C2G
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EVIDENCE BRIEF

# Direct Air Carbon Dioxide Capture & Storage (DACCS)

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## Summary

This briefing summarises the latest evidence around Direct Air Carbon Dioxide Capture and Storage (DACCS) technologies. It describes the techniques, explores their technical readiness, current research, applicable governance frameworks, and other socio-political considerations. It also provides an overview of the key governance instruments of relevance to DACCS. Information about other CDR techniques is available in C2G's Evidence Brief 'Carbon Dioxide Removal and its Governance.

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# Introduction

Over five years after the Paris Agreement on climate change entered into force, recognition is growing that without a rapid acceleration in action, limiting global average temperature rise to between 1.5 to 2 degrees Celsius (°C) will not be achieved through emissions reductions or existing carbon removal practices such as afforestation, alone. Scientists have begun exploring the additional use of large-scale interventions to limit climate impacts, including Carbon Dioxide Removal (CDR) and Solar Radiation Modification (SRM) techniques (for a review of potential approaches see (Florin et al., 2020)). This briefing focuses on Direct Air Carbon Capture Storage (DACCS) CDR techniques.

DACCS captures carbon dioxide ($CO_2$)directly from the atmosphere with subsequent storage (IPCC, 2018, p547), it is sometimes referred to as Direct Air Capture and Storage (DACS). DACCS should not be confused with Carbon Capture and Storage (CCS), which stops additional new $CO_2$ from entering the atmosphere at its point of source (IPCC, 2018, p544), nor Direct Air Capture (DAC), which is DACCS but without the removed carbon being stored. A range of C2G publications about other climate-altering technologies are available.

It is not the role of C2G to have a position on the appropriateness of DACCS; we seek only to broaden the discourse about the approach and catalyse debate about the future of the technologies by providing this impartial overview.

This briefing is not a comprehensive, detailed assessment of DACCS. Rather, it provides a description and brief analysis of the technological readiness, the research landscape, and governance issues associated with the technology. In section one, the technology is described and discussed. Section two explores governance issues and the tools and instruments of governance that may apply to DACCS.

# SECTION I: Why DACCS may be appropriate

DACCS technologies are one of many approaches to Carbon Dioxide Removal (CDR), also known as negative emissions techniques or technologies. CDR aims to address the primary physical driver of climate change by removing carbon dioxide ($CO_2$) from the atmosphere and ensuring its long-term storage. If deployed at a large-scale alongside emissions reductions, CDR would help slow the rate of global warming and ocean acidification. If the net reduction in $CO_2$ were greater than the amount of anthropogenic greenhouse gas (GHG) emissions, the global climate would cool, after a period latency.

According to the Intergovernmental Panel on Climate Change (IPCC) all pathways to keep global warming under 1.5°C project the need for CDR to remove between 100 – 1000 billion tonnes of accumulated $CO_2$ from the atmosphere by 2100 (IPCC, 2018). CDR methods that could potentially contribute to this target include nature-based approaches such as afforestation and enhancing wetlands, or engineering-based approaches, such as DACCS, that aim to directly capture $CO_2$ from ambient air. These approaches vary considerably in their potential, readiness, permanence, cost, and the associated risks of negative side-effects. No CDR techniques are currently able to be deployed at the speed or scale necessary to prevent overshooting the 1.5 – 2°C temperature goal agreed under the United Nations Framework Convention on Climate Change (UNFCCC), suggesting the full range of CDR approaches remain appropriate for further consideration.

While CDR is likely to become an important element of any plans to reach net zero, it is important to remember that it cannot be a substitute for rapidly reducing emissions of $CO_2$, and other GHGs. It is also important to note that the impact of any CDR deployment would be slow – due to the immense scale of the $CO_2$ to be captured it would not have any measurable effects on temperatures for decades (NAS, 2015, RS/RAE, 2018). Importantly, if CDR were to remove sufficient $CO_2$ to cause a decline in overall concentrations, $CO_2$ would outgas from the ocean into the atmosphere and land sinks would be less effective because primary productivity would decrease (NAS, 2015). These processes may replace up to half of the removed $CO_2$ (IPCC, 2013).

