“Public funding, patenting and investment in CDR have expanded dramatically in the past two years.”

Chapter 3 | Innovation

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Growing public funding, patenting and investment show that innovation in Carbon Dioxide Removal is active. But the pace is still modest compared with what is needed to meet industry targets and the Paris temperature goal.

Box 3.1 Key findings

- Global public investment in Carbon Dioxide Removal (CDR) Research, Development and Demonstration (RD&D) was approximately $4.1 billion between 2010 and 2022.
- Public RD&D funding is concentrated in a few regions. Proposed Direct Air Capture (DAC) demonstration hubs in the United States account for the vast majority of traceable public funding ($3.5 billion).
- Global CDR patenting activity has increased over the last 15 years, with a large and growing share occurring in China. In 2018 – the last year of complete data – China accounted for 36% of all CDR patents.
- DAC (a component of Direct Air Carbon Capture and Storage, DACCS) is dominant in the share of total CDR patents from 2000 to 2018. Ocean-based methods make up only a small portion of total CDR patents. The technological focus of patents has become more diverse in recent years.
- Investment in new CDR capacity totalled approximately $200 million between 2020 and 2022. The vast majority of announced purchases focus on DACCS, with biochar the next most prominent method.

3.1 Measuring growth in Carbon Dioxide Removal innovation

Innovation in Carbon Dioxide Removal (CDR) has expanded dramatically in the past two years, as measured by publicly funded Research, Development and Demonstration (RD&D), patents and investment in new capacity.

Examining innovation is important because it provides an understanding of how CDR methods are evolving, how fast they might become deployed and how costs are changing. Innovation requires multiple metrics to assess, given that it consists of a sequence of interlinked processes (Figure 3.1)[5]. This chapter assesses the state of CDR innovation using three sets of metrics[44]: public investment in CDR RD&D; patenting; and investment in new capacity. These indicators assess the rates of change in different stages of the innovation process (Figure 3.1). Public investment in RD&D measures supply factors, particularly early-stage inputs in the RD&D stage of innovation.

Patenting is a measure of inventive activity that relates to supply factors (Research and Development, demonstrations, and scale-up) as well as demand factors such as niche markets and demand pull. Investment in new capacity relates to demand factors (demand pull towards increased adoption while establishing public acceptance). Looking ahead, we examine the future rates of growth in CDR innovation (relating to the scale-up stage) implied by the targets set by companies and industry groups. We note that feedbacks from later stages to earlier ones have been crucial for other technologies (e.g. market experience identifies new directions for development). We expect these feedbacks to also be important for CDR.

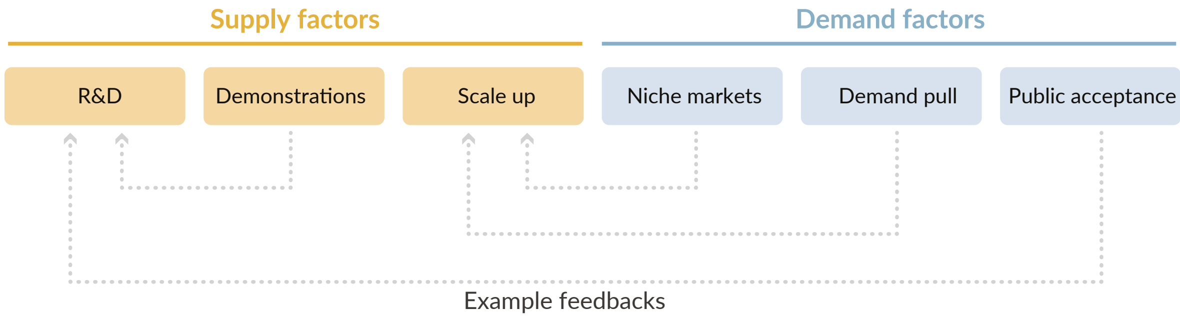

Figure 3.1. *The process of innovation for Carbon Dioxide Removal consists of a sequence of interlinked stages that feed back and build on one another. These stages are broadly split into two categories: supply factors (Research and Development [R&D], demonstrations and scale-up) and demand factors (niche markets, demand pull and public acceptance). Source: Nemet et al.*[5]

