Direct Air Capture

A key technology for net zero

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Abstract

Direct air capture plays an important and growing role in net zero pathways. Capturing CO_2 directly from the air and permanently storing it removes the CO_2 from the atmosphere, providing a way to balance emissions that are difficult to avoid, including from long-distance transport and heavy industry, as well as offering a solution for legacy emissions. Air-captured CO_2 can also be used as a climate-neutral feedstock for a range of products that require a source of carbon.

In the IEA Net Zero Emissions by 2050 Scenario, direct air capture technologies capture more than 85 Mt of CO_2 in 2030 and around 980 $MtCO_2$ in 2050, requiring a large and accelerated scale-up from almost 0.01 $MtCO_2$ today. Currently 18 direct air capture facilities are operating in Canada, Europe and the United States. The first large-scale direct air capture plant of up to 1 $MtCO_2$/year is in advanced development and is expected to be operating in the United States by the mid-2020s.

This report explores the growing momentum behind direct air capture, together with the opportunities and challenges for scaling up the deployment of direct air capture technologies consistent with net zero goals. It considers the current status of these technologies, their potential for cost reductions, their future energy needs, and the optimal locations for direct air capture facilities. Finally, the report identifies the key drivers for direct air capture investment and priorities for policy action.

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Executive summary

Capturing CO_2 from the air can support net zero goals

Direct air capture (DAC) plays an important and growing role in net zero pathways. Capturing CO_2 directly from the air and permanently storing it removes the CO_2 from the atmosphere, providing a way to balance emissions that are difficult to avoid, including from long-distance transport and heavy industry, as well as offering a solution for legacy emissions. In the IEA Net Zero Emissions by 2050 Scenario, DAC technologies capture more than 85 Mt of CO_2 in 2030 and around 980 $MtCO_2$ in 2050, requiring a large and accelerated scale-up from almost 0.01 $MtCO_2$ today.

DAC is a key part of the carbon removal portfolio. Carbon dioxide removal (CDR) is not an alternative to cutting emissions or an excuse for delaying action, but is part of a comprehensive strategy for "net" zero – where emissions being released are ultimately balanced with emissions removed. CDR approaches range from nature-based solutions such as afforestation to technology-based approaches underpinned by carbon capture and storage. DAC with geological CO_2 storage has several advantages as a CDR approach, including a relatively small land and water footprint, and high degree of assurance in both the permanence of the storage and the quantification of CO_2 removed.

The contribution of DAC goes beyond carbon removal. Air-captured CO_2 can be used as a climate-neutral feedstock for a range of products that require a source of carbon, from beverages to chemicals and synthetic aviation fuels. In the Net Zero Emissions by 2050 Scenario around 350 Mt of air-captured CO_2 is used to produce synthetic fuels in 2050, including for aviation, supporting one of the few options available to reduce emissions in the sector.

Momentum for direct air capture is growing

DAC plants currently operate at a small scale, but with plans to grow. Currently 18 DAC facilities are operating in Canada, Europe and the United States. All but two of these facilities sell their CO_2 for use, and the largest such plant – commissioned in Iceland in September 2021 – is capturing 4 000 tCO_2/year for storage (via mineralisation). The first large-scale DAC plant of up to 1 $MtCO_2$/year is in advanced development and is expected to be operating in the United States by the mid-2020s.

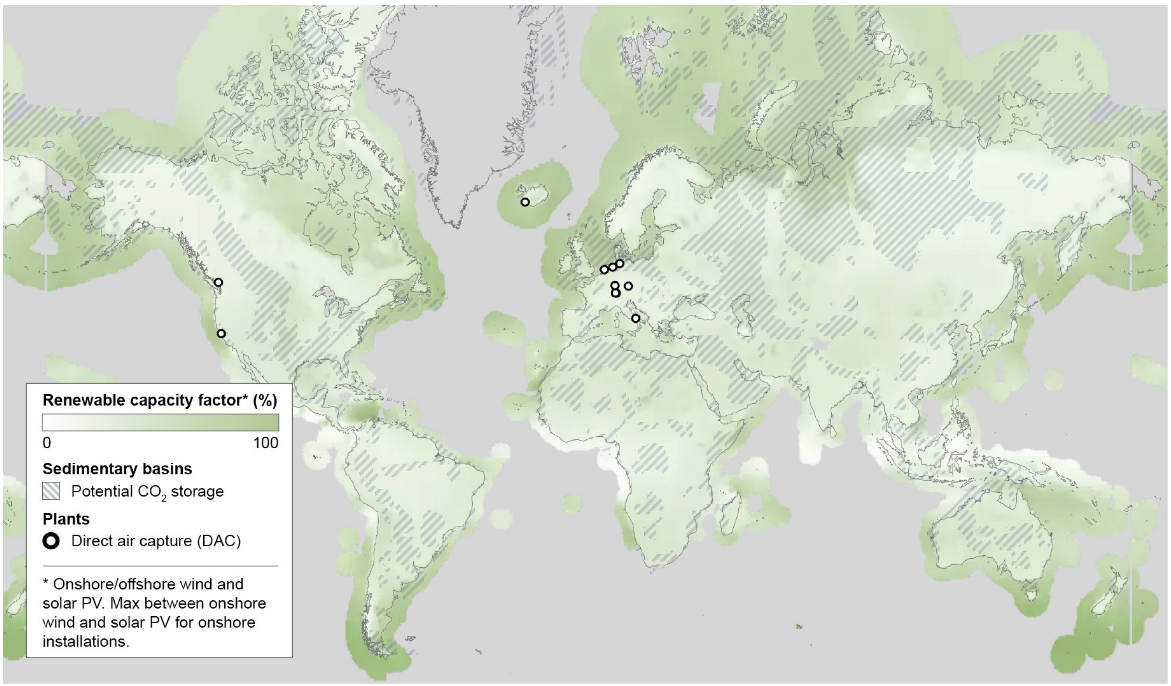
Governments and industry are getting behind DAC. Since the start of 2020, governments have committed almost USD 4 billion in funding specifically for DAC development and deployment. This includes USD 3.5 billion to develop four DAC hubs and a USD 115 million DAC Prize programme in the United States. New R&D funding is forthcoming in Australia, Canada, Japan, the United Kingdom and elsewhere. The United States also launched a Carbon Negative Shot during COP26, identifying DAC among a portfolio of CDR approaches with potential to remove CO_2 and durably store it, at scale, for under USD 100/tCO_2. Private and philanthropic investment is also growing: leading DAC companies have raised around USD 125 million in capital since the start of 2020 and companies ranging from Microsoft to United Airlines are investing in early projects. DAC is one of four technologies that Breakthrough Energy Catalyst is targeting for up to USD 1.5 billion in investment, and it is also an eligible technology for the USD 100 million Carbon Removal XPRIZE announced in 2021.

Costs are high today, but projected to fall

Capturing CO_2 from the air is the most expensive application of carbon capture. The CO_2 in the atmosphere is much more dilute than in, for example, flue gas from a power station or a cement plant. This contributes to DAC's higher energy needs and costs relative to these applications. But DAC also plays a different role in net zero pathways, including as a CDR solution. Future capture cost estimates for DAC are wide-ranging and uncertain, reflecting the early stage of technology development, but are estimated at between USD 125 and USD 335 per tonne of CO_2 for a large-scale plant built today.

With deployment and innovation, capture costs could fall to under USD 100/tCO_2. DAC costs are dependent on the capture technology (solid- or liquid-based technologies), energy costs (price of heat and electricity), specific plant configuration and financial assumptions. In locations with high renewable energy potential and using best available technologies for electricity and heat generation, DAC costs could fall below USD 100/tCO_2 by 2030. The Middle East and the People's Republic of China (hereafter "China") could be among the least-cost locations for DAC deployment, together with Europe, North Africa and the United States. However, the potential for costs to fall to these levels will be strongly dependent on increased public and private support for innovation and deployment.

Map of renewable energy source potential and CO_2 geological storage



Notes: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Sources: IEA analysis based on renewable.ninja for hourly solar data for utility-scale solar PV; Copernicus for hourly wind speed datal.

Innovation is needed across the direct air capture value chain

DAC technologies require significant amounts of energy. The two leading DAC technologies – solid DAC (S-DAC) and liquid DAC (L-DAC) – were initially designed to operate using both heat and electricity. The lower temperature heat needs of S-DAC mean it can be fuelled by renewable energy sources (including heat pumps and geothermal). The high temperature heat needs of L-DAC (up to 900 °C) underpin current plant designs that rely on natural gas for heat, although the CO_2 from the use of this gas is inherently captured within the process and not emitted. Innovation to support renewable energy options for high-temperature industrial heat would maximise the carbon removal potential of L-DAC plants.

DAC still needs to be demonstrated in different conditions. A major advantage of DAC is its flexibility in siting: in theory, a DAC plant can be situated in any location that has low-carbon energy and a CO_2 storage resource or CO_2 use opportunity. It can also be located near existing or planned CO_2 transport and storage infrastructure. Yet there may be limits to this siting flexibility. To date, DAC plants have been successfully operated in a range of climatic conditions in Europe and North America, but further testing is still needed in locations characterised, for instance, by extremely dry or humid climates, or polluted air.

Innovation in CO_2 use opportunities, including synthetic fuels, could drive down costs and provide a market for DAC. Early commercial efforts to develop synthetic aviation fuels using air-captured CO_2 and hydrogen have started, reflecting the important role that these fuels could play – alongside biofuels – in the sector. In the Net Zero Emissions by 2050 Scenario, around one-third of aviation fuel demand in 2050 is met by these synthetic fuels, but currently their cost can be more than five times conventional fossil-based options. Further innovation is needed to support cost reductions and faster commercialisation, and build a potentially large market for air-captured CO_2.

Robust certification of direct air capture can support future investment

Business models for DAC are linked to high-quality carbon removal services and CO_2 use opportunities. DAC companies are offering commercial CO_2 removal services to individuals and companies. Although DAC with CO_2 storage is among the most expensive options to balance emissions, it is attracting interest from companies seeking high-quality CDR that offers additionality, durability and measurability. The purchase of DAC-based carbon removal is currently limited to voluntary carbon markets.

Internationally agreed approaches to the certification and accounting of DAC are needed. The development of agreed methodologies and accounting frameworks based on life cycle assessment (LCA) for DAC – alongside other CDR approaches – will be important to support its inclusion in regulated carbon markets and national inventories. Notably, the latest IPCC Guidelines for National Greenhouse Gas Inventories do not include an accounting methodology for DAC, meaning that CDR associated with DAC cannot be counted towards meeting international mitigation targets under the United Nations Framework Convention on Climate Change (UNFCCC). Efforts to develop carbon removal certification, including for DAC-based CDR, have commenced in Europe and the United States, as well as through initiatives such as the Mission Innovation CDR Mission. These efforts should be co-ordinated with the aim of establishing internationally consistent approaches.

Six priorities for direct air capture deployment

DAC deployment must be accelerated for net zero. The Net Zero Scenario requires the immediate and accelerated scale-up of DAC, calling for an average of 32 large-scale plants (1 $MtCO_2$/year each) to be built each year between now and 2050. This will require increased public and private support to reduce costs, improve technologies and build the market for DAC technologies. The IEA has identified six near-term priorities for DAC deployment aligned with net zero goals:

1. **Demonstrate DAC at scale as a priority.** Targeted policies and programmes are needed for near-term demonstration and deployment. Governments should ensure that planned projects are able to progress to operation and provide essential learnings for DAC technologies and supply chains.

2. **Foster innovation across the DAC value chain.** Innovation will be critical to: reducing manufacturing and operational costs, as well as the energy needs for DAC plants; supporting the availability of low-emission energy sources for high-temperature heat; and developing and reducing the cost of CO_2 use applications including synthetic aviation fuels.

3. **Identify and develop CO_2 storage.** The potential for DAC to remove CO_2 from the atmosphere in large quantities rests on the development of suitable geological CO_2 storage. Although the storage potential is vast, the time to develop these resources can be as long as ten years and could act as a brake on the scale-up of DAC in some regions.

4. **Develop internationally agreed approaches to DAC certification and accounting.** Robust, transparent and standardised international certification and accounting methodologies for DAC are needed to facilitate its recognition in carbon markets and IPCC greenhouse gas inventory reporting.

5. **Assess the role of DAC and other CDR approaches in net zero strategies.** Improved understanding and communication of the anticipated role of DAC and other CDR approaches in net zero strategies will help identify the technology, policy and market needs within countries and regions. For example, the United Kingdom's Net Zero Strategy identifies a need for around 80 $MtCO_2$ of technology-based carbon removals by 2050.

6. **Build international co-operation for accelerated deployment.** Collaboration through international organisations and initiatives such as the IEA, Clean Energy Ministerial, Mission Innovation, and Technology Collaboration Programme on Greenhouse Gas R&D (GHG TCP/IEAGHG) can play an important role in promoting knowledge sharing, reducing duplication in research efforts, and harmonising approaches to LCA and accounting methodologies for DAC technologies.

Chapter 1. Growing interest in direct air capture for net zero

Introduction

Direct air capture (DAC) technologies can play an important role in meeting net zero goals. Capturing CO_2 directly from the air and permanently storing it removes the CO_2 from the atmosphere, providing a solution for legacy emissions as well as a way to balance emissions that are difficult to avoid. Air-captured CO_2 can also be used as a climate-neutral feedstock to produce a range of products, from synthetic aviation fuels to food and beverages.

The number of DAC installations has been growing in recent years, with 18 facilities now operating around the world. These are all small scale: in total, they have the capacity to capture almost 0.01 $MtCO_2$ each year, but the first large-scale DAC plant (1 $MtCO_2$/year) is in advanced development and could be operating in the United States by the mid-2020s. A major boost in DAC deployment this decade will be needed to meet net zero goals. In the IEA Net Zero Emissions by 2050 Scenario (Net Zero Scenario),[1] DAC deployment rapidly scales up to reach around 85 $MtCO_2$ in 2030 and 980 $MtCO_2$ in 2050.

The potential for DAC to contribute to climate change mitigation is increasingly being recognised, with the technology benefiting from new public and private initiatives. In 2021 the United States committed USD 3.5 billion to establish four DAC hubs and introduced a DAC Prize programme offering USD 100 million for commercial-scale projects and USD 15 million for pre-commercial projects. The United States also identified DAC as a key technology for its Carbon Negative Shot, announced during COP26. The United Kingdom has earmarked GBP 100 million (around USD 137 million) for carbon dioxide removal (CDR) approaches, including DAC, while funding programmes supporting DAC development and deployment have been established in Australia, Canada, Europe and elsewhere.

[1] The Net Zero Scenario is designed to show what is needed across different sectors by different actors, and by when, for the world to achieve net zero energy sector and industrial process CO_2 emissions by 2050. The scenario aims to ensure that CO_2 emissions are in line with the headline reductions included by the IPCC in its Special Report on Global Warming of 1.5°C, and that there are substantial reductions in energy-related methane emissions. In addition, the Net Zero Scenario incorporates concrete action on the other energy-related Sustainable Development Goals related to achieving universal energy access by 2030 and realising a major reduction in air pollution.

Private investors are also increasingly supporting DAC. It is one of four technologies being targeted for up to USD 1.5 billion in investment by Breakthrough Energy Catalyst, established by Bill Gates and a coalition of private investors, and it is an eligible technology for the USD 100 million Carbon Removal XPRIZE. Companies including Microsoft, Stripe and United Airlines are investing in DAC facilities and purchasing DAC-based carbon removal to support their corporate climate targets.

This report explores the growing momentum behind DAC, together with the opportunities and challenges for scaling up the deployment of DAC technologies consistent with net zero goals. It considers the current status of these technologies, their potential for cost reductions, their future energy needs, and the optimal locations for DAC facilities. Finally, the report identifies the key drivers for DAC investment and priorities for policy action.

The role of direct air capture in meeting net zero goals

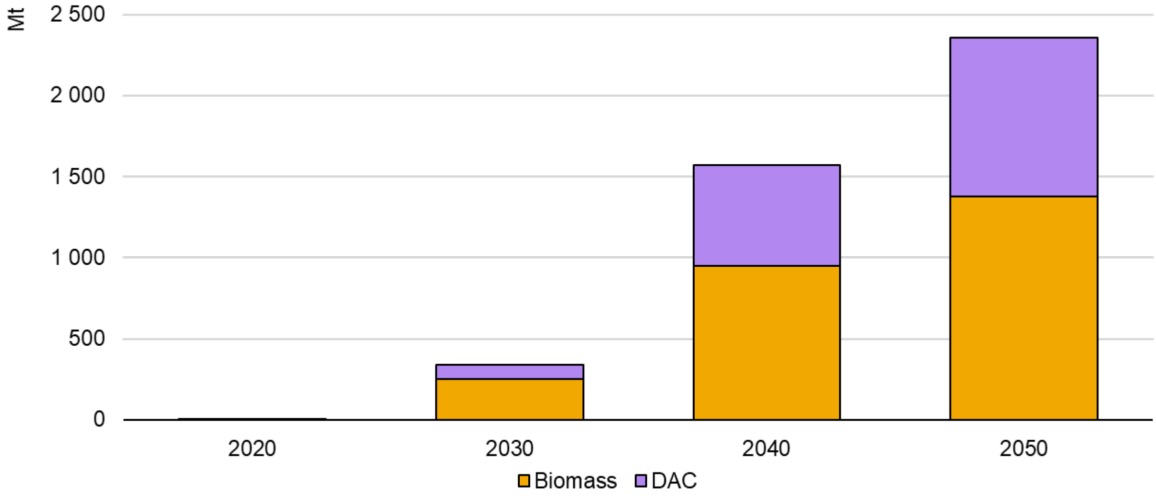
DAC can play an important role in meeting net zero targets, both as a key CDR approach and as a source of climate-neutral CO_2 needed to produce synthetic fuels and other products that require a source of carbon.[2]

Net zero targets inherently recognise that some form of CDR will be required: "net" refers to balancing any CO_2 that is released into the atmosphere from human activity with an equivalent amount being removed. A range of technologies and approaches are available to support CDR, including nature-based solutions (afforestation and reforestation, for example), enhanced natural processes (such as biochar) and technology-based approaches underpinned by carbon capture and storage (CCS) technologies. The advantages and challenges associated with direct air capture and storage (DACS) within this portfolio are discussed in Chapter 5.

The Net Zero Scenario does not rely on nature-based solutions, but instead incorporates technology-based CDR approaches, namely DACS and bioenergy with CCS (BECCS), to steer the global energy system to net zero emissions by 2050. The contribution of DACS and BECCS evolves over the projection period, with a limited but still ambitious role for CDR to 2030 and substantial deployment beyond that.

[2] The CO_2 captured from the atmosphere can be considered a climate-neutral feedstock for CO_2 use applications that result in the CO_2 being re-released to the atmosphere, including synthetic fuels. However this is subject to the life cycle emissions from the capture plant, including the energy used.

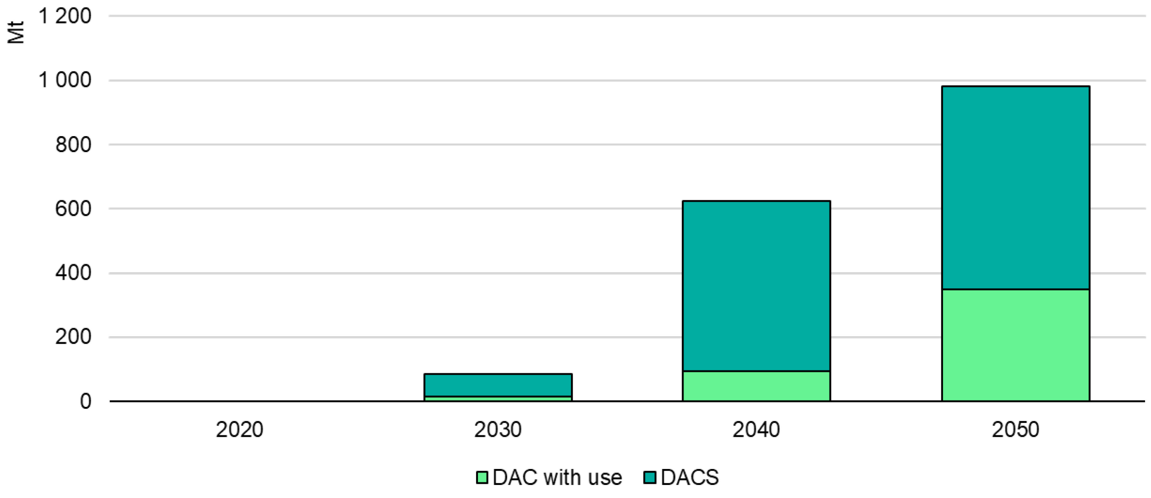
Global CO_2 capture from biomass and DAC in the Net Zero Scenario



In 2030 almost 90 $MtCO_2$/year is captured via DAC (from around 7 700 tCO_2/year today), accelerating significantly to reach 620 $MtCO_2$/year in 2040 and 980 $MtCO_2$/year in 2050. Cumulatively around 12 Gt of CO_2 is captured via DAC between 2020 and 2050, accounting for 11% of the growth in all CO_2 capture over that period. In 2050 about 13% of all CO_2 emissions captured are from DAC, 64% of which are stored, removing CO_2 from the atmosphere to balance (together with BECCS) all remaining emissions from transport, industry and buildings so as to achieve a net zero emissions energy system.

