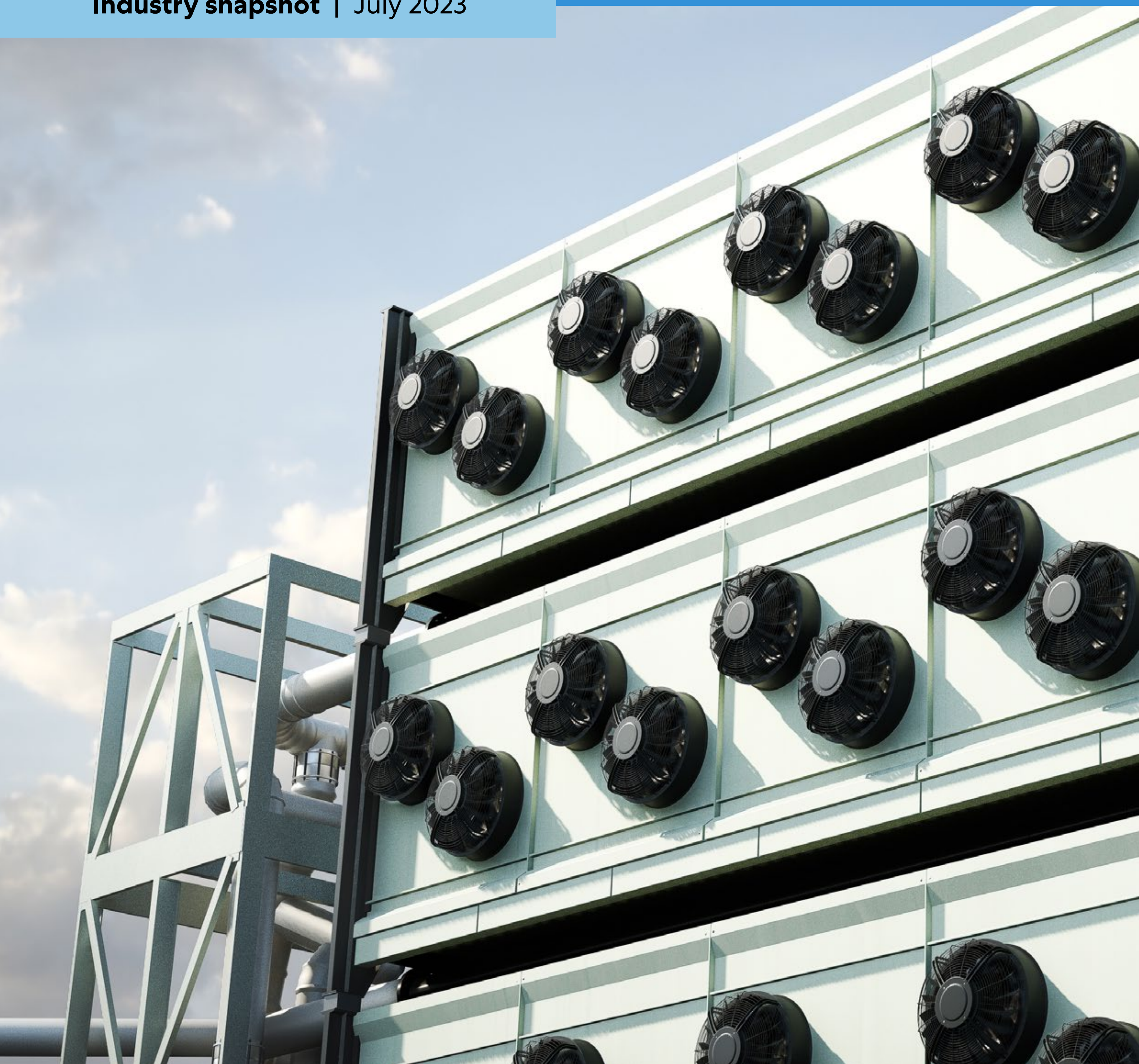
Supercharging carbon removal: a focus on direct air capture technology

Industry snapshot | July 2023



Introduction

Welcome to our third industry snapshot

The direct air capture (DAC) industry is entering a rapid growth phase, as the fourth Climeworks Direct Air Capture Summit recently highlighted. The industry is scaling up through deployment-led innovation from innovators and project developers, an increasing number of customers in the voluntary carbon market, and legislation coupled with demand signals from governments.