Box 3.2 Our methods for assessing growth in Carbon Dioxide Removal innovation

Research, Development and Demonstration (RD&D) – Data on RD&D spending specifically related to Carbon Dioxide Removal (CDR) is patchy, in contrast to other climate change mitigation methods, but it is also similar in that respect to energy RD&D in its early years. We use publicly available data from country plans, policies and announcements that are explicitly labelled as funding research on CDR, greenhouse gas removal or negative emissions methods. We do not include funding for elements that are not CDR methods in themselves but are important components (e.g. Carbon Capture and Storage [CCS] and biomass use). Nor do we include funding which is not labelled as CDR but may still include relevant methods (e.g. tree planting, soil management). Data on public RD&D investment is for 2010-2022. We convert currencies to US dollars for comparison using currency values from the Federal Reserve[45]. For more detail on CDR research directions, refer to Chapter 2 – Research landscape for a summary of the English-language, peer-reviewed scientific literature on CDR.

Patent activity – To measure patent activity for CDR methods and/or components over time and by method we use patent family counts, and to measure country activity we use patent application counts. We use the search methodology from Kang et al. in the Derwent Innovations Index to gather patent data[46]. Patent families avoid double-counting by grouping patents for the same invention that are filed in multiple countries or patent offices. Analysing patent applications, on the other hand, ensures that we account for each of the different countries where patents are filed. We use the patent application date for the time range of 1980-2020, using the search terms from Kang et al. The search terms for Direct Air Capture do not include storage. We do not include patents related to CCS without a CO_2 removal component, even though these patents are related to elements of some CDR methods (such as Direct Air Carbon Capture and Storage and Bioenergy with Carbon Capture and Storage).

Investment in new capacity – We use the Marginal Carbon database, which collects known announced purchases of durable CDR, including the year of purchase and CDR method. The announced purchases are included in the database, and thus in this chapter, if the CO_2 is stored for at least 100 years. For announced purchases without a purchase price, we apply a cost per tonne by method[47]. We assess the cost per tonne from the other announced purchases for each method and year. The database gives an indication of the level and relative share of CDR methods on the market. However, it is not a complete database and includes uncertainties. For example, the database lists "carbon dioxide from concrete" as a CDR method. It is unclear, however, if the CO_2 in this method is from a fossil origin or biogenic origin, which would classify it as fossil CCS rather than CDR (see Chapter 1 – Introduction, Box 1.2). These instances of uncertainty have been included in the total investment calculations to capture the full scope of investments.

Public Research, Development and Demonstration

Research, Development and Demonstration that is funded by the public sector (public RD&D) provides important information on where early-stage development is being directed and where gaps exist[45]. While public RD&D is typically smaller than private RD&D at the economy level, the former can play a much bigger role for nascent technologies and be crucial to entraining the latter[48]. Using publicly available data, we find global public investment in CDR RD&D of approximately $4.1 billion during the period 2010-2022. To put this in perspective, global annual spending on energy RD&D in 2021 alone was $17 billion for Organisation for Economic Co-operation and Development (OECD) countries, which excludes China.

Global public investment in RD&D funding is concentrated in a few regions, and the overwhelming majority of the total is $3.5 billion for Direct Air Capture (DAC) hubs in the US, spread over multiple years. This demonstration programme is open to projects that utilise or store the captured CO_2. While not all the CO_2 captured is therefore likely to be durably stored, we include this programme within our analysis of innovation because demonstration of the DAC components advances the Direct Air Carbon Capture and Storage (DACCS) method as a whole.

Below, we summarise the diverse sets of CDR activities covered by public RD&D funding in eight countries and regions that have accessible information on public CDR RD&D – either data on public RD&D funding or net zero targets that will require CDR. We have not found

RD&D programmes specifically labelled as CDR in the rest of the world. We are aware, however, that there is further public RD&D investment in programmes that incorporate CDR methods but that are not labelled as such, for example European Union (EU) funding for research into CDR from agricultural/forestry management practices[48,49]. Like other areas of science and technology, publicly funded RD&D is overwhelmingly concentrated in high-income economies, although other countries may have unique characteristics that make them well suited for conducting CDR research (such as energy sources and local climate) in the future. Financial flows and technology transfer between countries can aid CDR innovation beyond the countries described below[1].

Australia
In 2021, the Australian government funded an A$4 million (US$2.5 million) DACCS demonstration project[50]. Although the government has funded several Carbon Capture and Utilisation projects, no large-scale funding for CDR has yet been announced.