## The principle

DACCS seeks to separate $CO_2$ from ambient air (the atmosphere around us), using engineering approaches and store the sequestered carbon in ways that will not contribute to global warming. DACCS includes a family of technologies which use chemical engineering to remove $CO_2$. Air comes or is forced into contact with substances that bind with $CO_2$ in the air. The $CO_2$ is then removed from the substance by, for example, heating the substance in a closed container that capture the gas. This could, for example, be in geologic storage, in a mineralised form with the characteristics of rock. Currently, ambient air contains 413 parts of $CO_2$ per million (NOAA, 2020), meaning $CO_2$ comprises only 0.04 percent (%) of air by volume. Therefore, if large quantities of the gas are to be removed, significant volumes of air must be processed.

A key advantage of DACCS is that it directly captures emissions that are "stored in the air". It is then unlike Carbon Capture and Storage (CCS) technologies which separate $CO_2$ directly at the point of emission (Krekel et al., 2018). This gives DACCS an important advantage – it can capture emissions from both stationary and mobile emitters - in effect the atmosphere transports $CO_2$ from its emission source to its point of capture. Further, because the concentration of $CO_2$ around the world is in equilibrium (Goeppert et al., 2012) the location of DACCS units would not have to be tied to GHG emitting industrial infrastructure. Coupling DACCS to a low-carbon and low-cost thermal source while considering the most proximal utilisation or geological sequestration site allows for the realisation of the lowest-cost, most efficient pathways (McQueen, 2020). DACCS plants could therefore, for example, be near renewable or low emissions energy sources to power the process, over geological formations suitable for storing $CO_2$, and in areas that are neither environmentally sensitive nor densely populated (RS/RAE, 2018). Were nuclear power to be used to supply energy and/or heat for DACCS plants with geologic storage, the energy and heat source would be required to be distanced from plants for safety, diminishing efficiency (see McQueen (2020), for estimates of $CO_2$ storage capacity and appropriate proximity to nuclear facilities).

Safe and cost-effective permanent sequestration of the captured $CO_2$ is essential if DACCS is to have climate benefits. Effective prevention against leakage over the very long term will therefore be essential to maintain net-negative emission. A range of potential sequestration methods have been suggested in the literature (GESAMP, 2019 and IPCC, 2005), including:

- injecting liquid $CO_2$ into the oceans;
- injecting into the seabed, seabed depressions, sediments or trenches; and,
- mineralisation of injected $CO_2$ within geologic structures

## The technique and its readiness

To extract $CO_2$, two approaches receive most attention in the literature. Adsorption, in which a chemical gathers molecules on to its surface from another substance, or absorption, in which $CO_2$ is taken up into the volume of another material, i.e., absorbed. Other emerging approaches include electro-swing, humidity-swing, carbonate looping, and membrane separation (Voskian and Hatton, 2019, Fasihi, 2019, Samari, 2019, Fujikawa et al., 2021, Wang et al., 2013).

Absorption is a well understood process and processes similar to those that would be used in DACCS have been used in the paper industry for over 120 years (Sanz-Pérez et al., 2016). This means the required hardware is commonly available without further development. Processes that would use absorption to remove $CO_2$ would use hydroxide-based solvents. Potassium hydroxide, sodium hydroxide, and calcium hydroxide have been proposed for DACCS (Gambhir and Tavoni, 2019, Daggash et al., 2019). In the processor a carbonate is formed, and the processed air, which is unchanged aside from having a lower density of $CO_2$, is returned to the environment. To isolate the captured carbon and regenerate the absorbent, the energy that binds the $CO_2$ and hydroxide must be overcome. This requires a large energy input of heat at between 900 and 1000°C (Samari et al., 2019). This heat requirement creates a key challenge for DACCS, as discussed below.

