidy in BECC in each country/jurisdiction (shown in bars and estimated based on all innovations between 2009 and 2018). The right y-axis indicates the number of multi-application innovations in BECC between 2000 and 2020 (shown in dots). Countries/jurisdictions with fewer than 200 multi-application innovations in BECC in that period are not considered (*Brazil, which has 188 innovations, is an exception to this). Shaded bars indicate the part of the estimated returns retained domestically, and transparent bars indicate the part of the estimated returns which spills over to the rest of the world.*

Source: Authors' analysis based on PATSTAT Global 2021 (Autumn edition) and PATSTAT Global 2023 (Spring edition)

For DAC, we estimate returns to additional public investment in innovation in the 10 countries/ jurisdictions which have 50 or more multi-application innovations between 2000 and 2020. The Netherlands has the greatest estimated global returns by far (Figure 3.7.), though the country has a relatively low number of innovations in the field. The Netherlands is followed by the US, Canada, India, Germany, the UK, France and Japan, which all have similar estimated global returns (less than half the returns in the Netherlands). Except the US and Japan (which retain between 15% and 20% of estimated returns domestically), all of these countries retain less than 10% of their estimated global returns domestically. In contrast, China and South Korea have lower estimated global returns, but retain over 40% of these returns domestically.

Figure 3.7. Estimated global returns to additional public investments in innovation and percentage retained domestically — DAC (2009–18)



Notes: The y-axis indicates the estimated global returns as a percentage of 1 additional unit of R&D subsidy in DAC in each country. The x-axis indicates the proportion of these returns that is retained within the country. The shade of each dot denotes the number of multi-application DAC innovations in that country between 2000 and 2020. Countries are identified by their two-letter ISO country codes.
Source: Authors' analysis based on PATSTAT Global 2021 (Autumn edition) and PATSTAT Global 2023 (Spring edition)

Figure 3.8. shows estimated global returns (split into domestic and outside-country returns) to a unit of additional public investment in DAC innovation for the same 10 countries. Leading places are taken by the countries that stand out in Figure 3.7. for retaining the highest proportions of their estimated global returns domestically: China and South Korea followed by the US and Japan. The Netherlands presents a contrast. The proportion of the estimated global returns that the country retains domestically is relatively low but its estimated global returns are so high that it still ranks highly (in fifth place) here.[31]

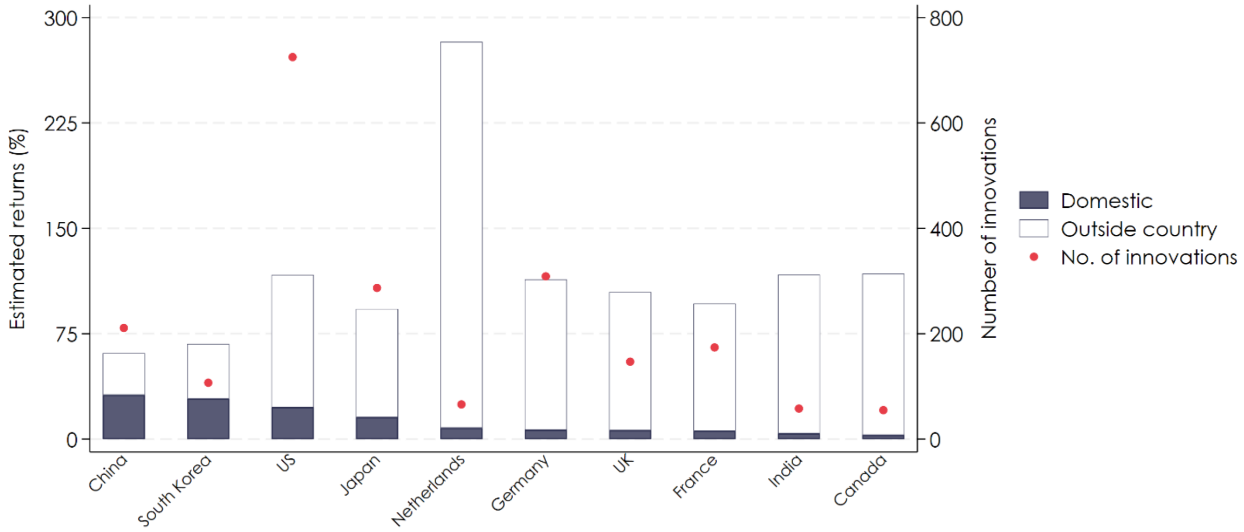
China and South Korea generate the highest estimated domestic returns on DAC and are also among the top three countries/jurisdictions for domestic estimated returns on BECC. This is largely because both countries retain a significant share of their estimated global returns domestically for both technologies. China is notable in our dataset in that much of its patenting is done by universities and research teams (Table A8 in the Appendix).[32] Interestingly, neither China nor South Korea currently exhibit strong RTA in BECC or DAC, suggesting that they are not yet

[31] This can be seen more clearly in Figure A7 in the Appendix which ranks countries by the size of their estimated outside-country returns per unit of additional public investment made in DAC innovation.

[32] Jiangnan University takes the top spot with the Dalian Institute of Chemical Physics, South China University of Technology, and Tsinghua University appearing later in the top 10.

specialised in geological CDR. Looking at the more granular level, China's RTA is negative for all value chain stages (in which it has a sufficient number of innovations for analysis) except for energy conversion within BECC (Figure A17 in the Appendix). The high domestic estimated returns for these countries imply that public investment in geological CDR innovation could deliver strong economic benefits domestically, even in the absence of current specialism. This highlights untapped potential for future technological leadership in these countries.[33]

Figure 3.8. Estimated global returns (split into domestic and outside-country returns) to additional public investments in DAC innovation — all analysed countries, ranked by domestic returns



Notes: The left y-axis indicates the estimated returns as a percentage of 1 additional unit of R&D subsidy in DAC in each country (shown in bars and estimated based on all innovations between 2009 and 2018) for the 10 countries which have 50 or more multi-application innovations in DAC between 2000 and 2020. The right y-axis indicates the number of multi-application innovations in DAC in that period (shown in dots). Shaded bars indicate the part of the estimated returns retained domestically, and transparent bars indicate the part of the estimated returns which spills over to the rest of the world.
Source: Authors' analysis based on PATSTAT Global 2021 (Autumn edition) and PATSTAT Global 2023 (Spring edition)

We can also view how estimated returns differ across the two technologies within each country (Figure A8 in the Appendix).[34] For most countries, estimated domestic returns from BECC innovation are not materially different from those of DAC. The one exception is South Korea, where estimated returns from BECC innovation are materially higher than for DAC innovation.

There are more visible differences when we compare estimated domestic returns from BECC and DAC versus average estimated domestic returns from clean technology innovation as a whole. In almost all countries/jurisdictions, BECC innovation yields lower estimated domestic returns than the average domestic estimated returns from clean technology innovation as a whole (Figure A9 in the Appendix). The story for DAC is similar (see Figure A10 in the Appendix). In the UK context, we can also compare estimated domestic returns from BECC and DAC to those from some other specific clean technologies by drawing on our previous work. For example, estimated domestic

[33] Other factors may influence the high estimated domestic returns in East Asian economies. Firstly, the dominance of large firms, particularly in economies like South Korea, where major Chaebols play a central role, enables more effective internalisation of knowledge spillovers compared to ecosystems centred on smaller firms, as seen in Europe. Secondly, language plays a significant role: patent citation analyses consistently show a strong bias towards citing patents in one's native language. Since languages like Korean, Chinese and Japanese are not commonly spoken outside their regions, this creates a natural inward orientation in knowledge flows, unlike more globally spoken languages such as English or French.

[34] Note that the set of countries/jurisdictions eligible for analysis is different for the two technologies (due to different minimum thresholds we apply on numbers of total innovation for a country/jurisdiction to be included in the analysis, as explained in the 'Approach and methodology' section). This comparison focuses on countries eligible for analysis for both BECC and DAC.

returns from both BECC and DAC innovation are higher than equivalent estimated returns from hydrogen, solar PV and heating and cooling, but lower than those from tidal stream, offshore wind, smart systems and nuclear (Serin et al., 2023).

The relatively low domestic estimated returns observed for geological CDR, compared to clean technology fields as a whole, may reflect both economic and technological factors. Many clean technologies — such as solar PV, wind, or electric vehicles — are relatively established, meaning the costs of R&D in such fields would be lower than for more nascent technologies. In these more established fields, there would likely be numerous ideas which are only slightly short of commercial viability and for which government subsidies can tip the balance and unlock significant additional innovation, resulting in high estimated knowledge spillovers and in turn, a higher IStraX.

By contrast, geological CDR technologies are currently more nascent, capital-intensive and subject to greater uncertainty. The R&D costs in these areas may therefore well exceed the expected private returns to innovation, so government subsidies of a similar scale would likely only generate modest increases in innovation. Moreover, IStraX captures innovation spillovers that have already been realised, so it would not reflect the future value of early-stage technologies that have not yet matured or triggered follow-on innovations. A lower IStraX for geological CDR therefore likely reflects the technology's nascency and a time lag in innovation diffusion rather than inherently low economic returns to public investments in related innovation.

Zooming in on the UK

The UK is theoretically well placed to be a leader in the development of geological CDR technologies given its abundant geological storage capacity, relatively low-carbon electricity supply (particularly relevant for DACCS to ensure net CO_2 removal [Mulligan et al., 2023]), committed investments in CO_2 transport and storage infrastructure, relevant policy frameworks that are advancing (e.g. the greenhouse gas removals business model), and a transferable skills base from a long-standing oil and gas industry. Looking specifically at DACCS, a recent study has comprehensively assessed the feasibility of large-scale deployment in the UK. It has concluded that while the UK is a higher-cost location for DACCS deployment than some other locations globally due to its high energy prices, the aforementioned advantages it holds may still make it an attractive location for deployment, at least in the short term (City Science, 2025). In terms of innovative specialism, our analysis supports this conclusion, as we outline below.

Beyond the physical infrastructure and supply chains, the UK also specialises in the ancillary services necessary to scale demand for durable CDR. This includes strengths in the development of carbon markets, having operated a domestic compliance market for over 20 years, a deep carbon market ecosystem consisting of market makers, ratings agencies and governance initiatives, as well as expertise in sustainable finance and commodity innovation (The Global City, 2025). Strong demand-side expertise places the UK in a competitive position to capitalise on the growth potential of geological carbon storage.

In terms of the size of the economic opportunity, one estimate suggests that, by 2050, the UK could potentially capture over £1 billion (~US$1.2 billion) per annum of the global market for DAC, which could be worth almost £60 billion (~US$75 billion) per annum by that year (Tony Blair Institute, 2025; estimates are in 2023 prices). Furthermore, if the UK delivers engineered removal capacity of 5 $MtCO_2$ per annum by 2030, this could represent a domestic market worth US$500 million by that year (Oliver Wyman, 2024).

What does our data say about where the UK is likely to sit in the innovation race on geological CDR? Based on a simple count of innovations between 2000 and 2020, the UK is the eighth largest innovator in BECC (with a 3.7% share) and the sixth largest innovator in DAC (with a 5.7% share) (Table A3 in the Appendix). Within Europe, that makes it the fourth largest innovator in BECC (after Germany, France and the Netherlands) and the third largest innovator in DAC (after

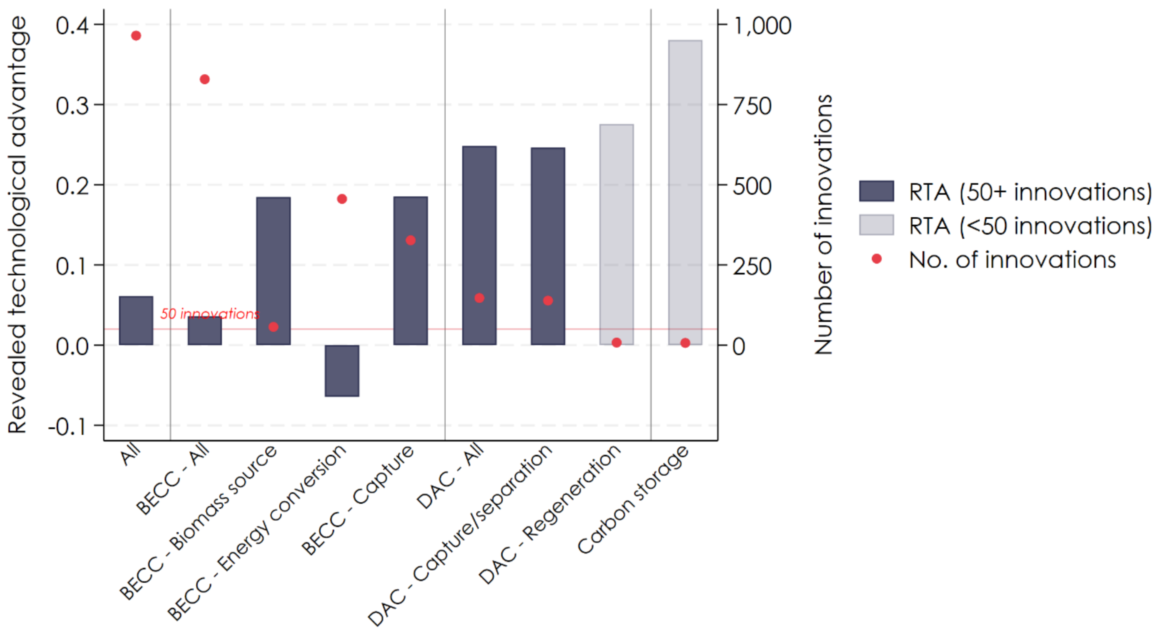
Germany and France). Carbon capture makes up a greater proportion of total BECC innovations in the UK compared to most other countries.

Turning to RTA (an indicator of innovative specialism), the UK is the tenth most specialised global innovator in BECC and the third most specialised global innovator in DAC.[35] Data from the DAC Coalition (DAC Coalition, 2024) — which tracks the formation of global DAC companies — show that the UK has a relatively high presence of domestic DAC companies. The UK's early specialism in the technology might have been a factor influencing these companies to locate here. Of the top 10 DAC RTA countries, the UK has the fourth highest number of companies (6), which is higher than the top ranked country, India (3), and the second ranked country, France (3). Only the US (89), Canada (11), Japan (7) and Germany (7) have a higher number of domestic DAC companies. The US, Canada and Germany also rank highly on innovative specialism.

Within Europe, the UK has the sixth-highest RTA in BECC and the second-highest RTA in DAC (within Europe, the UK also has the second highest number of DAC companies). Although the UK is the 10th most specialised innovator in BECC, its RTA (0.03) is far lower than other countries in the top 10 (France, which ranks ninth, has an RTA that is over six times the UK's). The UK has a higher RTA in DAC than it does in BECC.

Figure 3.9. shows the UK's innovative specialism in different stages of the relevant value chains, and sheds light on what drives its aggregate RTA values. Within BECC, there is material variation in the UK's specialism in different stages of the value chain. The UK appears to be particularly specialised in BECC – Capture, in which its RTA is more than five times its RTA in BECC overall. In fact, the UK has a negative RTA in energy conversion, which is the stage of the value chain in which it has the most innovations.

Figure 3.9. The UK's revealed technological advantage in specific stages across BECC, DAC and carbon storage (2000–20)



Notes: The left y-axis indicates RTA values (shown in bars and adjusted to lie between –1 and +1, where positive values indicate innovative specialism). The right y-axis indicates the number of multi-application innovations (shown in dots).
Source: Authors' analysis based on PATSTAT Global 2023 (Spring edition)

[35] The UK has developed its specialism in BECC over time, moving from a position of no overall RTA at the start of the data period to having slight RTA by the end (Figure A3 in the Appendix).

Within DAC, almost all UK innovations are associated with DAC – Capture, and the UK's RTA in DAC – Capture is therefore very similar to its overall RTA in DAC. The UK has insufficient innovations in DAC – Regeneration and carbon storage to estimate reliable RTAs for these value chain stages (i.e. fewer than 50 multi-application innovations), but RTA estimates for these are nevertheless shown in Figure 3.9. for completeness.

Between BECC and DAC overall, the UK has higher specialism in DAC. This is also true specifically for capture, with the UK's RTA in DAC – Capture/separation exceeding its RTA in BECC – Capture. The UK has a lower RTA in both BECC and DAC compared to France (a country which has appeared as a close competitor for the UK in previous analyses), although the difference in DAC is very marginal (Figure A18 in the Appendix). Within BECC, France's advantage is driven by its specialism in energy conversion and capture, which are both areas of considerable innovation activity globally. The UK, on the other hand, appears to be more specialised in innovations relating to biomass source (where not as many innovations take place globally).

Table 3.1. lists the UK's largest innovator organisations (by number of innovations) in geological CDR.[36] Similar to our observations for the US and Saudi Arabia, a substantial portion of the UK's geological CDR innovations come from oil and gas companies, including BP and Shell. Johnson Matthey, a forerunner in blue hydrogen development, has a significant number of innovations as well. Outside the top 10, Queens University in Belfast is the top performer among non-profit organisations.

Comparing the UK (Table 3.1.) to France (Table A9 in the Appendix), France has greater representation from large research institutes. The French Institute of Petroleum has a substantial presence in the top 10 innovators, as does the French National Centre for Scientific Research. Similar to the UK, chemical firms are well represented in France with firms like Arkema and Ceca SA.

Table 3.1. The UK's top 10 geological CDR innovator organisations by number of innovations (2000–20)

Rank	Organisation name	% of country's geological CDR innovations	Primary industry	Home country	Organisation's global total geological CDR innovations	% of organisation's total geological CDR innovations in the UK
1	Imperial Chemical Industries Limited	10.2	Paint and coating manufacturing	UK	238	89
2	Canliq 3 Limited	7.3	N/A	UK	151	100
3	Johnson Matthey PLC	6.8	Chemical manufacturing	UK	146	97
4	BP PLC	5.5	Petroleum refineries	UK	167	69
5	BP Chemicals Limited	5.1	Inorganic chemical manufacturing	UK	117	91
6	Unilever PLC	2.7	Consumer goods	UK	67	85
7	Menstrie Foods Limited	2.5	N/A	UK	68	76

[36] Similar tables for the US, China, India, Russia, Saudi Arabia and France are included in the Appendix (Tables A4–A9).

8	Shell Internationale Research Maatschappij BV	2.5	R&D in the physical, engineering and life sciences	Netherlands	497	10
9	Unilever NV	2.2	Consumer goods	Netherlands	62	74
10	Air Products & Chemicals Inc.	1.7	Industrial gas manufacturing	US	208	17

Note: We construct the table of top innovator organisations using Orbis IP, which allows us to match patent families to the organisation they are associated with. We match inventions to their most direct level of consolidation, meaning that patents are generally matched to the local subsidiary rather than the global ultimate owner of the corporate group. We match the organisations exactly as they appear in Orbis IP; due to the legal complexity of how patent portfolios are owned within large multinationals, some innovations may be mapped to holding companies or split between separate parts of a single corporate entity. Across this report, we use the location of the inventor to describe where innovation is happening. For the current table and Tables A4–A9, for a given country we consider foreign firms doing research with inventors based in the country, hence the column 'Home country' which describes the location of the organisation rather than the inventors. Companies for which the 'Primary industry' information was not available in the source database have been manually classified by the authors where possible through a web-based search on their activities.