Canada
Canada has committed to achieving net-zero greenhouse gas (GHG) emissions by 2050 through the Canadian Net-Zero Emissions Accountability Act[51]. While Canada has invested in RD&D for Carbon Capture and Utilisation and low-carbon technologies, the federal government has not yet announced investments explicitly for CDR. The Net Zero Accelerator Initiative and the Climate Action and Awareness Fund may both fund CDR research in the future[52,53].

China
China has established a target of carbon neutrality by 2060 that will require CDR methods[54]. Total investment from the Chinese government in 2018 on forestry and grasslands totalled about ¥140 billion ($21 billion), although only a portion of this funding is specifically focused on carbon storage via biological methods[55]. Data on total RD&D expenditures for CDR in China is not publicly available.

European Union
The European Climate Law includes a target for climate neutrality[56]. In April 2022, the European Commission announced funding for one Bioenergy with Carbon Capture and Storage (BECCS) project worth €180 million ($180 million) via the EU Innovation Fund, which is funded by revenues from the EU's Emissions Trading System[57]. The second mechanism for funding CDR is Horizon Europe, the EU's programme on research, development and innovation[58]. This supports a variety of CDR methods. An analysis from Carbon Gap, an environmental NGO, estimates that funding from Horizon Europe will be €185 million for activities both directly and indirectly related to CDR (funding 34 projects) and €161 million for projects directly related to CDR (funding 28 projects)[59]. The Horizon Europe programme includes funding for projects specifically on RD&D under the Climate, Energy and Mobility cluster: on CDR approaches (€21 million) as of 2021 and on Negative Emissions as of 2020[57,58].

Germany
Since 2021, the German Federal Ministry of Education and Research has funded two major research missions: one on ocean-based CDR methods and marine CO_2 storage methods (*CDRmare*) and the other on land-based CDR methods (*CDRterra*). *CDRmare* began funding six projects in 2021 worth a total of €26 million ($26 million)[60]. *CDRterra* began funding projects on DACCS, biochar, enhanced rock weathering, BECCS, and afforestation/reforestation worth a total of €21 million ($21 million)[61].

Japan
The Moonshot Research and Development Program in Japan was developed by the Council for Science, Technology and Innovation and the Headquarters for Healthcare Policy and includes a goal on sustainable resources[62,63]. The purpose of the programme is to promote "challenging R&D based on revolutionary concepts" and includes CDR in the "Moonshot for beyond Zero-Emission Society"[64]. In 2022, a call for proposals for Moonshot funding was announced with a maximum amount per project of ¥500 million ($3.6 million). Japan's Ministry of the Environment also provided funding for a large-scale BECCS plant in 2020[65].

United Kingdom
The UK has invested in RD&D on a wide range of GHG removal technologies – primarily CDR methods but also some methane removal projects. The first GHG removal RD&D programme ran from 2017 to 2021, funding 11 projects totalling £8.6 million ($9.7 million)[66]. The UK Government's Net Zero Strategy, published in 2021, includes CDR deployment goals and two new RD&D programmes focused on demonstration[67]. The first is a pre-commercial innovation competition funded through the Department for Business, Energy and Industrial Strategy[68]. In the first phase, 23 projects focusing on the design and feasibility of CDR methods each received £250,000 (a total of £5.9 million, or $6.7 million). In Phase Two, an additional £58 million ($65 million) will be awarded to pilot the 15 most promising designs (ending March 2025)[69]. Afforestation and other conventional CDR methods on land are excluded from the competition, though their role in meeting the net zero target is recognised. As the second programme, UK Research and Innovation announced over £30 million ($34 million) to investigate the viability of five GHG removal demonstration projects and a central research hub[70]. The projects vary in method and include peatland restoration, enhanced rock weathering, biochar, afforestation, and biomass crops for use in BECCS[71].