Adsorption based DACCS would build on technologies that have been used in air purification systems in hostile environments that have no ambient air, for example, in space craft and submarines. The most cited approach to $CO_2$ adsorption is to use amines derived from ammonia. Amines hold $CO_2$ onto their surface without any chemical reaction taking place. To release the $CO_2$ form the adsorbent the amine is subject to changes in temperature, pressure or humidity (Sanz-Pérez et al., 2016). However, unlike absorption, lower temperatures (approximately 120°C) are required to regenerate the adsorbent, meaning this approach has lower energy input requirements.

Currently DACCS technologies are situated between the pilot plant stage and small scale or prototype demonstration in the field. Conservative assumptions, such as Viebahan et al., (2019), suggest that DACCS is unlikely to be available on a large-scale before 2030. Hanna et el., (2021) have suggested that investing 1.2 to 1.9% of global Gross Domestic Product (GDP) in DACCS would only lead to the removal of in the order of 2 Gigatons (Gt) $CO_2$ per annum. However, financial commentators have suggested that DACCS may be a significant emerging new market and that this is being reflected in recent large investments in the technique's development (Clancy, 2021). This shift toward commercialisation may be reflected in an increasing number of DACCS related patents around the world, which include four each in the United States (US) and Canada, two in China, and one each in Croatia and Mexico. A further three European Patents (EP) and three World Intellectual Property Organization (WIPO) patents have been filed (Viebahn et al., 2019). A summary of selected DACCS developers is in table 1. In addition, a wide range of research is underway (see current research activities below).

Sequestration programmes, for example, the European Union (EU) funded *CarbFix* project and the US *CarbonSAFE* project have demonstrated a viable comprehensive geologic mineralisation process (Carbfix, 2021, CarbonSAFE, 2021). However, considerable further investigation is required before geologic sequestration can be expected, and relied upon to provide sufficient, appropriate $CO_2$ storage,

Before the technologies can be scaled up, some outstanding issues, including energy requirements, the longevity of $CO_2$ storage, and the natural resource requirements, require resolution (RS/RAE, 2018). It is suggested that, in the long term, DACCS has a global sequestration potential of between 0.5 and 5 Gt of $CO_2$ per annum by 2050 (Fuss et al., 2018). However, questions remain about the scalability of DACCS which may not be resolved until new systematic analysis is undertaken, in the light of greater certainty about the technologies and their energy requirements.

Both adsorption and absorption approaches have heat or energy requirements and would require a reliable and secure power supply to provide an air supply through the plant, to reactivate the agents and release the $CO_2$. Absorption techniques have a particularly high energy requirement. Water and a low-pressure vacuum are also required for adsorption DACCS.

Table 1. DACCS developers[1]

| Organisation | Approach | Model | Progress | Current permanency of sequestration | Energy efficiency per ton $CO_2$ | Cost per ton $CO_2$ |
|---|---|---|---|---|---|---|
| Climeworks (2019) | Seeking to capture 1% of global $CO_2$ emissions and permanently storing it as rock or use in horticulture or fuel synthesis. | Adsorption using amine functionalised sorbent. | Nine facilities, currently capturing up to 990 tons $CO_2$ per annum. Has a $CO_2$ removal subscription service. | One facility is using permanent geologic sequestration. The remaining $CO_2$ is being used in greenhouses or the beverage industry. | Thermal energy of 2.3 – 6.2 Giga Joules (GJ) and 200-1000 kilo Watt hours (kWh) of electricity. | In the order of United States Dollar (USD) $590. Target cost under USD $100. |
| Carbon Engineering (2019) | Seeking to capture 1 Million tons $CO_2$ per annum. | Absorption using sodium hydroxide. | 1 tonne (t) $CO_2$/day demonstration plant functioning. Working toward industrial-scale plant. | Exploring use of $CO_2$ in synthetic fuels. Otherwise, not known. | 8.81 GJ of natural gas, or 5.25 GJ of gas and 366 kWh of electricity. | Currently USD $600. |