We can also compare the UK's RTA in BECC and DAC against its RTA in some other clean technologies by drawing on our previous work on UK sustainable growth opportunities in the series (Serin et al., 2023).[37] Such an exercise is important for informing the prioritisation of policy support across different areas of the clean economy. This shows that the UK's innovative specialism in DAC exceeds its innovative specialism in all other clean technologies except for tidal stream (Figure 3.10.). Its specialism in BECC is somewhat lower, coming behind offshore wind and CCUS, though is still much higher than its specialism in various technologies like solar, clean cars and nuclear. The sector plan for clean energy industries of the UK's new industrial strategy published in June 2025 has identified CCUS, including greenhouse gas removals (which cover BECCS and DACCS), among its frontier industries which will be prioritised for policy support given their growth potential (UK Government, 2025).

The UK's estimated returns from BECC innovation are relatively low, both as a whole and as the percentage of those returns it retains domestically (Figures 3.5. and 3.6.). Germany, the Netherlands and Denmark are some European countries with higher estimated domestic returns from BECC innovation than the UK (Figure 3.6.). The UK also generates lower estimated spillovers for the rest of the world than some of its European counterparts (the Netherlands, Denmark, Spain, Italy, Belgium and Germany) (Figure A6 in the Appendix).

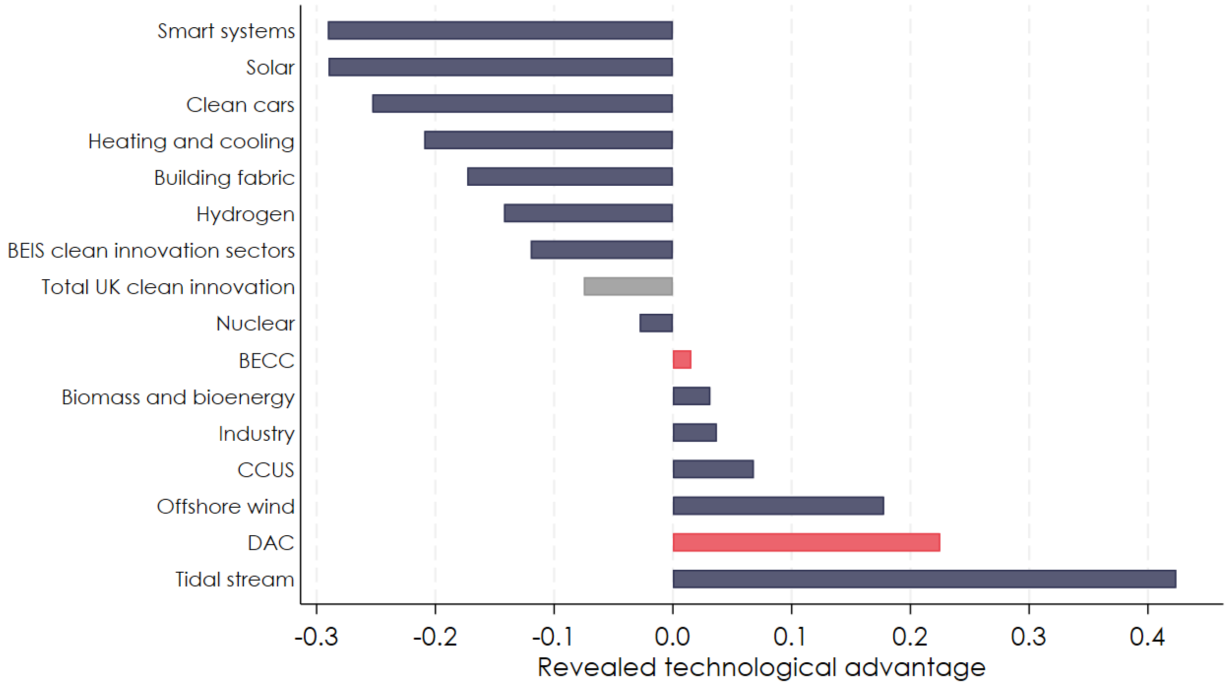
The UK is in a better position on DAC, with the seventh highest estimated domestic returns from DAC innovation globally (Figure 3.8.). This is within a smaller group of countries that can be considered substantive innovators of DAC in this period (i.e. have 50 or more multi-application innovations between 2000 and 2020). In the European context, the UK is again behind the Netherlands and Germany. This time, the UK yields stronger estimated returns for the rest of the world, taking fifth place in the world in that regard (Figure A7 in the Appendix).

Like most other countries, the UK's estimated domestic returns from BECC and DAC innovation are lower than its average estimated domestic returns from clean technology innovation as a

[37] Differently to the rest of this report, this analysis focuses on 1980–2018 as this is the period for which RTA calculations for the comparator clean technology categories are available based on our previous work. We assume that this will still provide good insight into the UK's relative performance in different fields during the focus period of the current study (i.e. 2000–20), as a much greater proportion of clean patenting activity (both in the UK and globally) lies in the years since 2000 than in the preceding years. Furthermore, it should be noted that the UK's RTA in BECC and DAC calculated in the current study are not fully comparable to its previously calculated RTA values for other clean technologies. This is because the grouping of patent families that represent BECC and DAC have been constructed through a keyword search approach in the current study, while analysis of other selected technologies relies on pre-defined CPC codes.

whole. However, its estimated returns from BECC and DAC innovation that spill over to the rest of the world (which by far exceed its estimated domestic returns) represent a significant upside opportunity. If a greater proportion of the country's global returns for BECC and DAC could be retained domestically, this could better support the twin goals of economic growth and decarbonisation.

Figure 3.10. The UK's revealed technological advantage in BECC and DAC compared to other selected clean technologies (1980–2018)



Notes: The x-axis indicates RTA values for the UK for the given technology categories (shown in bars and adjusted to lie between –1 and +1, where positive values indicate innovative specialism). CPC system codes underpinning the specific clean technology categories on the y-axis (except BECC, DAC and clean cars) are based on Martin and Verhoeven (2022), which were selected and designed in collaboration with the (then) Department for Business, Energy and Industrial Strategy (BEIS). The 'Clean cars' category was added based on Curran et al. (2022). 'BEIS clean innovation sectors' is an aggregation of the specific clean technology categories listed (apart from BECC, DAC and clean cars). 'Total UK clean innovation' refers to all UK innovations under the 'Y02' class from the CPC system, which corresponds to technologies or applications for mitigation or adaptation against climate change.
Source: BECC and DAC are authors' analysis based on PATSTAT Global 2023 (Spring edition); estimates of other technology categories are based on PATSTAT Global 2021 (Autumn edition) and drawn from Serin et al. (2023)

Overall, the UK is an important innovator in both BECC and DAC. It is one of the four countries which feature among the top 10 most specialised innovators for both technologies (the others are France, India and the Netherlands), and is in a strong position within Europe. Its performance in DAC particularly stands out, while it faces more competition in BECC. However, the UK appears to have had limited success so far in translating its innovative specialism to economic value. For example, it comes behind countries like South Korea, Japan and China in terms of its estimated domestic returns, despite it having greater innovative specialism than all those countries for both BECC and DAC. France, the Netherlands and Germany are neighbouring competitors for the UK, where Germany and the Netherlands have greater estimated returns (both overall and in terms of the percentage they retain domestically) than the UK from both BECC and DAC.

4. Discussion

The link between the innovation and domestic deployment of geological CDR

Including countries in our analysis that have deployed or are working to deploy BECCS and DACCS facilities domestically (which we take as a proxy for domestic demand for relevant technologies) has enabled us to explore the extent to which this may be a driver of patterns in relevant innovative performance.

Among the largest innovators in BECC, the US, France, the Netherlands, the UK and Canada are already operating or planning domestic BECCS projects. Brazil and Denmark, which are not particularly large innovators but are highly specialised innovators, are also both home to projects under development. Four countries among the largest and most specialised innovators in DAC — the US, France, the UK and Canada — already have operational or planned facilities. The US is notable, demonstrating innovative strengths across our different pieces of analysis. This is against the backdrop of the country having the largest number of facilities in development for both BECCS and DAC, as well as multiple operational facilities for both. Such deployment activity has been helped by the availability of a policy framework in the country which incentivises carbon sequestration (e.g. the 45Q tax credit which has been available since 2008 and has become more generous over time, though is facing an uncertain future now), low electricity and gas prices, and infrastructure in place to transport and store CO_2 (City Science, 2025). Nevertheless, with only a few countries in the world currently home to (planned or operational) facilities for BECCS or DAC(CS), we see that many countries that do not currently plan domestic facilities nonetheless hold innovative capabilities relevant for these technologies. For example, many countries we observe in leading positions in our analyses, like Saudi Arabia, India and China, do not yet have any projects coming forward that we have been able to identify.

Geological storage capacity and readiness does, however, appear to co-exist with innovative strengths in geological CDR. For example, almost all the top innovators in BECC and DAC appear in the top two bands of the Global CCS Institute's Storage Readiness Index (Consoli et al., 2016). Band A includes Canada, the US, Norway, the UK and Australia and Band B includes the Netherlands, China, Denmark, Germany and Japan. While we cannot claim causality, there is a high degree of overlap between leading innovators in BECC and DAC and countries with strong storage readiness.

So far we have discussed domestic deployment as a potential driver of innovation, but it could also be the other way around. Places that already demonstrate relevant innovative strengths could be attractive locations for investments in initial facilities and supply chains. However, this is unlikely to be the core determinant, with many other factors in play for deciding where deployment takes place, such as an abundance of low-cost, low-carbon energy, market drivers, labour availability, a supportive policy environment and high-quality geological storage capacity (Global CCS Institute, 2024).

DAC, in particular, has good location flexibility as it is not tied to a specific point source of CO_2. Indeed, according to the International Energy Agency (2024a), around 60% of announced DAC capacity for 2030 has not yet been linked to a specific location, with project developers awaiting favourable regulations before finalising their expansion plans. Those locations may well be different to where the original knowledge and inventions underpinning relevant technologies have been created.

As the industry matures, the relationship between domestic deployment and innovative capability may strengthen, with countries operating relevant technologies at home having better opportunities for learning by doing and further technological innovation. Future deployment activity might then gravitate towards these knowledge and innovation hubs.

The role of policy

Policy interest in geological CDR in many countries has emerged or been formalised since 2020, the impact of which cannot be captured in our analysis. Nevertheless, there appears to be some correlation between innovative strength in geological CDR and the presence of a policy framework or a stated policy interest in the field in a country.

Eight of the largest innovators in BECC demonstrate explicit policy interest in the technology. Many of these countries have high estimated domestic returns to additional public investments in BECC innovation. Among the leading countries on innovative specialism in the field, Brazil, Denmark, the Netherlands, France and the UK have stated policy intentions to support BECCS either through integration into domestic compliance markets (where they exist, such as in the UK and the EU) and through business model support via carbon contracts for difference (CCfDs).

Among the largest innovators in DAC, the US, the UK, South Korea, Canada, China and Japan have an explicit policy interest in developing the technology. These large innovator countries also have some of the highest estimated domestic returns to additional public investments they make in innovation in this field. The US, the UK and Canada also demonstrate innovative specialism in DAC.

In a few countries in which the relevant policy landscape is more mature, we might be seeing signs of a causal link between policy and innovative strength in geological CDR. In the case of the US, it would not be surprising that a country that has had a policy environment supportive of the deployment of CDR technologies would also have attracted investment in relevant innovative capabilities. Innovative strengths of the UK and Canada, especially in the context of DAC, could be explained in a similar way, with both countries having been exploring the development of the technology for some time (where Canada already has an operational pilot plant).

Going forward, the availability of policy support will have an undeniable role in deciding where investments in geological CDR take place, whether that be in the innovation, supply chains or domestic facilities of related technologies. As BECCS and DACCS can share CO_2 transport and storage infrastructure with point source CCUS applications, BECCS and DACCS development will be helped by not just CDR-specific mechanisms but also wider CCUS support. Several advancements have been made across the UK and the EU in this regard, including the UK's Dispatchable Power Agreement, which will support Net Zero Teesside's power CCS facility (Net Zero Teesside, 2024) and the SDE++ scheme designed by the Dutch Government, which will support the Porthos CCS plant in Rotterdam (Netherlands Court of Audit, 2024).

Given the nascency of these industries, opportunities will be available for both existing and new players which put forward a conducive policy environment. At a high level, the demand for technologies and services related to geological CDR will come down to countries' strong commitment to reaching global net zero. Evidence from other sectors suggests that creating demand could be a critical incentive for innovators and supply chain companies to invest in building related CDR capacity. For example, China is at the heart of the global battery supply chain, with the huge growth in battery and component production due to domestic demand for electric vehicles (IEA, 2025). In the US, in the last few years, new policies to scale up domestic demand and manufacturing capacity have significantly strengthened the heat pump market (ibid.).

In terms of CDR, BCG estimates that the global demand for CDR compatible with a 1.5°C warming scenario would represent double the market size by 2050 compared to a scenario compatible with 2°C warming (BCG, 2025). Countries, both individually and collectively, will be influencing investment decisions in CDR with not only their CDR-specific policies but also their broader climate policies and commitment to net zero.

Here, it is useful to reiterate that the relatively low estimated returns to public investment in innovation our analysis yields on geological CDR likely reflect the technology's nascency and a time lag in innovation diffusion rather than inherently low returns from this field. Crucially, this observation should be an incentive, not a deterrence, to public investment in geological CDR. The past decade is evidence of how policies supportive of research into, and development and deployment of, early-stage clean technologies can drive remarkable cost reductions[38] (Zenghelis et al., 2024). Most economists failed to predict such cost reductions and the markets alone would not have delivered these, as the technologies were initially too expensive to be viable (ibid.). The IEA (2025) points out areas of research need to reduce the costs of BECCS, DAC and storage technologies, primarily by minimising energy use and optimising plant designs.

Now, achieving global net-zero targets will almost certainly require large-scale deployment of geological CDR to address residual emissions from hard-to-abate sectors such as heavy industry, aviation and agriculture. Progress driven by policy in other clean technology fields offers important lessons for policymakers working to drive geological CDR development. Early technology-specific policy support remains essential to de-risk investment in the field and unlock future pathways to scalable, cost-effective removal technologies (Burke and Gambhir, 2022). Such support should be designed with a recognition that different policy combinations will be effective for different technology readiness levels (TRLs). For example, while tax breaks and direct grants are versatile and can be used for low TRL CDR methods, public procurement schemes, advanced market commitments (AMCs), CCfDs, ETS integration, and voluntary carbon markets (VCMs) are more suitable for demonstrated technologies in the deployment/diffusion stages (Feng et al., 2025).

As the technologies mature and market signals strengthen, the need for technology-specific policy support in driving development is likely to fall, and the spillover potential of geological CDR innovations is likely to grow.

Opportunities to capitalise on transferable knowledge and capabilities

In above discussions we have highlighted how innovative strengths in geological CDR co-exist with domestic deployment activities or policy interest for these technologies in some countries. However, these factors on their own do not sufficiently explain why countries perform as they do in our analyses more generally. This is evident in results such as Saudi Arabia and Russia taking top ranks on innovative specialism for BECC, and India appearing among the leading countries across the different pieces of analysis for both BECC and DAC, despite these countries not having explicit policy activities or emerging facilities we have been able to identify in the respective fields.

Our results are more likely driven by the fact that the innovations we have included in the scope of our analysis for BECCS and DACCS are not exclusive to these fields and may have originally been invented for applications in other, related sectors. This is particularly relevant for innovations from the 2000s captured in our analysis, when geological CDR was an especially early field. For example, the first commercial BECCS plant we have identified came online in 2009, and the first commercial DACCS plant in 2021.

Some of our results reflect countries' innovative activities in CCUS more broadly (which covers a broad group of technologies providing the technological foundation for BECCS and DACCS as well as other applications like industrial CCS and gas power with CCS). For example, we have not identified any BECCS projects in Saudi Arabia (though it has a focus on DACCS) or any geological CDR projects in India (two leading countries on our RTA analysis), but we know that they have other types of CCUS projects in development (Global CCS Institute, 2024).

One sector with strong innovative crossovers with BECCS and DACCS is oil and gas, with the extraction and processing of these fuels involving many processes that are similar to those that exist within BECCS and DACCS operations. Indeed, oil and gas companies represent substantial

[38] Over the past decade, the cost across the world of both solar PV generation and battery storage has fallen nearly tenfold, while offshore wind costs have fallen by more than half (Grubb et al., 2021; Way et al., 2022).

portions of innovation for geological CDR in many countries we have analysed, including China, India, Saudi Arabia, the UK and the US. In the UK context, we have previously found that there is a positive correlation between locations of innovation for CCUS and oil and gas extraction (Serin et al., 2021).

Furthermore, innovations we include within the scope of the biomass source and energy conversion stages of BECC might have originally been invented for use in traditional biomass power plants (without CCS). Given energy conversion represents a large portion of BECC innovations for all countries (see Figure 3.2.), this might explain certain countries in which we have not identified domestic activities explicitly related to BECC yielding a high number of innovations relevant for and/or innovative specialism in BECC.

Going forward, there are likely to be significant opportunities available for countries that can translate their relevant innovative strengths in other fields into explicit capability in geological CDR. These strengths represent a comparative advantage in knowledge that these countries can capitalise on to develop competitive products and services to serve the growing global geological CDR market. Current policy uncertainty facing the CDR industry in the US might create an opportunity for other countries to attract related investments. Anecdotal evidence suggests CDR development in the US might already be slowing down. For example, recent reports suggest one of the companies building a direct air capture hub in Louisiana has cancelled a project and laid off staff, and the Department of Energy missed a deadline to announce the latest winners of its CDR purchase prize competition (Giles, 2025).

5. Conclusion

Different countries demonstrate innovative strengths relevant for geological CDR in different ways, with opportunities available for all of them in the innovation race ahead. The US has been a significant player in the innovation of geological CDR so far and is where the greatest number of facilities for both BECCS and DACCS are currently in development. However, the stance of the current US administration on climate action, and the uncertainty that creates for the policies which have so far supported CDR development in the country, mean other countries can capitalise. The nascency of BECCS and DACCS means the competitive landscape may rapidly evolve, leaving scope for new players to emerge and break into relevant markets.

As governments work to drive innovation in geological CDR in support of their emissions reduction and growth objectives, with a future global market expected to be worth tens of billions of dollars, it will be important for that to be done in a way that does not deter investment in near-term emissions reductions. In the context of BECCS, countries will also have a responsibility to ensure emissions from proposed projects are accounted for across their whole lifecycle, including the source of the biomass, so that these projects result in genuine removals. Ultimately, the innovation race on geological CDR is not an end in itself, but a means for countries to contribute to global climate goals while benefiting their economies at home.

Recommendations for policymakers looking at geological CDR as a potential industrial opportunity in their country

- Policy support for geological CDR — which is an indispensable tool for global net zero — should be designed and allocated in a way that does not deter and instead complements vigorous emissions reduction efforts.
- Relevant existing capabilities in other sectors such as oil and gas that are transferable into geological CDR should be recognised and capitalised on to build competitive domestic supply chains around related technologies.
- A policy mix designed to maximise growth opportunities from geological CDR should tailor support to the different maturity levels of the different technologies involved, considering direct innovation support for earlier-stage technologies alongside market-based mechanisms such as emissions trading schemes to support more established technologies.
- Policy support for geological CDR should exist within a comprehensive and coordinated national decarbonisation strategy, capturing complementarities with other areas such as carbon capture, usage and storage (CCUS).