United States
In 2021, the US announced a target to achieve net-zero greenhouse gas emissions economy-wide[72]. The US Department of Energy (DOE) launched the Carbon Negative Shot as an RD&D initiative for CDR focused on storing CO_2 at gigatonne scales for less than $100/net tonne[73]. In 2020, the US Congress appropriated $40 million for CDR Research and Development (R&D), of which $15 million was specifically appropriated for DAC[74]. In 2021, $63 million was appropriated for CDR R&D, with $22 million specifically for DAC[75]. In 2021, RD&D projects worth $18 million were announced through the DOE and the Office of Fossil Energy and Carbon Management to fund DAC[74,76]. Congressional appropriation for CDR R&D increased to $104 million in 2022, with $75 million specifically for DAC[77]. In 2022, the DOE announced $3.5 billion in funding under the Bipartisan Infrastructure Law's programme on CDR to develop the Regional Direct Air Capture Hubs programme to support four DAC hubs[75]. As a part of the Carbon Negative Shot initiative, the DOE announced $30 million to fund RD&D on DAC and ocean-based CDR methods that include "permanent storage or utilization"[78]. Since 2010, the US DOE and the US Department of Agriculture have funded RD&D for land-based CDR totalling about $49 million, through "improved crops for soil carbon sequestration" and biochar research[79]. The National Science Foundation has also funded R&D ocean-based CDR methods, including iron fertilisation[79].

Patenting

Patenting activity can provide a useful measure of innovation by indicating the pace of invention. Inventive activity comes from supply-side RD&D, demonstration and scale-up and can also be supported by demand factors such as niche markets and demand pull. Our examination of CDR patenting activity at the global level suggests an overall increase over the last 15 years, with a large and growing share of patenting occurring in China. The most prominent component in terms of growth in patents is DAC. China is also a hotspot in terms of generating scientific research on CDR – though this is driven particularly by studies on biological CDR methods (see Chapter 2 – Research landscape). Patenting activity is one measure of innovation, and one with accessible data, but innovation can also occur outside of what firms choose to patent. Invention, experimentation and learning can be retained as tacit knowledge and trade secrets. Another alternative is a transparent approach, with inventions published unprotected as research papers (see Chapter 2 – Research landscape) or as freely available data and designs (e.g. OpenAir Collective)[80].