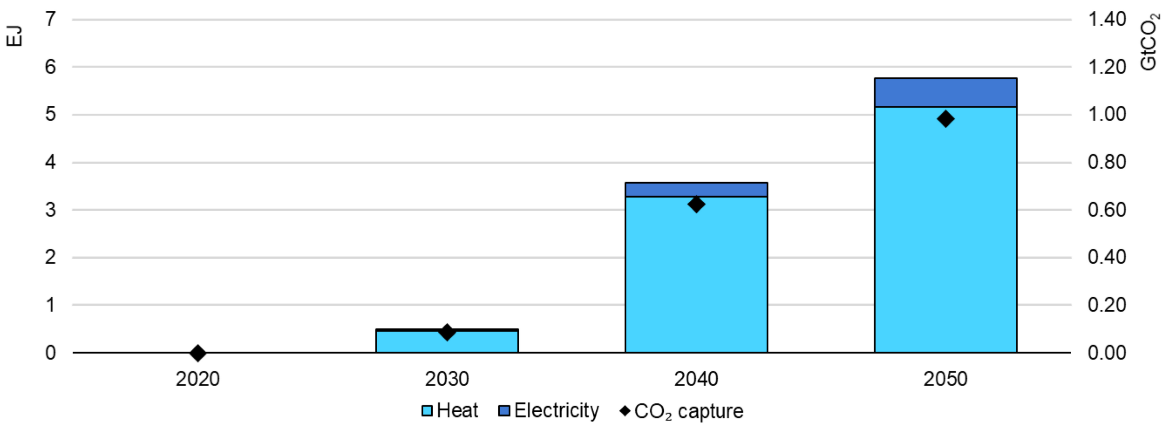
Around 350 Mt or 36% of the CO_2 captured directly from the air in 2050 is used in combination with hydrogen to produce synthetic hydrocarbon fuels, notably for use in aviation, where synthetic fuels meet around a third of aviation fuel demand that year. Using air-captured CO_2 enables these fuels to be climate-neutral over their life cycle, recognising that the CO_2 will be re-released to the atmosphere as the fuel is combusted. In this respect, DAC contributes to one of very few solutions available to reduce emissions in aviation transport, which remains one of the most challenging energy sectors to decarbonise.

Global CO_2 capture from DACS and DAC with use in the Net Zero Scenario



The scale-up of DAC deployment in the Net Zero Scenario implies an average of more than 30 DAC plants of 1 Mt/year being added each year during 2020-2050. This deployment will depend on ensuring cost-competitiveness with other mitigation measures as well as the availability of low-carbon energy and key consumables such as CO_2 solvents. Capturing almost 1 $GtCO_2$ from the air through DAC in 2050 will require around 6 EJ of low-carbon energy, with around 90% of this low-carbon energy need being for heat. The supply chain implications of this expansion are discussed in Chapter 3.

Global energy consumption (left) and CO_2 capture (right) from DAC in the Net Zero Scenario



Note: Global CO_2 capture from DAC based on the deployment of both L-DAC and S-DAC.

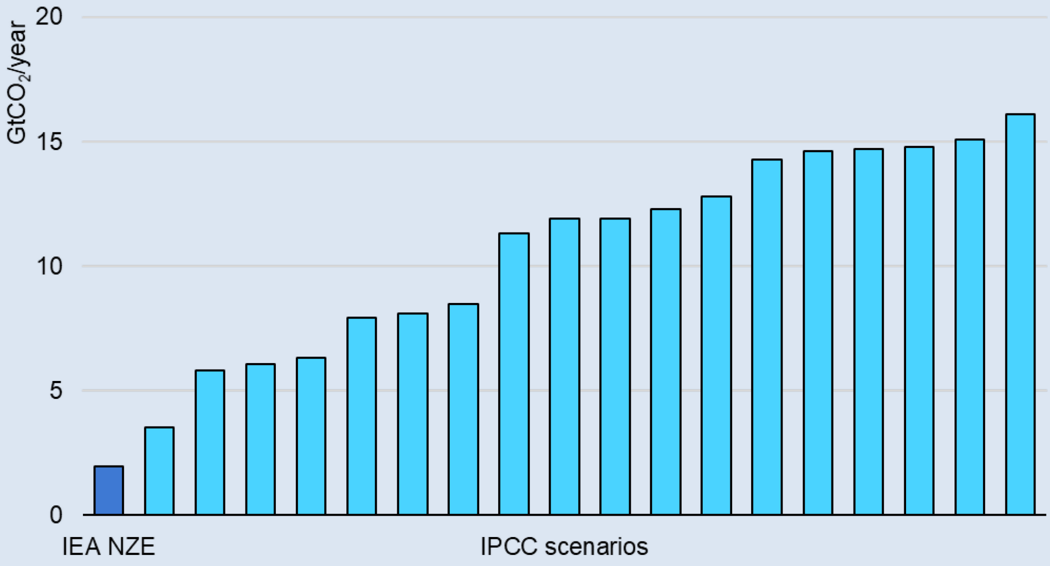
CDR in IPCC and IEA scenarios

Both the IPCC Fifth Assessment Report and the IPCC Special Report on Global Warming of 1.5°C rely on CDR technologies to meet climate targets (respectively 2°C and 1.5°C above the pre-industrial global average temperature). This reliance reflects the many scenarios that constitute the IPCC scenario database and which highlight potential pathways for the decarbonisation of the energy system.

The four representative pathways reported in the IPCC Special Report on Global Warming of 1.5°C all rely on some form of removal, the extent of which depends on the rate and scale of emissions reduction: from P1 (low energy demand pathways), which achieves 1.5°C only by using land use management and afforestation, to P4 (fossil fuel pathway), which relies heavily on CDR exemplified by BECCS. Out of the 90 individual scenarios that have at least a 50% chance of limiting warming to 1.5°C in 2100, only 18 have net zero energy sector and industrial process CO_2 emissions in 2050 (the same level of emissions reduction as the Net Zero Scenario).

The scenarios assessed by the IPCC have a median of around 15 $GtCO_2$ captured using carbon capture, utilisation and storage (CCUS) in 2050, double the level in the Net Zero Scenario. Moreover, CO_2 emissions captured and stored with BECCS and DACS in the IPCC scenarios are in the range of 3.5-16 $GtCO_2$ in 2050, compared with 1.9 $GtCO_2$ in the Net Zero Scenario.

Comparison of energy-related CDR in 2050 under the IPCC scenarios and the Net Zero Scenario

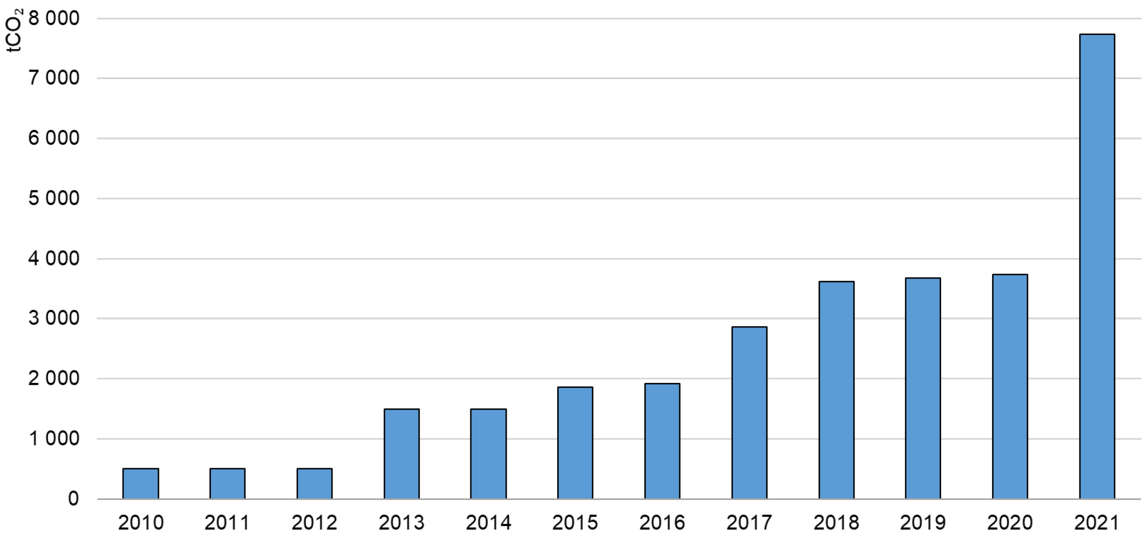


Source: IEA (2021), A closer look at the modelling behind our global Roadmap to Net Zero Emissions by 2050.

Deployment of direct air capture today

Eighteen DAC plants are currently operational globally and are located in Canada, Europe and the United States. Most of these plants are small and sell the captured CO_2 for use, including for Power-to-X[3] (chemicals and fuels), beverage carbonation and in greenhouses. In Iceland, Climeworks (S-DAC) and Carbfix are capturing CO_2 from the atmosphere and blending it with CO_2 captured from geothermal fluids for injection and underground storage in basaltic rock formations. This is the first operating application of this type, turning CO_2 into rocks within a couple of years through mineralisation. The plant was expanded in October 2021 in order to capture 4 000 tCO_2/year, making "Orca" the world's largest DAC plant removing CO_2 from the atmosphere.

DAC global operating capacity, 2010-2021



The first large-scale DAC plant is now being financed and developed in the United States by 1PointFive (a development company owned by Oxy Low Carbon Ventures). The plant, which will use Carbon Engineering's DAC technology (L-DAC), will have the capacity to capture up to 1 $MtCO_2$ per year[4] and could become operational as early as 2024. A plant of this size would be eligible for the 45Q tax credit (currently providing USD 35 per tonne of CO_2 used in enhanced oil recovery and USD 50 per tonne for CO_2 storage). Moreover, it could also be

[3] Power-to-X refers to a suite of technologies that convert electricity into other forms of energy, such as ammonia, hydrogen and even heat.
[4] The project will be developed in steps, with the first train capturing 500 000 tCO_2/year.

eligible for the California Low Carbon Fuel Standard (LCFS) credit, with these credits trading at an average of around USD 200/tCO_2 in 2020.

DAC plants in operation worldwide

Company	Country	Sector	CO_2 storage or use	Start-up year	CO_2 capture capacity (tCO_2/year)
Global Thermostat	United States	R&D	Not known	2010	500
Global Thermostat	United States	R&D	Not known	2013	1 000
Climeworks	Germany	Customer R&D	Use	2015	1
Carbon Engineering	Canada	Power-to-X	Use	2015	Up to 365
Climeworks	Switzerland	Power-to-X	Use	2016	50
Climeworks	Switzerland	Greenhouse fertilisation	Use	2017	900
Climeworks	Iceland	CO_2 removal	Storage	2017	50
Climeworks	Switzerland	Beverage carbonation	Use	2018	600
Climeworks	Switzerland	Power-to-X	Use	2018	3
Climeworks	Italy	Power-to-X	Use	2018	150
Climeworks	Germany	Power-to-X	Use	2019	3
Climeworks	Netherlands	Power-to-X	Use	2019	3
Climeworks	Germany	Power-to-X	Use	2019	3
Climeworks	Germany	Power-to-X	Use	2019	50
Climeworks	Germany	Power-to-X	Use	2020	50
Climeworks	Germany	Power-to-X	Use	2020	3
Climeworks	Germany	Power-to-X	Use	2020	3
Climeworks	Iceland	CO_2 removal	Storage	2021	4 000

Companies leading the development of DAC technologies

Companies that are leading the commercialisation of DAC technologies include:

- Climeworks AG, founded in Switzerland in 2009 as a spin-off of the research university ETH Zurich. The company has to date commissioned 15 plants worldwide and has been supported by both public[5] and private investors (including the largest private investment to date in DAC), while also acquiring

[5] Including the Swiss Confederation, the EU Framework Programme Horizon 2020 and the German Federal Ministry of Education and Research.

the competing company Antecy BV in 2019. Active collaborations include a joint development agreement with Svante Inc. on carbon capture and participation within the Norsk e-Fuel AS consortium (aiming to convert renewable electricity resources and captured CO_2 into renewable synthetic fuels). Further collaborations include one with Carbfix and Northern Lights to explore the potential for a DAC and CO_2 removal project, and another with 44.01 to test their DAC technology in Oman.

- Carbon Engineering Ltd, founded in 2009 in Squamish (British Columbia, Canada) from academic work conducted on carbon management technologies at the University of Calgary and Carnegie Mellon University. The company is currently privately owned and is funded by investment or commitments from private investors and government agencies in both Canada and the United States. Carbon Engineering has so far commissioned one pilot plant, and has recently signed a licensing agreement with 1Point5 to finance and deploy the world's largest DAC facility (which should start capturing CO_2 from the atmosphere by 2024). It has also commenced pre-FEED (front-end engineering and design) with Pale Blue Dot Energy (a Storegga group company) on the development of a DAC facility in Scotland, United Kingdom. Carbon Engineering has just started engineering on an air-to-fuel plant that is due to become operational in Canada in 2026.
- Global Thermostat, founded in the United States in 2010 by two academics from Columbia University. The company has so far commissioned two DAC pilot plants and is collaborating with ExxonMobil to advance and scale up its capture technology. In April 2021 Global Thermostat signed an agreement with HIF to supply DAC equipment to the Haru Oni eFuels pilot plant in Chile, which will utilise captured CO_2 blended with electrolytic hydrogen to produce synthetic gasoline. The plant is designed to capture up to 250 kg of CO_2 per hour, equivalent to around 2 000 tCO_2/year.

Other smaller companies developing DAC technologies include Hydrocell (capturing CO_2 and recovering heat from exhaust air), Infinitree (providing CO_2 enrichment solutions for enclosed agricultural applications), Skytree (focusing on air quality management for electric vehicles), Soletair Power (combining ventilation with CO_2 capture for buildings), CarbonCapture (capturing CO_2 using molecular sieves) and Heirloom (proposing a hybrid DAC approach based on carbon mineralisation). Kawasaki Heavy Industries is also developing a novel DAC technology based on their existing CCUS technology, originally developed for power generation applications. Finally, Carbon Collect Limited is currently commercialising the DAC technology developed at the Center for Negative Carbon Emissions (Arizona State University) called "MechanicalTrees™" and based on moisture swing adsorption.

Chapter 2. Technologies to capture CO_2 from the air

Two technology approaches are currently being used to capture CO_2 from the air: solid and liquid DAC. Solid DAC technology makes use of solid sorbent filters that chemically bind with CO_2. When the filters are heated,[6] they release the concentrated CO_2, which can be captured for storage or use. Liquid systems pass air through chemical solutions (e.g. a hydroxide solution), which removes the CO_2 while returning the rest of the air to the environment. Emerging approaches at prototype level include electro-swing adsorption and membrane-based separation.

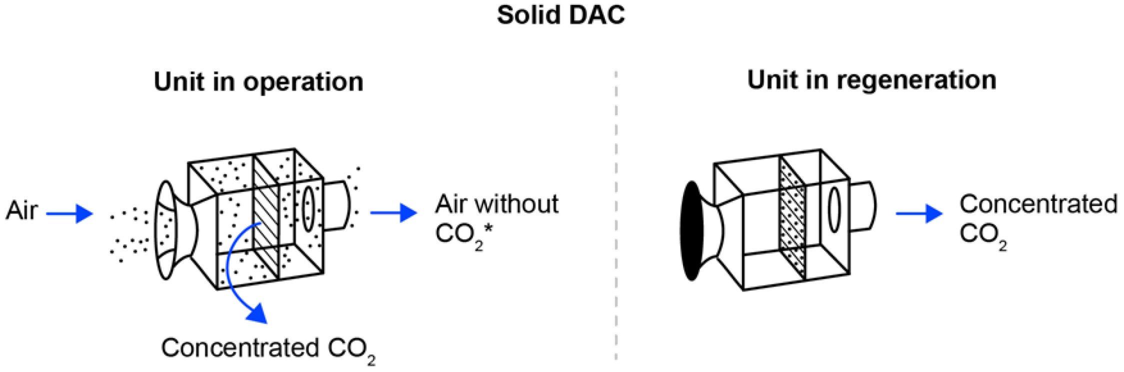
Solid and liquid direct air capture

Solid DAC (S-DAC) is based on solid adsorbents operating through an adsorption/desorption cycling process. While the adsorption takes place at ambient temperature and pressure, the desorption happens through a temperature–vacuum swing process, where CO_2 is released at low pressure[7] and medium temperature (80-100°C). A single adsorption/desorption unit has a capture capacity of several tens of tonnes of CO_2 per year (e.g. 50 tCO_2/year) and can be used to extract water from the atmosphere where local conditions allow (early prototypes were able to remove around 1 tonne of water per tonne of CO_2).[8] An S-DAC plant is designed to be modular and can include as many units as needed. For instance, the largest operating S-DAC plant currently captures 4 000 tonnes of CO_2 a year.

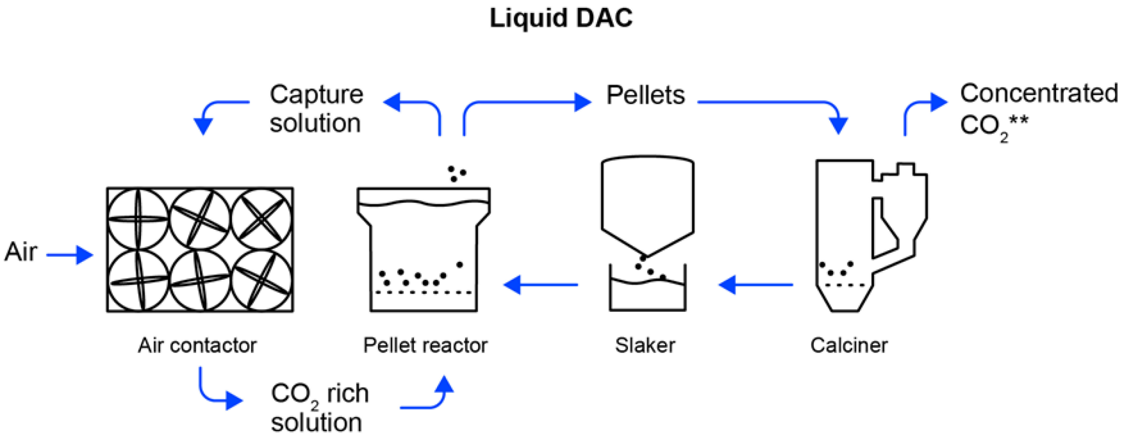
Liquid DAC (L-DAC) is based on two closed chemical loops. The first loop takes place in a unit called the contactor, which brings atmospheric air into contact with an aqueous basic solution (such as potassium hydroxide) capturing CO_2. The second loop releases the captured CO_2 from the solution in a series of units operating at high temperature (between 300°C and 900°C). A large-scale L-DAC plant can capture around 1 $MtCO_2$/year from the atmosphere. Water top-up may be required depending on local weather conditions. For instance, around 4.7 tonnes of water per tonne of captured CO_2 would be required for this plant configuration at ambient conditions of 64% relative humidity and 20°C.

[6] Alternative S-DAC approaches rely on moisture or pressure swing-based processes.
[7] Lower than atmospheric pressure, therefore under vacuum.
[8] CO_2 capture capacity and water removal vary on a case-by-case basis, with the capture capacity highly sensitive to proprietary technology, and water removal dependent on both technology and air humidity.

S-DAC (top) and L-DAC (bottom) configurations



Air is drawn into the collector where the CO_2 is captured by a filter.
Once the filter is saturated, the collector is closed and heated to release the captured CO_2 (regeneration).
** Very low CO_2 concentration.*



The capture solution reacts with the CO_2 in air to form a carbonate salt.
The salt is separated into small pellets that are then heated in a calciner to release the CO_2 in pure gas form.
Processed pellets are hydrated in a slaker and recycled back into the capture solution.
*** May include CO_2 captured from the energy used in the process as well as from the air.*

Sources: IEA analysis based on Carbon Engineering and Climeworks.