Recommendations for UK policymakers

- Policy should be designed explicitly to retain more of the follow-on economic value from geological CDR innovation — in which the UK demonstrates notable strengths especially, in direct air capture (DAC) — maximising domestic jobs and supply chain opportunities from this growing industry.
- The UK's industrial strategy for clean technologies and the forthcoming Greenhouse Gas Removal Review should nurture the country's comparative advantages in geological CDR, and invest in necessary infrastructure and skills, given the country's relatively high innovative specialism — especially in DAC — as well as its geological and policy strengths.

References

Allen MR, Friedlingstein P, Girardin CAJ, Jenkins S, Malhi Y, Mitchell-Larson E, et al. (2022) Net zero: science, origins, and implications. *Annual Review of Environment and Resources*. https://doi.org/10.1146/annurev-environ-112320-105050

Boston Consulting Group [BCG] (2024) *Carbon dioxide removal: Europe and Germany's role in catalyzing a trillion-euro industry*. https://negative-emissions.bcg.com/home/

Boston Consulting Group [BCG] (2025) *Carbon dioxide removal: reaching the full potential of France*. https://web-assets.bcg.com/5b/5d/2769ece643b38516dd0ecd991bd6/carbondioxide-removal-reaching-the-full-potential-of-france.pdf

Brunner C, Hausfather Z, Knutti R (2024) Durability of carbon dioxide removal is critical for Paris climate goals. *Communications Earth & Environment* 5: 645. https://doi.org/10.1038/s43247-024-01808-7

Burke J, Fankhauser S (2023) *Who is buying greenhouse gas removal credits and does it matter?* Grantham Research Institute on Climate Change and the Environment, 5 June. https://www.lse.ac.uk/granthaminstitute/news/who-is-buying-greenhouse-gas-removal-credits-and-does-it-matter/

Burke J, Gambhir A (2022) Policy incentives for greenhouse gas removal techniques: the risks of premature inclusion in carbon markets and the need for a multi-pronged policy framework. *Energy and Climate Change*: 100074. https://doi.org/10.1016/j.egycc.2022.100074

Carbon Gap (2025) *EU–US comparison: funding for RD&I*. https://tracker.carbongap.org/regional-analysis/eu-us-comparison/funding-for-rdi/

CDR.fyi (2025a) Homepage. https://www.cdr.fyi/ [Accessed 10 June 2025]

CDR.fyi (2025b) *Keep calm and remove on — CDR.fyi 2024 year in review*. https://www.cdr.fyi/blog/2024-year-in-review

Chen T (2024) *Japan's GX-League and carbon removal in GX-ETS*. https://www.cdr.fyi/blog/japans-gx-league-and-carbon-removal-in-gx-ets

City Science (2025) *Assessing the feasibility for large-scale DACCS deployment in the UK*. https://www.theccc.org.uk/publication/assessing-the-feasibility-for-large-scale-daccs-deployment-in-the-uk/

Climate Change Committee [CCC] (2020) *Sixth carbon budget*. https://www.theccc.org.uk/publication/sixth-carbon-budget/

Climate Change Committee [CCC] (2025) *Seventh carbon budget*. https://www.theccc.org.uk/publication/the-seventh-carbon-budget/

Consoli C, Havercoft I, Irlam L (2016) *Carbon capture and storage readiness index*. https://www.globalccsinstitute.com/archive/hub/publications/201168/Carbon%20capture%20and%20storage%20readiness%20index.pdf

Curran B, Martin R, Muller S, Nguyen-Tien V, Oliveira-Cunha J, Serin E, et al. (2022) *Growing clean: identifying and investing in sustainable growth opportunities across the UK*. London: Resolution Foundation and the London School of Economics and Political Science. https://economy2030.resolutionfoundation.org/reports/growing-clean/

DAC Coalition (2024) *The mega DAC database*. https://docs.google.com/spreadsheets/d/1NGV-ZW-mS5I-RfHnQG307s82DWEfXvoMdMWL7x6NaR4/edit?gid=0#gid=0

Department for Energy Security and Net Zero [DESNZ] (2024) *Accelerating to net zero: responding to the CCC progress report and delivering the Clean Energy Superpower Mission*. Corporate report, HC 468, presented to Parliament pursuant to Section 37 of the Climate Change Act (2008), 17 December. https://www.gov.uk/government/publications/committee-on-climate-change-2024-

progress-report-government-response/accelerating-to-net-zero-responding-to-the-ccc-progress-report-and-delivering-the-clean-energy-superpower-mission-accessible-webpage

Department for Energy Security and Net Zero [DESNZ] (2025a) *2023 UK greenhouse gas emissions, final figures*. https://www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-statistics-1990-to-2023

Department for Energy Security and Net Zero [DESNZ] (2025b) *Independent review of greenhouse gas removals: terms of reference*. https://www.gov.uk/government/publications/greenhouse-gas-removals-ggrs-independent-review/independent-review-of-greenhouse-gas-removals-terms-of-reference

European Central Bank (2025) *Euro reference exchange rates US dollar (USD)*. https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html [Accessed 12 May 2025]

European Commission (2024) *Impact assessment report: securing our future — Europe's 2040 climate target and path to climate neutrality by 2050: building a sustainable, just and prosperous society*. Commission Staff Working Document, Part 3, SWD(2024) 63 final, 6 February. https://publications.europa.eu/resource/cellar/6c154426-c5a6-11ee-95d9-01aa75ed71a1.0001.03/DOC_3

Feng S (2025, forthcoming) *Innovation in geological CDR along the value chain: examples of BECCS and DACCS*.

Feng S, Stemmler J, Arlinghaus J, Fankhauser S, Smith SM (2025) *Policy evaluation and selection to accelerate geological carbon dioxide removal deployment*. CO_2RE. https://co2re.org/wp-content/uploads/2025/05/economic-policies-pb.pdf

Giles J (2025) U.S. carbon removal industry in turmoil as federal support remains uncertain. *Trellis*, 7 May. https://trellis.net/article/carbon-removal-industry-setbacks-federal-support-uncertain/

Global CCS Institute (2024) *Global status of CCS 2024*. https://www.globalccsinstitute.com/resources/global-status-report/

Grubb M, Drummond P, Poncia A, McDowall W, Popp D, Samadi S, et al. (2021) Induced innovation in energy technologies and systems: a review of evidence and potential implications for CO_2 mitigation. *Environmental Research Letters* 16(4): 043007. https://doi.org/10.1088/1748-9326/abde07

Guillard C, Martin R, Mohnen P, Thomas C, Verhoeven D (2023) *Efficient industrial policy: standing on the shoulders of hidden giants*. CEP Discussion Paper No. 1813. London: Centre for Economic Performance. https://cep.lse.ac.uk/_NEW/publications/abstract.asp?index=8614

Hall BH, Jaffe A, Trajtenberg M (2005) Market value and patent citations. *The RAND Journal of Economics* 36(1): 16–38. http://www.jstor.org/stable/1593752

Intergovernmental Panel on Climate Change [IPCC] (2023) *AR6 synthesis report: climate change 2023*. https://www.ipcc.ch/report/ar6/syr/

International Energy Agency [IEA] (2024a) *Direct air capture*. https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/direct-air-capture

International Energy Agency [IEA] (2024b) *Energy technology patents data explorer*. https://www.iea.org/data-and-statistics/data-tools/energy-technology-patents-data-explorer

International Energy Agency [IEA] (2025) *The state of energy innovation*. https://www.iea.org/reports/the-state-of-energy-innovation

Kang J-N, Wei Y-M, Liu L-C, Wang J-W (2021) Observing technology reserves of carbon capture and storage via patent data: paving the way for carbon neutral. *Technological Forecasting and Social Change* 171: 120933. https://doi.org/10.1016/j.techfore.2021.120933

Kang J-N, Zhang Y-L, Chen W (2022) Delivering negative emissions innovation on the right track: a patent analysis. *Renewable and Sustainable Energy Reviews* 158: 112169. https://doi.org/10.1016/j.rser.2022.112169

Kessler J, Sperling D (2016) Tracking U.S. biofuel innovation through patents. *Energy Policy* 98: 97–107. https://doi.org/10.1016/j.enpol.2016.08.021

Kogan L, Papanikolaou D, Seru A, Stoffman N (2017) Technological innovation, resource allocation, and growth. *The Quarterly Journal of Economics* 132(2): 665–712. https://doi.org/10.1093/qje/qjw040

Martin R, Verhoeven D (2022) *Knowledge spillovers from clean and emerging technologies in the UK*. CEP Discussion Paper No. 1834. https://cep.lse.ac.uk/_NEW/PUBLICATIONS/abstract.asp?index=9256

McKinsey & Company (2023) *Carbon removals: how to scale a new gigaton industry*. https://www.mckinsey.com/capabilities/sustainability/our-insights/carbon-removals-how-to-scale-a-new-gigaton-industry#/

Minx JC, Probst BS, Lück S, Müller-Hansen F, Toetzke M, Diaz Anadon L, et al. (2024) Chapter 2: Research and development. In: Smith SM et al. (eds) *The state of carbon dioxide removal 2024 — 2nd edition*. https://www.stateofcdr.org

Mittal S (2025) TikTok inks carbon removal deal with Climeworks. *Edie*, 21 February. https://www.edie.net/tiktok-inks-carbon-removal-deal-with-climeworks/

Mulligan J, Ellison G, Levin K, Lebling K, Rudee A, Leslie-Bole H (2023) *6 ways to remove carbon pollution from the atmosphere*. World Resources Institute. https://www.wri.org/insights/6-ways-remove-carbon-pollution-sky

Nemet GF, Edwards MR, Greene J, Dayathilake L, Thomas ZH, Surana K, et al. (2024) Chapter 3: Demonstration and upscaling. In: Smith SM et al. (eds) *The state of carbon dioxide removal 2024 — 2nd edition*: 3. https://www.stateofcdr.org

Net Zero Teesside (2024) *Greenlight for Net Zero Teesside power*, 10 December. https://www.netzeroteesside.co.uk/news/greenlight-for-net-zero-teesside-power/

Net Zero Tracker (2025) *Data explorer*. https://zerotracker.net/ [Accessed 19 May 2025]

Netherlands Court of Audit (2024) *Carbon storage under the North Sea*. https://english.rekenkamer.nl/publications/reports/2024/03/28/carbon-storage-under-the-north-sea

Office for National Statistics [ONS] (2025) *Average sterling exchange rate: US dollar XUMAUSS*. https://www.ons.gov.uk/economy/nationalaccounts/balanceofpayments/timeseries/auss/mret [Accessed 12 May 2025]

Oliver Wyman (2024) *Unlocking the potential of carbon dioxide removal*. https://www.oliverwyman.com/our-expertise/insights/2024/jun/carbon-dioxide-removal-solutions.html

Popp D, Pless J, Haščič I, Johnstone N (2022) *Innovation and entrepreneurship in the energy sector*. University of Chicago Press. https://www.nber.org/books-and-chapters/role-innovation-and-entrepreneurship-economic-growth/innovation-and-entrepreneurship-energy-sector

Probst B, Touboul S, Glachant M, Dechezleprêtre A (2021) Global trends in the invention and diffusion of climate change mitigation technologies. *Nat Energy* 6: 1077–1086. https://doi.org/10.1038/s41560-021-00931-5

Rhodium Group (2025) *The benefits of innovation: an assessment of the economic opportunities of highly durable carbon dioxide removal*. https://rhg.com/research/the-benefits-of-innovation-an-assessment-of-the-economic-opportunities-of-highly-durable-carbon-dioxide-removal/

Serin E, Andres P, Martin R, Read M, Shah A, Valero A (2024) *The green industrial policy matrix: informing an industrial strategy for clean energy technologies*. London: London School of Economics and Political Science. https://cep.lse.ac.uk/_NEW/publications/abstract.asp?index=11272

Serin E, Andres P, Martin R, Shah A, Valero A (2023) *Seizing sustainable growth opportunities from tidal stream energy in the UK*. London: London School of Economics and Political Science. https://www.lse.ac.uk/granthaminstitute/publication/seizing-sustainable-growth-opportunities-from-tidal-stream-energy-in-the-uk/

Serin E, Valero A, Martin R, Shah A, Andres P, Mealy P (2021) *Seizing sustainable growth opportunities from carbon capture, usage and storage in the UK*. London: London School of Economics and Political Science. https://www.lse.ac.uk/granthaminstitute/publication/seizing-sustainable-growth-opportunities-from-carbon-capture-usage-and-storage-in-the-uk/

Shindell D, Rogelj J (2025) Preserving carbon dioxide removal to serve critical needs. *Nature Climate Change* 15: 452–457. https://doi.org/10.1038/s41558-025-02251-y

Smith SM, Geden O, Gidden MJ, Lamb WF, Nemet GF, Minx JC, et al. (eds) (2024) *The state of carbon dioxide removal 2024 — 2nd edition*. https://www.stateofcdr.org/edition-2-resources

The Global City (2025) *The role of the UK in carbon markets: a path to global leadership*. https://www.theglobalcity.uk/insights/the-role-of-the-uk-in-carbon-markets

Tony Blair Institute for Global Change [TBI] (2025) *Making UK industrial strategy work: a hard-headed approach guided by green industry*. *https://institute.global/insights/economic-prosperity/making-uk-industrial-strategy-work-a-hard-headed-approach-guided-by-green-industry*

UK Government (2025) *Clean energy industries sector plan*. https://www.gov.uk/government/publications/clean-energy-industries-sector-plan

Unsworth S, Valero A, Martin R, Verhoeven D (2020) *Seizing sustainable growth opportunities from zero emission passenger vehicles in the UK*. London: Centre for Climate Change Economics and Policy, Grantham Research Institute on Climate Change and the Environment and Centre for Economic Performance, London School of Economics and Political Science. https://www.lse.ac.uk/granthaminstitute/publication/seizing-sustainable-growth-opportunities-from-zero-emission-passenger-vehicles-in-the-uk/

U.S. Department of Energy [DOE], Office of Energy Efficiency and Renewable Energy [EERE], Bioenergy Technologies Office [BETO] (2021) *The influence of bioenergy conversion patents funded by the U.S. Department of Energy's Bioenergy Technologies Office and other DOE Offices*. https://www.energy.gov/eere/analysis/influence-bioenergy-conversion-patents-funded-us-department-energys-bioenergy

Volcovici V (2025) US carbon removal hub funding may face Energy Department cuts, sources say. *Reuters*, 28 March. https://www.reuters.com/sustainability/climate-energy/us-carbon-removal-hub-funding-may-face-energy-department-cuts-sources-say-2025-03-28/

Way R, Ives MC, Mealy P, Farmer JD (2022) Empirically grounded technology forecasts and the energy transition. *Joule* 6(9): 2057–2082. https://doi.org/10.1016/j.joule.2022.08.009

Zenghelis D, Serin E, Stern N, Valero A, Van Reenen J, Ward B (2024) *Boosting growth and productivity in the United Kingdom through investments in the sustainable economy*. London: Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science. https://www.lse.ac.uk/granthaminstitute/publication/boosting-growth-and-productivity-in-the-united-kingdom-through-investments-in-the-sustainable-economy/

Appendix

Further detail on the IStraX methodology

The methodology for calculating IStraX is introduced and thoroughly explained in Guillard et al. (2023). In this methodology, we infer the economic value of an innovation based on the sum of its private value and a share of the total value of its downstream citations (knowledge spillovers). Private value of an innovation is assumed to be captured by the short-term response of the US stock market price of innovating companies when a patent is granted. Private values of patents for non-stock-listed companies are based on the most similar patents from stock-listed companies. The value of the knowledge spillovers is decided by the importance of that innovation within the network of citations using PageRank centrality. Intuitively, the PageRank algorithm apportions the value of a given patent to its backward citations, which in turn redistributes their value to their backward citations. The stable distribution of this process is the patent rank used to assign importance of the patents. All else being equal, a patent will have higher patent rank if more patents cite it or if the patents that cite it are in turn cited frequently.

To determine IStraX, we compare this expected increase in economic value from an innovation to the expected cost of R&D. This cost measure is computed from averages across 32 technology classes for each year of the data. Where innovations are cross-cutting — as determined by CPC technology codes — the costs from each relevant technology class are averaged. We infer the average R&D investment required to generate an innovation from the observed shape of the private value distribution in a particular technology area. Since innovations must reach a threshold to be worthwhile for investment, we can look for kinks in the distribution of private values for each technology class as a metric for the revealed threshold for that industry. If the distribution of private values for a given technology peak at a relatively high value, it is a sign that the costs of R&D projects in that area are higher; that is, innovators will ensure that they can recover those higher costs — on average — by only pursuing the most promising ideas. If average R&D costs in a technology area are high, it will require more government funding to increase innovation. This threshold is inferred to be the spot where the marginal R&D spending required meets the marginal private benefit of the said R&D. The IStraX estimates the social value of additional spending past this threshold.

Selection of countries of interest for analysis

A country of interest on BECCS or DACCS for us is one that is home to existing or planned facilities for the respective technology, and/or has a policy programme or interest to develop it domestically. We have identified these countries by scanning web-based information, covering key industry reports in particular. Sources we have drawn upon are specified in Tables A1 and A2.

BECCS countries

In the list of facilities in Table A1, information from the CO_2RE Facilities Database (GCCSI, 2024a) is presented in normal text, information from the Global Status of CCS 2024 report by the Global CCS Institute (GCCSI, 2024c) is presented in red text, and information from any other source is presented in green text (with the source specified in parentheses). Please note that some of this information, especially with regard to the status and expected operation dates of facilities, may be outdated at the time of writing. For example, as of July 2025, the last comprehensive update to the CO_2RE Facilities Database was made in August 2023 (GCCSI, 2024b). Facilities are commercial unless specified as 'Pilot and Demonstration Facility'.

Given definitional complexities and different classification approaches used by different organisations, we make several upfront choices on what we count as a BECCS project for the purposes of this exercise. Firstly, we focus on BECCS projects in the energy sector only, that is facilities whose end product is bioenergy (biofuels, electricity or heat). It must be noted that some of the BECCS facilities we include here may not result in net removals of CO_2 as this depends on how their supply chains are configured (in particular, with regard to their biomass source), which is not readily available public information in most cases.

In contrast, we exclude BECCS projects in non-energy sectors, that is facilities which use biomass to generate heat, coupled with CCS, to produce other final products, such as paper or cement (which may theoretically be classified as BECCS and result in removals, depending on the configuration of their supply chain). For simplicity, we also exclude energy from waste projects from our scope and only consider projects which involve the dedicated sourcing of biomass.

Limiting our scope to certain sectors in this way applies only to our qualitative discussions of country-level deployment of BECCS. It affects which countries we consider to be explicit players in the BECCS space but does not influence the way we have constructed our patent dataset described in the 'Approach and methodology' section. The dataset includes innovations relevant to any BECCS project regardless of sector, since these projects often share the same or similar technological foundations, and an innovation in one would also be relevant in others.