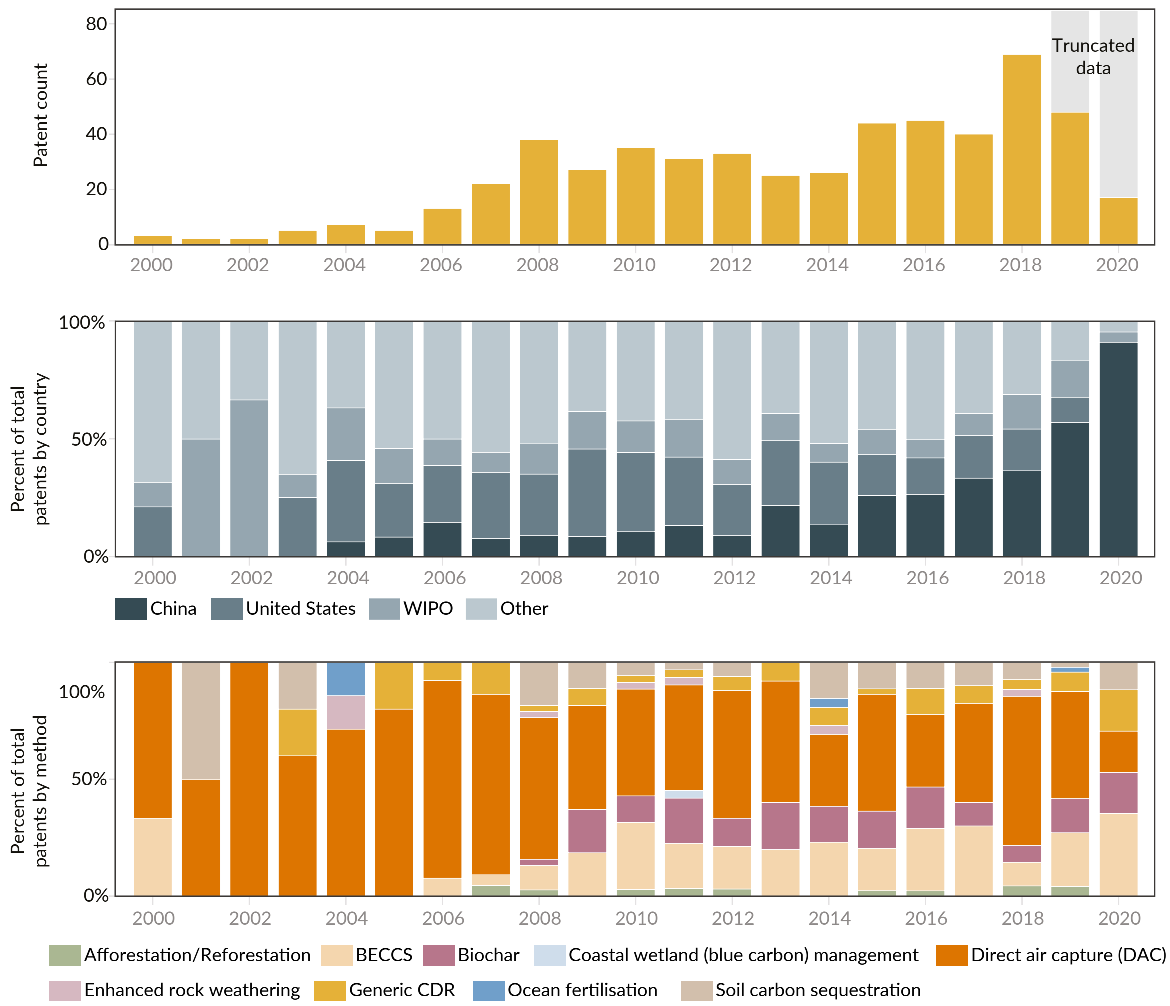

Figure 3.2. *Global increase in Carbon Dioxide Removal (CDR) patenting activity. Total number of patents per year for 2000-2020, grouped by patent families (top). Families refer to the same invention files in multiple countries. In 2019 and 2020, the data is truncated because of the time it takes to process the application before publishing. Percent of individual patent applications per year by the country where the patent was filed (middle). The World Intellectual Property Organization (WIPO) is a centralised patent office. Percent of total patent families per year by method/component (bottom). Definition: Bioenergy with Carbon capture and Storage (BECCS).*

Over the past 20 years, the number of CDR patents has increased (Figure 3.2, top panel). This, in turn, indicates an increase in innovation in CDR. The last year of full data is 2018, whereas 2019 and 2020 data is truncated due to the typical two-year time it takes to review applications.

In terms of distribution of patents between different countries, China has had an increasingly large share of CDR patents since 2004 (Figure 3.2, middle panel). In the last year of complete data (2018), patents filed in China made up 36% of all CDR patents filed. China's share of total patents is very high in the truncated data for 2019 and 2020, which may, at least in part, be a result of a faster time to approval in China's patent offices compared with other countries, such as the US. The US has also had a large share of all CDR patents, accounting for an average of 23% of annual applications from 2000 to 2018. However, from 2015 to 2018, the share of patents filed in the US decreased to 15-20% of annual patent applications, compared to 23-37% from 2003 to 2014. WIPO, the World Intellectual Property Organization, is a centralised patent office where approximately 5-10% of total CDR patents were filed during 2003-2018. In a majority of cases in which a patent was filed with WIPO (88%), the patent was also filed in at least one other country. All other countries are grouped into an "Other" category, which makes up a large portion of total annual patents during 2000-2018 (31-68%, with an average of 48% per year). The patents represented by this category are split between many regions and countries. By 2018, the last year of full data in the analysis, the split is about equal between China (36%), the United States and WIPO (19% and 15%, respectively, for a total of 34%), and all other countries combined (31%).

In terms of CDR method/component technologies, DAC is dominant in the share of total CDR patents during 2000-2018 (Figure 3.2, bottom panel). BECCS made up 33% of CDR patents in 2000, then an average of 18% during 2006-2018. Ocean-based CDR methods make up only a small portion of CDR patents, with 11 patents on ocean-based methods filed sporadically during 2000-2018: coastal wetland (blue carbon) management (one patent), enhanced rock weathering (seven patents) and ocean fertilisation (three patents). Biochar patents began in 2008 and have continued through 2020. We observe a decline in technological concentration in the last few years of the data (i.e. smaller shares for the largest CDR technologies).