In this third edition of the Climeworks industry snapshot, our bi-annual publication focusing on the DAC industry, we feature contributions from scientists, industry and policy experts discussing DAC technology and exploring how it can help to 'supercharge' carbon removal.

First, we explain the technology behind DAC, with perspectives summarizing the different DAC technologies existing today, how DAC works and what it can be used for.

Second, we examine the potential of DAC and storage (DAC+S) as a carbon removal solution, outlining its role within a CDR portfolio. Here, we hear from experts on what life cycle assessments can tell us about DAC's potential as a CDR solution, how scalable DAC is and why its measurability is key to a responsible deployment of the technology.

Carbon removal is key to mitigate climate change in addition to drastic emissions reductions[1], and DAC technology can play a vital role in this. As the viewpoints in the following pages outline, DAC has great potential to supercharge carbon removal as its technological features enable CDR that is highly durable, verifiable and scalable. Rigorous industry standards, investments from the private and public sectors as well as further optimization of the technology will help to unlock DAC's potential in the coming years.

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Adobe Stock. Sunset at Eystrahorn, Iceland.

The fundamentals of DAC technology

How direct air capture works

Maxime Tornier

Head of R&D Programs and NPI, Climeworks

How does direct air capture (DAC) technology work and what can it be used for?

Direct air capture (DAC) is a technology that removes CO_2 from ambient air through chemical processes. Typically, large amounts of ambient air are moved through a DAC system, which contains a filter material (sorbent) that captures the CO_2 molecules in the air. In a second step, the CO_2 is released from the filter and can be collected for further use or sequestration. Different DAC technology approaches exist today, but two main ones have crystallized over the past years: DAC using either solid sorbents or liquid ones.

Solid DAC uses highly porous solid sorbents with a high surface area to adsorb the CO_2 molecules – Climeworks specializes in this approach. Liquid DAC on the other hand relies on a solution to absorb the CO_2. Apart from these two main approaches, alternative approaches exist as well, such as electrochemical processes.

DAC requires different resources for the capture process. For example, it needs energy to release the captured CO_2 from the filter: solid DAC requires low-grade heat of around 100°C, while liquid DAC requires temperatures around 800-900°C. Using renewable energy is important to minimize the grey emissions of the technology and thus maximize the net amount of CO_2 removed. DAC machines moreover require materials such as steel or sorbent.

The two main use cases of DAC are utilizing the aircaptured CO_2 (DAC+U) and storing the air-captured CO_2 (DAC+S).

With the help of DAC+U, e-fuels and e-chemicals can be produced, which will play an important role in decarbonizing the economy.

When DAC is combined with durable CO_2 storage (DAC+S), it is an important carbon dioxide removal (CDR) solution. By removing CO_2 directly from the air, DAC can remove residual and historic emissions and help the world transition to net zero. This is a clear point of differentiation from carbon capture and storage (CCS), which typically captures fossil CO_2 at the point source; therefore preventing new fossil CO_2 emissions from entering the atmosphere. DAC+S, on the other hand, removes CO_2 from ambient air, making for a different outcome compared to emission reductions/avoidance: it removes CO_2 emissions that are already in the atmosphere and subsequently locks them away, resulting in CDR. Figure 1 illustrates the CO_2 flow for DAC+S and fossil CCS.