Table A1. BECCS countries of interest

	Facilities**	Policy
Brazil	Early development • FS Lucas do Rio Verde BECCS; Operation date: Under evaluation; Capacity: 0.423 million tonnes per annum of carbon dioxide (Mtpa CO_2); Storage method: Under evaluation	Brazil enacted CCS-specific legislation in 2023, with further progress on several related bills in 2024 (GCCSI, 2024c). An energy transition support programme was launched which includes incentives for energy production with CCS (ibid.). Brazil's agricultural sector is a particular source of interest in BECCS (ibid.).
Canada	Operational • Aylmer CCU; **Utilisation Facilities**; Operation date: 2018 • Johnstown CCU; **Utilisation Facilities**; Operational; Operation date: 2018 Advanced development • Minnedosa Ethanol Plant; Operation date: Under evaluation • FCL Belle Plaine Ethanol Complex; Operation date: 2027; Capacity: 3 Mtpa CO_2; Storage method: Enhanced oil recovery Early development • North Star CCS; Operation date: 2027	Canada is exploring the roles that different CDR methods may play in reaching its 2050 net zero target, with BECCS and DACCS being explicitly considered (Schenuit et al., 2024). Several CDR-related policies and strategies are currently under development or published, including a Carbon Management Strategy and a Greenhouse Gas Offset Credit System (ibid.). In June 2024, the Canadian Parliament passed a bill introducing an investment tax credit for CCUS projects, with the credit rate set at up to 50% for qualifying BECCS projects (Government of Canada, 2024; Natural Resources Canada, 2024).
China	No projects identified in the sources scanned.	Reports from national studies on the status of CCUS indicate that innovation in DACCS and BECCS is coming to the attention of decision-makers (Schenuit et al., 2024). BECCS and DACCS are included among areas for which the government is seeking proposals in preparation for the fifth edition of its National Key Low Carbon Technologies List (ibid.).
Denmark	In construction • Ørsted – Asnæs Power Station (Kalundborg); Operation date: 2026; Capacity: 0.28 Mtpa CO_2; Storage method: Dedicated storage (Ørsted, 2023) • Ørsted – Avedøre Power Station (Greater Copenhagen); Operation	Denmark has targets for climate neutrality by 2045, and 110% emissions reductions by 2050 (Carbon Gap, 2025a). The country's Climate Program 2022 considered a variety of CDR methods which could be used to reach the country's climate goals, including BECCS (ibid.). Denmark has significant geological CO_2 storage capacity and ambitions to become a carbon storage hub in Europe, and is one of the few countries in the world with operational deployment incentives dedicated

	date: 2026; Capacity: 0.15 Mtpa CO_2; Storage method: Dedicated storage (Ørsted, 2023) Advanced development • BioCirc biogas plant; Operation date: 2026; Capacity: 0.13 Mtpa CO_2: Storage method: Dedicated storage (Danish Energy Agency, 2024) • Bioman ApS; Operation date: 2026; Capacity: 0.025 Mtpa CO_2; Storage method: Dedicated storage (Danish Energy Agency, 2024) Early development • Sindal Biogas Hjørring; Operation date: Under evaluation	to CCS and CDR, providing subsidies for an 8 to 15-year period per tonne of CO_2 removed/captured and stored (ibid.). In May 2023, two BECCS plants were awarded a contract by the Danish Energy Agency (DEA) as part of the first tender of its CCS subsidy scheme, and started construction (IEA, 2024a). In April 2024, the DEA awarded contracts to three more BECCS projects as part of its subsidy scheme for negative emissions (the NECCS fund) (ibid.). The country is also covered by EU-level policies detailed below the table.*
Finland	No projects identified in the sources scanned.	Finland's achievement of its carbon neutrality by 2035 target will likely require CDR (Carbon Gap, 2025b). In September 2023, Finland's Minister of Environment and Climate name-checked BECCS and DACCS as potential technological carbon sinks for the country (ibid.). Finland has several bioenergy plants which could be installed with carbon capture technology, though it lacks suitable geological formations for the durable storage of CO_2 and will need to export CO_2 (ibid.). The country is also covered by EU-level policies detailed below the table.*
France	Early development • Carbon Impact and C-Questra BECCS; Operation date: N/A; Storage method: Dedicated storage (Quantum Commodity Intelligence, 2025)	France's National Low Carbon Strategy sets a net zero target by 2050 and refers to the role of several CDR methods in getting there (Carbon Gap, 2025c). The second iteration of the Strategy explicitly mentioned BECCS (though these mentions were removed in the third iteration) (ibid.). Furthermore, France has a Carbon Standard acting as a national certification framework for emissions reductions and removals (ibid.). The country is also covered by EU-level policies detailed below the table.*
Germany	No projects identified in the sources scanned.	The government recognises the need for both nature-based and novel CDR methods to achieve its net zero by 2045 and net negative by 2050 targets, but scale-up will depend on key decisions yet to be made (e.g. specific methods to be used, an associated legal framework) (Carbon Gap, 2025d). A Negative Emission Strategy is upcoming which will set separate targets for CDR and provide clarity on how CDR will be financed nationally (ibid.). The government is also expected to set its stance on biomass use for CDR in a future sustainable biomass strategy (ibid.). The country is also covered by EU-level policies detailed below the table.*
Hungary	Early development • Pannonia Bio refinery; Operation date: 2026; Capacity: Under evaluation; Storage method: Under evaluation	The National Clean Development Strategy was developed in 2021 to support Hungary's climate goals (i.e. carbon neutrality by 2050) (Carbon Gap, 2025e). The Strategy relies heavily on carbon removals in the LULUCF sector, while also including BECCS as a potential area of development (ibid.). The country is also covered by EU-level policies detailed below the table.*

Japan	No projects identified in the sources scanned.	Japan has been developing CCS strategies and policies in recent years, many of which are relevant to BECCS and DACCS (Schenuit et al., 2024). Furthermore, Japan's carbon market (i.e. GX-ETS) now accepts removal credits from BECCS and DACCS (Chen, 2024).
Netherlands	No projects identified in the sources scanned.	The CDR roadmap released in 2025 and the Dutch Long-Term Strategy clarify the key role that CDR, including BECCS, will play in Dutch climate policy (Carbon Gap, 2025g). The government is supporting the development of several big CCS projects, which can provide CO_2 transport and storage infrastructure for future BECCS and DACCS projects (ibid.). Furthermore, the SDE++ scheme provides a subsidy that could be applicable to CCS-based CDR projects, including BECCS and DACCS (ibid.). The country is also covered by EU-level policies detailed below the table.*
Sweden	Advanced development • BECCS Stockholm (Stockholm Exergi); Operation date: 2028; Capacity: 0.8 Mtpa CO_2; Storage method: Deep saline formation (Climate Insider, 2025) Early development • Nordbex CCS; Operation date: Under evaluation • Sundsvall Energi FlagshipTWO; Utilisation Facilities; Operation date: 2027 • Växjö Energi CHP Sandviksverket; Pilot and Demonstration Facility; Operation date: 2028 • Soderenergi bio-CCS; Operation date: 2030; Capacity: 0.5 Mtpa CO_2; Storage method: Under evaluation	Sweden's 2045 net zero target explicitly allows for 'supplementary' measures (inc. BECCS) in addition to emissions reductions (Carbon Gap, 2025i). Sweden has uniquely favourable conditions for BECCS in its existing facilities burning biomass (ibid.). The Industrial Leap initiative (Industriklivet) provides state-funded support for carbon removal R&D (ibid.). Around 30 CDR projects have received support so far, many of which are feasibility studies for BECCS (ibid.). Additionally, in July 2024, the EU Commission approved Sweden's reverse auction scheme under the state aid rules which will allocate €3 billion for BECCS, with the first auction opened in August 2024 (ibid.). The country is also covered by EU-level policies detailed below the table.*
UK	Advanced development • Drax BECCS; Operation date: likely post-2031 (UK Parliament Hansard, 2025); Capacity: 8 Mtpa CO_2, Storage method: Deep saline formation Early development • BIG Ince Bio Power; Operation date: 2027	The UK's 2021 Net Zero Strategy set the ambition to deploy at least 5 $MtCO_2$ per year of 'engineered' removals (inc. BECCS and DACCS) by 2030. To support deployment, the government: is developing business models to provide revenue certainty for removal suppliers (inc. a dedicated model to support power BECCS); is working to develop CCUS 'clusters' (and looking explicitly at BECCS and DACCS projects as part of the first clusters); is thinking formally about integrating removals into the UK ETS; has dedicated £100 million in research, development and demonstration (RD&D) funding to support various CDR methods (inc. a competition on DAC) (Carbon Gap, 2025j). The government also published its Biomass Strategy in August 2023, alongside a report on the validity of BECCS as a removal method, which found no 'insurmountable scientific barriers' to removals via BECCS (ibid.).
US	Operational • Bonanza BioEnergy CCS; Operation date: 2012; Capacity: 0.1 Mtpa CO_2; Storage method: Enhanced oil recovery	BECCS has benefited from the US's 45Q tax credit which was expanded and extended by the 2022 Inflation Reduction Act from US$50/tonne to US$85/tonne for the permanent storage of CO_2 captured from industrial and power generation facilities, and from US$35/tonne to US$60/tonne if the captured CO_2 is utilised rather than permanently stored (Clean Air Task Force, 2022).

- Harvestone Blue Flint Ethanol; Operation date: 2023; Capacity: 0.2 Mtpa CO_2; Storage method: Deep saline formation
- Red Trail Energy Richardton Ethanol; Operation date: 2022; Capacity: 0.18 Mtpa CO_2; Storage method: Deep saline formation
- ADM Illinois Industrial; Operation date: 2017; Capacity: 1 Mtpa CO_2; Storage method: Deep saline formation
- Arkalon CO_2 Compression Facility; Operation date: 2009; Capacity: 0.5 Mtpa CO_2; Storage method: Enhanced oil recovery

In construction

- Summit York Biorefinery; Operation date: 2025; Capacity: 0.14 Mtpa CO_2; Storage method: Deep saline formation
- Summit Wood River Biorefinery; Operation date: 2025; Capacity: 0.35 Mtpa CO_2; Storage method: Deep saline formation
- Summit Central City Biorefinery; Operation date: 2025; Capacity: 0.33 Mtpa CO_2; Storage method: Deep saline formation

Advanced development

- Madison Biorefinery; Operation date: Under evaluation
- Marquis Industrial Complex; Operation date: Under evaluation; Capacity: 1.2 Mtpa CO_2; Storage method: Deep saline formation
- Mount Vernon Biorefinery; Operation date: Under evaluation
- Pelican Rindge Tract CCS; Operation date: Under evaluation; Capacity: 2 Mtpa CO_2; Storage method: Deep saline formation
- Russel Storage Complex; Operation date: Under evaluation; Capacity: 0.15 Mtpa CO_2; Storage method: Deep saline formation
- Summit Absolute Energy; Operation date: 2026
- Summit Gevo Lake Preston Biorefinery; Operation date: Under evaluation; Capacity: 0.29 Mtpa CO_2; Storage method: Deep saline formation
- Summit Gevo (**3 further locations**); Operation date: 2030–31; Capacity (same for all): Under evaluation; Storage method (same for all): N/A

To receive the tax credit, capture from power generation must exceed 18,750 tonnes per year and achieve a capture rate greater than 75% (ibid.).

The US Government launched its first major RD&D support programme for CDR in 2021 called the Carbon Negative Shot (one of the Department of Energy's Earthshot innovation efforts) (US Department of Energy, 2024). The programme selected 11 projects in 2024 to receive a combined US$58.5 million in federal funding (ibid.).

Facilities (continued)

Advanced development (continued)

- Alto's Pekin CCS; Operation date: 2026; Capacity: 0.6 Mtpa CO_2; Storage method: Under evaluation
- Bridgeport Ethanol; Operation date: 2025; Capacity: 0.17 Mtpa CO_2; Storage method: Deep saline formation
- Sustainable Fuels Group (CIP blue ammonia plant); Operation date: 2027; Capacity: 5 Mtpa CO_2; Storage method: N/A
- Babcock & Wilcox Filer City CCS; Operation date: Under evaluation; Capacity: Under evaluation; Storage method: Under evaluation
- Summit Marion Ethanol; Operation date: Under evaluation; Capacity: 0.45 Mtpa CO_2; Storage method: N/A
- Summit Biorefineries – part of Midwest Carbon Express Project (**32 different locations**): Operation date (same for all): 2026 (except for Mount Vernon and Madison, which are 2024); Capacity (total of all): 8.2 Mtpa CO_2; Storage method (same for all): Deep saline formation (except Bushmills, which is N/A)
- Project Intersect – Plainview Ethanol Plant; Operation date: 2026; Capacity: 0.35 Mtpa CO_2; Storage method: Enhanced oil recovery
- Project Intersect – Hereford Ethanol Plant; Operation date: 2026; Capacity: 0.35 Mtpa CO_2; Storage method: Enhanced oil recovery

Early development

- Front Range Energy Ethanol plant; Operation date: Under evaluation
- Harvestone Iroquois Bioenergy; Operation date: Under evaluation; Capacity: Under evaluation; Storage method: Deep saline formation
- Hoosier (Cardinal ethanol facility); Operation date: Under evaluation; Capacity: 0.4 Mtpa CO_2; Storage method: Deep saline formation
- Valero (**multiple locations**: Albert City, Albion, Aurora, Charles City; Fort Dodge, Hartley, Lakota, Welcome); Operation date (same for all): 2030; Capacity (same for all): 0.3875 Mtpa CO_2; Storage method (same for all): Deep saline formation
- Carbon America Sterling Ethanol CCS; Operation date: 2025
- Harvestone Dakota Spirit AgEnergy; Operation date: Under evaluation; Capacity: 0.2 Mtpa CO_2; Storage method: Deep saline formation

	• Summit Hanlontown; Operation date: 2030; Capacity: Under evaluation; Storage method: N/A • Summit St. Ansgar, Iowa; Operation date: 2030; Capacity: Under evaluation; Storage method: N/A • One Earth Energy Ethanol; Operation date: 2025; Capacity: 0.5 Mtpa CO_2; Storage method: N/A • Aemetis Keyes Ethanol; Operation date: 2025; Capacity: 0.4 Mtpa CO_2; Storage method: Deep saline formation • Aemetis Riverbank Ethanol; Operation date: Under evaluation; Capacity: 0.4 Mtpa CO_2; Storage method: Deep saline formation [list continued in the next column]	• ADM Cedar Rapids; Operation date: Under evaluation; Capacity: Under evaluation; Storage method: Deep saline formation • Fidelis New Energy Cyclus Power Generation; Operation date: Under evaluation; Capacity: 2 Mtpa CO_2; Storage method: Under evaluation • ADM Clinton; Operation date: 2025; Capacity: Under evaluation; Storage method: Deep saline formation • Poet (18 different locations); Operation date (same for all): 2025; Capacity (same for all): 0.28 Mtpa CO_2; Storage method (same for all): N/A • Drax (two sites selected); Capacity (combined): 6 Mtpa CO_2 (Drax, 2023)

*Note: *EU-level policy: Under the Net-Zero Industry Act, the EU aims to achieve a CO_2 injection capacity of at least 50 million tonnes per year by 2030 (European Commission, 2024). This can include CO_2 captured through DAC or from biogenic sources as in the case of BECCS. In November 2024, the European Parliament and the Council of the EU published their agreed Carbon Removals Certification Framework (an EU-wide voluntary framework for certifying carbon removals) (European Council, 2024), which can facilitate investment in carbon removal technologies including BECCS and DACCS. In the latest revision of the EU Innovation Fund (which is funded by the EU ETS), it became possible to introduce CCfDs that use money from the Fund to bridge the price gap between the market price of CO_2 and the cost of operating CCS and CDR methods such as DACCS and BECCS (Carbon Gap, 2025k). In terms of research and innovation support, the Horizon Europe programme opened a call in September 2024 for BECCS and DAC projects, earmarking €15 million to support innovation in these two fields (Ranevska, 2024). **Most of the list relies on source data last updated in 2023 (standard text) or 2024 (red text) and may therefore include outdated information.*

DACCS countries

In the list of facilities in Table A2, information from the CO_2RE Facilities Database (GCCSI, 2024a) is presented in normal text, information from the Global Status of CCS 2024 report by the Global CCS Institute (GCCSI, 2024c) is presented in red text, and information from any other source is presented in green text (with the source specified in parentheses). As explained under BECCS countries, please note that some of this information, especially with regard to the status and expected operation dates of facilities, may be outdated at the time of writing. Facilities are commercial unless specified as '**Pilot and Demonstration Facility**'.

Please note that the facilities list captures not only DACCS facilities but also DAC facilities (i.e. facilities in which the captured CO_2 is used rather than permanently stored). The two applications share the technological foundation up until the storage stage in the value chain, making it relevant to look at countries with activities on DAC as well.

Table A2. DACCS countries of interest

	Facilities*	Policy
Australia	Early development • AspiraDAC; Operation date: 2025; Capacity: 0.00031 Mtpa CO_2; Storage method: Under evaluation	The Government is supporting the R&D of new ways to capture and use CO_2 through its Carbon Capture Technologies Program (CCTP) (Australian Government, 2024). So far the programme is investing AU$65 million in seven projects, four of which focus specifically on DAC technologies (ibid.).
Canada	Operational • Carbon Engineering DAC; **Pilot and Demonstration CCS Facility**; Operation date: 2015 (Carbon Engineering, 2018)	Refer to the BECCS table (Table A1), which summarises Canada's policy approach to CDR which is relevant for DACCS as well. The credit rate for qualifying DACCS projects under the investment tax credit is set at up to 60% (higher than that for qualifying BECCS projects)