1 This summary captures information about some leading DACCS developers with nascent techniques, others may be evolving.

| | | | | | | |
|---|---|---|---|---|---|---|
| Global Thermostat (2019) | Seeking to enable profitable re-use of captured $CO_2$ | Adsorption using amine functionalised sorbent. | Commercial demonstration scale products to date. | Not currently permanently stored. $CO_2$ used in greenhouses. | Not known. | Costs expected to be approx. USD $50. |
| Infinitree LLC (2019) | Seeks to concentrate ambient $CO_2$ for enclosed agricultural applications to enhance crop growth rates. | Utilises an ion exchange sorbent material to concentrate $CO_2$. | Not publicly available to date. A free-standing modular system, powered by a 120-volt supply is planned. | Not currently permanently stored. $CO_2$ used in greenhouses. | Not known. | Not known. |
| Skytree (2019) | A European Space Agency spin out developing a system for citizens to produce fuel at home from $CO_2$ and water. Also working with food producers on $CO_2$ enriched environments. | Adsorption and the conversion of $CO_2$ into methanol for storage, heating, or power generation. | Patents awarded and in-house testing in hand. | Not known. Exploring use of $CO_2$ in synthetic fuels. | Not known. | Not known. |

In a meta review of DACCS energy requirements by Daggash et al., (2019) it is suggested that absorption based DACCS would require an energy input of 1500-2500 kilo Watt hours (kWh) for heat and a further 220-500 kWh of electricity per ton of $CO_2$ removed. Adsorbent energy requirements have received less attention, possibly, as suggested by Daggash (2019), because the adsorbent materials are rarely specified in the literature. Climeworks (2019) have, however, provided energy and economic costs estimates including the need for 200-1000 kWh electricity and 640-1700 kWh for heat per ton of $CO_2$. Having extracted $CO_2$, sequestration, in whatever form is chosen, will have some additional energy resource demands. For example, for transportation to, and pumping into reservoirs.

To maximise the net carbon removal potential of DACCS, the energy required would be best drawn from low-carbon, low impact sources such as solar, wind and nuclear power or by co-locating plants with industrial processes that emit waste heat, such as gas power plants. However, the energy requirements for both approaches, in the context of the higher volumes of $CO_2$ removals that will be required, are high.

In 2018 global wind turbine generation was 0.597 Terawatt hours (TWh) (WWEA, 2019). In 2018 the global solar power generation was 0.512 TWh (IEA, 2019). However, the electricity requirements of absorption and adsorption to capture and isolate only 1 Gt of $CO_2$ are estimated at 220 to 500 TWh and 200 to 1,000 TWh respectively, disregarding the required thermal energy (1,000-2,500 TWh and 640-1,700 TWh respectively) and additional sequestration energy costs (Daggash et al., 2019). This suggests, if large-scale DACCS is to rely on renewable energy sources, greater efficiency and a step change in renewables capacity is required. Noting that global nuclear power generation was 2,563 TWh in 2018 (WNA, 2019), an uplift in total global energy provision will be required before climate-altering scale DACCS were to be deployed. In addition to the energy and heat requirements, there are other costs that require consideration, for example:

- water resources – between 1 and 30 $M^3$ of water per ton of $CO_2$ (Climeworks, 2019, Smith et al., 2016);
- natural resources - whilst DACCS does not require biomass and it would not harm ecosystems, a life cycle assessment of DACCS technologies is required (RS/RAE, 2018);
- sorbent replacement costs and other maintenance (Fuss et al., 2018);
- $CO_2$ sequestration costs – including preparation for deposition, transport and, depending on location and type of storage, storage costs; and,
- capital investment and opportunity costs.