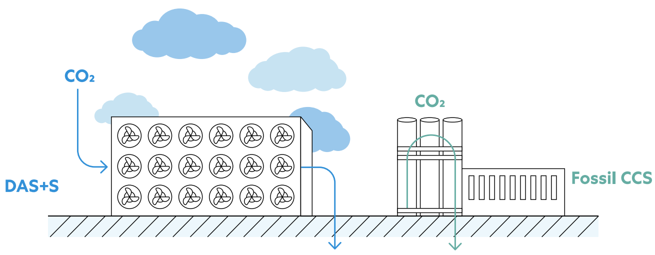


Figure 1: the difference between DAC+S (removal) and fossil CCS (reduction)

The fundamentals of DAC technology

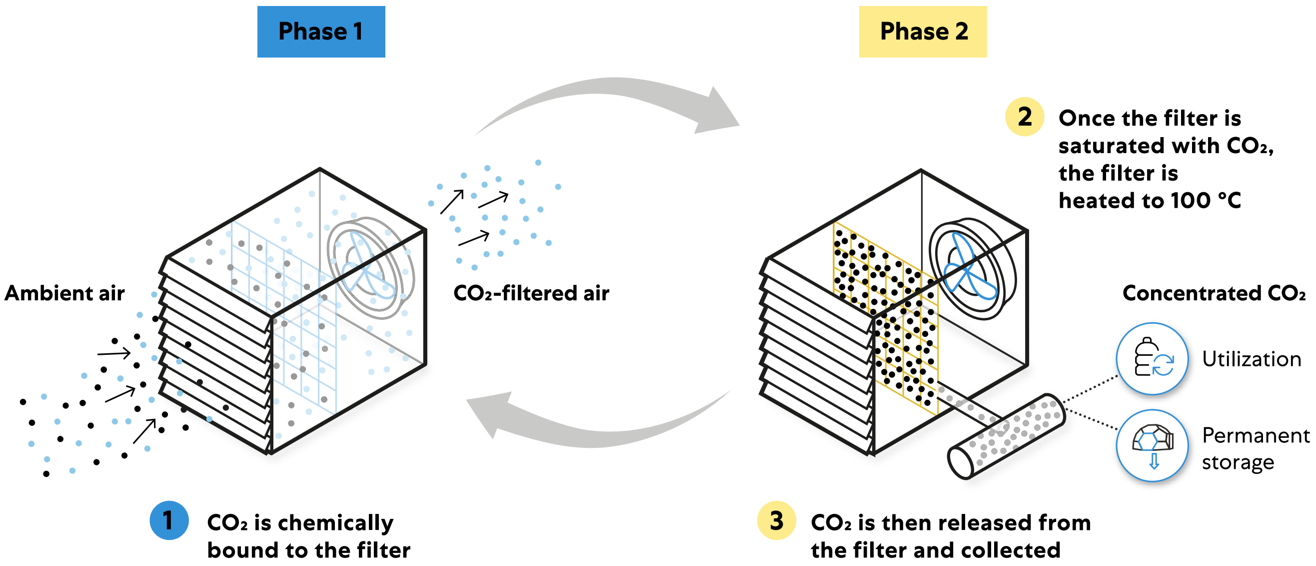
How direct air capture works

How does Climeworks' technology work specifically?

Climeworks focuses its DAC technology on CDR, meaning it combines it with the permanent storage of CO_2. The full DAC+S process can be summarized in three steps:

1 » 2 » 3

1. Air is drawn into the CO_2 collector containers through a fan, where it passes through a solid sorbent located inside the collector that captures the CO_2 molecules
2. When the sorbent is full of CO_2, the collector closes and the temperature is increased to around 100°C, which releases the CO_2 from the filter.
3. Climeworks collects the pure CO_2 and provides it to its CO_2 storage partner for the permanent removal of the CO_2.



In Iceland, Climeworks collaborates with Carbfix who specializes in underground mineralization of CO_2: the CO_2 is pumped deep underground, where it reacts with the local basalt and mineralizes, i.e. turns into stone and is thus permanently removed.