	Early development • St. Lawrence River Valley DAC hub; Operation date: 2025; Capacity: Under evaluation; Storage method: Deep saline formation	(Government of Canada, 2024; Natural Resources Canada, 2024).
China	No projects identified in the sources scanned.	Refer to the BECCS table (Table A1), which summarises several measures in China relevant for both BECCS and DACCS. Specifically on DAC, the technology was mentioned in the 2021 US-China Joint Glasgow Declaration on Enhancing Climate Action (US Department of State, 2021).
France	Early development • RepAir Carbon DACS; Operation date: 2030	Refer to the BECCS table (Table A1), which summarises France's policy approach to CDR; these are relevant for, though not specific to, DACCS. The country is also covered by EU-level policies detailed in the note to Table A1.
Iceland	Operational • Climeworks Carbfix Mammoth; Operation date: 2024; Storage method: 0.03 Mtpa CO_2; Storage method: Mineral carbonation • Climeworks' ORCA; Operation date: 2021; Capacity: 0.004 Mtpa CO_2; Storage method: Mineral carbonation	Iceland is home to the largest active DACCS plant in the world (Carbon Gap, 2025f). The country is exploring becoming a CO_2 storage hub in Europe given its large geological storage capacities (with an ongoing Swiss research project demonstrating the feasibility of cross-border CO_2 transport for storage in Iceland) (ibid.). The Coda Terminal under development in Iceland has received a grant from the Innovation Fund (funded by the EU ETS) of €115 million (ibid.).
Japan	No projects identified in the sources scanned.	Refer to the BECCS table (Table A1) for measures in Japan relevant to BECCS and DACCS. Additionally, Japan has a cabinet-level Moonshot R&D programme whose target technologies include DAC (Schenuit et al., 2024). Japan is also considering government procurement of DAC carbon credits in a bid to boost demand (Carbon Pulse, 2024).
Kenya	Early development • Climeworks and Great Carbon Valley Direct Air Capture and Storage (DAC+S) Kenya; Operation date: 2028; Capacity: 1 Mtpa CO_2; Storage method: Mineral carbonation • Project Hummingbird (Octavia Carbon in partnership with Cella Mineral Storage); **Pilot and Demonstration CCS Facility**; Operation date: N/A; Capacity: 1,000 tCO_2 pa (Klimate, 2023)	While no CDR-specific policy measures could be identified in the sources scanned, Kenya is committed to net zero by 2050. In 2024, the country introduced its Climate Change (Carbon Markets) Regulations, which seek to provide the legal framework for the operation of carbon projects (inc. removals) and carbon markets (EY, 2024).
Norway	Advanced development • NorDAC Kollsnes; Operation date: 2026; Capacity: 0.5 Mtpa CO_2; Storage method: Deep saline formation Early development • Climeworks DAC+S Facility; Operation date: Under evaluation	Norway has multiple R&D and innovation support programmes dedicated to CCS, which also support CCS-based CDR methods (inc. DACCS) to some extent (Carbon Gap, 2025h). The Norwegian Environmental Agency, a government body within the Ministry of Climate and Environment, recently recommended some incentives for CDR such as implementing a reversed CO_2 tax and offering monetary rewards for every tonne of CO_2 removed (ibid.).
Oman	Operational • 44.01 Project Hajar; **Pilot and Demonstration Facility**; Operation date: 2024; Capacity: 0.001Mtpa CO_2; Storage method: Mineral carbonation	Oman's updated second Nationally Determined Contribution focuses on the importance of large-scale CCUS, including the possibility for the country to leverage engineered CDR methods such as DAC, to reduce emissions beyond 2030 (GCCSI, 2024c).
Saudi Arabia	No projects identified in the sources scanned.	Saudi Arabia considers DACCS the highest-potential CDR option, with research underway to determine its potential in the country (Schenuit et al., 2024). The country is one of the co-founders of Mission Innovation's CDR Mission launched in 2021 (ibid.). Additionally, Saudi Aramco — the

		country's majority state-owned oil company — has a pilot DAC project (Reuters, 2025).
South Korea	In development • Project Octopus (Capture6 & K-water); Operation date: N/A; Capacity: 0.5 Mtpa CO_2 (EFI Foundation, 2024)	DACCS is explicitly considered in South Korea's climate change mitigation efforts (Oh, 2024). In 2023, while formulating an implementation plan for meeting the country's Nationally Determined Contribution for 2030, the government considered (though not pursued at that stage) setting a separate target for DAC alongside the existing target for CCUS (ibid.).
UAE	Early development • ADNOC and Occidental DAC; Operation date: Under evaluation (Memorandum of Understanding signed to explore joint project); Capacity 1 Mtpa CO_2 (to provide emissions reduction solutions for hard-to-abate sectors within the UAE, including aviation and maritime) (Oxy, 2023)	The UAE states in its third Nationally Determined Contribution that it is committed to removing CO_2 from the atmosphere, including through engineering-based solutions (UAE Ministry of Climate Change & Environment, 2024). The country will also explore innovative DAC solutions, which it sees as critical for reaching net zero in the long term (ibid.). By 2035, the UAE aims to enhance negative emission capacity to 9.3 $MtCO_2e$ (ibid.)
UK	Advanced development • Northeast Scotland DAC; Operation date: 2026; Capacity: 1 Mtpa CO_2; Storage method: N/A • Project TENET (TEesside Negative Emissions Technology); **Pilot and Demonstration Facility**; Operation date: Q2 2025 (Airhive, 2025; latest project status unclear)	Refer to the BECCS table (Table A1), which summarises the UK's DACCS-relevant policies as well. This includes CDR-wide policies as well as some DACCS-specific measures.
US	Operational • Heirloom DAC California (Tracy); Operation date: 2023; Capacity: 0.001 Mtpa CO_2; Storage method: Mineral carbonation (utilisation) • 280 Earth Oregon Test Facility; **Pilot and Demonstration Facility**; Operation date: 2024 • Heimdal's Bantam DAC Oklahoma; Operation date: 2024; Capacity: 0.005 Mtpa CO_2; Storage method: Enhanced oil recovery (EOR) In construction • STRATOS (1PointFive Direct Air Capture); Operation date: 2025; Capacity: 0.5 Mtpa CO_2; Storage method: Deep saline formation Advanced development • Heirloom Shreveport DAC; Operation date: 2026; Capacity: 0.017 Mtpa CO_2; Storage method: N/A • Orchard One; Operation date: 2026 • NuDACCS – Nuclear Direct Air CCS Project; **Pilot and Demonstration Facility**; Operation date: N/A • Southern Company Farley DAC; Operation date: Under evaluation; Capacity: Under evaluation; Storage method: Under evaluation • South Texas DAC Hub; Operation date: Under evaluation; Capacity: 1	The US has a number of policies and programmes that support DAC, including the 45Q tax credit and the California Low Carbon Fuels Standard (IEA, 2024b). The 2022 Inflation Reduction Act expanded and extended the 45Q tax credit from US$50 to US$180/tonne for the permanent storage of CO_2 from DAC and to US$130/tonne for the utilisation of CO_2 from DAC (Clean Air Task Force, 2022). Despite the revocation of some clean energy subsidies in the US, the 45Q tax credit remains intact under the One Big Beautiful Bill Act (Committee for a Responsible Federal Budget, 2025). The 2021 Infrastructure Investment and Jobs Act allocated approximately US$12 billion for carbon management, including US$3.5 billion for the development of four regional DAC hubs that can each remove at least 1 Mtpa CO_2 (Office of Fossil Energy and Carbon Management, 2022). In August 2023, the US issued US$1.2 billion of this funding to two large-scale DAC hubs (Project Cypress in Louisiana and the South Texas DAC Hub in Texas), and also allocated funding to nearly 20 additional projects to support earlier stages of project development for future DAC hubs (IEA, 2024b). Additionally, in 2022, the US launched a CDR purchase pilot prize (with a US$35 million budget), which is a public procurement mechanism to offer offtake agreements from the federal government to companies across different removal pathways including DACCS (ibid.). In 2025, the Office for Clean Energy Demonstrations (OCED) terminated US$3.6 billion worth of contracts for CCS and decarbonisation initiatives (US Department of Energy, 2025).

	Mtpa CO_2; Storage method: Deep saline formation • Project Bison Wyoming; Operation date: Under evaluation; 5 Mtpa CO_2; Storage code: N/A • Project Cypress; Operation date: Under evaluation; Capacity: 1 Mtpa CO_2; Storage method: N/A Early development • Byron Generation Station Nuclear DACS; Operation date: Under evaluation; Capacity: 0.25 Mtpa CO_2; Storage method: N/A • Colorado (Pueblo) Regional DAC Hub; Operation date: Under evaluation • Florida Regional DAC Hub; Operation date: Under evaluation; Capacity: 0.05 Mtpa CO_2; Storage method: Deep saline formation • Osage CCS; Operation date: Under evaluation; Capacity: 0.007 Mtpa CO_2; Storage method: EOR • Pelican Gulf Coast Carbon Removal; Operation date: Under evaluation; Operation date: Under evaluation; Storage method: Deep saline formation	

*Note: *Most of the list relies on source data last updated in 2023 (standard text) or 2024 (red text) and may therefore include outdated information.*

Supplementary analysis on BECC and DAC

Table A3. Country/jurisdiction shares of total innovations by field (2000–20)

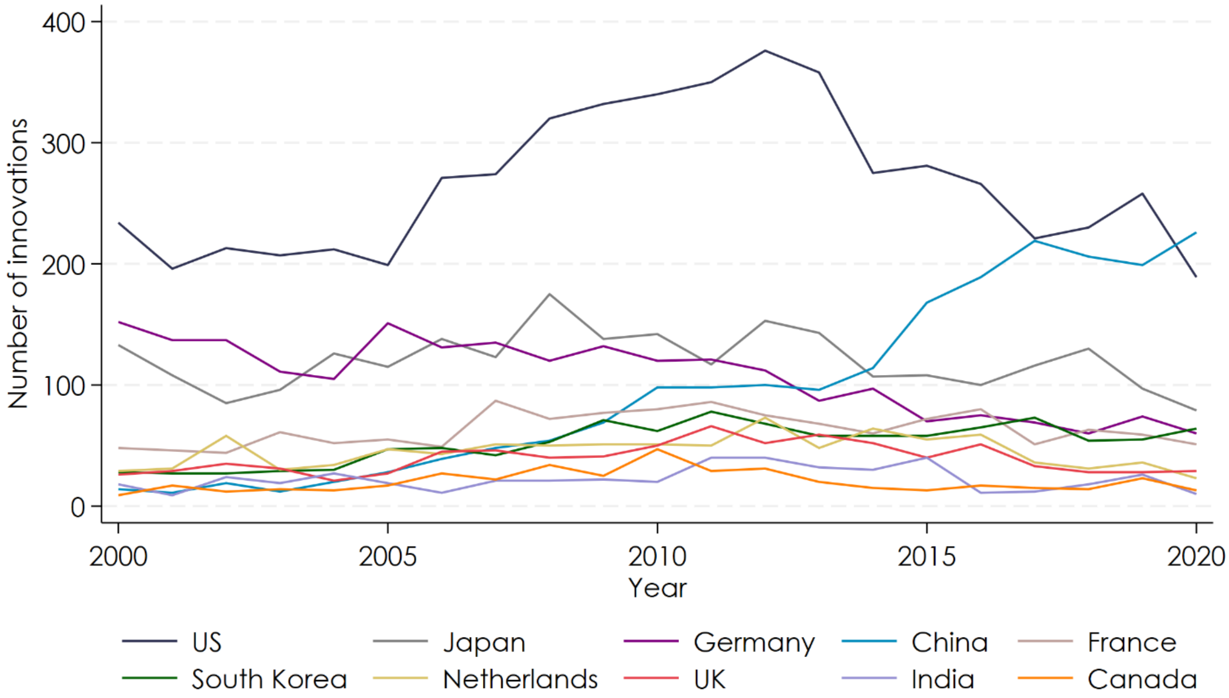
BECC		
Country/ jurisdiction	Number of innovations	% of global innovations
US	5,602	24.8
Japan	2,529	11.2
Germany	2,256	10.0
China	2,027	9.0
France	1,336	5.9
South Korea	1,095	4.8
Netherlands	950	4.2
UK	829	3.7
India	470	2.1
Canada	427	1.9
Switzerland	423	1.9
Belgium	405	1.8
Italy	396	1.8
Denmark	346	1.5
Saudi Arabia	314	1.4
Spain	313	1.4
Russia	246	1.1
Taiwan	203	0.9
Brazil	188	0.8
Sweden	177	0.8

DAC		
Country/ jurisdiction	Number of innovations	% of global innovations
US	725	28.0
Germany	309	11.9
Japan	287	11.1
China	211	8.1
France	174	6.7
UK	147	5.7
South Korea	107	4.1
Netherlands	66	2.5
India	58	2.2
Canada	55	2.1
Belgium	47	1.8
Switzerland	45	1.7
Italy	29	1.1
Taiwan	25	1.0
Austria	24	0.9
Denmark	23	0.9
Russia	21	0.8
Spain	20	0.8
Finland	14	0.5
Australia	13	0.5
Mexico	13	0.5
Portugal	13	0.5

Carbon storage		
Country/ jurisdiction	Number of innovations	% of global innovations
US	21	22.8
South Korea	13	14.1
China	13	14.1
UK	7	7.6
Japan	6	6.5
Germany	6	6.5
Netherlands	4	4.3
Italy	3	3.3
Saudi Arabia	2	2.2
France	2	2.2
Monaco	2	2.2
Canada	2	2.2

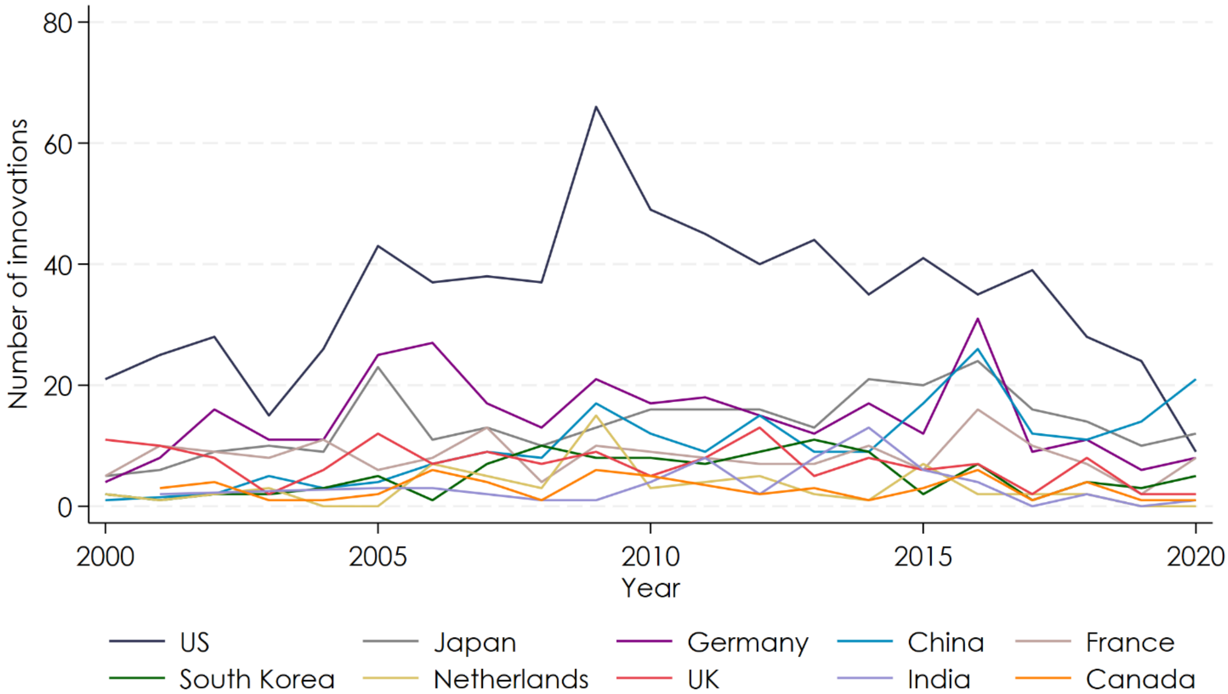
Notes: The tables report number of multi-application innovations between 2000 and 2020. Tables report top 20 countries/jurisdictions by number of multi-application innovations for BECC and DAC, and all countries/jurisdictions with at least two multi-application innovations for carbon storage. When calculating each country/ jurisdiction's share of global innovations, a small number of innovations where the country/jurisdiction of the inventor is unknown are excluded from the number of global innovations.
Source: Authors' analysis based on PATSTAT Global 2023 (Spring edition)

Figure A1. Annual number of innovations of the top 10 countries by total innovations in BECC (2000–20)



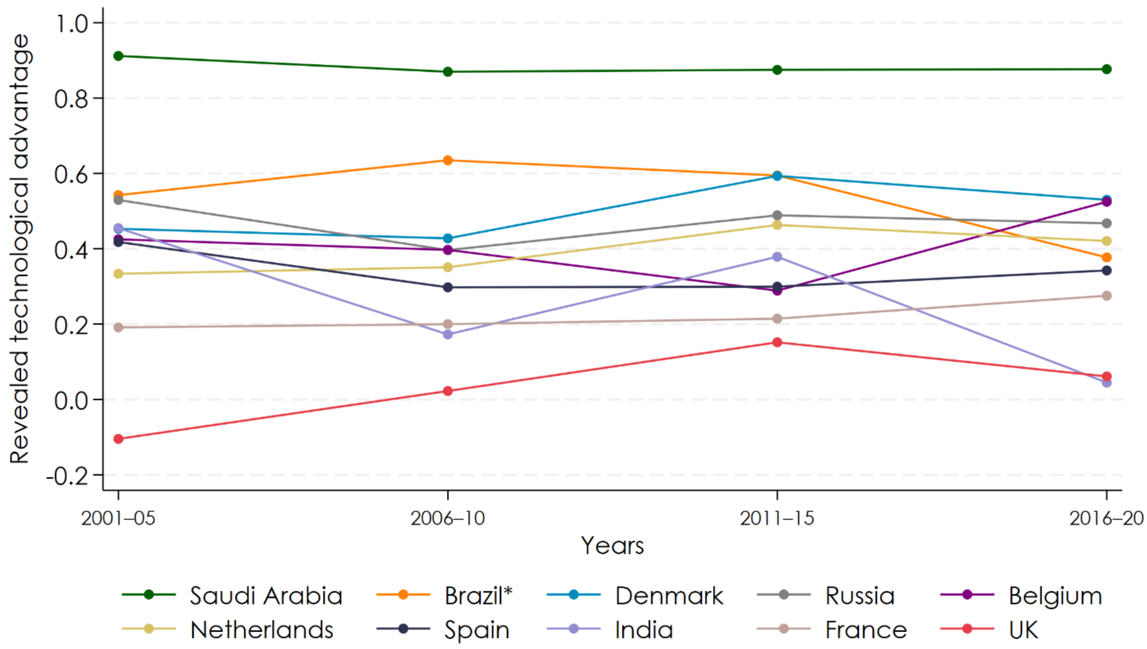
Notes: The y-axis indicates the number of multi-application BECC innovations between 2000 and 2020.
Source: Authors' analysis based on PATSTAT Global 2023 (Spring edition)

Figure A2. Annual number of innovations of the top 10 countries by total innovations in DAC (2000–20)



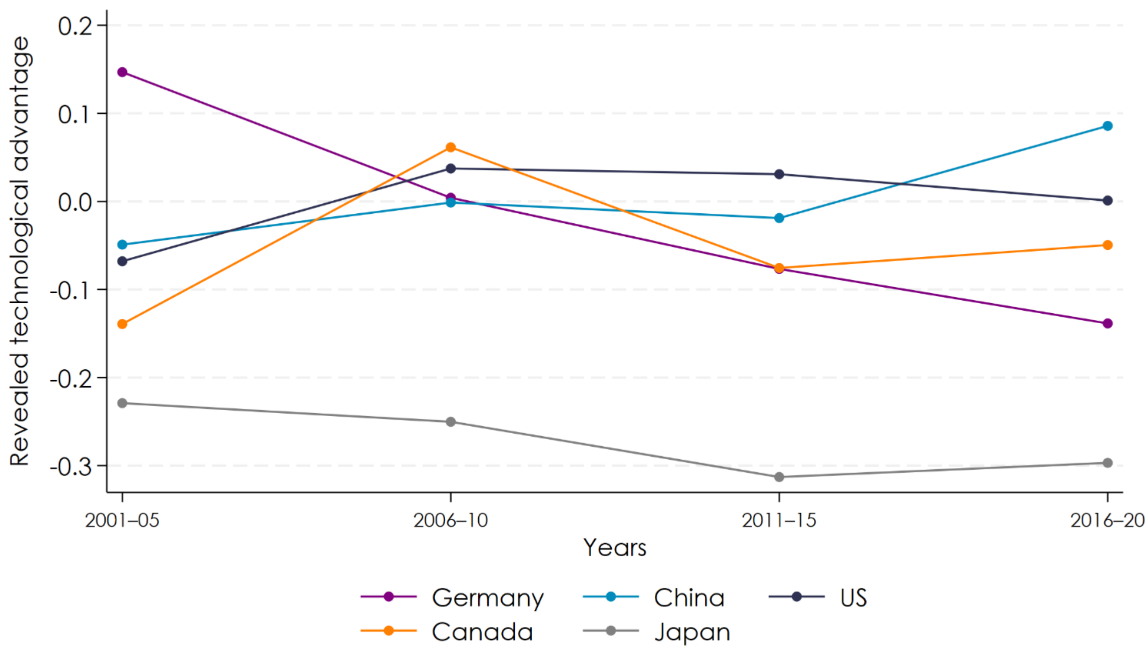
Notes: The y-axis indicates the number of multi-application DAC innovations between 2000 and 2020.
Source: Authors' analysis based on PATSTAT Global 2023 (Spring edition)

Figure A3. Evolution of the revealed technological advantage (RTA) in BECC of the top 10 countries (5-year intervals between 2001 and 2020)