In Fuss et al's (2018) meta review of potential DACCS environmental costs, it is suggested that the use of natural gas to provide the required heat, would result in $CO_2$ being emitted into the atmosphere. Therefore, a DACCS plant designed to capture 1 Megatonne (Mt) $CO_2$ per annum, may only avoid a fraction of this due to the emissions generated from the use of natural gas to provide energy to the plant. The use of renewable energy or low-grade waste heat would lead to the maximum amount of $CO_2$ capture (Fuss et al., 2018).

In 2018, the National Academies of Sciences Engineering and Medicine summary of estimated energy requirements for the $CO_2$ removal element of DACCS (NAS, 2018) suggested that the net avoided $CO_2$ emissions, after accounting for emissions from energy use ranged between 0 and 0.99 Mt $CO_2$ per annum.

Estimates of financial costs of scaled up DACCS range widely. For example, Sanz-Pérez et al., estimate costs at USD $30 to $1,000 per tonne of $CO_2$ captured (2016) whilst Fuss et al., (2018) estimate a cost of between USD $100 and $300 per tonne. Small scale pilot projects are currently operating at less than USD $600 per ton (Climeworks, 2020). Estimates vary depending on assumptions about processes, energy and thermal costs and sorbent regeneration. Some estimates include the costs of preparation for and long-term storage of $CO_2$, whilst others include only the costs up to the point of the production of $CO_2$.

In the light of the costs, current carbon prices and the absence of credit for CDR, DACCS may not be commercially viable in the short term (Daggash et al., 2019).

## Current research activities

In addition to the initiatives described in table 1, there is a wide range of ongoing DAC or DACCS related research. Currently, the largest programmatic funding for GHG removal including DACCS is funded by United Kingdom (UK) Research and Innovation, which is committing USD $44 million to the topic over five-years, commencing 2021 (UKRI, 2019) whilst the X Prize Foundation offers USD $100 million to solutions that can remove one ton of $CO_2$ per day and scale to gigaton levels.

At the Arizona State University, a Centre for Negative Carbon Emissions is researching a DACCS process based on an anionic exchange resin. Currently, the estimated costs of the technology are unknown, and the details of the engineering are not, yet, public (Sandalow et al., 2018)

The VTT Technical Research Centre of Finland has demonstrated a system based on an amine-functionalised polymer resin sorbent which is currently removing between 1 and 2 kilograms (kg) a day and further research is on-going (Sandalow et al., 2018) In the US, Oak Ridge National Laboratory has demonstrated a proof-of-concept system using an aqueous amino acid solution (Brethomé et al., 2018).

Looking to the future research agenda, a number of studies have provided an overview of research gaps, or 'needs' (Goeppert et al., 2012, Koytsoumpa et al., 2018, Sanz-Pérez et al., 2016). The Innovation for Cool Earth Forum (ICEF) reviewed the key innovation steps required over the next 20 years in a roadmap for DACCS (Sandalow et al., 2018), Gambhir and Tavoni (2019) identified a need for an understanding of potential environmental and biological effects of rapid large-scale $CO_2$ absorption from the atmosphere and the National Academies of Sciences reviewed the research agenda of the wider field of negative emissions technologies in 2019 (NAS). A reading of these suggests the following are key areas for DACCS research in the future, in no order of priority:

- achieving greater energy, heat and water efficiency;
- developing a better understanding of the sustainability impacts of DACCS;
- resolving remaining carbon cycle uncertainties;
- improving the production of synthetic renewable fuels using captured carbon;
- gaining a better understanding of how to deliver environmentally neutral secure, permanent carbon removal and storage;
- the economics and policy of a DACCS compatible carbon market;
- the social acceptability of DACCS;
- understanding interactions between DACCS and mitigation policy; and,
- global carbon accounting and governance.