S-DAC and L-DAC have distinct features that may offer particular advantages depending on the environment in which they are operating. Both have potential to remove CO_2 from the atmosphere (when the captured CO_2 is permanently stored) or to be a source of climate-neutral CO_2 for use in products. Neither option requires valuable arable land that would be suitable for agriculture, and therefore they do not compete with the food or bioenergy industry for the use of land. They operate at different temperatures and are suitable for large-scale operations (L-DAC), or small-scale but modular and therefore scalable operations (S-DAC). Their capital and operating costs are determined by the size of the plant (with total costs increasing with overall size) and its energy needs, together with its operational requirements. While L-DAC can theoretically operate continuously at steady state without interruption (excluding regular maintenance), S-DAC relies on batch operation, which necessitates having multiple units in parallel, with some in operation actively capturing CO_2 and others in regeneration, releasing the captured CO_2 from the filters.[9] DAC operation is also affected by its water requirement: while S-DAC can produce water by extracting it from the air, L-DAC needs water for its continuous operation.

Key features of S-DAC and L-DAC technology approaches

	S-DAC	L-DAC
CO_2 separation	Solid adsorbent	Liquid sorbent
Specific energy consumption (GJ/tCO_2)	7.2-9.5	5.5-8.8
Share as heat consumption (%)	75-80%	80-100%
Share as electricity consumption (%)	20-25%	0-20%
Regeneration temperature	80-100°C	Around 900°C
Regeneration pressure	Vacuum	Ambient
Capture capacity	Modular (e.g. 50 tCO_2/year per unit)	Large-scale (e.g. 0.5-1 $MtCO_2$/year)
Net water requirement (tH_2O/tCO_2)	-2 to none	0-50
Land requirement ($km^2/MtCO_2$)	1.2-1.7	0.4
Life cycle emissions (tCO_2emitted/tCO_2captured)	0.03-0.91	0.1-0.4
Levelised cost of capture (USD/tCO_2)	Up to 540	Up to 340

[9] Continuous operation also depends on the energy source, with energy storage becoming a requirement to guarantee reliable supply if powered by variable renewable energy.

	S-DAC	L-DAC
Main advantages	• Possible net water production • Less capital-intensive • Modular • Operation can rely on low-carbon energy only • Novel and therefore more likely to see cost reduction	• Less energy-intensive • Large-scale capture • Operation relies on commercial solvents • Technology adapted from existing commercial units
Main trade-offs	• More energy-intensive • Manual maintenance required for adsorbent replacement	• More capital-intensive • Relies on natural gas combustion for solvent regeneration (with potential for full electrification in the future)

Notes: Land requirement excludes land use associated with electricity and heat generation. Life cycle emissions do not take into account upstream emissions. Please note that the carbon intensity of the electricity supplied via the grid varies substantially by jurisdiction. Net water requirements affected by regional factors such as air temperature and humidity, with S-DAC technology potentially better suited to dry climates and L-DAC technology to humid climates.

Sources: Madhu (2021), Understanding environmental trade-offs and resource demand of direct air capture technologies through comparative life-cycle assessment; Climeworks (2021), Direct air capture and storage and carbon dioxide removal; Keith et al. (2018), A Process for Capturing CO_2 from the Atmosphere; McQueen et al. (2021), A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future; Fasihi et al. (2019), Techno-economic assessment of CO_2 direct air capture plants; Beuttler et al. (2019), The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions; WRI (2021), Direct Air Capture: Resource Considerations and Costs for Carbon Removal; IEAGHG (2021), IEA Greenhouse Gas R&D Programme.

Emerging direct air capture technologies

Emerging DAC technologies (at a technology readiness level [TRL] below 6) include electro-swing adsorption (ESA) and membrane-based DAC (m-DAC).

ESA is based on an electrochemical cell where a solid electrode adsorbs CO_2 when negatively charged and releases it when a positive charge is applied (swinging therefore the electric charge, rather than the operating temperature or pressure as happens in other physical separation techniques). This approach has the potential to separate CO_2 from both highly concentrated sources and from the air, require limited space as the cells are theoretically stackable, and operate without additional equipment for conditioning or pumping, unlike L-DAC.

The ESA separation process developed first at the Massachusetts Institute of Technology and now at Verdox has been tested at lab scale (TRL 4) for CO_2 concentrations from 10% (e.g. power plant exhaust) down to 0.6% (e.g. ambient indoor air) with an efficiency of around 90%. In order to reach commercial application, further understanding of performance, costs, materials, operation and maintenance is needed. Moreover, this ESA technology is not yet suitable for CO_2

removal from atmospheric air as it is not technically able to separate CO_2 at such a low concentration. At the same time, the company is not excluding this application, which would require improved capacity and kinetics due to the lower initial concentration of CO_2 in atmospheric air.

Other companies focusing on electrochemical separation methods for DAC include Mission Zero Technologies (a spin-out of Deep Science Venture) and Holy Grail (which recently raised USD 2.7 million in seed funding to develop its technology).

m-DAC has been proposed as another feasible option for capturing CO_2 from the air; however, it is still in its infancy and major challenges are yet to be overcome. Generally speaking, membrane-based approaches are technically challenged by the low concentration of CO_2 in the air, and show low CO_2 selectivity at ambient pressure, requiring the expensive compression of a very large amount of ambient air to separate CO_2 efficiently. In the literature it has also been argued that better gas permeance (i.e. the ratio between the gas permeability of the membrane and its thickness) could play a larger role than CO_2 selectivity in membrane cost reduction. If true, polymeric materials with high CO_2 permeance could represent a suitable option for DAC. In more traditional CCUS applications, membrane-based separation technologies are currently at TRL 4 for the cement industry and at TRL 6 for natural gas processing.[10]

Fundamental research into alternative DAC approaches is currently taking place at a number of institutes. For instance, the Oak Ridge National Laboratory is separating CO_2 from the air at lab scale and regenerating the solvent at relatively mild temperatures (15-120°C) (Brethomé et al., 2018) (Custelcean et al., 2021), while the Center for Negative Carbon Emissions at Arizona State University is prototyping “mechanical trees” that rely on wind instead of fans for air recirculation.

The TRL scale

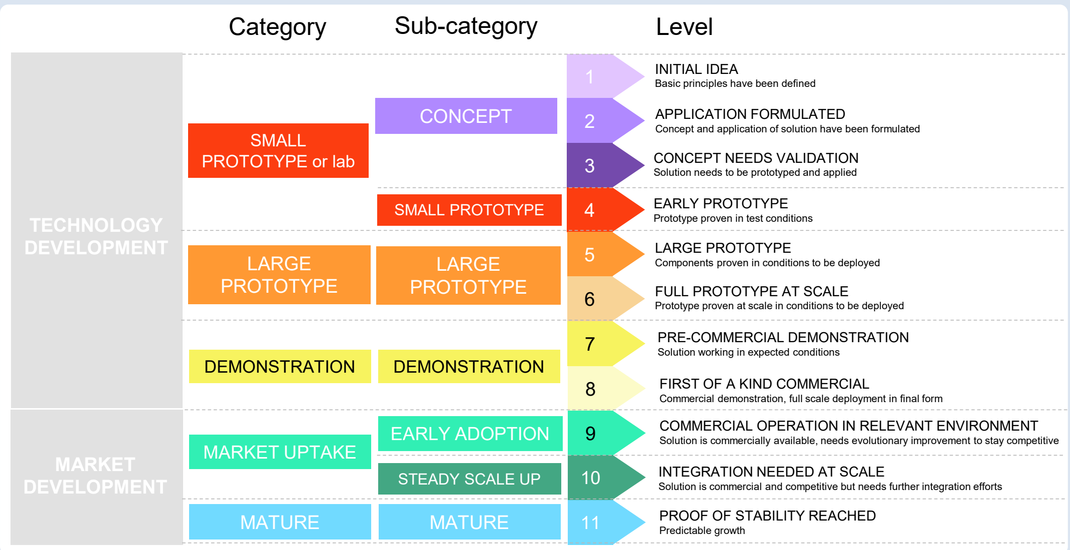
One way to assess where a technology is on its journey from initial idea to market is to use the TRL scale. Originally developed by the National Aeronautics and Space Administration (NASA) in the United States in the 1970s, the TRL provides a snapshot in time of the level of maturity of a given technology within a defined scale. The scale provides a common framework that can be applied consistently to any technology, to assess and compare the maturity of technologies across sectors.

[10] TRL 9 for commercial separation of CO_2 for natural gas processing.

The technology journey begins from the point at which its basic principles are defined (TRL 1). As the concept and area of application develop, the technology moves into TRL 2, reaching TRL 3 when an experiment has been carried out that proves the concept. The technology now enters the phase where the concept itself needs to be validated, starting from a prototype developed in a laboratory environment (TRL 4), followed by testing of components in the conditions it will be deployed (TRL 5), through to testing the full prototype in the conditions in which it will be deployed (TRL 6). The technology then moves to the demonstration phase, where it is tested in real-world environments (TRL 7), eventually reaching a first-of-a-kind commercial demonstration (TRL 8) on its way towards full commercial operation in the relevant environment (TRL 9).

Arriving at a stage where a technology can be considered commercially available (TRL 9) is not sufficient to describe its readiness to meet energy policy objectives, for which scale is often crucial. Beyond the TRL 9 stage, technologies need to be further developed to be integrated within existing systems or otherwise evolve to be able to reach scale; other supporting technologies may need to be developed, or supply chains set up, which in turn might require further development of the technology itself. For this reason, the IEA has extended the TRL scale it uses in its reports to incorporate two additional readiness levels, which focus on market (rather than technology) development: one where the technology is commercial and competitive, but needs further innovation for its integration into energy systems and value chains when deployed at scale (TRL 10), and a final one where the technology has achieved predictable growth (TRL 11).

Maturity categories and TRLs along innovation cycles

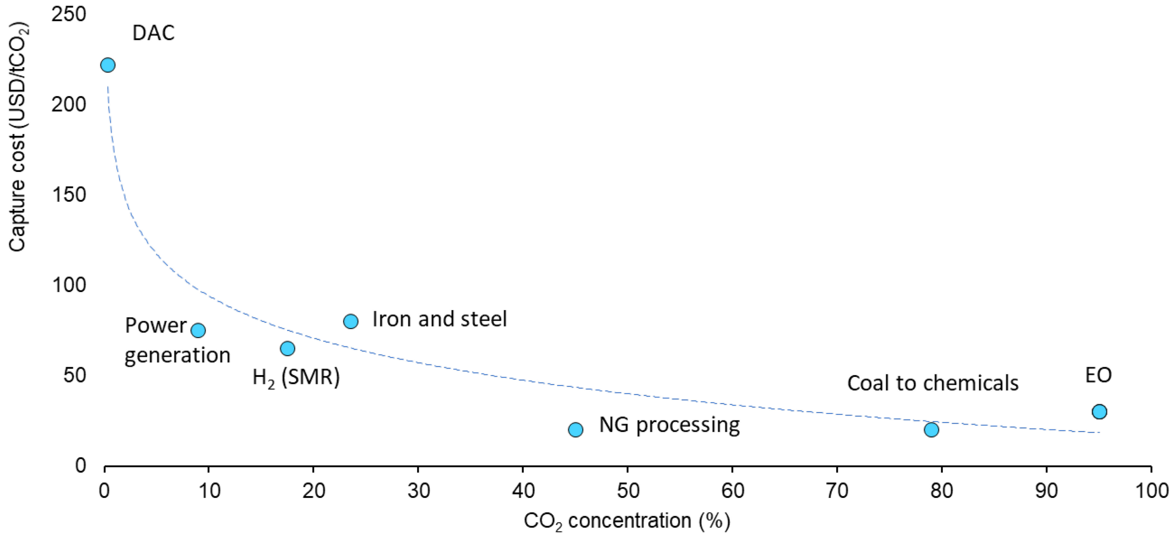


Cost of capturing CO_2 directly from the air

Current capture costs via DAC are high and uncertain

Capturing CO_2 from the air is more expensive than capturing it from a point source. This is because the CO_2 in the atmosphere is much more dilute than, for example, in the flue gas of a power station or a cement plant.[11] This contributes to the higher energy need and cost of DAC relative to other CO_2 capture technologies and applications.

CO_2 capture cost at varying CO_2 concentrations, 2020



Notes: Average values by application. H_2 = hydrogen; SMR = steam methane reforming; NG = natural gas; EO = ethylene oxide. The empirical trend line shows the correlation between capture cost and CO_2 concentration.

As DAC technology has yet to be demonstrated on a large scale (1 $MtCO_2$/year and over), its costs are extremely uncertain. Capture cost estimates reported in the literature are wide, typically ranging anywhere from USD 100/t to USD 1 000/t, while cost estimates from the main technology providers vary across USD 95-230/tCO_2 for L-DAC and USD 100-600/tCO_2 for S-DAC (Keith et al., 2018; European Commission Joint Research Centre, 2019; Clean Energy Solutions Center, 2020; The Catalyst Group, 2019). A recent assessment by IEAGHG estimates DAC costs for removal to be in the range of

[11] CO_2 concentration: in air = 410 ppm = 0.041 mol%; in flue gas from natural gas based power generation = 4-8 mol%; in flue gas from cement production = 14-33 mol%.

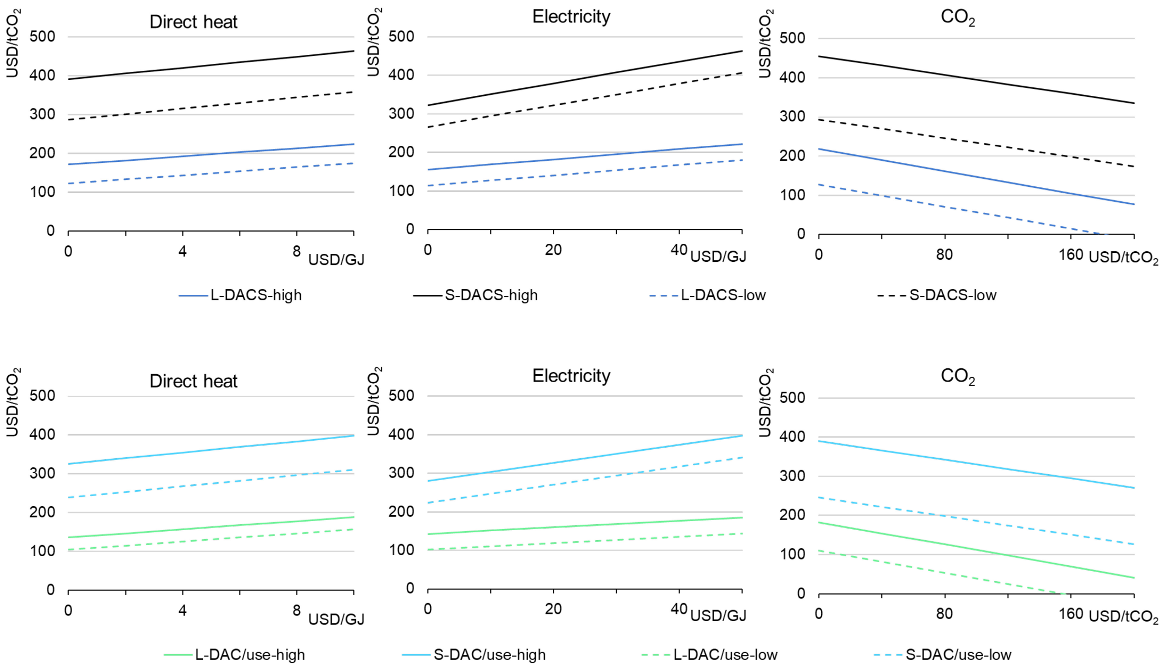
USD 200-700/tCO_2.[12] For context, carbon removal via BECCS costs USD 15-80/tCO_2, while afforestation/reforestation can cost as little as USD 10/tCO_2.

Costs and energy needs vary according to the type of technology (solid or liquid), the source of energy (fuel, electricity, or both) and whether the captured CO_2 is going to be geologically stored or used immediately at low pressure. For CO_2 storage, the CO_2 needs to be compressed at a very high pressure to be injected into geological formations. This step increases both the capital cost of the plant (due to the requirement for additional equipment such as a compressor) and the operating costs (to run the compressor).[13] Other relevant factors affecting capture costs include the scale of deployment, the plant load factor when DAC is powered by variable renewable energy sources, and the carbon intensity of the energy source. The carbon intensity of the energy source is the main determinant of the difference between the cost of capture and the cost of removal, with the latter estimated as the cost per tonne of CO_2 removed from the atmosphere.[14]

According to our own estimates, the cost of capture via DAC for large-scale applications (1 MtCO_2/year) has a range of USD 125-335/tCO_2,[15] depending on capture technology (solid- or liquid-based technologies), energy costs (price of heat and electricity), financial assumptions, specific plant configuration, and whether the captured CO_2 is stored or used. Low heat and electricity prices can lower projected costs of capture via DAC to just above the industry target of USD 100/tCO_2. If captured emissions were to be monetised using some form of carbon pricing scheme, the levelised cost of capture for DAC could fall well below USD 100/tCO_2. Moreover, a carbon price above around USD 160/tCO_2 could make DAC-based capture profitable.

[12] The IEAGHG study reports the net levelised cost of DACS, taking into account carbon removal as well as life cycle emissions, and includes CO_2 transport and storage costs (not just capture).
[13] Alongside geological sequestration through injection, CO_2 mineralisation is emerging as an alternative for long-term underground CO_2 storage, with the potential to lower the energy demand for CO_2 compression by up to 30% compared to traditional injection.
[14] Quantified as CO_2 captured directly from the atmosphere minus CO_2 re-emitted on an LCA basis (please refer to the section "Carbon footprint and cost of carbon removal" for further details).
[15] Reference year = 2020; reference location = United States of America. Direct heat assumed to be generated by means of natural gas combustion. Electricity price = USD 21/GJ (USD 75.6/MWh); natural gas price = USD 2/GJ (USD 2.1/MBtu). No price on CO_2 is imposed. CO_2 compression cost included; transport and storage costs not included. CAPEX comprises process equipment, but excludes engineering, procurement and construction costs. For all equipment, discount rate = 8%; lifetime = 25 years; capacity factor = 90%.

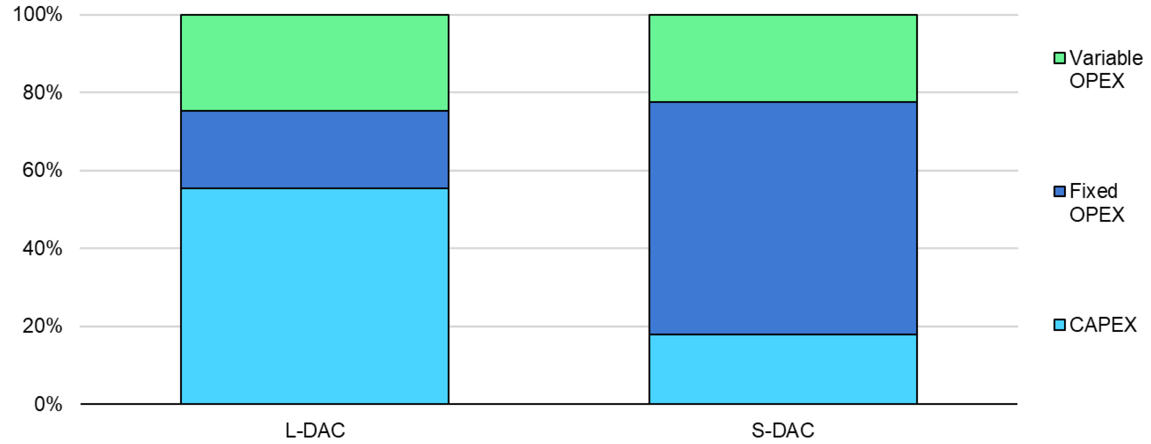
Levelised cost of capture at varying heat, electricity and CO_2 prices, DACS (upper) and DAC with CO_2 use (lower), 2020



Notes: Direct heat price based on natural gas combustion. For left and right graphs: electricity cost = USD 47/GJ (USD 169/MWh) for high and USD 10/GJ (USD 36/MWh) for low. For middle and right graphs: natural gas cost = USD 9/GJ (USD 9.5/MBtu) for high and USD 1/GJ (USD 1.1/MBtu) for low. For left and middle graphs, no price on CO_2 is imposed. CO_2 compression cost for storage included for DACS only (upper graphs), transport and storage costs not included. CAPEX comprises process equipment, but excludes engineering, procurement and construction costs. For all equipment, discount rate = 8%; lifetime = 25 years; capacity factor = 90%. Reference capture capacity scale = 1 $MtCO_2$/year.

Regular maintenance, which is needed to maintain a satisfactory level of performance of the DAC plant, includes sorbent replacement, which is currently performed manually. This operation is particularly burdensome for S-DAC due to the layout of the system. DAC sorbent replacement rates (0.25-38 kg/tCO_2) affect operating costs, which could increase even further if more frequent replacement is needed due to site-specific conditions such as air humidity or pollution.