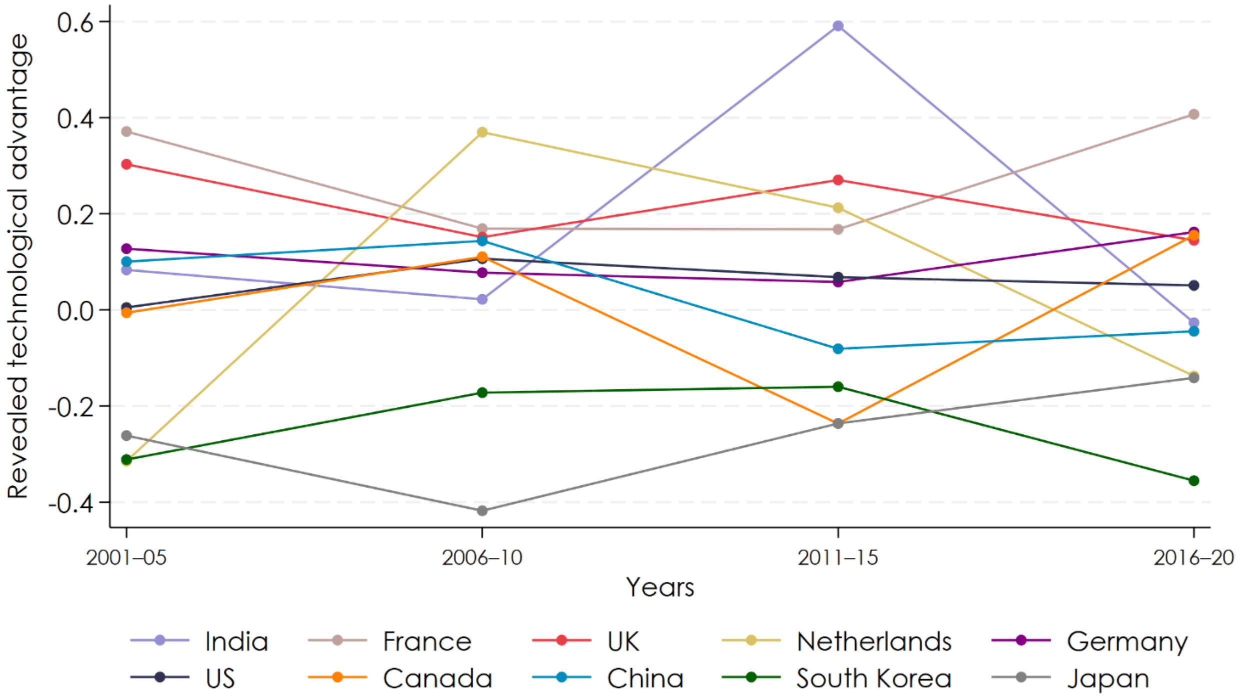
*Notes: The y-axis indicates RTA values (adjusted to lie between –1 and +1, where positive values indicate innovative specialism). The figure includes the top 10 countries (with at least 200 multi-application BECC innovations) based on average RTA for 2000–20. *Although Brazil has fewer than 200 BECC innovations (which is our minimum threshold to estimate an RTA), we include it in our analysis given it is a country of interest, and it has 188 BECC innovations, which is only slightly lower than the 200 threshold.*
Source: Authors' analysis based on PATSTAT Global 2023 (Spring edition)

Figure A4. Evolution of the revealed technological advantage (RTA) in BECC of the additional countries of interest (5-year intervals between 2001 and 2020)



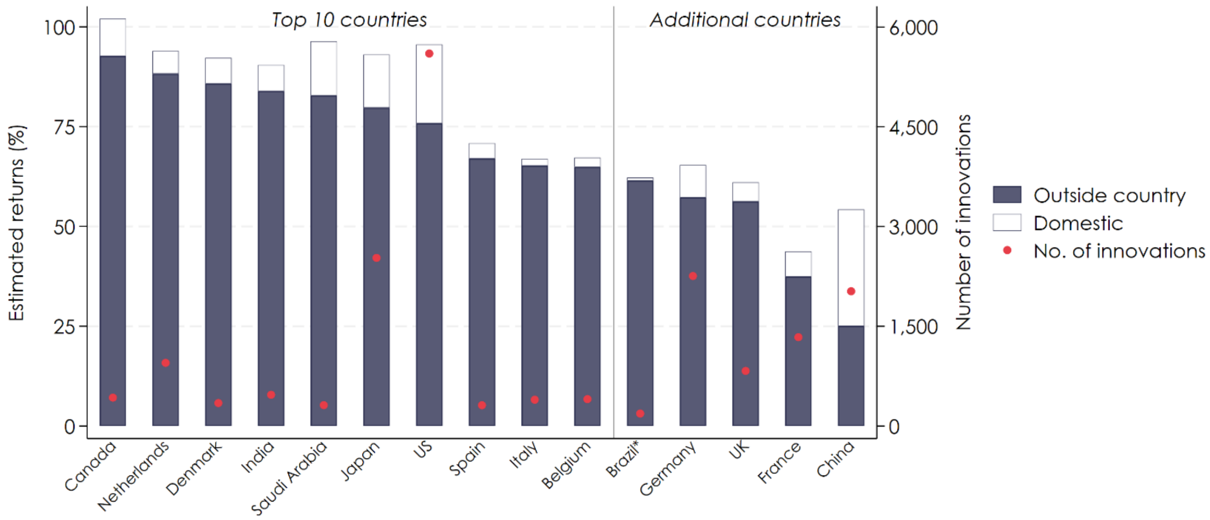
Notes: The y-axis indicates RTA values (adjusted to lie between –1 and +1, where positive values indicate innovative specialism).
Source: Authors' analysis based on PATSTAT Global 2023 (Spring edition)

Figure A5. Evolution of the revealed technological advantage (RTA) in DAC of all analysed countries (5-year intervals between 2001 and 2020)



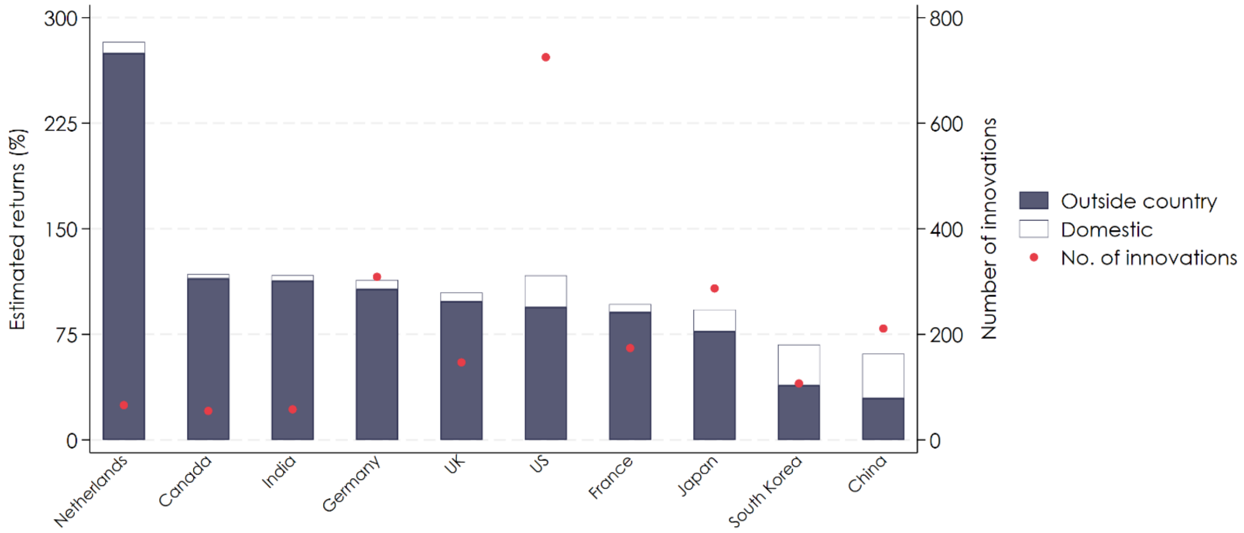
Notes: The y-axis indicates RTA values (adjusted to lie between −1 and +1, where positive values indicate innovative specialism) for the 10 countries with 50 or more multi-application DAC innovations between 2000 and 2020.
Source: Authors' analysis based on PATSTAT Global 2023 (Spring edition)

Figure A6. Estimated global returns (split into domestic and outside-country returns) to additional public investments in BECC innovation — top 10 countries by outside-country returns, and additional countries of interest



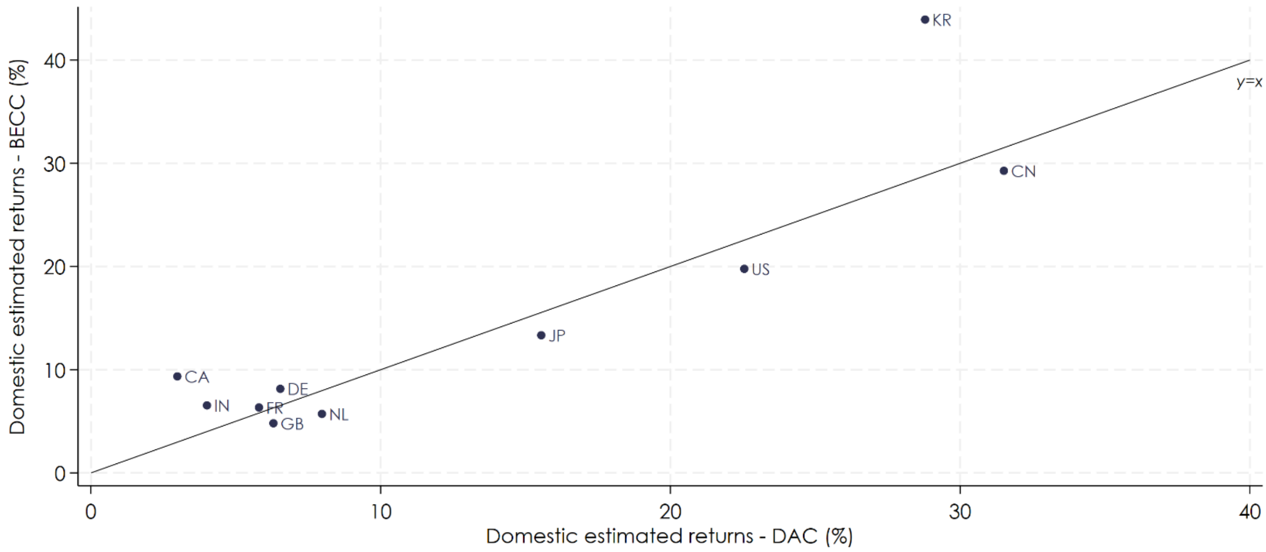
*Notes: The left y-axis indicates the estimated returns as a percentage of 1 additional unit of R&D subsidy in BECC in each country (shown in bars and estimated based on all innovations between 2009 and 2018). The right y-axis indicates the number of multi-application innovations in BECC between 2000 and 2020 (shown in dots). Countries with fewer than 200 multi-application innovations in BECC in that period are not considered (*Brazil, which has 188 innovations, is an exception to this). Shaded bars indicate the part of the estimated returns that spills over to the rest of the world, and transparent bars indicate the part of the estimated returns that is retained domestically.*
Source: Authors' analysis based on PATSTAT Global 2021 (Autumn edition) and PATSTAT Global 2023 (Spring edition)

Figure A7. Estimated global returns (split into domestic and outside-country returns) to additional public investments in DAC innovation — all analysed countries, ranked by outside-country returns



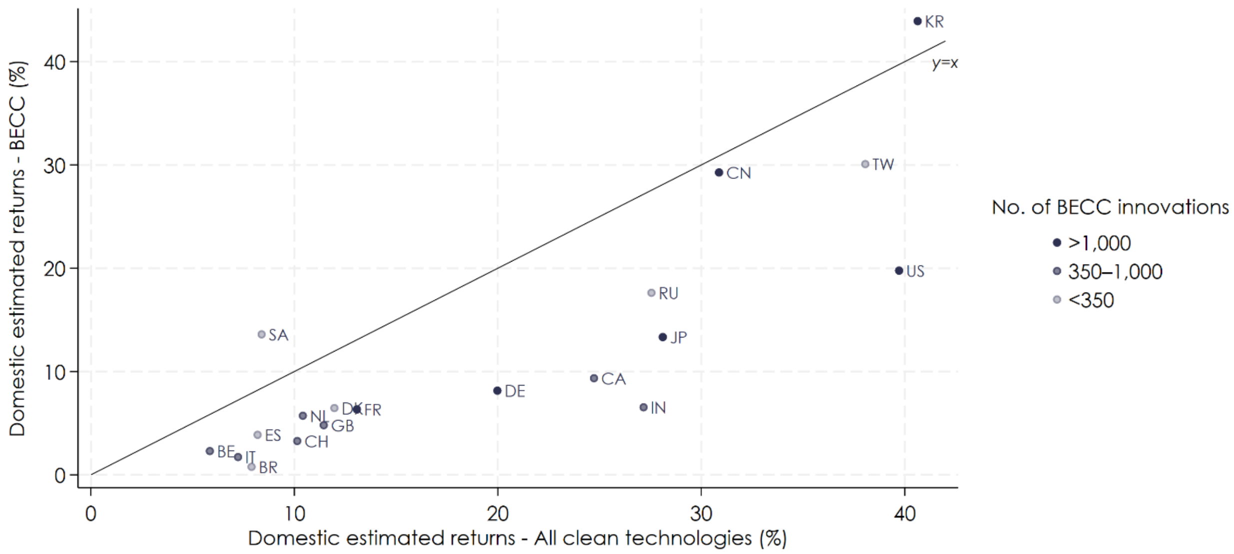
Notes: The left y-axis indicates the estimated returns as a percentage of 1 additional unit of R&D subsidy in DAC in each country (shown in bars and estimated based on all innovations between 2009 and 2018) for the 10 countries which have 50 or more multi-application innovations in DAC. The right y-axis indicates the number of multi-application innovations in DAC between 2000 and 2020 (shown in dots). Shaded bars indicate the part of the estimated returns that spills over to the rest of the world, and transparent bars indicate the part of the estimated returns that is retained domestically.
Source: Authors' analysis based on PATSTAT Global 2021 (Autumn edition) and PATSTAT Global 2023 (Spring edition)

Figure A8. Estimated domestic returns to additional public investments in innovation in DAC versus BECC (2009–18)



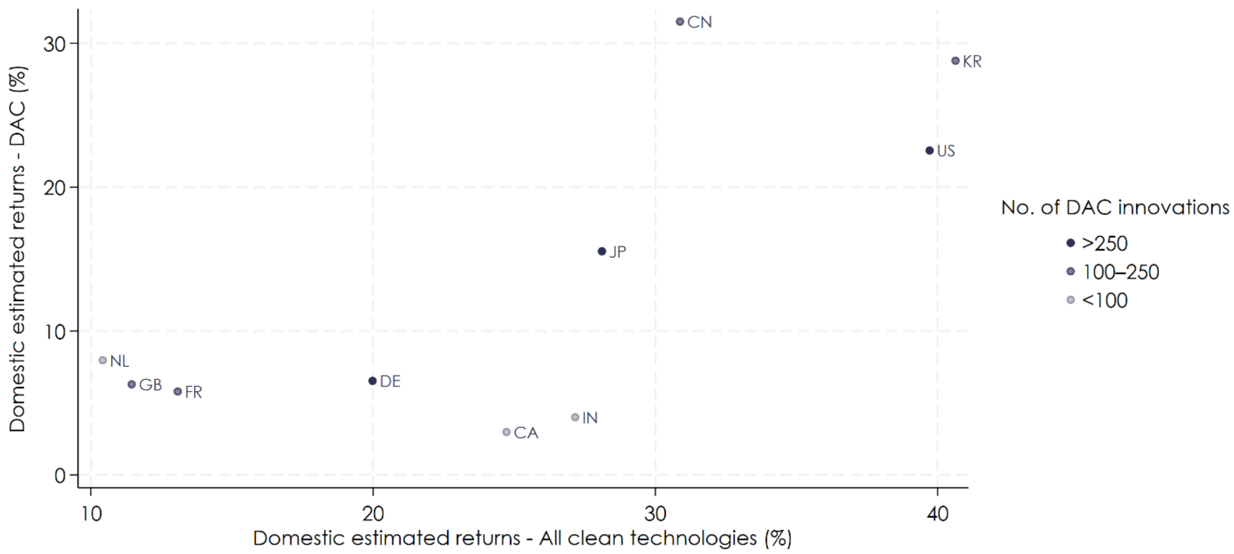
Notes: The y-axis indicates the estimated domestic returns as a percentage of 1 additional unit of R&D subsidy in BECC in each country, and the x-axis indicates corresponding domestic returns for DAC. Only countries/jurisdictions with an estimated IStraX for both BECC and DAC are included. Countries are identified by their two-letter ISO country codes.
Source: Authors' analysis based on PATSTAT Global 2021 (Autumn edition)

Figure A9. Estimated domestic returns to additional public investments in innovation in all clean technologies versus BECC (2009–18)



Notes: The y-axis indicates the estimated domestic returns as a percentage of 1 additional unit of R&D subsidy in BECC in each country/jurisdiction, for all countries/jurisdictions with at least 200 multi-application BECC innovations. The x-axis indicates the corresponding calculation for clean technologies as a whole (identified as innovations under the 'Y02' class from the CPC system). The shade of each dot denotes the number of multi-application BECC innovations in that country/jurisdiction between 2000 and 2020. Countries/jurisdictions are identified by their two-letter ISO country codes.
Source: Authors' analysis based on PATSTAT Global 2021 (Autumn edition) and PATSTAT Global 2023 (Spring edition)

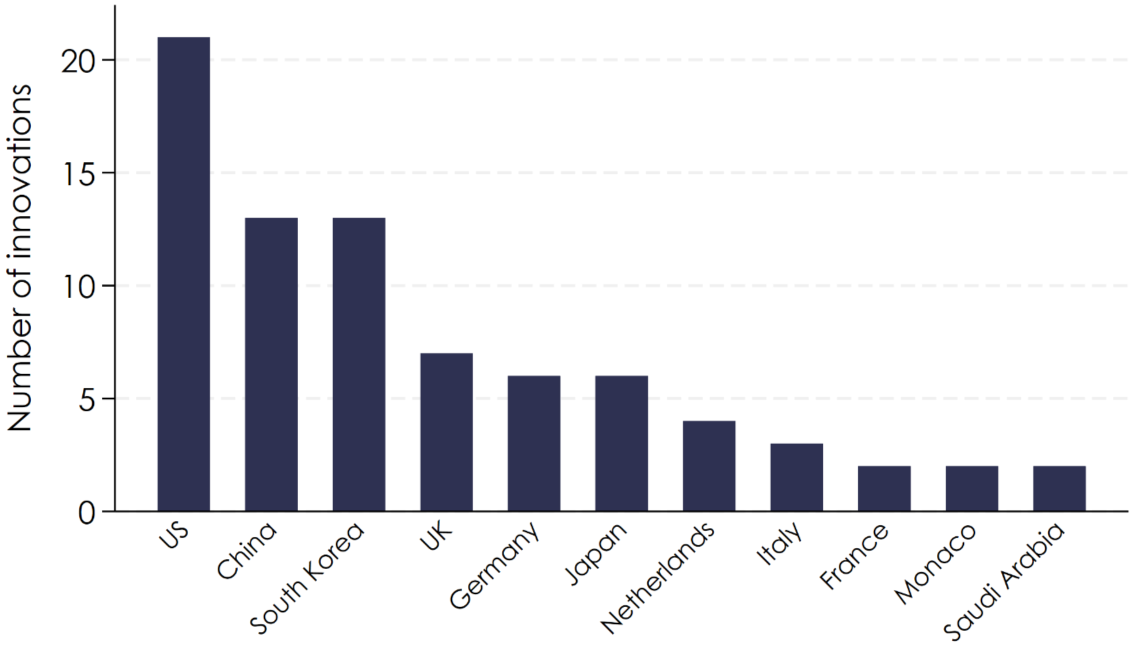
Figure A10. Estimated domestic returns to additional public investments in innovation in all clean technologies versus DAC (2009–18)