## Socio-political considerations

Blackstock and Low (2018) suggest that the social acceptability of DACCS cannot be assumed. Whilst there have been critical reports and analyses of CDR technologies and Carbon Capture and Storage (CCS) (Anderson and Peters, 2016, Thomas et al., 2018), there are no acceptance studies available about the use of DACCS. Nonetheless, it has been suggested that there may be some opposition to DACCS if its deployment is seen to create a form of moral hazard by delaying climate change mitigation efforts (Nemet et al, 2018). Further research on this may be appropriate.

DACCS plants are likely to have a small footprint, compared to medium-sized industrial facilities, and they will not create any threats regarding land availability, including to ecosystems services or food security. Further, because DACCS plants are not geographically constrained, aside from having access to energy and water supplies, facilities need not be in sensitive areas or close to populations. The locating of DACCS plants is not then expected to give rise to significant social acceptability issues, aside from those that arise from the proposals for any medium-size industrial facility, such as issues regarding noise and loss of amenity arising from either the infrastructure or increased transport disruption from carbon removal to offsite storage (RS/RAE, 2018).

Were DACCS to become suitable for large-scale removal it is uncertain to what extent the technology will be accessible for deployment. There may, for example, be constraints arising from patents and intellectual property rights, costs and the challenges of responsible carbon removal and sequestration.

# SECTION II: Governance

## Introduction

DACCS installations will be situated within nation state boundaries and are not currently expected to cause environmental, economic, social and political transboundary harm requiring international governance. This section provides a summary of DACCS governance agenda, for a more detailed review of the issues see Mace et al., (2021).

## Governance issues

If large-scale DACCS were adopted, it will be essential to have transparent monitoring, reporting and verification (MRV) of achieved sequestration in place. This will be required to monitor global progress against climate change targets, and to provide accurate accounting of states' contributions and any carbon sequestration credits that may accrue (Zakkour, 2014). It is unclear how the international community might agree, set and stabilise, over the long-term, atmospheric carbon dioxide concentrations. Nor is it clear how this process, and the outcomes of the decisions taken, can balance the individual interests of nation states with the global need to reduce $CO_2$ concentrations in the atmosphere. These challenges will likely be subject to on-going debate through the UNFCCC and its associated mechanisms.

DACCS raises novel challenges for carbon life-cycle accounting. The $CO_2$ captured by DACCS may or may not be anthropogenic and its origin will be unknown. Further, $CO_2$ captured by DACCS will not necessarily be permanently stored within the capturing country's borders. These issues may affect not only accounting standards, but also industrial standards and practice, financial practice, and regulation.

Removed $CO_2$, which is deposited in geologic sites, or potentially in the oceans will require governance attention (Hubert, 2020) (see GESAMP, 2019 and C2G, 2019 for a review of oceanic sequestration). Currently the transportation of captured $CO_2$ across state boundaries is precluded. Specifically, Article 6 of the London Convention/Protocol creates a de-facto ban on transboundary transport of $CO_2$ for geological storage (IMO, 2016). Although Parties agreed an amendment to resolve this issue in 2009, only eight of the 53 Parties have ratified it and a two thirds majority is required before the amendment can enter into force.

In addition, sequestration permits maybe necessary and injection sites will require ongoing monitoring and management. Questions regarding any future liability for abandoned wells or leakage may also require governance attention.

Choices regarding the use of DACCS will involve trade-offs, for example, in relation to energy, investment, water usage, equity and research priorities (Honegger, 2020). Within the policy context, these trade-offs will be negotiated at the local, regional and global level, where actors are expected to seek to balance the most effective mitigation possible verses securing or maintaining other benefits that the delivery of DACCS might undermine which may include the delivery of the Sustainable Development Goals (SDGs) (for a full discussion of trade-offs and the potential interrelationships with the SDGs see Honegger, 2020). How these trade-offs might be resolved is uncertain. However, Honegger (2020) suggests, the strengthening of capacities for international inter-agency collaboration;

improving understanding of how specific challenges match particular agencies' mandates; and, conducting policy assessments in the context of national mitigation policy planning will play important roles.