Contribution to levelised cost of DAC by type of expenditure, 2020

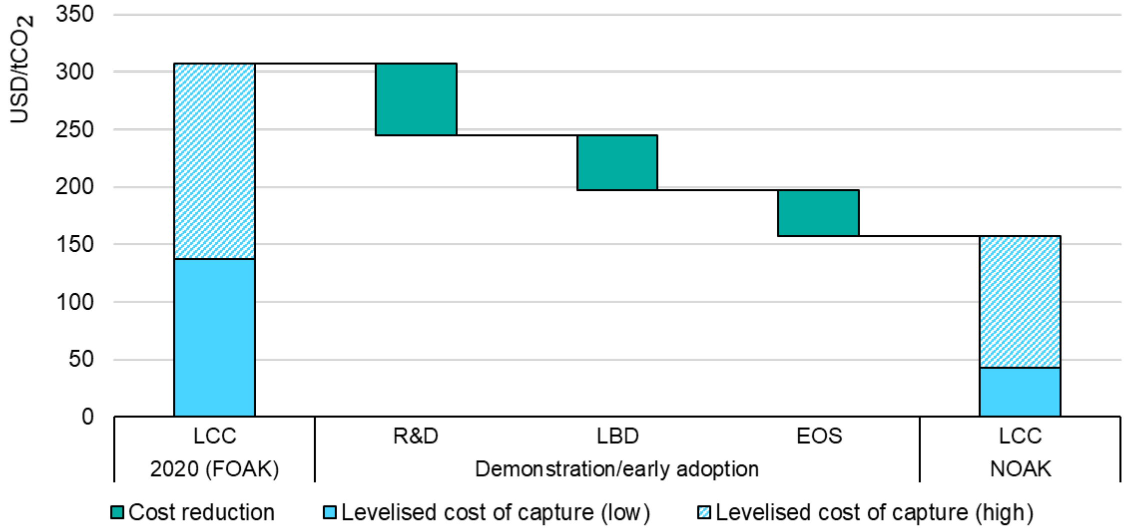


The potential for reductions in the cost of direct air capture is considerable

DAC is an emerging technology currently at the demonstration stage (TRL 6) and, as such, has considerable potential for performance improvement and cost reduction. Research has estimated that massive DAC deployment as a policy response to the climate crisis could substantially decrease its levelised cost of capture. The industry target appears to be USD 100/tCO_2, as it would make DAC competitive with mitigation options for certain industrial and transport sectors. The US Department of Energy has chosen this target for the Carbon Negative Shot, launched in November 2021 and aiming to bring the cost of DAC below USD 100/tCO_2 in a decade. Capture costs below USD 200-250/tCO_2 could already be commercially attractive in the United States where facilities are able to access the California LCFS credits (around USD 200/tCO_2) together with tax credits such as the 45Q (USD 50/tCO_2).

According to the main technology providers, capture costs are expected to decrease substantially in the next five to ten years, underpinned by a major increase in DAC deployment worldwide, from the thousand-tonne scale to the million-tonne scale. The anticipated fall in cost from the first large prototype (first of a kind [FOAK]) to the nth of a kind (NOAK) plant has been attributed to specific components as well as improved constructability and well-established supply chains. For L-DAC the expected cost reduction from FOAK to NOAK is 27%, of which 42% comes from a single key equipment: the air contactor. While this unit is based on commercial cooling-tower technology, its expected cost reduction comes from a number of modifications to the standard commercial design, including packing geometry (allowing for cross flow exchange between solvent and air) and depth (reducing pressure drop and increasing packing wetting and therefore performance). For S-DAC, technology providers are expecting a threefold to sixfold cost reduction in the short to medium term.

Contribution to decline in cost of DAC by high-level driver



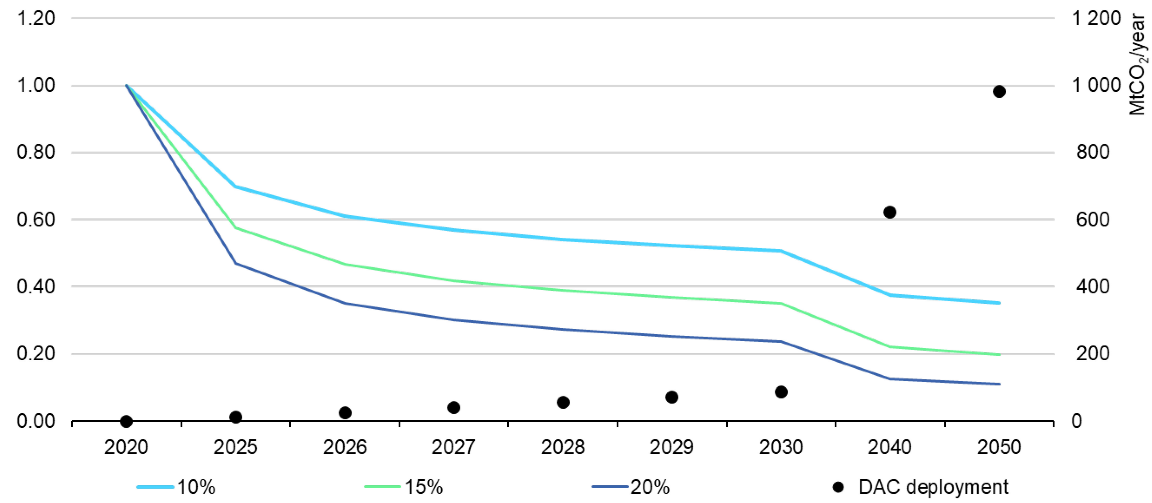
Note: LCC = average levelised cost of capture; FOAK = first of a kind; NOAK = nth of a kind; R&D = research and development, representing learning by researching; LBD = learning by doing; EOS = economies of scale. The "low" levelised cost of capture represents the average cost for L-DAC while the "high" levelised cost of capture represents the average cost for S-DAC. Reference capture capacity scale = 1 $MtCO_2$/year. Please note that cost reductions based on learning by researching, learning by doing and economies of scale are not fully independent and therefore cumulative; however, they have been represented here as such for simplicity.

Performance improvement is expected to come mainly from innovative solvents able to reduce DAC-specific energy consumption ("learning by researching") and from technology spillovers from other sectors and applications. Further cost reduction can be driven by deployment ("learning by doing") and economies of scale:

- Learning by researching: much DAC research focuses on reducing the energy consumption needed to separate CO_2 at low concentrations from atmospheric air. Compared to established technologies such as S-DAC and L-DAC, emerging separation technologies could require up to 90% less energy per tonne of CO_2. This huge potential comes from innovative approaches to regenerating the solvent at low to medium temperatures, or by different CO_2 separation techniques (e.g. membrane-based separation).
- Learning by doing: technology deployment drives costs down as experience in designing, producing, commissioning and operating DAC plants accumulates along a learning curve. Within the energy system, learning rates (quantifying the steepness of the learning curve: the higher the learning rate, the steeper the learning curve, the faster the cost decrease) have ranged between 10-15% on average, with exceptionally rapid drops for specific, very successful technologies such as solar PV (around 20%). For DAC technologies, L-DAC has been

compared in the literature to more traditional amine-based, point-capture technologies (which are currently already commercial) and are therefore expected to have a 10% learning rate, while S-DAC is expected to have higher learning rate (around 15%) due to its modular nature.

Potential for reduction in CAPEX of DAC due to learning by doing



Notes: Initial average CAPEX per tonne of CO_2 capture capacity indexed to 1; reference capture capacity scale = 1 $MtCO_2$/year; minimum deployment for learning = 1 $MtCO_2$/year; learning rate = 10-20%; rate of deployment based on Net Zero Scenario.

- Economies of scale: these represent cost advantages related to either mass production of a certain piece of equipment or the production of the same equipment at a larger scale compared to its initial design. Mass production allows for shared infrastructure and facilities and relies on an optimised supply chain. Economies of scale benefit small, modular units that can be mass produced (such as S-DAC modules), and also large equipment (such as those required for L-DAC) whose cost becomes cheaper per unit of output than the same equipment on a smaller scale. Modular systems undergoing mass production, such as household appliances, have historically seen a steep decrease in price. As an example, the price of air-conditioning units decreased by 21% between the early 1990s and early 2010s, while their energy efficiency performance increased. They have multiple similarities with solid-DAC due to the presence of a rotating element (i.e. a fan), cooling and drying loops, and closed and open circuits. For large-scale units, the "rule of 6/10" gives satisfactory results (i.e. within a 20% margin of error). It estimates a cost reduction proportional to six tenths of the ratio between the size of a large-scale unit and a small-scale unit. For L-DAC, this would mean a cost reduction of more than 50% per tonne of CO_2 captured when scaling up from (for example) 1 Mt of capture capacity to 5 Mt.
- Technology spillover: this takes place when a technology developed for a specific sector or application is unintentionally beneficial to another application. Examples

of technology spillovers have been seen between batteries, fuel cells and electrolysers, between lightweight wind turbines, road vehicles and aircraft, between air conditioners and heat pumps, and between CCUS applications. DAC development has already benefited from spillovers from more traditional amine-based CCUS (for liquid-based CO_2 separation), from low pressure drop configurations developed by the automotive industry for catalytic converters (for solid adsorbents), and from electrochemistry (which led to the development of ESA-DAC). While technology spillovers are typically unexpected and therefore difficult to predict, performance optimisation of CO_2 separation solvents in any industrial application (e.g. chemical industry, natural gas refining, aerospace technology) would greatly benefit DAC. Unfortunately, there is no consensus on how to quantify technology spillovers, due to the complexity of the interactions among different sectors.

Chapter 3. Key considerations for direct air capture deployment

Scaling up direct air capture value chains

Reaching the level of DAC deployment envisaged by 2050 in the Net Zero Scenario will be a significant but not insurmountable challenge, requiring on average eight large-scale (1 $MtCO_2$/year) DAC plants to be built each year during the current decade, 50 plants to be built each year during 2030-2040 and almost 40 plants a year to be built between 2040 and 2050.[16]

Building up a market from such a small base will require the expansion of global supply chains for a number of commodities. To deliver 1 Gt of CO_2 removal via DAC would require 17-36 Mt of steel, concrete, copper and aluminium (in total) to build the plants, as well as 3-7 Mt of chemical commodities for liquid solvents and solid adsorbents. The specific demand for steel and cement (demand per tonne of CO_2) for DAC plants could decrease over time as a result of process design intensification. This is particularly true for S-DAC, where the process layout is brand new and not based on existing technology.[17] DAC R&D efforts are focusing on CO_2 solvents and sorbents, with the aim of finding less energy-intensive alternatives. Based on existing commercial DAC technology, substantial deployment of L-DAC could put pressure on the market for hydroxide solutions, currently side products of chlorine,[18] while amine sorbents for S-DAC are likely to be produced from ammonia[19] and ethylene oxide.

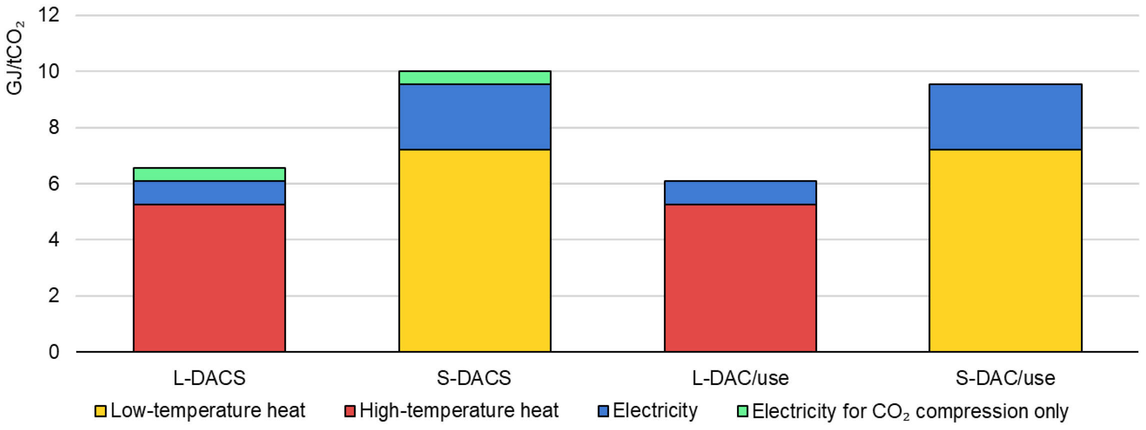
Capturing almost 1 $GtCO_2$/year from the atmosphere by 2050, in line with the Net Zero Scenario, could require up to 50 Gt of water per year (around a third of Lake Tahoe, United States) and around 6 EJ of energy per year. This is equivalent to all the energy exported by the Netherlands in 2019. If the energy was supplied exclusively by, for example, solar PV, the integrated plant (including DAC plant and solar PV field) would require up to 23 000 km^2 of land (with most of the land needed for the panels). This is equivalent to the size of Sardinia.

[16] 32 plants a year on average during 2020-2050.
[17] Climeworks recently developed sliding doors to isolate DAC units actively capturing from units in regeneration, substantially decreasing the amount of steel needed to build a plant. Source: https://climeworks.com/orca.
[18] Average energy intensity of hydroxide solutions production = 7-13.3 GJ/t.
[19] Average energy intensity of ammonia production = 41 GJ/t.

Direct air capture energy needs

The energy needs of DAC plants are strongly influenced by the operating temperature of the technologies. While both L-DAC and S-DAC were initially designed to operate using heat and electricity (with flexible configurations allowing for heat-only operation),[20] the option to operate them using only renewable electricity would be very attractive from an environmental perspective. However, for L-DAC this would require further innovation in the provision of high-temperature heat from electricity.

Energy needs of DACS and DAC with CO_2 use by technology and CO_2 destination



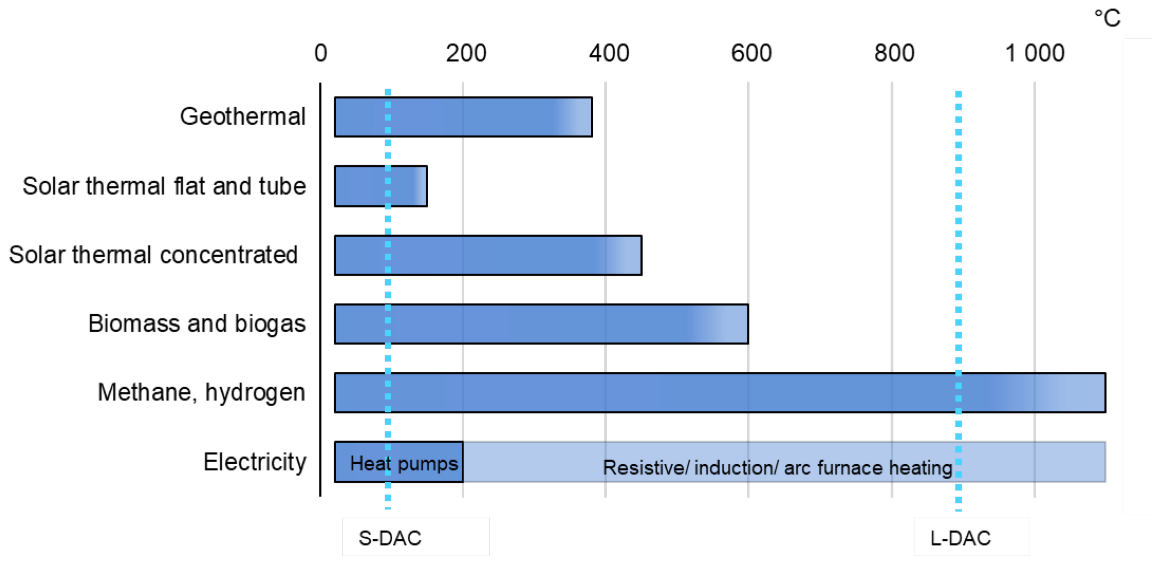
Based on the current commercial technology, electricity is able to provide operating temperatures above around 500°C only for very specific large-scale applications within the iron and steel sector (e.g. smelting reduction, electric arc furnaces) and the aluminium sector (e.g. Hall–Héroult process). Electricity-based calcination is emerging, but currently still at TRL 3, and may therefore take a while to become commercially available for large-scale operation. Further, while numerous renewable technologies can provide low-temperature heat (below 150°C), fewer options are suitable for medium- and high-temperature processes.

Therefore, while S-DAC could be powered by a variety of renewable energy sources (e.g. heat pumps, geothermal, solar thermal, biomass-based fuels), the current high-temperature needs of today's L-DAC configuration does not allow that level of flexibility and could at best operate using low-carbon fuels such as biomethane or renewables-based electrolytic hydrogen. Large-scale L-DAC plants

[20] Reliance on fuel is more economical, but some electricity is required to operate rotating equipment.

have been designed to use natural gas for heat and to co-capture the CO_2 produced during combustion of the gas without the need for additional capture equipment. This integration substantially reduces the L-DAC plant's overall emissions and can still enable carbon removal.[21] However, any future ability of renewable energy to supply high-temperature heat could reduce the process emissions to near zero, maximising the potential for carbon removal and associated revenue streams. Accelerating the commercial availability of large-scale electric calcination technology is considered a high priority to enable L-DAC plants to operate purely on renewable energy.

Operating temperature for various heat-generating technologies



Notes: The vertical dashed lines indicate the maximum operating temperatures for S-DAC and L-DAC respectively.
Sources: IEA (2019), Renewables 2019.

Carbon footprint and cost of carbon removal

Reducing the environmental impact of DAC during its construction, commissioning, operation and decommissioning is of paramount importance to optimise the value of this technology as a climate mitigation solution. This is why it makes little sense to power DAC using anything other than low-carbon energy sources. While not all DAC plants will be focused on carbon removal (some may supply CO_2 for use), the potential for a DAC plant to effectively remove CO_2 is not guaranteed and will depend on 1) whether the CO_2 is permanently stored, and

[21] Any upstream methane emissions would also need to be minimised, in addition to the CO_2 capture from the gas combustion, to support negative life cycle emissions.

2) whether the emissions from DAC construction, commissioning, operation and decommissioning are lower than the CO_2 emissions captured and removed from the atmosphere over the lifespan of the plant.

Life cycle assessment (LCA) is needed to quantify the amount of carbon removed (if any) by DAC technologies.[22] LCA is a cradle-to-grave or cradle-to-cradle analysis technique to assess environmental impacts associated with “all the stages of a product’s life, which is from raw material extraction through materials processing, manufacture, distribution, and use”.[23] The result depends on a number of factors, which include, for instance, the choice of the reference system and its boundaries, the quantification of changes in land management and use, and the timing of emissions and removals.

Most LCA studies currently available on CDR technologies focus on BECCS or carbon utilisation for biochar production. Only a limited number of LCAs are available for DAC, with most studies concluding that DACS is carbon negative, while DAC for CO_2 use can be carbon reducing when powered by low-carbon energy sources. For DACS configurations relying on natural gas and electricity from the grid, the carbon removal efficiency[24] has been estimated to be higher than 60%, potentially up to around 90% for configurations co-capturing CO_2 emissions from natural gas combustion and under optimistic assumptions (e.g. long lifetime, low specific energy consumption). For DACS configurations relying on low-carbon heat sources (such as waste heat and heat pumps), life cycle emissions strongly depend on the carbon intensity of the regional electricity grid. If low-carbon or off-grid (i.e. renewable) electricity is available, the carbon removal efficiency can be as high as 97%.

DACS carbon removal efficiencies by energy source

Source of heat	Source of electricity	Carbon removal efficiency
Direct heat (natural gas)	Grid	60-90%
Heat pump (power-to-heat)	Solar PV	79-89%
Heat pump (power-to-heat)	Wind	95%
Heat pump (power-to-heat)	Grid	9-95%

[22] LCAs on CDR technologies can not only quantify their carbon footprint, but can also assess other aspects such as freshwater ecotoxicity and eutrophication, human toxicity, metal depletion, particulate matter emissions, photochemical ozone formation, terrestrial acidification and land occupation (Gibon [2017], Life cycle assessment demonstrates environmental co-benefits and trade-offs of low-carbon electricity supply options).

[23] https://www.sciencedirect.com/topics/earth-and-planetary-sciences/life-cycle-assessment.

[24] The carbon removal efficiency is defined here as the share (%) of net permanent CO_2 removal (where “net” is the gross minus indirect LCA-related emissions) of the initial gross CO_2 removal (100%) by the DAC unit, in accordance with Terlouw et al. (2021).