Notes: The y-axis indicates the estimated domestic returns as a percentage of 1 additional unit of R&D subsidy in DAC in each country, for the 10 countries with at least 50 multi-application DAC innovations. The x-axis indicates the corresponding calculation for clean technologies as a whole (identified as innovations under the 'Y02' class from the CPC system). The shade of each dot denotes the number of multi-application DAC innovations in that country between 2000 and 2020. Countries are identified by their two-letter ISO country codes.
Source: Authors' analysis based on PATSTAT Global 2021 (Autumn edition) and PATSTAT Global 2023 (Spring edition)

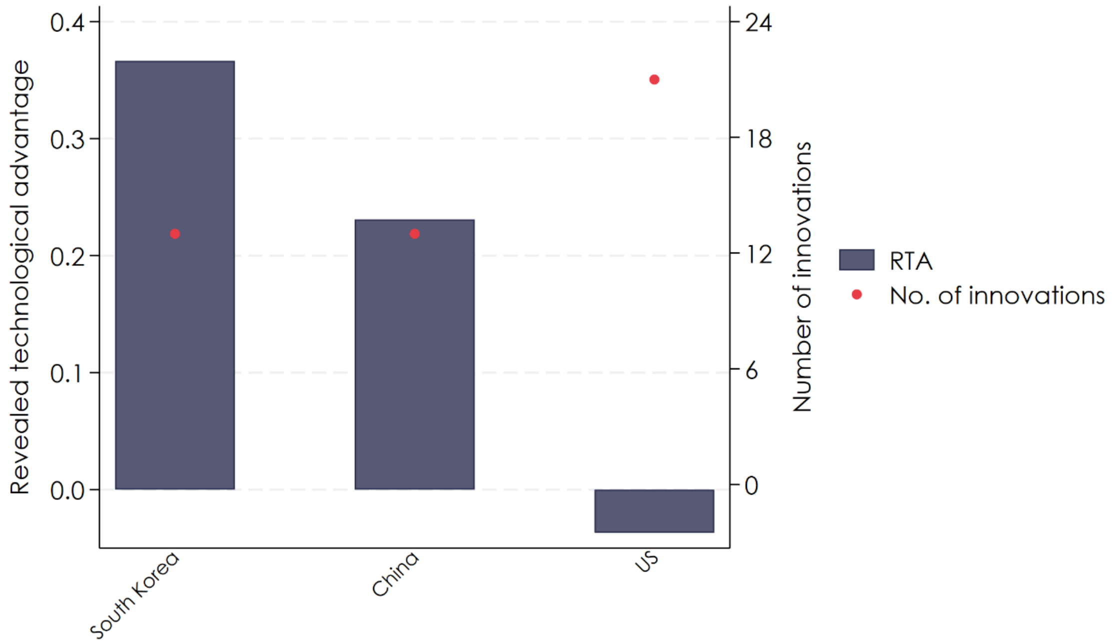
Supplementary analysis on carbon storage

Figure A11. Top countries by total number of innovations in carbon storage (2000–20)



Notes: The y-axis denotes the number of multi-application innovations in carbon storage. Bars are arranged in descending order of number of innovations. The figure includes 11 countries since there is a tie between three countries: France, Monaco and Saudi Arabia each have two innovations.
Source: Authors' analysis based on PATSTAT Global 2023 (Spring edition)

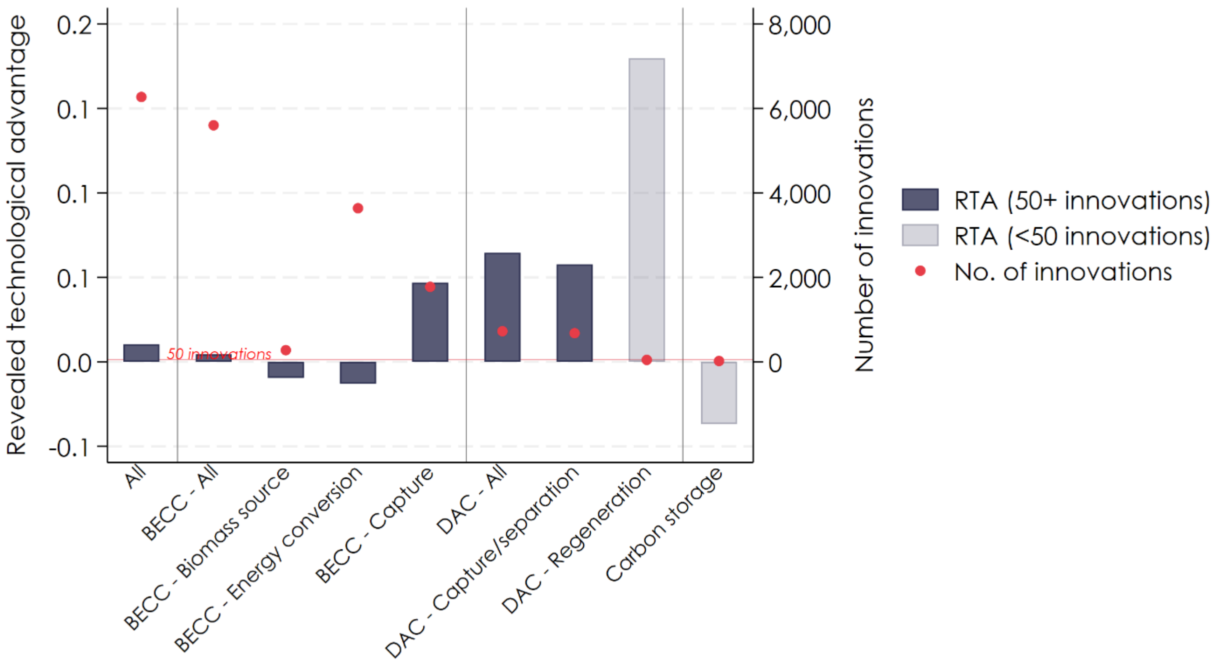
Figure A12. Revealed technological advantage (RTA) of selected countries in carbon storage (2000–20)



Notes: The left y-axis indicates RTA values (shown in bars and adjusted to lie between −1 and +1, where positive values indicate innovative specialism). The right y-axis indicates number of multi-application carbon storage innovations (shown in dots). The figure includes the only three countries with more than 10 multi-application innovations in carbon storage between 2000 and 2020.
Source: Authors' analysis based on PATSTAT Global 2023 (Spring edition)

Supplementary analysis on selected countries

Figure A13. The US's revealed technological advantage in specific stages across BECC, DAC and carbon storage (2000–20)



Notes: The left y-axis indicates RTA values (shown in bars and adjusted to lie between –1 and +1, where positive values indicate innovative specialism). The right y-axis indicates number of multi-application innovations (shown in dots).
Source: Authors' analysis based on PATSTAT Global 2023 (Spring edition)

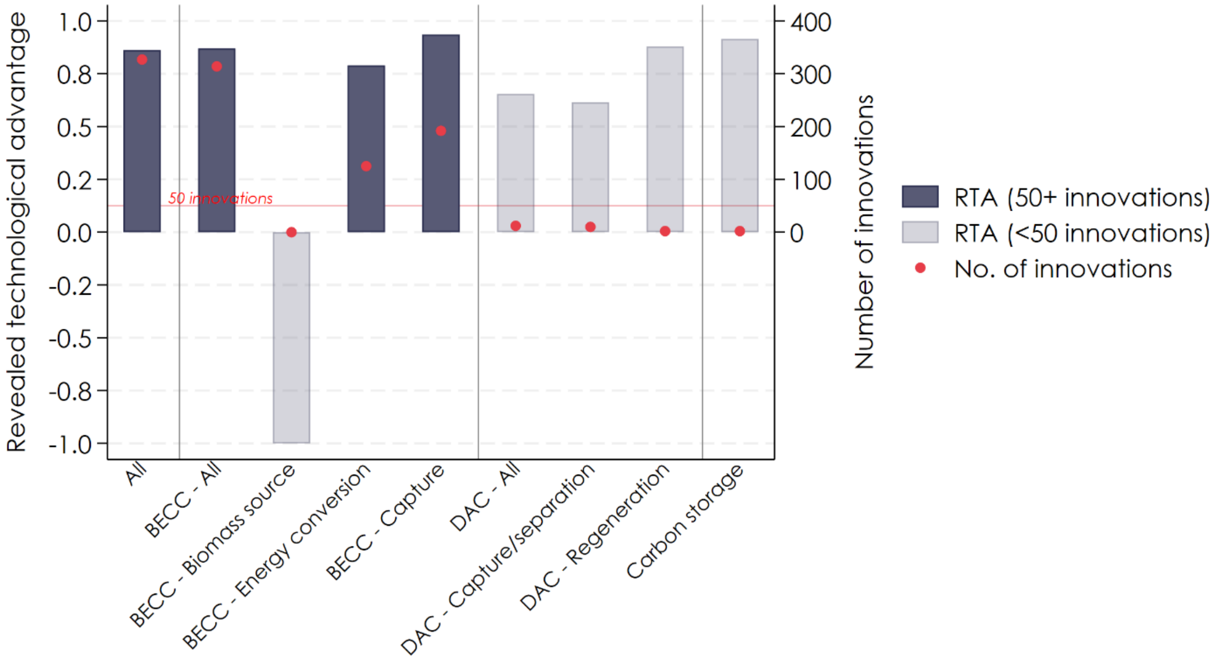
Table A4. The US's top 10 geological CDR innovator organisations by number of innovations (2000–20)

Rank	Organisation name	% of country's geological CDR innovations	Primary industry	Home country	Organisation's global total geological CDR innovations	% of organisation's total geological CDR innovations in the US
1	Rave Financial Credit Union	5.5	Credit unions	US	701	95
2	UOP Inc.	4.2	Aircraft engine and engine parts manufacturing	US	511	99
3	Exxon Mobil Corp.	3.4	Petroleum refineries	US	448	92
4	Chevron Corporation	3.1	Petroleum refineries	US	384	98
5	ExxonMobil Egypt SAE	2.9	Petroleum bulk stations and terminals	Egypt	354	99
6	Shell Internationale Research Maatschappij BV	2.5	R&D in the physical, engineering and life sciences	Netherlands	497	62

7	E. I. du Pont de Nemours and Company	2.3	Plastics material and resin manufacturing	US	306	92
8	Shell Nederland BV	1.9	Natural gas extraction	Netherlands	258	89
9	Air Products & Chemicals Inc.	1.7	Industrial gas manufacturing	US	208	98
10	Union Carbide Corp.	1.7	Organic chemical manufacturing	US	231	87

Note: See note on Table 3.1.

Figure A14. Saudi Arabia's revealed technological advantage in specific stages across BECC, DAC and carbon storage (2000–20)



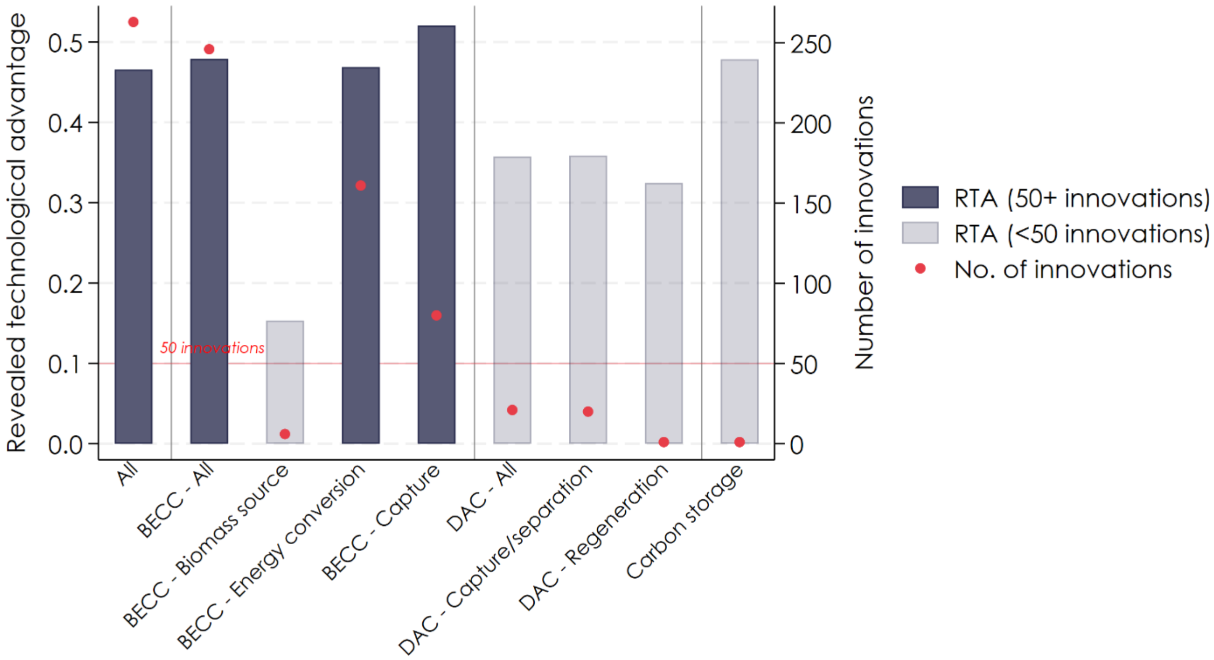
Notes: The left y-axis indicates RTA values (shown in bars and adjusted to lie between −1 and +1, where positive values indicate innovative specialism). The right y-axis indicates number of multi-application innovations (shown in dots).
Source: Authors' analysis based on PATSTAT Global 2023 (Spring edition)

Table A5. Saudi Arabia's top 10 geological CDR innovator organisations by number of innovations (2000–20)

Rank	Organisation name	% of country's geological CDR innovations	Primary industry	Home country	Organisation's global total geological CDR innovations	% of organisation's total geological CDR innovations in Saudi Arabia
1	Saudi Arabia Oil Company (Saudi Aramco) Saudi Joint Stock Company	38.5	Oil and gas	Saudi Arabia	131	100%
2	Aramco Services Co.	28.5	Oil and gas	US	97	100
3	Saudi Basic Industries Corporation Sabic	24.7	Organic chemical manufacturing	Saudi Arabia	85	99
4	Saudi Arabian Oil Company Ltd	21.2	Oil and gas	UK	72	100
5	SABIC Global Technologies BV	18.5	Organic chemical manufacturing	Netherlands	162	39
6	King Fahd University of Petroleum and Minerals	6.8	Colleges, universities and professional schools	Saudi Arabia	23	100
7	King Abdullah University of Science and Technology	3.2	Colleges, universities and professional schools	Saudi Arabia	11	100
8	SABIC Petrochemicals BV	2.6	Plastics material and resin manufacturing	Netherlands	9	100
9	JGC Catalysts and Chemicals Ltd	2.1	Inorganic chemical manufacturing	Japan	39	18
10	Universitat Politecnica de Valencia	1.8	Colleges, universities and professional schools	Spain	57	11

Note: See note on Table 3.1.

Figure A15. Russia's revealed technological advantage in specific stages across BECC, DAC and carbon storage (2000–20)



Notes: The left y-axis indicates RTA values (shown in bars and adjusted to lie between -1 and +1, where positive values indicate innovative specialism). The right y-axis indicates number of multi-application innovations (shown in dots).
Source: *Authors' analysis based on PATSTAT Global 2023 (Spring edition)*

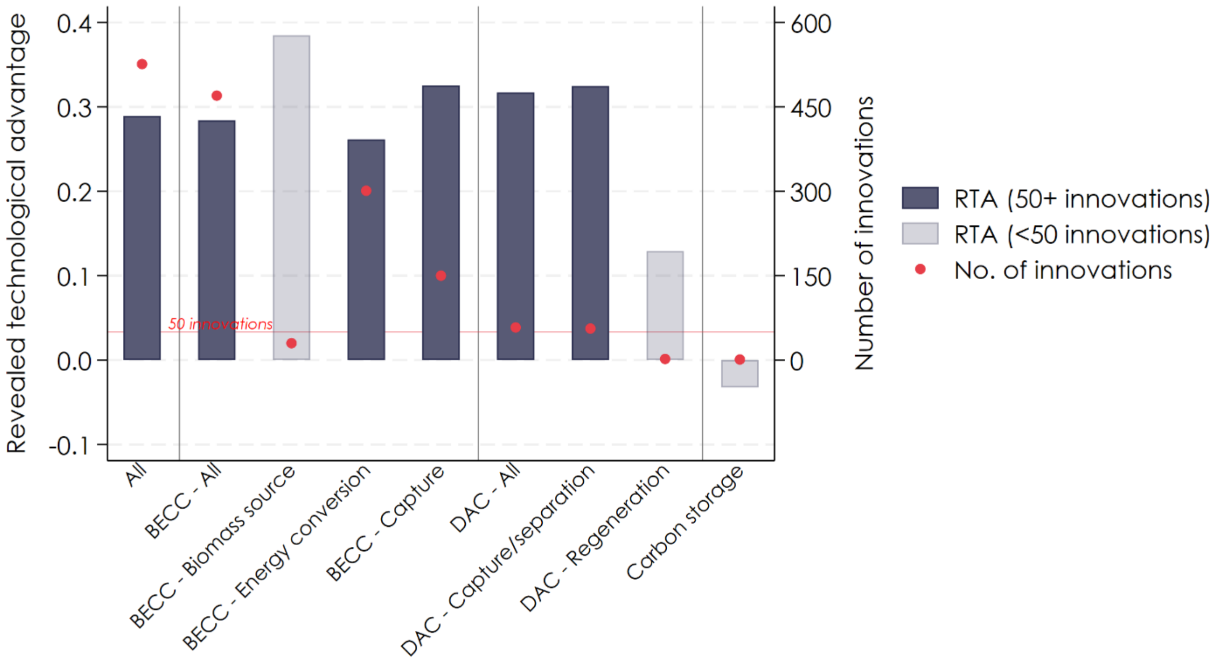
Table A6. Russia's top 10 geological CDR innovator organisations by number of innovations (2000–20)

Rank	Organisation name	% of country's geological CDR innovations	Primary industry	Home country	Organisation's global total geological CDR innovations	% of organisation's total geological CDR innovations in Russia
1	Ajinomoto Co., Inc.	9.1	Food manufacturing	Japan	242	12
2	Ajinomoto (Singapore) Private Limited	5.5	Food manufacturing	Singapore	121	15
3	Boreskov Institute of Catalysis	4.3	R&D in the physical, engineering and life sciences	Russia	14	100
4	Ajinomoto-Genetika Research Institute (AGRI)	2.7	R&D in the physical, engineering and life sciences	Russia	9	100
4	SABIC Global Technologies BV	2.7	Organic chemical manufacturing	Netherlands	162	6
6	UOP Inc.	2.4	Aircraft engine and engine parts manufacturing	US	511	2

6	General Electric Company	2.4	Aircraft engine and engine parts manufacturing	US	77	10
8	TotalEnergies One Tech Belgium	2.1	R&D in the physical, engineering and life sciences	Belgium	42	17
9	Prof Business Ltd	1.8	Photography	Russia	6	100
9	Devonn Investments Limited	1.8	N/A	British Virgin Islands	6	100

Note: See note on Table 3.1.