It is unclear how the required scale and speed of implementation implied by the IPCC's Special Report (IPCC, 2018) might be achieved and it is suggested that the incentives to secure this rapid change, in terms of new financial and policy options do not yet exist (Florin, 2020). Gross (2018) has suggested some incentive measures, such as support for basic, strategic and applied research, alongside focussed efforts to guarantee the permanency of carbon storage. However, in the light of innovation literature, which demonstrates long time lags and complex social challenges in the innovation chain toward reducing environmental impacts and poverty (Hall et al., 2014), these research investment measures alone may not be sufficient.

Policy and financial support, in the form of subsidies, carbon pricing and support for geological storage, as well as the creation or support of nascent new markets for captured carbon, such as long-duration products or synthetic fuels, may also require multinational governance (Viebahn et al., 2019).

## Current international governance

DACCS is expected to lie under the scope of the UNFCCC, and its associated Protocols and Agreements, because decisions taken under the UNFCCC are used in the construction of the IPCC GHG inventories, which in turn drive how anthropogenic carbon removals are reported.

Provisions in the Kyoto Protocol, which set out how removals will contribute to achieving reduction targets, were not designed to incorporate the large-scale removals that DACCS may have the potential to deliver. A brief overview of how DACCS could potentially be incorporated under the three main international governance instruments, the UNFCCC, Kyoto Protocol and the Paris Agreement, follows

## The UNFCCC

Whilst DACCS is not specifically covered, it could, were the technologies to evolve sufficiently to warrant reporting, be incorporated through changes to Article 4.1(d) of the UNFCCC, or by other amendments to the Convention. Article 4.1 (d) requires all Parties to "Promote sustainable management and promote and cooperate in the conservation and enhancement of sinks and reservoirs of all GHGs not controlled by the Montreal Protocol, including biomass, forests and oceans, as well as other terrestrial, coastal and marine ecosystems" (UNFCCC, 2006). Under this article, States are required to regularly report a national inventory of anthropogenic emissions by sources and critically for the purposes of climate-altering technologies, removals by sinks using comparable methods.

If DACCS were to be incorporated within the Convention, it is expected to create difficulties in establishing appropriate reporting guidelines (RS/RAE, 2018). To be rigorous, the reporting framework would likely be based on the best available science and include a level of detail comparable to those for other processes, such as agricultural emissions.

In addition, any new reporting guidelines will need to address any long-term risks of DACCS, including leakage from storage (RS/RAE, 2018).

## The Paris Agreement

The lack of guidance about the presentation of NDCs under the Agreement, means Parties account for their Contributions in varied ways. This could potentially encumber the capacity to track DACCS removals if they are not reported and, in turn, the absence of DACCS in Parties returns may hide the scale of its uptake and discourage adoption, were it to become available. Certainly, consistent reporting of NDCs would help project 2030 net-emission levels and aid future planning for DACCS, and CDR more widely. Such information gaps could be addressed through the future negotiating processes under the Paris Agreement.

Article 10 of the Agreement commits parties to work collaboratively (under the UNFCCC Technology Mechanism) to collaborate on research and development of new technologies and to facilitate access to technologies in the early stages of their development. DACCS would likely be encompassed by this commitment and may then be expected to be included in the 2023 global stocktake required under Article 14 (2) and any new measures that arise from that.

## Conclusions

The use of DACCS to remove $CO_2$ from ambient air at sufficient scale to affect the global climate would be a major undertaking requiring significant investment, potentially requiring trade-offs. To date the evidence base for the technical and commercial viability of DACCS is limited and significant uncertainties regarding the financial and environmental viability of DACCS exist. Alongside the need for further technical and whole systems research, if DACCS is to ever become a mainstream tool, a range of governance issues require resolution.

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