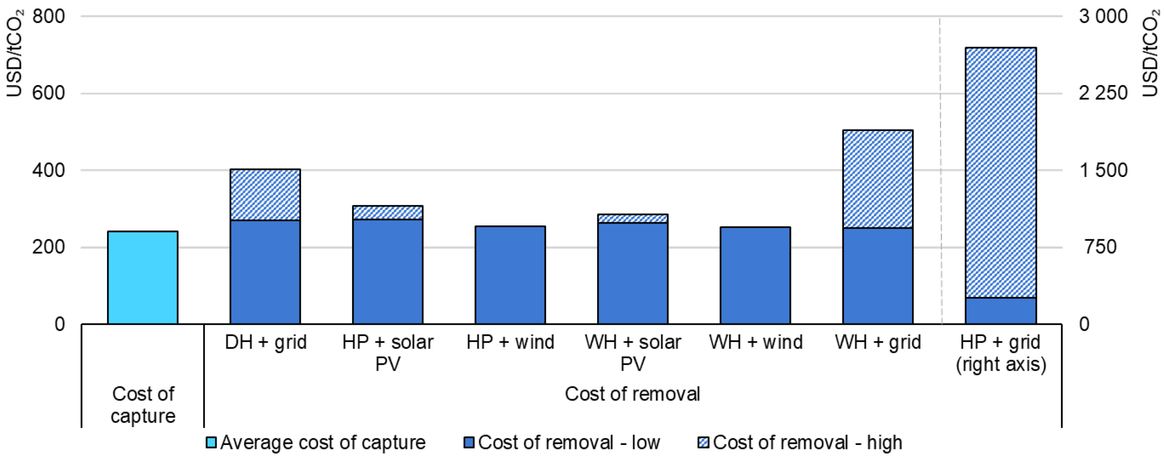
Source of heat	Source of electricity	Carbon removal efficiency
Waste heat	Solar PV	85-92%
Waste heat	Wind	96%
Waste heat	Grid	48-97%

Notes: Direct heat assumed to be generated by means of natural gas combustion. Carbon removal efficiency defined as net permanent greenhouse gas (GHG) removal as a share (%) of initial gross GHG removal by the DAC unit. Net removal comprises gross GHG emissions minus indirect (LCA-related) emissions. Note that the carbon intensity of the electricity supplied via the grid varies substantially by jurisdiction.

Sources: Liu (2020), A life cycle assessment of greenhouse gas emissions from direct air capture and Fischer–Tropsch fuel production; NETL (2021), Life Cycle Greenhouse Gas Analysis of Direct Air Capture Systems; Terlouw et al. (2021), Life Cycle Assessment of Direct Air Carbon Capture and Storage with Low-Carbon Energy Sources; Deutz and Bardow (2021), Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption; de Jonge (2019), Life cycle carbon efficiency of Direct Air Capture systems with strong hydroxide sorbents; Keith et al. (2018), A Process for Capturing CO_2 from the Atmosphere; Madhu et al. (2021), Understanding environmental trade-offs and resource demand of direct air capture technologies through comparative life-cycle assessment.

Carbon removal costs decrease with increasing carbon removal efficiencies. When the electricity is provided from the grid, its carbon intensity has the largest effect on the final carbon removal cost, especially when it is used to generate heat through power-to-heat technologies such as heat pumps, whose coefficient of performance (ranging across 2.4-5.8 for technologies at TRL 6-11) depends on the local climate. The benefits of reducing the carbon intensity of the energy used for DACS extends to decarbonising distributed energy sources as well as centralised energy sources.

DACS cost of carbon removal by energy source for heat and electricity, 2020



Notes: grid = electricity grid; DH = direct heat; HP = heat pump; WH = waste heat. Average cost of capture and cost of removal both include average transport and storage costs (USD 20/tCO_2). Direct heat assumed to be generated by means of natural gas combustion. Reference capture capacity scale = 1 $MtCO_2$/year.

Sources: Carbon removal efficiencies based on Liu et al. (2020); NETL (2021); Terlouw et al. (2021); Deutz and Bardow (2021); de Jonge et al. (2019); Keith et al. (2018).

Water and land footprint

The water and land footprints of DAC plants are relatively limited compared to other CDR approaches; however, they can influence the choice of the DAC technology and its energy source.

Based on the information available to date, L-DAC requires water for its operation (up to 50 tonnes of water per tonne of CO_2 captured from the atmosphere), while S-DAC can extract water from the air, alongside CO_2 (0.8-2 tonnes of water per tonne of CO_2 captured from the atmosphere). The wide ranges depend on DAC technology, ambient temperature and humidity and also capture solution concentration for L-DAC.

In dry climates S-DAC could provide water (for its own use or, for instance, to feed a water electrolyser to produce hydrogen and subsequently synthetic fuels together with the captured CO_2), whereas in extremely humid climates S-DAC could struggle to keep up with the amount of water to be removed from the atmosphere. Water removal is in fact a side-effect of removing CO_2 and affects the plant's performance,[25] although only marginally. Moreover, high levels of pollution can clog filters and therefore require more frequent maintenance, increasing operational expenditure.

In contrast, L-DAC could add strain to an already stretched water resource. Desalinisation and transport of water could be possible for plants located near the ocean, but this would slightly increase the cost of capture (by around EUR 3-8/tCO_2, equivalent to USD 3.5-9.5/tCO_2). Therefore, L-DAC would operate best in locations where water is not scarce.

The land footprint of DAC is smaller than the land footprint of alternative CDR approaches, especially those relying on biomass-based removal (such as afforestation). According to the latest estimates, in order to capture 1 MtCO_2/year from the atmosphere an L-DAC plant would require around 0.4 km^2, and an S-DAC plant in the range of 1.2-1.7 km^2 (excluding provision of input energy needs). For comparison, an emerging DAC technology based on electro-swing adsorption (ESA-DAC) has the potential for an even smaller land footprint, as little as 0.02 km^2/MtCO_2. While this would be a clear advantage of ESA-DAC, its current TRL is too low to be able to quantify its potential when deployed on a large scale. The choice of the source of energy can substantially increase the DAC land footprint, from an additional 1.5 km^2/MtCO_2/year for geothermal (L-DAC, geothermal power meeting electricity demand, natural gas from the grid meeting heat demand) to 23 km^2/MtCO_2/year for solar PV (S-DAC).

[25] According to Climeworks, local climate, weather conditions and altitude have "a certain effect on performance characteristics".

Public acceptance of DAC

To date there have been very few studies that investigate the public's perception of DAC amongst other CDR approaches. The Climate Assembly in the United Kingdom formed a citizen's assembly in 2020 to learn about climate change and the different approaches the country could take to combat it further. During this assembly, 108 citizens were presented with information about reducing carbon emissions, including greenhouse gas removal strategies. They were then able to discuss the co-benefits and potential consequences that they thought could come from implementing these practices to assist in the United Kingdom reaching its net zero goal. When surveyed about which of these strategies should be a part of the net zero portfolio, respondents showed:

- Mostly favourable opinions toward nature-based carbon removal solutions.
- Concern with the newness of DAC technology.
- Some concern with the reliability of geological storage.

This led some respondents to recommend scaling up nature-based solutions today, and furthering R&D into DAC so it could then be used later.

In addition to the study conducted by the Climate Assembly, Cox et al. (2020) conducted a national survey to gather information about the public perception of BECCS, DAC and enhanced rock weathering from constituents in the United Kingdom and the United States. The authors found that before conducting informative workshops, a low percentage of respondents had prior understanding of CDR. In general, respondents did not believe that CDR methods deal with the root cause of climate change and feared that these measures could encourage mitigation deterrence.

When respondents were asked specifically about DAC, their main concerns were:

- Fully understanding the idea of capturing CO_2 from the ambient air.
- Practical and societal concerns of storing CO_2 underground.
- Being able to simultaneously decarbonise and generate enough energy to meet the energy requirements of DAC systems.

From these findings, Cox et al. suggest that DAC could face further public opposition due to a lack of engagement and understanding from the public or due to the timing of the project. Some participants were sceptical of CDR options because they seemed to take too long to deploy, not address the urgency with which climate change needs to be dealt, and require sufficient testing to avoid adverse consequences. Lastly, it was suggested that participants would want to see CDR approaches being co-deployed with emission mitigation efforts to avoid CDR being used to justify the continued use of fossil fuels where other options may exist.

Chapter 4. Optimal locations for direct air capture

A major advantage of DAC is that a plant can be located virtually anywhere, for example near a suitable storage site for carbon removal, or an industrial facility seeking a supply of atmospheric (rather than fossil) CO_2 feedstock, reducing the need for long-distance CO_2 transport. Moreover, this technology requires limited water and land compared to other CDR options, especially those relying on biomass-based removal.

However, this siting flexibility does have limitations. While DAC plants have been successfully operated in a wide range of climatic conditions across Europe and in North America, further testing would be needed in locations characterised by extremely dry, humid or polluted climates, for instance. Additionally, the choice of location needs to take into account the energy source to run the plant, which has a large influence on capture cost and will ultimately determine how carbon-negative the system is. Both S-DAC and L-DAC technologies could be fuelled by renewable energy sources, while S-DAC could also be powered by recovering low-grade waste heat, which would considerably reduce capture costs and life cycle emissions.[26]

Capture cost by location

DAC has already been demonstrated in Europe and North America. These two regions are well-suited to host further DAC facilities as a result of this experience and also due to the potential for co-siting with existing industrial hubs as well as existing and planned CO_2 transport and storage infrastructure.

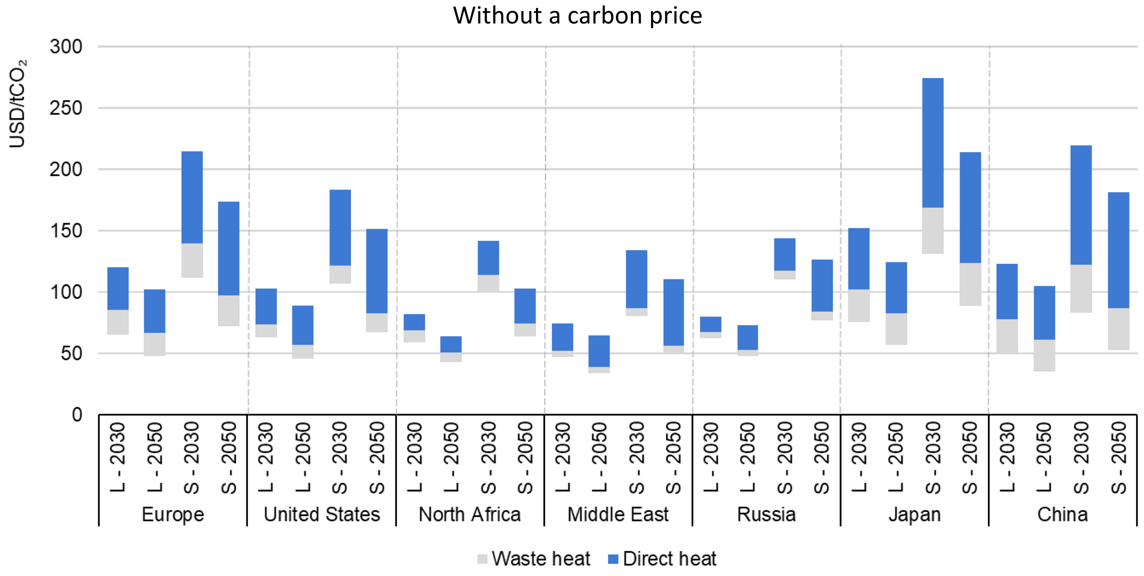
Other regions that can be cost-competitive for DAC deployment are those characterised by very high renewable energy potential (e.g. North Africa, the Middle East), low natural gas prices (e.g. the Middle East, Russia Federation), and/or a strong interest in CO_2 use and the carbon circular economy (e.g. Japan).

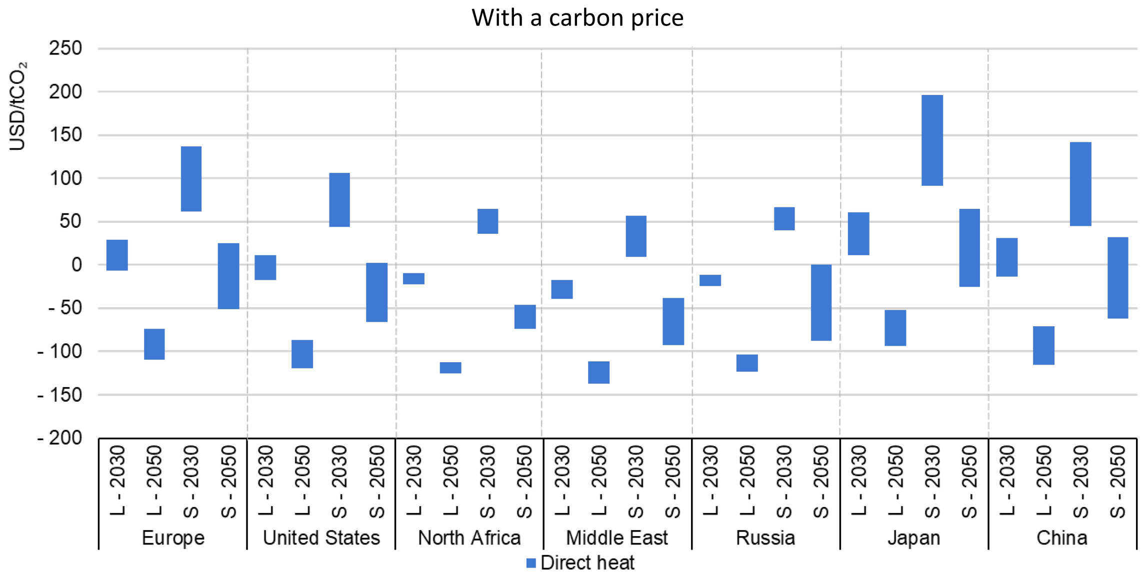
In these regions, the cost of capture via DAC varies according to CAPEX and energy and CO_2 prices. A global DAC deployment rate in line with the Net Zero Scenario (i.e. 90 $MtCO_2$ and 980 $MtCO_2$ captured in 2030 and 2050 respectively) would mean a substantial decrease in CAPEX, up to 49-65% lower in 2030 and 65-80% lower in 2050 compared to 2020. On a regional scale, CAPEX is expected to be lower in China, the Middle East, Russia Federation and North Africa than in Europe and the United States, due to cheaper materials and manufacturing. Regions characterised by abundant gas resources (such as Russia Federation and the Middle East) are expected to have lower gas prices than Europe and the United States, while CO_2

[26] This would, however, limit the location flexibility of the plant.

prices are expected to be higher in Europe, the United States and Japan (up to USD 250/tCO_2) than in the other selected regions. All of these factors contribute to the regional cost of carbon captured via DAC decreasing by 31-43% during 2020-2030 and by 10-24% during 2030-2050.

Levelised cost of capturing carbon by DACS technology for selected regions, 2030 and 2050

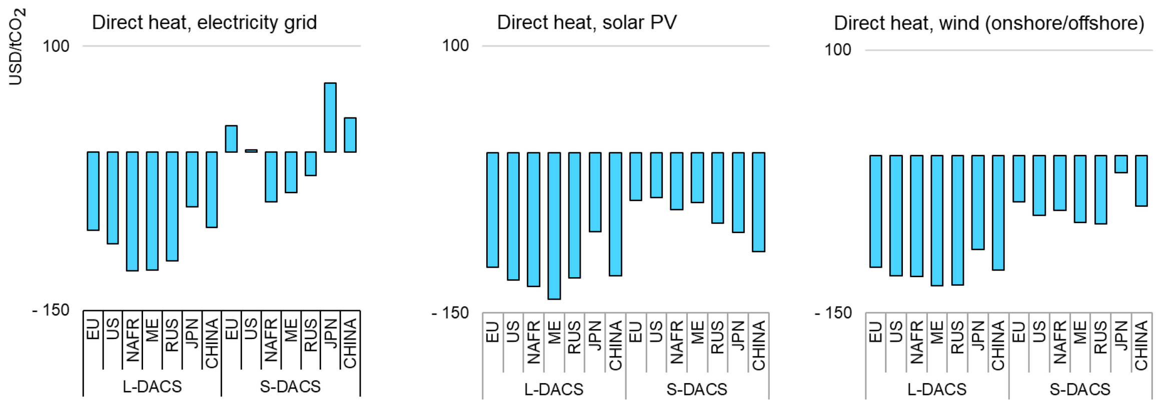




Notes: L = L-DACS; S = S-DACS. CAPEX learning rate = 10% for L-DAC, 15% for S-DAC (due to higher degree of modularity for the latter technology), with DAC deployment based on Net Zero Scenario; heat assumed to be generated by means of natural gas combustion (direct heat) or be provided as free waste heat, electricity provided by grid, solar PV, onshore or offshore wind power generation; regional natural gas prices and electricity prices consistent with Net Zero Scenario for the years 2030 and 2050: natural gas price = USD 1-5/GJ; electricity price = USD 4-49/GJ; CO_2 price = USD 130/tCO_2 in 2030, USD 250/tCO_2 in 2050; emission factor for electricity production = 0, for natural gas = 0.056 tCO_2/GJ based on IPCC guidelines for stationary combustion according to https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/. Reference capture capacity scale = 1 MtCO_2/year.

Without a carbon price in place, all the selected regions have the potential to capture CO_2 directly from the air for less than USD 100/tCO_2, with the Middle East reaching capture costs for DAC below USD 50/tCO_2 thanks to a combination of all the factors mentioned above (low CAPEX, low natural gas price and low electricity price). High renewable energy potential coupled with best available technologies for electricity and heat generation can substantially decrease the capture cost of DAC. A carbon price of USD 250/tCO_2 in 2050 allows DAC to become profitable in all regions when powered by heat and renewable electricity, from either solar PV, or onshore and offshore wind.

Levelised cost of capturing carbon (including USD 250/t carbon price) by DACS technology and energy source for selected regions, 2050



Notes: Direct heat assumed to be generated by means of natural gas combustion. L = L-DACS; S = S-DACS. CAPEX learning rate = 10% for L-DAC, 15% for S-DAC (due to higher degree of modularity for the latter technology), with DAC deployment based on Net Zero Scenario; heat provided by means of natural gas combustion, electricity provided by grid, solar PV, onshore or offshore wind power generation; regional natural gas prices and electricity prices consistent with Net Zero Scenario for the year 2050: natural gas price = USD 1-5/GJ; electricity price = USD 4-44/GJ; CO_2 price = USD 250/tCO_2; emission factor for electricity production = 0, for natural gas = 0.056 tCO_2/GJ based on IPCC guidelines for stationary combustion according to https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/. Reference capture capacity scale = 1 MtCO_2/year. EU = European Union; US = United States; NAFR = North Africa; ME = Middle East; RUS = Russia Federation; JPN = Japan.

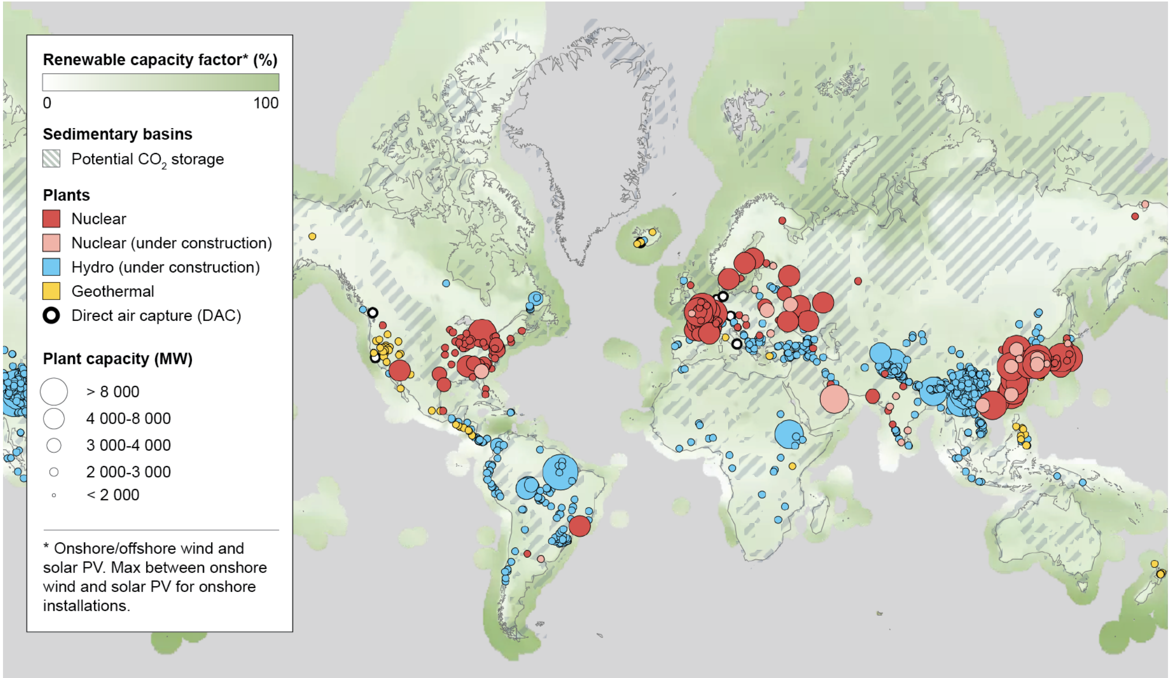
Energy sources

Locations characterised by high renewable potential are best placed to host DAC plants, especially if also characterised by substantial CO_2 storage potential where carbon removal is the objective. For example, at the Orca plant in Iceland geothermal power is being used to produce electricity and to power S-DAC for CO_2 capture and subsequent storage through mineralisation. The same DAC technology will soon be tested in Oman, which has large potential for solar PV and abundant natural peridotite formations for CO_2 mineralisation. Renewable energy sources such as solar and wind are characterised by a certain level of siting flexibility; however, they generate electricity and heat in a discontinuous manner, resulting in low utilisation rates for a DAC plant solely reliant on them.