Figure A16. India's revealed technological advantage in specific stages across BECC, DAC and carbon storage (2000–20)



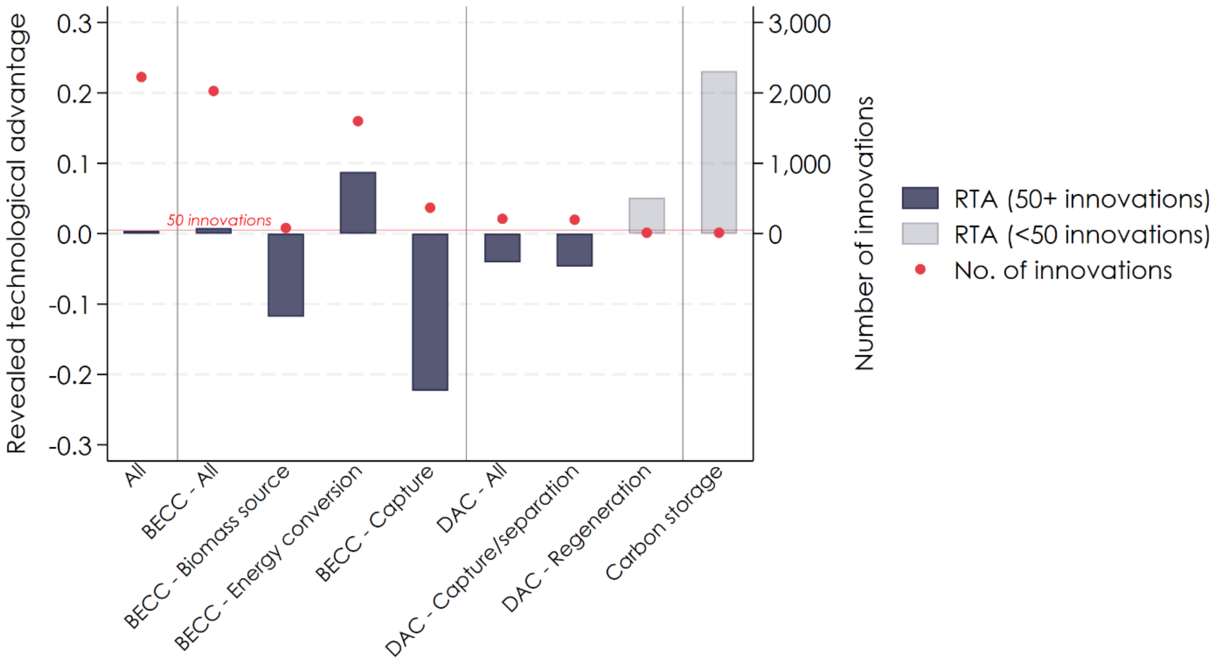
Notes: The left y-axis indicates RTA values (shown in bars and adjusted to lie between –1 and +1, where positive values indicate innovative specialism). The right y-axis indicates number of multi-application innovations (shown in dots).
Source: Authors' analysis based on PATSTAT Global 2023 (Spring edition)

Table A7. India's top 10 geological CDR innovator organisations by number of innovations (2000–20)

Rank	Organisation name	% of country's geological CDR innovations	Primary industry	Home country	Organisation's global total geological CDR innovations	% of organisation's total geological CDR innovations in India
1	Department of Scientific and Industrial Research (DSIR)	8.6	R&D in the physical, engineering and life sciences	India	52	100
2	Reliance Industries Limited	7.1	Plastics material and resin manufacturing	India	43	100
3	SABIC Global Technologies BV	5.9	Organic chemical manufacturing	Netherlands	162	22
4	Indian Oil Corporation Limited	4.8	Petroleum and coal products manufacturing	India	29	100
5	Saudi Basic Industries Corporation Sabic	4.6	Organic chemical manufacturing	Saudi Arabia	85	33
6	Biocon Limited	2.8	Pharmaceutical preparation manufacturing	India	17	100
6	Shell Nederland BV	2.8	Natural gas extraction	Netherlands	258	7
6	Shell Internationale Research Maatschappij BV	2.8	R&D in the physical, engineering and life sciences	Netherlands	497	3
9	Air Products & Chemicals Inc.	2.3	Industrial gas manufacturing	US	208	7
10	Hindustan Petroleum Corporation Limited	2.0	Natural gas extraction	India	12	100

Note: See note on Table 3.1.

Figure A17. China's revealed technological advantage in specific stages across BECC, DAC and carbon storage (2000–20)



Notes: The left y-axis indicates RTA values (shown in bars and adjusted to lie between -1 and +1, where positive values indicate innovative specialism). The right y-axis indicates number of multi-application innovations (shown in dots).
Source: Authors' analysis based on PATSTAT Global 2023 (Spring edition)

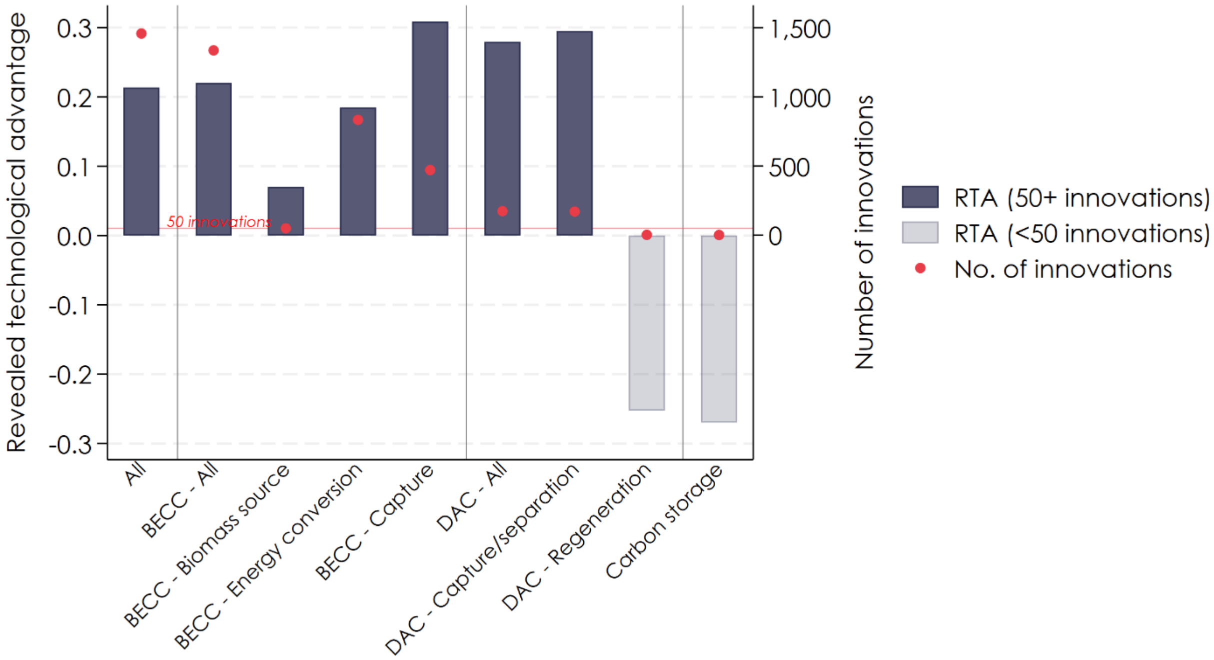
Table A8. China's top 10 geological CDR innovator organisations by number of innovations (2000–20)

Rank	Inventor name	% of country's geological CDR innovations	Inventor's primary industry	Home country	Inventor's global total geological CDR innovations	% of inventor's total geological CDR innovations in China
1	Jiangnan University	3.9	Colleges, universities and professional schools	China	98	97
2	China Petroleum & Chemical Corporation	3.4	Support activities for oil and gas operations	China	87	97
3	Sinopec Corp. Research Institute of Petroleum Processing	2.5	R&D in the physical, engineering and life sciences	China	61	100
4	China Petrochemica l Corporation	2.2	Oil and gas	China	55	100
5	Basf SE	2.2	Chemical manufacturing	Germany	1,206	4
6	Dalian Institute of Chemical Physics, Chinese	2.0	R&D in the physical, engineering and life sciences	China	49	100

	Academy of Sciences					
7	China Petro-chemical Technology Co., Ltd	1.3	Scientific and technical consulting services	China	32	100
8	Tsinghua University	1.1	Colleges, universities and professional schools	China	29	97
9	Wuhan Kaidi Engineering Technology Research Institute Co., Ltd	1.1	R&D in the physical, engineering and life sciences	China	28	100
10	South China University of Technology	1.0	Colleges, universities and professional schools	China	24	100

Note: See note on Table 3.1.

Figure A18. France's revealed technological advantage in specific stages across BECC, DAC and carbon storage (2000–20)



Notes: The left y-axis indicates RTA values (shown in bars and adjusted to lie between –1 and +1, where positive values indicate innovative specialism). The right y-axis indicates the number of multi-application innovations (shown in dots).
Source: Authors' analysis based on PATSTAT Global 2023 (Spring edition)

Table A9. France's top 10 geological CDR innovator organisations by number of innovations (2000–20)

Rank	Organisation name	% of country's geological CDR innovations	Primary industry	Home country	Organisation's global total geological CDR innovations	% of organisation's total geological CDR innovations in France
1	IFP Energies Nouvelles	28.4	R&D in the physical, engineering and life sciences	France	789	97
2	L'Air Liquide Societe Anonyme Pour l'Etude et l'Exploitation DES Procedes Georges Claude	6.7	Industrial gas manufacturing	France	188	96
3	Arkema	6.4	Inorganic chemical manufacturing	France	191	90
4	Institut Francais du Petrole	5.0	R&D in the physical, engineering and life sciences	Mexico	133	100
5	Centre National de LA Recherche Scientifique	3.0	R&D in the physical, engineering and life sciences	France	81	100
6	ENI S.P.A.	2.8	Natural gas extraction	Italy	204	36
7	Rhone Poulenc Chimie SA	2.5	Chemical manufacturing	France	67	100
8	Ceca SA	2.1	Other basic inorganic chemical manufacturing	France	57	100
9	Totalenergies SE	2.0	Natural gas extraction	France	53	100
10	Arkema France	1.9	All other basic organic chemical manufacturing	France	50	100

Note: See note on Table 3.1.

Appendix — references

Airhive (2025) *Projects*. https://www.airhive.earth/projects

Australian Government (2024) *Carbon capture technologies program grant recipients announced, 23 July*. https://www.dcceew.gov.au/about/news/carbon-capture-technologies-program-grant-recipients-announced

Carbon Engineering (2018) *Carbon Engineering's large-scale direct air capture breakthrough, 7 June*. https://carbonengineering.com/news-updates/climate-change-breakthrough/

Carbon Gap (2025a) *Carbon removal in Denmark — national policy overview*. https://tracker.carbongap.org/regional-analysis/national/denmark/

Carbon Gap (2025b) *Carbon removal in Finland — national policy overview*. https://tracker.carbongap.org/regional-analysis/national/finland/

Carbon Gap (2025c) *Carbon removal in France — national policy overview*. https://tracker.carbongap.org/regional-analysis/national/france/

Carbon Gap (2025d) *Carbon removal in Germany — national policy overview*. https://tracker.carbongap.org/regional-analysis/national/germany/

Carbon Gap (2025e) *Carbon removal in Hungary — national policy overview*. https://tracker.carbongap.org/regional-analysis/national/hungary/

Carbon Gap (2025f) *Carbon removal in Iceland — national policy overview*. https://tracker.carbongap.org/regional-analysis/national/iceland/

Carbon Gap (2025g) *Carbon removal in Netherlands — national policy overview*. https://tracker.carbongap.org/regional-analysis/national/netherlands/

Carbon Gap (2025h) *Carbon removal in Norway — national policy overview*. https://tracker.carbongap.org/regional-analysis/national/norway/

Carbon Gap (2025i) *Carbon removal in Sweden — national policy overview*. https://tracker.carbongap.org/regional-analysis/national/sweden/

Carbon Gap (2025j) *Carbon removal in United Kingdom — national policy overview*. https://tracker.carbongap.org/regional-analysis/national/united-kingdom/

Carbon Gap (2025k) *EU — US carbon removal policy comparison — final report*. https://tracker.carbongap.org/regional-analyses/eu-us-final-report/

Carbon Pulse (2024) *Japan considers government procurement of DAC carbon credits, draft methodologies for project development, 4 July*. https://carbon-pulse.com/301120/

Chen T (2024) *Japan's GX-League and carbon removal in GX-ETS*. https://www.cdr.fyi/blog/japans-gx-league-and-carbon-removal-in-gx-ets

Clean Air Task Force (2022) *Carbon capture provisions in the Inflation Reduction Act of 2022*. https://cdn.catf.us/wp-content/uploads/2022/08/19102026/carbon-capture-provisions-ira.pdf

Climate Insider (2025) *Stockholm Exergi to build one of the world's largest carbon capture facilities, 28 March*. https://climateinsider.com/2025/03/28/stockholm-exergi-to-build-one-of-the-worlds-largest-carbon-capture-facilities/

Committee for a Responsible Federal Budget (2025) Breaking down the One Big Beautiful Bill, *4 June*. https://www.crfb.org/blogs/breaking-down-one-big-beautiful-bill

Danish Energy Agency (2024) *Three new CCS projects have been pledged support to capture and store biogenic CO_2, 17 April*. https://ens.dk/en/press/three-new-ccs-projects-have-been-pledged-support-capture-and-store-biogenic-co2

Drax (2023) *Progressing global BECCS opportunities*. https://www.drax.com/investors/progressing-global-beccs-opportunities/

EFI Foundation (2024) *Direct air capture: a rapidly expanding landscape — from kiloton to megaton scale*. https://efifoundation.org/wp-content/uploads/sites/3/2024/11/DAC-Case-study.pdf

European Commission (2024) *The EU's 2030 carbon storage target*. https://climate.ec.europa.eu/eu-action/industrial-carbon-management/eus-2030-carbon-storage-target_en

European Council (2024) *Council greenlights EU certification framework for permanent carbon removals, carbon farming and carbon storage in products, 19 November*. https://www.consilium.europa.eu/en/press/press-releases/2024/11/19/council-greenlights-eu-certification-framework-for-permanent-carbon-removals-carbon-farming-and-carbon-storage-in-products/

EY (2024) *Kenya publishes climate change (carbon markets) regulations, 2024*. https://www.ey.com/en_gl/technical/tax-alerts/kenya-publishes-climate-change--carbon-markets--regulations--202

Global CCS Institute [GCCSI] (2024a) *CO_2RE facilities database*. https://co2re.co/FacilityData

Global CCS Institute [GCCSI] (2024b) *CO_2RE updates*. https://co2re.co/COREUpdates

Global CCS Institute [GCCSI] (2024c) *Global status of CCS 2024*. https://www.globalccsinstitute.com/resources/global-status-report/

Government of Canada (2024) *Carbon Capture, Utilization, and Storage (CCUS) Investment Tax Credit (ITC)*. https://www.canada.ca/en/revenue-agency/services/tax/businesses/topics/corporations/business-tax-credits/clean-economy-itc/carbon-capture-itc.html

Guillard C, Martin R, Mohnen P, Thomas C, Verhoeven D (2023) *Efficient industrial policy: standing on the shoulders of hidden giants*. CEP Discussion Paper No. 1813. London: Centre for Economic Performance. https://cep.lse.ac.uk/_NEW/publications/abstract.asp?index=8614

International Energy Agency [IEA] (2024a) *Bioenergy with carbon capture and storage*. https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/bioenergy-with-carbon-capture-and-storage

International Energy Agency [IEA] (2024b) *Direct air capture*. https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/direct-air-capture

Klimate (2023) *Project Hummingbird*. https://www.klimate.co/project/project-hummingbird

Natural Resources Canada (2024) *Carbon Capture, Utilization and Storage Investment Tax Credit (CCUS-ITC): technical guidance document*. https://natural-resources.canada.ca/sites/nrcan/files/pdf/CCUS-ITC%20Technical%20Guidance%20Document.pdf

Office of Fossil Energy and Carbon Management (2022) *The Infrastructure Investment and Jobs Act: opportunities to accelerate deployment in fossil energy and carbon management activities*. https://www.energy.gov/sites/default/files/2022-09/FECM%20Infrastructure%20Factsheet-revised%209-27-22.pdf

Oh C (2024) Contestation in social acceptance of direct air capture (DAC) technologies in Korea by differing framings over governance principles. *Journal of Open Innovation: Technology, Market, and Complexity* 10(4): 100403. https://doi.org/10.1016/j.joitmc.2024.100403

Ørsted (2023) Ørsted *begins construction of Denmark's first carbon capture project, 4 December*. https://orsted.com/en/media/news/2023/12/oersted-begins-construction-of-denmarks-first-carb-13757543

Oxy (2023) *Occidental and ADNOC to evaluate carbon management projects in the United States and United Arab Emirates to accelerate net zero goals, 1 August*. https://www.oxy.com/news/news-releases/occidental-and-adnoc-to-evaluate-carbon-management-projects-in-the-united-states-and-united-arab-emirates-to-accelerate-net-zero-goals/

Quantum Commodity Intelligence (2025) *BECCS developer signs France's first biogenic CO_2 storage deal, 4 February*. https://www.qcintel.com/carbon/article/beccs-developer-signs-france-s-first-biogenic-co2-storage-deal-35629.html

Ranevska S (2024) EU amps up its carbon removal strategy with new call for DACCS and BECCS innovations. *Carbon Herald, 6 November*. https://carbonherald.com/eu-amps-up-its-carbon-removal-strategy-with-new-call-for-daccs-and-beccs-innovations/

Reuters (2025) *Saudi Aramco launches first direct air capture test unit, 20 March*. https://www.reuters.com/sustainability/saudi-aramco-launches-first-direct-air-capture-test-unit-2025-03-20/

Schenuit F, Buck H, Geden O, Hofbauer V, Odeh N, Schell K, et al. (2024) Chapter 5: Policy and governance. In: Smith SM et al. (eds) *The state of carbon dioxide removal 2024 — 2nd edition*: 3. https://www.stateofcdr.org

UAE Ministry of Climate Change & Environment (2024) *The United Arab Emirates' third Nationally Determined Contribution (NDC 3.0): accelerating action towards mission 1.5C*. https://unfccc.int/sites/default/files/2024-11/UAE-NDC3.0.pdf

UK Parliament Hansard (2025) *Drax Power Station: biomass, 10 February*. https://hansard.parliament.uk/commons/2025-02-10/debates/25021013000012/DraxPowerStationBiomass

US Department of Energy (2024) *Funding notice: Carbon Negative Shot pilots*, *18 October*. https://www.energy.gov/fecm/funding-notice-carbon-negative-shot-pilots

US Department of Energy (2025) *Secretary Wright announces termination of 24 projects generating over $3 billion in taxpayer savings*, 30 May. https://www.energy.gov/articles/secretary-wright-announces-termination-24-projects-generating-over-3-billion-taxpayer

US Department of State (2021) *U.S.-China joint Glasgow declaration on enhancing climate action in the 2020s, 10 November*. https://2021-2025.state.gov/u-s-china-joint-glasgow-declaration-on-enhancing-climate-action-in-the-2020s/