Investment in new CDR capacity

The ultimate manifestation of innovation is widespread adoption of a technology. This happens when it is relatively advantageous compared with other technologies, demand pull is sufficient and the technology is publicly accepted. Using the Marginal Carbon database (see Box 3.2 on methods), we find announced purchases totalling approximately $200 million and 510,000 tonnes of CDR for 2020-2022. Some of this is for offtake agreements for future purchases (in which the payment comes at the time of delivery) while some is for pre-purchases, where the tonnes have been paid before the project is complete. This data includes efforts to increase demand for CDR to spur innovation (demand pull) such as the Frontier advance market commitment (a funding mechanism that involves aggregating funding and facilitating purchases of CDR)[81]. Only a small fraction of purchases have actually been delivered to customers, however (see Chapter 6 – Deployment).

The vast majority (75%, worth $150 million) of announced purchases are focused on DACCS. This is largely driven by one announcement from 1PointFive/Carbon Engineering (two companies that work to design and deploy DAC facilities) of 100,000 tonnes per year for four years, with a 2022 average cost per tonne of DACCS of $270. In order of value, following this there are two announced purchases of a combined $6.4 million, which include several CDR methods but do not delineate monetary or tonnage amounts per method. Otherwise, where methods are specified, biochar features as the second most prominent method among announced purchases.

Some method costs per tonne have gone up from 2020 to 2022 (including DACCS: $780 in 2020 to $1,200 in 2021; and biochar: $250 in 2021 to $430 in 2022). This could be seen as surprising, but the changes are largely driven by single purchases. For example, Shopify purchased 2,500 tonnes of CO_2 removed through biochar for $570/tonne from one supplier in 2022, driving up the average price. It could also be argued that there are no real market prices for CDR at this early stage. We see that many early backers of novel CDR (by which we mean methods other than the well-established land-based methods already deployed at scale, such as afforestation/reforestation, soil carbon sequestration, etc.; see Chapter 1 – Introduction for our definitions) are paying for the cost of production as a way of supporting early development, rather than buying a commodity at market prices. Diffusion theory and learning rate theories hypothesise that, over time, method costs will decrease as the methods develop and supply increases, but novel CDR methods might not have entered the phase where this starts to happen.

To put this data in perspective, Bloomberg estimates global climate-technology investments (for all mitigation technologies, not just CDR) at $170 billion in 2021 – of which only $0.3 billion relates to CDR[82]. That means the size of equity investments in CDR is similar to amounts of pre-purchases and offtake agreements. An additional data source, ClimateTech VC, estimates that the level of CDR equity investments in 2021 was $170 million, and in 2022 $830 million, totalling about $1 billion[83]. Although this data is not directly comparable to announced purchase levels, the data is on the same order of magnitude.

3.2 Future growth targets

The novel CDR industry needs to grow by four to six orders of magnitude by mid-century to meet its own targets and to meet the Paris temperature goal.

We provide an indication of the challenge to scale up CDR by comparing announcements of CDR targets from companies and industry groups with the current size of the industry and with estimates of the CDR potential of different methods by 2050. Mid-century CDR potential is the magnitude of CO_2 that can be removed and durably stored from each CDR method by 2050, while taking into account biophysical limits, economic costs and potential side effects of deployment.

Box 3.3 Our methods for assessing future growth in Carbon Dioxide Removal innovation

Growth rates – We use publicly announced company and industry targets for Carbon Dioxide Removal (CDR) as an indicator for growth in innovation. To calculate company announcements and capacity for Direct Air Capture (DAC) from 2021 to 2035, we combine the announced scale-up targets from Carbon Engineering and Climeworks, two DAC companies[84,85]. Biochar estimates are from the European Biochar Industry Consortium, a biochar industry group[86]. Company announcement targets for Bioenergy with Carbon Capture and Storage (BECCS) scale-up are from Drax Global[87], a UK-based energy company with a BECCS plant, and Stockholm Exergi[88]. These targets are publicly available and, although not comprehensive of all CDR companies or industry groups, illustrate the expectations for direction and scale of the market in the coming decades.

For the mid-century potentials of individual CDR methods (Direct Air Carbon Capture and Storage, BECCS and biochar), we use low and high estimates of sustainable global technology potentials in 2050 from a systematic literature review from Fuss et al[4].

The figure below shows the growth trajectories of three specific CDR methods, incorporating both announced and built capacities from industry and businesses. The shaded areas show how the last year of company capacity announcements compares with the range in the mid-century potential (the low and high data points shown for 2050) for each CDR method[4].