Powering DAC exclusively with renewable electricity that would otherwise be curtailed would increase the cost of capture even further, due to low utilisation rates. While energy storage could ensure the continuous operation of the DAC plant, it would increase the capital cost of the system. Other renewable energy sources that could be considered for powering DAC include geothermal and hydropower (only available in very specific locations), biomethane (requiring substantial land and water, and potentially competing with food production as well as other uses for limited bioenergy resources) and concentrated solar power (which has seen only limited deployment to date).

Renewable heat and electricity production opportunities vary among and within regions. When a region is characterised by high renewable potential, the assessment of its suitability for substantial DAC deployment should take into account a number of additional factors related to land use and land use changes. These include, for instance, the degree of urbanisation and the presence of natural habitats and ecosystems, and marine protected areas. According to a recent IEA analysis, most coastal regions are characterised by high wind potential, which can also be found in the central United States, the southern region of South America, and in the United Kingdom and Ireland. The potential from solar power (both concentrated solar and PV) is more spread out globally, with high potential in regions across the south western United States and Mexico, eastern South America, the Middle East and eastern Australia.

Map of renewable and nuclear energy source potential and CO_2 geological storage



Note: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area. Operating hydro plants have been omitted from the map as their connection to a standalone DAC plant would be technically challenging.

Sources: IEA analysis based on renewable.ninja for hourly solar data for utility-scale solar PV; Copernicus for hourly wind speed data; Pilorgé, H. et al. (2021), Global mapping of CDR opportunities, CDR Primer for nuclear, hydro and geothermal.

Co-locating DAC facilities with existing assets and infrastructure where waste heat is available presents another option to power DAC plants. Sources of waste heat include power and industrial plants (such as chemical plants, pulp and paper mills, and steel and glassmaking plants), combined heat and power plants, synthetic fuel production processes, incineration processes and cooling towers (at power generation plants, e.g. nuclear, or on buildings). In 2020 Southern Company in the United States announced its interest in testing DAC technologies for their potential co-siting with existing assets at the National Carbon Capture Center. EDF is actively seeking partners able to operate hydrogen and DAC plants using waste heat recovered from the planned Sizewell C nuclear power plant in the United Kingdom. A DAC plant based in Hinwil (Switzerland), feeding CO_2 to a local greenhouse, is currently powered mainly by waste heat from a nearby waste recovery facility, while another in Apulia (Italy) relies on waste heat from the cooling circuits of a methanation reactor producing transport fuel from hydrogen and air-captured CO_2.

Other sources of energy that could be used to power DAC include nuclear, geothermal and hydropower plants. Most geothermal plants are located along the west coast of the United States and Mexico, and in Japan and the Philippines, while many hydropower plants are located across South America, Eastern

Europe/Eurasia and southern China. Nuclear plants are mainly located in the eastern United States, Europe (especially in France), along the east coast of China and in Japan (where a number of reactors are being decommissioned).

Co-location is important not only for access to already available low-carbon energy sources, but also for CO_2 infrastructure. Air-captured CO_2 can be transported alongside CO_2 captured from more concentrated sources (e.g. power and industrial plants) to facilities that use it, or to geological storage sites. The latter configuration would allow CO_2 removal as well as CO_2 abatement (from concentrated sources). An extensive network of CO_2 infrastructure is already present in countries such as the United States, while part of the oil and gas infrastructure could be repurposed in regions such as Europe to transport CO_2.

Use and storage of air-captured CO_2

Once CO_2 has been captured from the atmosphere, it can be stored underground for permanent removal, or it can be used directly (e.g. for beverage carbonation, in greenhouses fertilisation, or as a refrigerant) or indirectly (e.g. as a feedstock for processes producing chemicals, fuels and building materials). Out of the 18 DAC plants currently operating worldwide, only two are storing CO_2 in a dedicated storage site, while the remaining 16 are capturing the CO_2 for use in nearby industrial facilities.

Carbon removal requires the CO_2 to be permanently stored. Most large-scale CO_2 use applications, including synthetic fuels, result in the CO_2 ultimately being re-released into the atmosphere.[27] CO_2 use can still deliver clear climate benefits, particularly when the application is scalable, uses low-carbon energy and displaces a product with higher life cycle emissions. In the decarbonisation path towards net zero emissions, atmospheric CO_2 will eventually need to displace the use of fossil-based carbon. While CO_2 use can deliver climate benefits under the circumstances mentioned above, it is a complement rather than an alternative to CO_2 storage, which is expected to be deployed at a much larger scale in order to reach international climate goals. In the IEA Net Zero Emissions Scenario, around 95% of total captured CO_2 (across all CCUS applications) is destined for CO_2 storage rather than use. Of the 980 $MtCO_2$ captured via DAC in 2050, 630 $MtCO_2$ is permanently stored while 350 $MtCO_2$ is for CO_2 use (mainly for aviation fuels).

CO_2 captured from the atmosphere through DAC can be stored geologically in deep saline aquifers (having the largest storage capacity), in depleted oil and gas fields, and also in other rock formations such as basalt. There is substantial

[27] A notable exception includes low-carbon concrete with CO_2, which represents an example of CO_2 utilisation with a high level of permanence.

experience with large-scale geological storage of CO_2: the Sleipner CO_2 storage project started operations in 1996, and was followed by the Snøhvit CO_2 storage project (2008), the Quest project (2015), the Illinois industrial project (2017), Qatar LNG (2019) and the Gorgon project (2019). These six projects are now storing almost 10 $MtCO_2$/year in dedicated storage sites.[28] Measuring, monitoring and verification (MMV) is needed to ensure that CO_2 is injected and retained within the storage site, and to measure the storage rate and total stored volume within a site.

The overall technical capacity for storing CO_2 underground worldwide is understood to be vast, but detailed site characterisation and assessment are still needed in many regions. Total global storage capacity in saline aquifers and depleted oil and gas fields has been estimated at between 8 000 Gt and 55 000 Gt. The availability of storage differs considerably across regions, with Russia Federation, North America and Africa holding the largest capacities. Substantial capacity is also thought to exist in Australia. The costs and time needed to develop CO_2 storage facilities will be location-specific and influenced by the availability of existing subsurface data and by reservoir properties and characteristics. CO_2 storage costs can be quite low; for example, more than half of onshore storage in the United States is estimated to be available at below USD 10/tCO_2, while about half its offshore storage is estimated to be available at costs below USD 35/tCO_2. The siting flexibility of DAC could enable facilities to be built where the lowest-cost CO_2 storage resources are available.

The timelines associated with developing storage – up to ten years from project conception to CO_2 injection – could become a bottleneck for DAC deployment (and CCUS deployment in general) without accelerated efforts to identify and develop CO_2 storage sites. As identified above, co-locating DAC facilities where CO_2 transport and storage infrastructure is already available or planned can serve to reduce costs and support faster project deployment.

Mineralisation of CO_2 for permanent storage

CO_2 can be stored in rock formations (such as basalts and peridotites) that have high concentrations of reactive minerals. Injected CO_2 becomes trapped when it reacts with minerals in the formation to form solid carbonate minerals. While the theoretical storage capacity of basalts has been estimated to be very large (100k-

[28] Almost 30 commercial CCUS projects are operating around the world, with capacity to capture more than 40 $MtCO_2$/year. Of this, around 30 $MtCO_2$/year is being injected into oil and gas reservoirs for enhanced oil recovery.

250k $GtCO_2$), further testing and research is required to develop this storage option (currently at TRL 4), notably to determine water requirements, which can be considerable.[29]

Large basalt formations exist in several regions around the world, including in areas where there may be limited conventional storage capacity, such as India. This potentially opens up new opportunities for CCUS, particularly as both onshore and offshore formations could be considered for storage.

There are only two DAC plants currently storing CO_2 through mineralisation, both in Iceland: the plants capture CO_2 from the air and blend it with CO_2 captured from geothermal fluid before injecting it into underground basalt formations, where it is mineralised, i.e. converted into a mineral. Again in Iceland, Carbfix has recently announced the intention to build a CO_2 mineral storage terminal, able to store CO_2 received from a number of customers located in northern Europe. The development of this hub is in three phases, starting in 2025-2027 with the mineralisation of 300 000 tCO_2 a year, up to 3 $MtCO_2$/year by the mid-2030s.

The storage potential for air-captured CO_2 in basalt formations will be soon investigated in Oman as well. The project aims to provide insights for DAC deployment in the Middle East, which is characterised by very different climatic conditions than other regions where DAC is currently deployed (namely Europe and North America).

[29] The CO_2 can be dissolved in water to speed up in situ carbonisation.

Chapter 5. Direct air capture as part of a carbon dioxide removal portfolio

What is carbon dioxide removal?

CDR (carbon dioxide removal) is an umbrella term that refers to approaches that draw CO_2 from the atmosphere, directly or indirectly, and permanently store it. DACS is one of a portfolio of CDR approaches, which include nature-based solutions, enhanced natural processes and technology-based solutions. Removing carbon from the atmosphere will play an important role in meeting climate goals as it can 1) balance or neutralise emissions in hard-to-abate sectors that are otherwise technically difficult or too costly to abate directly, and 2) enable "net negative" emissions at a global scale, removing historical emissions that have accumulated in the atmosphere and compensating for near-term "overshoots" where emission reductions are not delivered fast enough to meet 1.5°C pathways.

Virtually all climate models considered by the IPCC that seek to limit future temperature increases to 1.5°C include significant CDR deployment, including for net negative emissions in the second half of the century. The rate of CDR adoption from 2050 onward strongly depends on what has been assumed for the first half of the century, with early inaction or emissions overshoot requiring steep adoption after 2050. Some scenarios demonstrate that the limited adoption of CDR technologies (10 $GtCO_2$/year maximum by 2050 and 20 $GtCO_2$/year maximum by 2100) or no adoption at all may be possible. But these scenarios require an aggressive technology replacement strategy, together with stabilisation of both the global population and energy demand (Grubler et al., 2018; van Vuuren et al., 2013; van Vuuren et al., 2018).

Despite the high reliance on CDR in many climate models, there is considerable uncertainty in the future scalability and climate impact of these approaches. Scientific understanding does not yet provide confidence that we can rely on CDR at some point in the distant future as a retroactive means of counteracting an overshoot of the emissions trajectory required to meet climate goals. According to the Sixth Assessment Report of the IPCC, the response of the climate system to CDR deployment is expected to be delayed by years to centuries, and so is the response of the carbon pool (accumulated carbon in the atmosphere) to net negative emissions.

This uncertainty surrounding CDR approaches, including DACS, underscores the importance of these approaches being a complement and not an alternative to cutting emissions now, or an excuse for delayed action.

What are the main carbon dioxide removal options?

The range of carbon removal approaches includes nature-based and technology-based options, and options that enhance a naturally occurring process. They remove CO_2 either directly from the air (e.g. DAC) or indirectly (e.g. biomass growing) and store the CO_2 either geologically, within the terrestrial biosphere (within soils, minerals or biomass), or in the ocean. These approaches differ in their carbon, land and resource footprint, potential scale of deployment, TRL, life cycle emissions and impact on the biosphere, cost and performance, supply chains, and configuration and modularity.

Together with DACS, the most promising CDR options include afforestation and reforestation (AR) and bioenergy with CCS (BECCS). This evaluation is based on their current status and on their techno-economic potential for scalability. DACS and BECCS have been identified by the Sixth Assessment Report of the IPCC as the CDR options with the highest storage permanence, while AR as the option with the lowest storage permanence. While CDR options relying on biosphere-based storage (e.g. biomass, soil and ocean) are generally characterised by low storage permanence, they still represent a large share of what it is currently available on the CDR market. For example, in 2020 Microsoft and Stripe cumulatively received 236 proposals for CDR solutions, with more than 95% of them (in CO_2 volume terms) being for low permanence options (less than 100 years). These were not considered reliable by the companies and were not selected for investment.

While DACS, BECCS and AR are currently in operation, other CDR options are still in the R&D phase and further studies are needed to better understand their potential role and scalability, as well as their environmental impacts.

Key features of the main CDR approaches and technologies

Approach	BECCS	DACS	Enhanced weathering of minerals	Land management and biochar production	Ocean fertilisation/ alkalinisation	AR
Approach type	Technology-based	Technology-based	Enhanced natural processes	Enhanced natural processes	Enhanced natural processes	Nature-based
Current maturity category (TRL)	Large prototype (TRL 6)	Large prototype (TRL 6)	Concept (TRL 1-3)	Small prototype (TRL 4)	Concept (TRL 1-3)	Large prototype (TRL 6)
Storage type and permanence	Geological, high	Geological, high	Biosphere, high	Biosphere, medium	Ocean, medium	Biosphere, low
Carbon removal potential (cumulative to 2100, $GtCO_2$)	100-1 170	108-1 000	100-367	78-1 468	55-1 027	80-260
CO_2 capture cost (USD/tCO_2)	15-80	125-335	50-200	30-120	-	5-50
Water requirement	High	Low	High	Low	-	High
Land requirement	Medium	Low	Medium	Medium	-	High

Notes: BECCS = bioenergy with CCS; CCS = carbon capture and storage; DACS = direct air capture and storage; TRL = technology readiness level. Estimates for carbon removal potential are not additive, as CDR approaches partially compete for resources. Land requirement excludes energy sources. Please note that carbon removal potential is scenario-dependent.

Sources: IEA analysis; IEA (2020); IPCC (2021); CDR Primer (2021); EASAC (2018); Fuss et al. (2018); Iyer et al. (2021).

DACS presents a number of advantages compared to other CDR approaches. DAC as a capture technology is at TRL 6 (large prototype) due to numerous plants being in operation. Geological storage of air-captured CO_2 ensures very high storage permanence (1 000+ years), which is essential when aiming for high-quality removal. According to the literature cited in the table above, the cumulative carbon removal potential of DACS to 2100 is four times higher than the potential from AR, with a much smaller water and land footprint, which is high in general for any biomass-based CDR option (including AR and BECCS). Moreover, it takes around a couple of years to build and start operating a DACS plant at full capacity, which could run for up to 25 years (based on similar industries). AR takes up to ten years to ramp up to the maximum sequestration rate, to then saturate in 20-100 years' time (depending on the species), effectively ceasing CO_2 removal unless sustainably managed.

Main CDR options

In addition to DACS, CDR options include BECCS, AR, enhanced weathering, biochar, and ocean-based approaches.

BECCS (bioenergy with CCS) involves the capture and permanent storage of CO_2 from processes where biomass is converted to energy. As it grows, biomass absorbs CO_2 via photosynthesis; the CO_2 is released during refining or on combustion (to produce energy), but can be permanently captured and stored. Its applicability is broad as it can include power plants using biomass (or a mix of biomass and fossil fuels); pulp mills for paper production; lime kilns for cement production; and refineries producing biofuels through the fermentation (ethanol) or gasification (biogas, biodiesel, hydrogen) of biomass. Waste-to-energy plants may also remove CO_2 from the atmosphere when fed with biogenic fuel. BECCS is at TRL 6, with more than ten facilities currently capturing CO_2 from bioenergy production and utilisation around the world; however, its large-scale deployment will be limited by the availability of sustainable biomass.

AR (afforestation and reforestation) comprises two approaches aimed at enhancing the natural CO_2 cycle by means of land use management. While afforestation aims to repurpose land use by growing forests (or any form of biomass) where there was none before, reforestation aims to re-establish a forest where there was one in the past. Among all CDR options, AR and BECCS are the only techniques currently widely included in climate mitigation scenarios (Gambhir et al., 2019; IPCC, 2018; Rogelj et al., 2018), although the range of storage estimates is quite large (0.5-5 $GtCO_2$/year in 2050). While AR has already been applied, has relatively low costs and can provide positive side effects (such as enhancement of biodiversity and reduced soil erosion), it can also compete with bioenergy production and food production for land use. Moreover, AR has a large land and water footprint, and its carbon removal potential is not permanent and is also difficult to measure.

Enhanced weathering is a natural process that takes place when acid rain dissolves minerals, which then react with CO_2 to form carbonates. Enhanced weathering aims to accelerate this process, for instance by reacting CO_2 with olivine or calcium-silicates in autoclaves, or by spreading fine-powdered olivine on farmland or forestland. Although a number of reviews on CDR options mention this approach (Fuss et al., 2016; Haszeldine et al., 2018; Minx et al., 2018), further investigation and R&D are needed, especially for the purpose of climate change mitigation (enhanced weathering has been tested for accelerating recovery from acid rain or to increase harvest yields for sugarcane production).

Biochar is produced by slowly heating biomass in the absence of oxygen in a process called slow pyrolysis. The product of this thermal conversion process is carbon-rich (60-90%) solid char, which can be used to enrich soils and therefore to remove CO_2 from the atmosphere. Although this approach has potential, it is yet to be tested on a large scale. Moreover, further studies are needed in order to quantify biochar's carbon removal potential, the stability and persistence of carbon in soils in the long term, biochar's effect on biological organisms, and potential co-benefits such as improved fertilisation efficiency and reduced N_2O emissions.

Approaches enhancing the use of the ocean as a carbon sink include **ocean alkalinisation** (geochemical, direct air capture) and **ocean fertilisation** (biological, indirect air capture). The ocean is the largest natural carbon sink, currently removing around a third of anthropogenic carbon emissions from the atmosphere. While ocean alkalinisation is the direct consequence of enhanced weathering, ocean fertilisation aims to increase the amount of CO_2 that is biologically removed from the atmosphere. The most common and known side effect of ocean fertilisation is eutrophication. Neither ocean alkalinisation nor ocean fertilisation have been tested on a large scale, and environmental concerns together with public acceptance may prevent this technology from being deployed at scale.

Additional CDR options include **soil carbon sequestration** (based on agricultural management practices to improve soil carbon storage), **blue carbon** (the restoration of vegetated coastal ecosystems) and **peatland restoration** (storing carbon in soil by creating or restoring peatlands). According to the IPCC, these methods present the highest environmental co-benefits, although they are also characterised by low storage permanence.

Chapter 6. Scaling up the deployment of direct air capture

Support for direct air capture

Growing recognition of DAC technologies' important role in meeting net zero goals is translating into increased policy support and investment. Since the start of 2020, almost USD 4 billion in funding has been announced specifically for DAC research, development and deployment (RD&D), while leading DAC companies have raised around USD 125 million in capital.

Plans for nine DAC facilities are now in development. If all of these planned projects were to go ahead, DAC deployment would reach around 3 $MtCO_2$ by 2030; this is more than 380 times today's capture rate, but a mere 3.4% of the level of deployment needed in the Net Zero Scenario.

DAC projects in development

Name	Country	Target operation date	Capture capacity (tCO_2/year)	CO_2 use or storage
DAC pilot plant	Australia	2022	365	Storage (injection)
Haru Oni eFuels pilot plant	Chile	2022	-	Use (synthetic fuels)
Norsk e-fuel project	Norway	2023	-	Use (synthetic fuels)
DAC 1 project	United States	2025	1 million	Storage (injection)
Dreamcatcher project	United Kingdom	2026	Up to 1 million	Storage (injection)
Air-to-fuels plant	Canada	2026	-	Use (synthetic fuels)
AtmosFUEL project	United Kingdom	2029	-	Use (synthetic fuels)
Sizewell C nuclear-powered DAC	United Kingdom	-	100	Storage (injection)
Kollsnes project	Norway	-	Up to 1 million	Storage (injection)

Government support for DAC is growing

Countries and regions that have taken an early lead in supporting DAC research, development, demonstration and deployment include Canada, the European Union, the United Kingdom and the United States. Countries including Australia, Japan and Norway are also actively supporting DAC development.