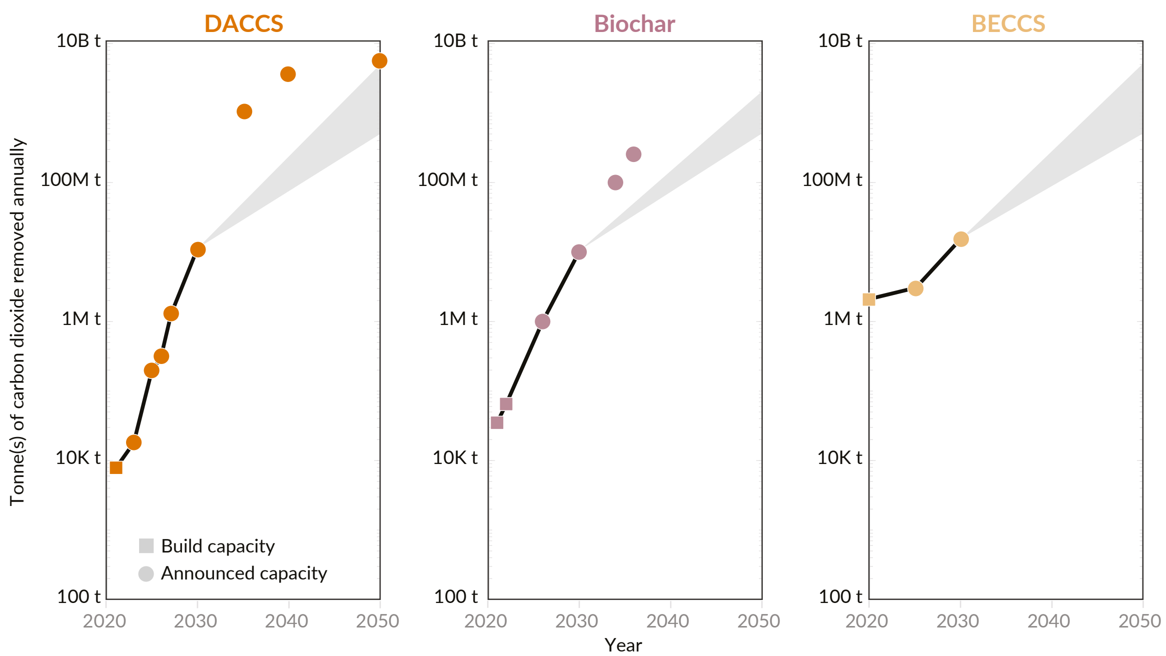

Figure 3.3. *Announced Carbon Dioxide Removal (CDR) targets from industry groups and companies imply faster growth than has been seen historically for most technologies. Squares represent built capacity in three example CDR methods (Direct Air Carbon Capture and Storage [DACCS], biochar and Bioenergy with Carbon Capture and Storage [BECCS]). Circles represent announced plans for capacity additions. The shaded areas for each CDR method show how the last year of company capacity announcements could grow to meet CDR socio-technical potential by mid-century: the low and high data points in 2050 represent the range of maximum potential removal, which is dependent on biophysical limits, economic costs and side effects of deployment.*

The figure suggests that the CDR targets of companies and industry groups are generally aligned with achieving mid-century CDR potentials (see Box 3.3)[4], particularly for DACCS and biochar, because the slopes of the curves for those mid-term targets are steeper than those after. However, the figure also makes clear that the CDR industry is currently five orders of magnitude smaller than those mid-century potentials. In the particular case of DACCS, for example, we assess that in mid-2022 about 8,000 tonnes of annual removal capacity exists[89], compared with a mid-range potential of 2 billion tonnes annually by 2050[4].

Growing from the current level to maximum mid-century potential implies an exponential growth rate of over 50% per year. That exceeds most previous technologies, but not all (such as the production of liberty ships in the United States during World War Two and worldwide computing growth).

3.3 Spurring growth in innovation

There is an urgent need for comprehensive policy support to spur growth in CDR.

To achieve the growth rate in investment in new capacity indicated in our analysis of over 50% per year, there is an urgent need for comprehensive, durable policy support for CDR. Policies can spur growth in the CDR market to achieve mid-century goals for CDR – and these expectations are crucial for private investment in CDR innovation and deployment to reach gigatonne scale. Ensuring that data on CDR RD&D funding, patents and investment in new capacity is comprehensive and publicly available can support the type of policies needed for CDR scale-up.