Major publicly funded DAC initiatives by region

Programme/ instrument	Description
Canada	
Climate Action and Awareness Fund	The fund is investing CAD 206 million (USD 164 million) to support projects that will reduce Canada's GHG emissions, including efforts to understand the potential for, and implications of, carbon removal technologies including DAC.
Net Zero Accelerator	Part of the Strategic Innovation Fund, this initiative was announced in December 2020 and further enhanced by Canada's Budget 2021 to provide a total of CAD 8 billion (USD 6.4 billion) over seven years to support the decarbonisation of the industrial sector. DAC with CO_2 use is eligible as a climate-neutral CO_2 feedstock to produce low-carbon products.
Clean Fuel Standard	The standard will require liquid fuel suppliers to gradually reduce the carbon intensity of the fuels they produce and sell. Low-carbon-intensity fuels include those made from sustainably sourced biomass and DAC.
Budget 2021	The budget included CAD 319 million (USD 254 million) over seven years for Natural Resources Canada to fund RD&D to improve the commercial viability of CCUS technologies, including DAC.
European Union	
Horizon Europe	DAC projects are eligible for support under Horizon Europe, the main EU funding programme for research and innovation, with a total budget across all areas of EUR 95.5 billion (around USD 113 billion).
Innovation Fund	The EUR 10 billion (USD 11.8 billion) fund was launched in 2020 to support innovation in low-carbon technologies and processes, including CCUS and DAC.
Communication on Sustainable Carbon Cycles	The communication, released in December 2021, sets out a strategy to increase removals of carbon from the atmosphere. It suggests that 5 Mt of CO_2 should be removed annually by 2030.
United Kingdom	
DAC and GHG Removal Competition	This competition, announced in 2020, will provide funding for technologies that enable the removal of GHGs from the atmosphere. Total budget is up to GBP 100 million (USD 137 million).
Net Zero Strategy	The strategy identifies a need for 75-81 $MtCO_2$ of engineered carbon removals via DACS and BECCS by 2050. DAC may also benefit from announced funding of GBP 180 million (USD 248 million) to support production of sustainable aviation fuels.

Programme/ instrument	Description
United States	
45Q tax credit	This tax credit (introduced in 2008 and expanded in 2018) provides USD 35 per tonne of CO_2 used in enhanced oil recovery and USD 50 per tonne of CO_2 stored. The credit is available for DAC only if the capture capacity of the plant is above 100 000 tCO_2/year. There are a number of proposals to increase the value of the 45Q tax credit, including in the Build Back Better Act, which would provide USD 180/tCO_2 for DACS.
California Low Carbon Fuel Standard	DAC projects anywhere in the world are eligible to receive LCFS credits, provided the projects meet the requirements of the Carbon Capture and Sequestration Protocol (including 100 years of storage monitoring). The LCFS credits traded at an average of around USD 200/tCO_2 in 2020.
Infrastructure Investment and Jobs Act	Almost USD 12 billion in CCUS support was included in this act, which was enacted in November 2021. This includes USD 3.5 billion in funding to establish four DAC hubs (1 $MtCO_2$ per year and above) and related transport and storage infrastructure. DAC projects are also eligible for additional CCUS funding support included in the act of around USD 0.5 billion. A DAC Prize programme was also fully funded by the infrastructure package, with USD 100 million for commercial-scale projects and USD 15 million for pre-commercial projects.
Carbon Negative Shot	This was announced during COP26 in November 2021 as a call for innovation in technologies and approaches that will remove CO_2 from the atmosphere and durably store it at meaningful scales for less than USD 100/tonne of CO_2-equivalent, including DAC.
DOE funding programmes	Multiple funding programmes specifically for DAC were announced in March 2020 (USD 22 million), January 2021 (USD 15 million), March 2021 (USD 24 million) and October 2021 (USD 14.5 million).
Japan	
Moonshot Goal 4	The Moonshot Goal 4 (a subset of the Moonshot R&D Program, launched in 2019 with a total budget of YEN 100 billion [USD 1 billion]) focuses on “the realisation of a sustainable resource circulation to recover the global environment by 2050”. In order to reach this goal, the Moonshot Goal 4 includes R&D funding of YEN 20 billion (USD 200 million) for multiple innovative technologies, including DAC.

Notes: GHG = greenhouse gases; DOE = Department of Energy.

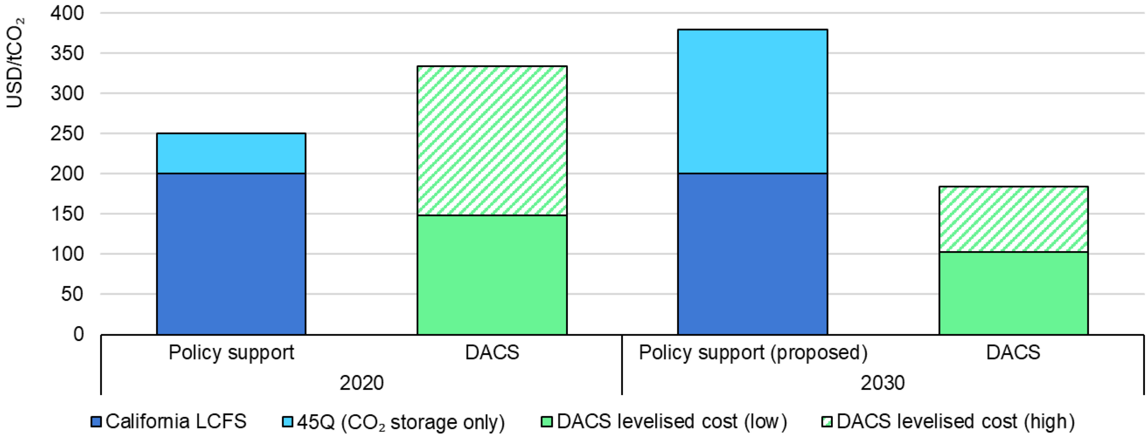
United States

The United States has established a number of policies and programmes to support DAC RD&D. DAC plants with a capture capacity above 100 000 tCO_2/year are eligible for the 45Q tax credit, providing USD 35 per tonne of CO_2 used in enhanced oil recovery and USD 50 per tonne of CO_2 stored. DAC plants of any size are eligible for the California LCFS credit (with these credits trading at an average of USD 200/tCO_2 in 2020), provided the projects meet the requirements of the Carbon Capture and Sequestration Protocol. The California LCFS and the 45Q tax credit are complementary policies that allow DAC projects to take advantage of both incentives. There are a number of proposals to increase the value of the 45Q tax credit, including in the Build Back Better Act (passed by the House of Representatives in November 2021) which would allow a credit of USD 85 per tonne of CO_2 captured and stored via certain industrial applications and USD 180 per tonne for DACS. Moreover, the act proposes to lower the DAC capacity threshold for 45Q from 100 000 tCO_2 to 1 000 tCO_2.

The Department of Energy announced funding specifically for DAC R&D in March 2020 (USD 22 million), January 2021 (USD 15 million), March 2021 (USD 24 million) and October 2021 (USD 14.5 million). Furthermore, almost USD 12 billion in CCUS support was included in the USD 1 trillion Infrastructure Investment and Jobs Act signed into law in November 2021. This includes funding (USD 3.5 billion) to establish four DAC hubs (1 $MtCO_2$ and above) and related transport and storage infrastructure, as well as additional funding for which CCUS and DAC projects are eligible (around USD 8.5 billion). A DAC Prize programme was also fully funded by the infrastructure package, including USD 100 million for commercial-scale projects and USD 15 million for pre-commercial projects.

During COP26 in November 2021, the Department of Energy launched the Carbon Negative Shot, an initiative aimed at supporting various CDR approaches – including DAC – to achieve large-scale deployment within a decade at USD 100/tCO_2 or less. This initiative has defined good-quality, large-scale removals as not only low-cost removals, but also those achieving storage permanence (100 years or more) and with robust accounting of full life cycle emissions.

Policy support for and levelised cost of DACS in 2020 and 2030, United States



Notes: DAC is eligible for the 45Q tax credit only for capture capacities above 100 000 tCO_2/year. Proposed policy support in 2030 includes the increased USD 180/tCO_2 tax credit (CO_2 storage only). Reference capture capacity scale = 1 $MtCO_2$/year.

Canada

In December 2020, Canada announced investment of up to CAD 3 billion (USD 2.4 billion) in a new Strategic Innovation Fund (SIF) Net Zero Accelerator Initiative, which was further enhanced by Canada's Budget 2021 in April 2021 to provide a total of up to CAD 8 billion (USD 6.4 billion) over seven years to support projects that will help reduce greenhouse gas emissions across the Canadian economy. The company Carbon Engineering was successful in securing a CAD 25 million (USD 20 million) grant from an earlier stream of SIF funding in 2019, which follows Government of Canada support via Natural Resources Canada of CAD 4.25 million (USD 3.4 million) under the Energy Innovation Program as well as the Impact Canada Sky's the Limit Challenge to produce made-in-Canada sustainable aviation fuel. Alongside private funding of over CAD 100 million (USD 80 million), these investments are supporting the construction and operation of Carbon Engineering's new Innovation Centre in Squamish (British Columbia) and also a fully integrated DAC and air-to-fuels plant (capture capacity 4.5 tCO_2/day). Additionally, the government of British Columbia's Innovative Clean Energy Fund is contributing CAD 2 million (USD 1.6 million) to support preliminary engineering and design of a commercial facility capable of producing up to 100 million litres of ultra-low carbon fuel each year using air-captured CO_2.

The Canadian federal government has also launched the Climate Action and Awareness Fund, which is positioned to invest CAD 206 million (USD 164 million) over five years to support Canadian projects that will reduce Canada's greenhouse gas emissions. Under the advancing climate science and technology category, one of the themes is to understand the potential for, and implications of, CDR technologies, with an emphasis on DAC and measurement and monitoring tools for nature-based carbon removal.

Similar to the California LCFS, the Canadian federal government has proposed the implementation of the Canada Clean Fuel Standard. This standard is aimed at reducing the carbon intensity of liquid fuels through a system where credits can be generated by undertaking projects that reduce the life cycle intensity of fossil fuels. Such projects include CCUS, supplying customers with low-carbon-intensity fuels, and investing in advanced vehicle technologies. Low-carbon-intensity fuels include those made from sustainably sourced biomass and DAC. The Clean Fuel Standard should be finalised and enforced in 2022.

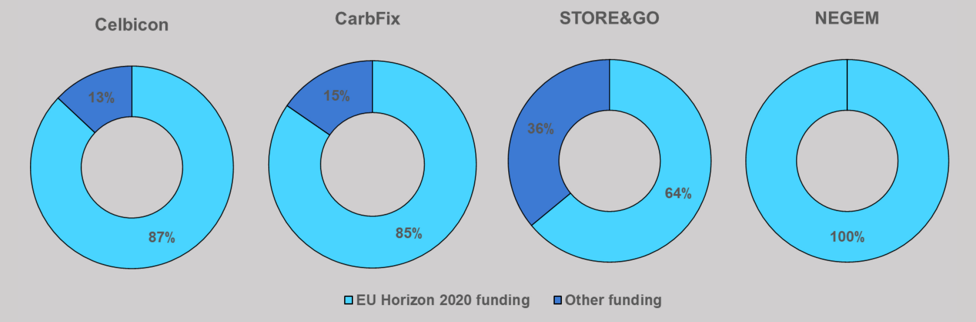
An investment tax credit for CCUS was proposed in the Canadian Budget 2021. This tax credit, which could become available as soon as 2022, is anticipated to be available across different industrial sectors, including DAC for CO_2 use or geological storage (not for enhanced oil recovery). In addition to the proposed investment tax credit, the federal budget includes CAD 319 million (USD 254 million) directed towards Natural Resources Canada for CCUS RD&D.

European Union

The European Commission has been supporting DAC through various research and innovation programmes, including the Seventh Framework programme and its successors (i.e. the Horizon 2020 programme and the Horizon Europe programme), and also through the Innovation Fund.

Celbicon, Carbfix, STORE&GO and NEGEM are notable projects that have been (at least in part) funded by the European Commission and have a DAC component. These projects, which range from techno-economic assessments to demonstration of DAC technologies, may not have been possible without the Horizon 2020 grant as it made up a large portion of their total budget.

Selected DAC projects that received public funding in Europe

	Celbicon	Carbfix and Carbfix 2	STORE&GO	NEGEM
Duration	2016-2019	2011-2021	2016-2020	2020-2024
Focus	CO_2 to chemicals (PHA bioplastic, methane)	CO_2 removal via mineralisation in basalt formation	Renewable power to gas (methane)	Techno-economic and social assessment of CO_2 removal
Funding sources	EU H2020, European Science Foundation, Austrian government Vienna Research Group for Young Investigators	EU FP7, EU H2020, US DOE, the Nordic Council of Ministers, GEORG	EU H2020, Swiss government	EU H2020
Total funding (EUR million)	6.2	3.8	28	5.8
Funding distribution				

Notes: GEORG = Icelandic Geothermal Research Cluster; H2020 = Horizon 2020; FP7 = Seventh Framework Programme; PHA = polyhydroxyalkanoates.

Sources: IEA analysis based on Celbicon (2022), Capture, ELectrochemical and BIochemical CONversion technologies; Carbfix/Carbfix 2; STORE&GO (2020) Power-to-Gas technology into the future European energy system; NEGEM (2022), Quantifying and Deploying Responsible Negative Emissions; Snæbjörnsdóttir, (2018), Reaction path modelling of in-situ mineralisation of CO_2 at the CarbFix site at Hellisheidi, SW-Iceland; Abdel Azxim, (2017), The physiology of trace elements in biological methane production; Rittmann, (2018), Kinetics, multivariate statistical modelling, and physiology of CO_2-based biological methane production; Mauerhofer (2018), Physiology and methane productivity of Methanobacterium thermaggregans.

The EU Innovation Fund was launched in 2020, with an initial budget of EUR 10 billion (USD 11.8 billion) over ten years, 2020-2030. Projects eligible to receive funding include those aimed at decarbonising energy-intensive or carbon-intensive industrial production, CCUS, renewable energy generation, and energy storage. Grant awards are dependent on project size, but can cover up to 60% of relevant project costs.

The European Union has also begun to enact policy that can either directly or indirectly support DAC. In April 2021 the European Parliament and Council reached a provisional agreement on the European Climate Law, including a legal objective for the European Union to achieve climate neutrality by 2050 and a commitment to negative emissions after 2050. To achieve these goals, the European Union recognises the need to enhance cost-effective carbon removal technologies. In July 2021 it launched the Fit for 55 package, aimed at revising its climate, energy and transport-related legislation. The package includes a proposal to revise the regulation on greenhouse gas emissions and removals from land use, land use change and forestry (LULUCF). While land-based CDR approaches are explicitly mentioned in the package, technology-based options such as BECCS and DACS are not currently included. The package is also proposing to increase the budget for the Innovation Fund and to include CO_2 mineralisation as an eligible emissions avoidance technology under the EU emissions trading system (ETS).

Another legislative proposal within the Fit for 55 package is the ReFuelEU Aviation, which will introduce an obligation for jet fuel suppliers to blend a percentage of sustainable aviation fuels into fossil-derived jet fuel (2% in 2025 and 5% in 2030). Sustainable aviation fuels can come from biofuels or in the form of e-kerosene, which is produced from renewable energy and atmospheric CO_2, sourced from DAC operations.[30]

In December 2021 the European Commission released its first Communication on Sustainable Carbon Cycles, which includes a short- to medium-term action plan and a long-term strategy on carbon removal. The strategy looks at carbon removal certification schemes and future policy frameworks, including land-based approaches (based on soil- and biomass-based removal) as well as wood-based construction materials, BECCS and DACS. The communication suggests that 5 Mt of CO_2 should be removed annually by 2030 from the atmosphere and permanently stored through these solutions.

[30] It should be noted that in 2030 the target for e-kerosene used in jet fuel is 0.7%, with biofuels making up the remaining 4.3%.

United Kingdom

In June 2020 the UK government announced the New Deal for Britain, which outlined a budget of GBP 100 million (USD 137 million) to go towards R&D for DAC. In response, the Department for Business, Energy & Industrial Strategy launched the DAC and Greenhouse Gas Removal competition, with the first-stage selection of proposals announced in 2021. Out of the 24 winners, five projects were specifically focused on the advancement of DAC technologies.[31] The government is also showing interest in adapting the post-Brexit ETS scheme to include carbon removal. Carbon removal credits would be traded alongside traditional allowances and could support DAC deployment.

In October 2021 the government set out a Net Zero Strategy aimed at achieving net zero emissions by 2050. The strategy identifies a need for between 75 Mt and 81 Mt of engineered carbon removals via DACS and BECCS by 2050 (equivalent to around 45-80% of the total emissions captured across the United Kingdom). Under the Net Zero Strategy, DAC may also benefit from announced funding of GBP 180 million (USD 248 million) to support the production of sustainable aviation fuels.

Private support and investment for direct air capture is taking off

Private-sector support for and investment in DAC has expanded in recent years, with organisations such as Breakthrough Energy Ventures, Prelude and Lower Carbon Capital investing in early-stage start-ups as well as more established companies that are already capturing CO_2 from the atmosphere. These private investments can assist in the development of large-scale operations, de-risking newer or emerging technologies, and propelling DAC forward in the absence of other incentives for carbon removal and storage.

Further support for DAC has come from programmes such as the XPRIZE (offering up to USD 100 million for as many as four promising carbon removal proposals, including DAC) and Breakthrough Energy's Catalyst Program (which raises money from philanthropists, governments and companies to invest in critical decarbonisation technologies, including DAC). Private investment rounds for DAC firms have also been successful: in 2020 Climeworks raised the largest-ever DAC investment, securing USD 110 million.

[31] These are: Direct Air Capture powered by Nuclear Power Plant, led by Sizewell C; DRIVE (Direct Removal of CO_2 through Innovative Valorisation of Emissions), led by Mission Zero Technologies; Project Dreamcatcher – Low Carbon Direct Air Capture, led by Storegga; SMART-DAC Sustainable Membrane Absorption & Regeneration Technology for Direct Air Capture, led by CO2CirculAir; and Environmental CO_2 Removal, led by Rolls-Royce and CSIRO.

In parallel, there has been substantial growth in new commercial partnerships and agreements to develop and deploy DAC technologies. DAC 1, a project financed and developed by 1PointFive (part of Oxy Low Carbon Ventures), is set to become the world's largest DAC facility, with commissioning planned for 2024. The project is to be located in the Permian Basin in the United States and will use Carbon Engineering's DAC technology. The project is supported by a multi-million dollar investment from United Airlines, and may be eligible for California LCFS and 45Q tax credits.

In June 2019 Global Thermostat and ExxonMobil signed a joint development agreement (which was subsequently expanded in September 2020) aiming to assess the feasibility of using Global Thermostat's carbon capture technology for industrial as well as atmospheric carbon capture applications. A further example includes the joint development agreement signed by Svante (a carbon capture company that uses solid adsorbents to capture CO_2 from industrial flue gases) and Climeworks to advance the deployment of their technologies for both industrial and atmospheric CO_2 capture. The companies are planning to use waste heat from Svante's CCUS technology to power Climeworks' DAC plant to deliver high-value-added CO_2 products to customers. Finally, the collaboration between Carbon Engineering and Storegga (the project developer of the Acorn CCS project in the United Kingdom) plans to deploy a commercial-scale DAC project in the United Kingdom by 2026.

Potential sources of finance for DAC companies

DAC companies, including start-ups, have a number of ways in which they can secure private investment:

Angel investors or angel groups: money provided by high-net-worth individuals or groups of individuals, usually from personal funds, in exchange for a percentage of the company's equity. Before committing to purchase equity, angel groups may require additional detailed documentation and evaluations for projects to be eligible for sustained funding.

Venture capital: money provided by high-net-worth firms in exchange for a percentage of the company's equity. This type of financial investment has been provided by Breakthrough Energy Ventures (started by Bill Gates and a limited number of private investors) and Lower Carbon Capital (started by Chris Sacca).

Preliminary customer agreements: money provided to companies through the sale of a product or service. In relation to DAC, this can take place as a funding entity buying carbon removal as a service at a higher initial price so the profits can be used to further business or physical asset development. This type of financial investment has been made by Stripe and Microsoft in their carbon removal investment portfolios.

Philanthropic activity: money received through philanthropic activities either as donations or via competition. An investment like this is not in exchange for any equity and does not require any payback. An example of this is the USD 100 million XPRIZE Carbon Removal administered by the XPRIZE Foundation and funded by Elon Musk through the Musk Foundation.

Business loans: money lent by banks or other financial institutions in the form of debt that must be repaid in addition to interest on the loan. Some start-up companies prefer this method to avoid having to split equity and to retain decision autonomy. As attitudes towards climate-friendly and clean technology advance, more banks and financial institutions are providing loans to these sectors at competitive interest rates. An example is the Industrial, Clean and Energy Technology Venture fund through the Business Development Bank of Canada. Many of their environmentally focused investments so far have been in companies that aim to provide decarbonised energy. It has also invested in CarbonCure, but has not invested in any DAC companies to date.

Business models for direct air capture

There are two primary commercial drivers for investing in DAC technologies: 1) selling high-quality carbon removal services when DAC is combined with CO_2 storage, and 2) selling climate-neutral CO_2 as a feedstock for a range of products, including aviation fuels and beverage carbonation. To date, most DAC facilities are relatively small and are selling the CO_2, with only two facilities providing carbon removal services.

High-quality carbon removal to balance emissions

The growing number of governments and corporations announcing net zero goals, together with maturing markets for low-carbon products, have boosted interest and demand for carbon removal solutions. For many companies, meeting their climate targets will require some form of removal to balance emissions for which there are limited near-term mitigation opportunities (including in sectors such as aviation and heavy industry). In the case of Microsoft, an ambitious corporate target to be carbon negative by 2030 inherently requires CDR.

At the moment technology-based CDR approaches, including DAC, are among the most expensive CDR options, yet are still attracting commercial interest due to their high quality when assessed against key criteria, particularly additionality, durability and measurability.

An assessment of DACS as high-quality CDR

CDR investment criteria*	Description	DAC evaluation of performance
1. Additionality	The carbon removal activity would not otherwise occur and so results in net carbon removal compared to a baseline scenario in the absence of investment.	**Very high**
2. Durability	The intended method of storage for a carbon removal solution is permanent, with low likelihood of being re-released into the atmosphere from voluntary or involuntary events.	**Very high**
3. Minimal emissions displacement	The carbon removal activity has minimal risk of displacing activities and thus causing further CO_2 emissions.	**Medium to high**
4. Carbon accounting	The carbon removal activity results in net negative carbon emissions to the atmosphere when upstream and downstream emissions are also accounted for. These activities can quantify the carbon that is removed.	**High**
5. Do no harm	The negative impacts of the solution at large scale should be minimal.	**Medium to high**

* Criteria adapted from Carbon Direct, https://carbon-direct.com/wp-content/uploads/2021/03/CD-Principles-for-Carbon-Removal.docx.pdf.

DAC companies are offering commercial removal services to individuals as well as companies willing to pay a recurring subscription to have CO_2 removed from the atmosphere and stored underground on their behalf. The price of the subscription varies (depending on the amount of removal purchased) from USD 600/tCO_2 to USD 1 000/tCO_2, although price details for the larger commercial deals are not available.

Companies including Microsoft, Stripe, Shopify and Swiss Re have purchased future DAC removal units, each representing a unit of CO_2 to be removed from the atmosphere, and building an early market for DAC-based CDR. Some of these agreements are hybrid, wherein the company purchasing the removal units is effectively supporting the capital investment to build the DAC plant that is eventually going to capture CO_2 from the atmosphere. For instance, United Airlines is directly investing in DAC in line with its commitment to become carbon neutral by 2050, while Microsoft is purchasing DAC removal from Climeworks and, through its Climate Innovation Fund, is also investing in Orca, the largest operating DAC plant for carbon removal.

The value of DAC in a CDR portfolio has been highlighted by Microsoft, which documented the lessons and challenges of securing "high-quality" CDR. The company reflected on its experience of purchasing 1.3 Mt of CO_2 removal, offers of which ranged from projects to expand forests in Peru, Nicaragua and the United States to the investment in the Orca plant. Ultimately Microsoft identified a range of issues for the CDR market. This included inconsistent definitions of net zero, poor measurement, monitoring and verification (MMV), poor carbon accounting, immature markets for removals and offsets, questions about the permanence of the carbon storage, and certain positive and negative externalities not being accounted for (e.g. water use, land use and biodiversity). Out of 189 proposals received by Microsoft (offering 154 $MtCO_2$ of removal), only 55 Mt were immediately available, and a mere 2 $MtCO_2$ – including DAC – met the company's criteria for high-quality CO_2. The findings underscored that the supply of solutions capable of permanently removing and storing carbon viably is currently a very small proportion of that needed to reach net zero emissions by 2050.

Much of the purchasing of CDR currently occurs in voluntary carbon markets rather than being driven by regulatory requirements or compliance schemes. In fact, carbon removal has yet to be incorporated into most domestic, regional or international trading schemes, including the EU ETS, although the European Commission is now developing a carbon removal certification scheme that aims to provide a robust and transparent carbon accounting framework for carbon removal activities. Crediting baseline methodologies for issuing carbon removal credits from DACS in international carbon markets are currently lacking, although some initiatives, such as the CCS+ initiative, are working to develop them.

Further, the IPCC Guidelines for National Greenhouse Gas Inventories do not currently include a methodology for accounting for the emissions removed by DACS. This means that the abatement from DAC facilities cannot be counted towards meeting international emissions mitigation targets under the UNFCCC. This was cited as a reason for not including DAC in the Australian Emissions Reduction Fund, which incorporated a new methodology for CCUS in 2021.

DAC certification and accounting within a CDR portfolio

The scale-up of DAC consistent with net zero goals will require robust regulatory frameworks and certification schemes that can provide the market with confidence in the use of DAC-based carbon removal. In many ways, the carbon accounting for DAC is not as challenging as for some nature-based CDR solutions, as the CO_2 captured and stored can be accurately measured. But major considerations and future needs for the certification and accounting of DAC within a CDR portfolio include:

- **Transparent and consistent LCA methodologies:** LCA tools are needed to verify that more CO_2 has been captured and stored than emitted by DAC operations and therefore that carbon has been removed. Critical factors will include the energy used by the DAC facility, any embodied CO_2 in the DAC facility, emissions associated with consumables, and any leakage during the capture, transport and storage of the CO_2. Having a consistent and internationally agreed methodology for the LCA of DAC facilities alongside other CDR approaches can support future markets and enable comparison across CDR options.
- **Measurement, monitoring and verification (MMV) of CO_2 stored:** the permanence of CO_2 storage is a vital factor for carbon removal via DAC facilities. International standards (ISO 27914:2017) and country-level regulatory frameworks have been developed for geological storage of CO_2, including MMV technical requirements and best practices that can be adopted by policy makers and regulators. Carbon accounting frameworks for CDR will need to consider the potential for reversal or re-release of the CO_2; in the case of geological storage this risk is very low.
- **Avoidance of double-counting:** the double-counting of emission removals can happen if carbon removals are issued, claimed or sold by two different schemes or by the same scheme twice. Certification of carbon removal (including through carbon removal certificates, or CRCs) can mitigate the risk of double-counting by providing a verified and traceable credit for removal.
- **International transferability:** the eligibility of DAC facilities under Article 6 of the Paris Agreement will be important to facilitate international co-operation and investment, including directing investment to those regions where DAC can be deployed at least cost.
- **Accounting for DAC in national inventories:** IPCC Guidelines for National Greenhouse Gas Inventories will need to be updated to include a methodology for DAC in order for these facilities to be counted in national abatement efforts.

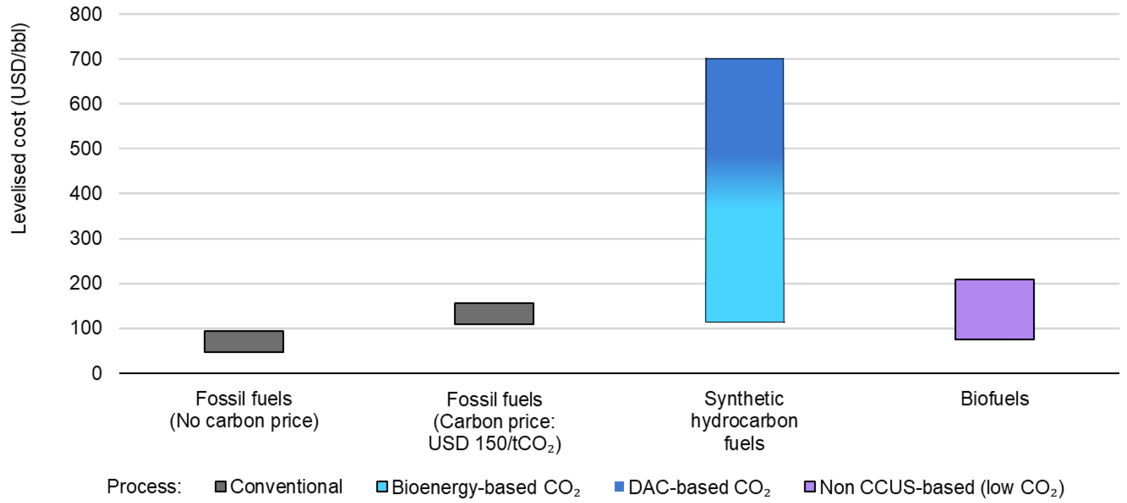
Efforts to develop robust accounting and certification for DAC and other CDR approaches are underway, including through the Mission Innovation CDR Mission launched at COP26. In July 2021 the XPRIZE Carbon Removal announced awards of USD 100 000 for projects focused on technologies or methodologies for improving the standards of assessment, or the precision, accuracy and time required for carbon measurements.

Selling the CO_2 for use in industrial applications

Most DAC facilities currently in operation generate revenue from selling the captured CO_2, including for beverage carbonation and greenhouse crops. While the largest industrial uses of CO_2 today are in fertiliser production and enhanced oil recovery – together accounting for more than 200 $MtCO_2$ every year – future large-scale opportunities to use CO_2 include the production of chemicals, fuels and building materials. While some of these applications can result in the CO_2 being stored (including in building materials and some plastics), most uses will result in the CO_2 being released to the atmosphere in the near term, including (for example) when the CO_2-containing fuels are combusted. For this reason, compatibility with net zero increasingly requires the CO_2 used in these applications to be biogenic or captured from the air. In the IEA Net Zero Scenario, around 350 Mt of air-captured CO_2 is used to produce synthetic fuels in 2050, including for aviation, supporting one of the few pathways to decarbonise this sector.

Companies such as Norsk e-fuels are today developing synthetic fuels with CO_2 captured from DAC, but the process remains expensive and these fuels currently cost more than five times fossil-based fuels. Successful commercialisation of these fuels will require further innovation and policy support to achieve cost reductions.

Simplified levelised cost of low-carbon fuels for long-distance transport, 2020



Notes: For long-distance transport modes, fossil fuel costs reflect a USD 50/bbl to USD 100/bbl crude oil cost range, and the carbon price variant represents a USD 150/tCO_2 shadow carbon price, which in practice could take the form of other regulatory policy measures such as fuel standards. Synthetic hydrocarbon fuel cost ranges consider CO_2 from bioenergy or DAC, and hydrogen from electrolysis powered by a dedicated renewable energy system. Electricity prices for hydrogen production range from USD 25/MWh to USD 150/MWh across regions and sources (grid, solar PV, on/offshore wind). Biofuels covers hydrotreated vegetable oils (HVO) and biomass-to-liquids (BTL). Reference capture capacity scale for DAC = 1 MtCO_2/year.

Six priorities for direct air capture deployment

Increased investment and policy support will be critical to scale up DAC deployment this decade. This support should target opportunities to reduce costs, refine technologies and improve global understanding of the technical and economic potential for DAC to support net zero goals.

In the near term, large-scale demonstration of DAC technologies will require targeted government support, while longer-term deployment opportunities will be closely linked to robust CO_2 market mechanisms and accounting frameworks that recognise and value CDR and air-captured CO_2 as a feedstock.

1. Demonstrate DAC at scale as a priority

DAC must be demonstrated at scale, sooner rather than later, to reduce uncertainties around future deployment potential and costs. It is important that today's planned large-scale projects are able to become operational, providing essential learnings for DAC technologies and supply chains and paving the way for the many projects that must follow.

Targeted policies to support early investment in DAC facilities include capital grants and operational subsidies such as tax credits. These can be complemented by market-based mechanisms including emissions trading frameworks or voluntary carbon markets, although these market-based mechanisms alone are unlikely to support investment in DAC deployment at the scale and pace needed for net zero. Certification of DAC within these frameworks remains a deployment barrier to be overcome (see below).

Support for DAC deployment should recognise that these technologies are at an early stage of commercialisation and that capturing CO_2 from the air is inherently more expensive that point-source capture. It is therefore appropriate to consider specific targets or support for DAC technologies within or in parallel with broader CCUS policies or programmes, for example through higher tax credits for DAC.

Main policy instruments for DAC development and deployment

Category	Types	Global examples (applicable to DAC)
Grant support	Capital funding provided directly to targeted projects or through competitive programmes to overcome high upfront costs.	UK CCS Infrastructure Fund, US funding for DAC hubs (Infrastructure Bill), EU Innovation Fund
Operational subsidies	**Tax credits** based on CO_2 captured/stored/used. **Contract-for-difference** (CfD) mechanisms covering the cost differentials between production costs and market price. **Feed-in tariff** mechanisms with long-term contracts. **Cost-plus open book** mechanisms in which governments reimburse some costs as they are incurred, reducing risk for the contractor.	United States 45Q tax credit
Carbon pricing	**Carbon taxes** which impose a financial penalty on emissions. **ETSs** involving a cap on emissions from large stationary sources and the trading of emissions certificates.	European ETS*
Market-based and demand-side measures	**Public procurement** of low-CO_2 building materials, transport fuels and power, including those produced with CCUS. **Carbon removal units or credits** based on a verified record of CO_2 securely stored.	Voluntary markets, California LCFS
Innovation and RD&D support	**Funding** for RD&D, either directly in state-run research institutions or indirectly through grants and other types of subsidy for private activities. **Competitive approaches** to support RD&D for low-carbon technology.	Carbon Removal XPRIZE, EU Horizon Europe, US Department of Energy R&D programmes

* DAC is not currently recognised in the EU ETS.
Note: RD&D = research, development and deployment.

2. Foster innovation across the DAC value chain

Innovation will be central to reducing the cost of DAC technologies and supporting accelerated commercialisation. Priority innovation needs for DAC include:

- Reducing the energy consumption needed to separate CO_2 through emerging separation technologies (e.g. electro-swing adsorption, membrane-based separation, moisture swing adsorption) and innovative approaches able to regenerate the solvent at low to medium temperatures.
- For L-DAC, advancing engineering maturity and market conditions to support the availability of renewables-based high-temperature heat to maximise the carbon removal potential and provide an alternative to current designs based on co-capture of CO_2 from natural gas.
- Reducing the cost of large-scale opportunities to use air-captured CO_2, particularly for synthetic fuels.

Increased RD&D spending to drive innovation in DAC technologies at a national and global level will be essential in the near term. Although not specifically targeted at DAC, initiatives such as the US Carbon Negative Shot and the USD 100 million Carbon Removal XPRIZE have strong potential to support DAC technologies and drive cost reductions. Similarly, the Mission Innovation CDR Mission aims to increase R&D on CDR and is targeting at least 100 Mt of CO_2 removal via BECCS, DAC and enhanced mineralisation by 2030.

3. Identify and develop CO_2 storage resources

The potential for DAC to support the large-scale removal of CO_2 from the atmosphere rests on the development and availability of geological storage. Although global CO_2 storage resources are considered well in excess of likely need, the time needed to identify, characterise and develop specific CO_2 storage sites can be between five and ten years, depending on the location and availability of existing data. Without a substantial increase in investment in developing CO_2 storage resources, the availability of storage could act as a brake on the potential for DAC and other CCUS applications to contribute to net zero pathways.

Governments will need to play a leading role in identifying and developing CO_2 storage in many regions, and particularly where geological resources have yet to be well explored. Policy priorities will include:

- Developing and publishing CO_2 storage atlases where limited data is available. Such atlases have been developed in many regions and are now complemented by the CO_2 storage resources catalogue released by the Oil and Gas Climate Initiative and Global CCS Institute. The US Geological Survey and Department of Energy are also able to partner with other organisations and governments to provide technical expertise to evaluate CO_2 storage resources.

- Providing incentives for commercial development of CO_2 storage and related infrastructure. This includes through direct funding support (including grants) or operational support, such as the Norwegian government's commitment to the Northern Lights CO_2 transport and storage project (part of the Longship integrated CCS project).
- Implementing robust legal and regulatory frameworks that ensure appropriate selection and operation of CO_2 storage sites, as well as ensuring the safe and secure long-term storage of CO_2.

In 2022 the IEA plans to publish two CCUS handbooks as a guide for policy makers on developing CO_2 storage resources and on legal and regulatory frameworks for CCUS.

4. Develop internationally agreed approaches to DAC certification and accounting

The development of robust and transparent international certification and accounting methods for DAC will be important to facilitate its inclusion in regulated carbon markets and to provide confidence in the emission reductions (including through CO_2 use) and removals associated with DAC. This should include agreed methodologies for the LCA of DAC facilities, ideally developed in a way that can enable effective comparison with other CDR options. Efforts to develop certification and accounting standards for DAC have commenced in several countries and regions, including in the European Union, the United Kingdom and the United States as well as through international initiatives such as the new Mission Innovation CDR Mission. Co-ordination across these efforts will be important to promote international consistency.

Mitigation or removal associated with DAC cannot currently be counted in national reporting due to the absence of an accounting methodology in the latest IPCC Guidelines for National Greenhouse Gas Inventories. This represents a major barrier to scaling up investment in DAC.

5. Assess the role of DAC and CDR in net zero strategies

As an increasing number of countries and companies pledge net zero targets, the focus of decision makers has shifted to how to turn these pledges into clear and credible policy actions and strategies. To date, very few countries and companies have developed detailed strategies or pathways to achieve their net zero goals, but a critical question for all will be the extent to which these strategies will need to rely on CDR approaches alongside direct emission reductions.

From a global perspective, it is clear that CDR will play an important – and likely essential – role in meeting net zero targets. On a national or regional level, the role for CDR will vary considerably, recognising that countries will take different pathways to net zero and the ultimate balance of remaining emissions vs removals will depend on a range of factors, from the opportunities and challenges for direct mitigation in major sectors to the cost and availability of natural sinks (nature-based CDR) or technology-based CDR approaches.

The IEA has consistently stressed the absolute priority of direct mitigation efforts: CDR is not an alternative to early action or to decisively cutting emissions. DAC and other CDR approaches are part of the portfolio of technologies and measures needed in a comprehensive response to climate change. Promoting transparency and planning for the anticipated role of CDR in net zero strategies can support the identification of technology, policy and market needs within countries and regions while supporting public understanding of these approaches.

6. Build international co-operation

The IEA Net Zero by 2050 Roadmap highlighted the importance of international collaboration for innovation and investment. The Low International Co-operation Case found that, without greater international co-operation, global CO_2 emissions will not fall to net zero by 2050. For DAC technologies, international co-operation can drive faster deployment and accelerated cost reductions through shared knowledge and reduced duplication of research efforts. International co-operation can also support the development and harmonisation of LCA methodologies for DAC technologies.

International organisations and initiatives such as the IEA, Mission Innovation CDR Mission, the Clean Energy Ministerial CCUS Initiative, and the Technology Collaboration Programme on Greenhouse Gas R&D (GHG TCP/IEAGHG) can provide important platforms for knowledge-sharing and collaboration. International finance entities, such as the World Bank, the European Bank for Reconstruction and Development and the Asian Development Bank, could support investment in DAC facilities in emerging markets and developing economies consistent with nationally determined contributions and climate goals.

Annex

Abbreviations and acronyms

AR	afforestation/reforestation
BECCS	bioenergy with carbon capture and storage
BTL	biomass to liquids
CAPEX	capital expenditure
CCS	carbon capture and storage
CCUS	carbon capture, utilisation and storage
CDR	carbon dioxide removal
CfD	contract for difference
CO_2	carbon dioxide
COP	Conference of the Parties
DAC	direct air capture
DACS	direct air capture and storage
DOE	Department of Energy
EO	ethylene oxide
EOS	economies of scale
ESA	electro-swing adsorption
ETS	emissions trading system
FEED	front-end engineering and design
FOAK	first of a kind
GEORG	Icelandic Geothermal Research Cluster
GHG	greenhouse gas
HVO	hydrotreated vegetable oil
H_2	hydrogen
H_2O	water
IEA	International Energy Agency
IEAGHG	Technology Collaboration Programme on Greenhouse Gas R&D
IPCC	Intergovernmental Panel on Climate Change
LBD	learning by doing
LCA	life cycle assessment
LCC	levelised cost of capture
LCFS	Low Carbon Fuel Standard
L-DAC	liquid DAC
LULUCF	land use, land use change and forestry
m-DAC	membrane-based DAC
MMV	measuring, monitoring and verification
NOAK	nth of a kind
Net Zero Scenario	Net Zero Emissions by 2050 Scenario
OPEX	operating expenses

PHA	polyhydroxyalkanoates
PV	photovoltaic
R&D	research and development
RD&D	research, development and deployment
S-DAC	solid DAC
SMR	steam methane reforming
TRL	technology readiness level

Units of measure

bbl	barrel
GJ	gigajoule
Gt	gigatonne
$GtCO_2$	gigatonnes of carbon dioxide
kg	kilogramme
km^2	square kilometre
MBtu	million British thermal units
Mt	million tonnes
$MtCO_2$	million tonnes of carbon dioxide
MWh	megawatt hour
t	tonne
tCO_2	tonne of carbon dioxide
tH_2O	tonne of water

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