The fundamentals of DAC technology

How Heirloom's DAC technology works

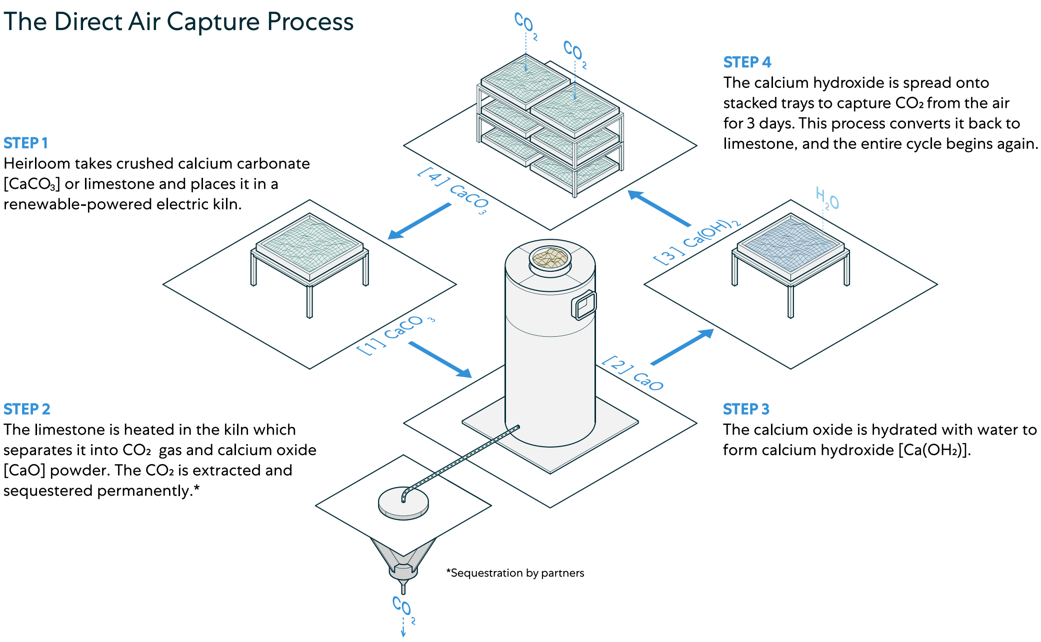
Shashank Samala
CEO, Heirloom

Heirloom is developing a novel DAC technology – how does it work?

Heirloom's direct air capture process uses the world's second most abundant material, limestone (calcium carbonate - $CaCO_3$) to capture carbon dioxide (CO_2) directly from the atmosphere, and then permanently and safely stores that CO_2 so that it doesn't return to the air.

Limestone is made up of calcium oxide (CaO) and CO_2. When CO_2 is removed from the limestone, the calcium oxide wants to return to its natural limestone state. It becomes "thirsty" for CO_2 and acts like a sponge – pulling CO_2 from the atmosphere. Heirloom's technology accelerates this natural property of limestone, reducing the time it takes to absorb CO_2 from years to just 3 days.

Heirloom heats limestone mineral powder in a renewable-energy powered kiln to remove the CO_2. The powder is laid on vertically-stacked trays where well-trained algorithms inform us how to treat the limestone to optimize its ability to uptake CO_2. Heirloom loops limestone mineral powder through the facility to continuously sponge CO_2 from the atmosphere - a cyclic process that not only reduces costs but also reduces how much mineral must be mined.



The fundamentals of DAC technology

Looking at different DAC technologies

Matteo Gazzani

Associate Professor, Utrecht University

> "Gigaton-scale DAC infrastructure must be operational by the net-zero target date, which makes early deployment of commercial DAC technologies essential."

Can you elaborate on the current portfolio of DAC technologies, including their pros and cons?

Recent reports from the Intergovernmental Panel on Climate Change (e.g. IPCC AR6-2023) clearly indicate that achieving global net-zero CO_2 emissions necessitates the large-scale removal of carbon dioxide from the atmosphere, reaching the order of gigatons of CO_2 per year. When contemplating existing and future direct air capture (DAC) technologies, two crucial dimensions should be considered: scale and time of deployment.

In terms of scale, removing gigatons of CO_2 from the air annually would require hundreds of thousands of DAC plants equivalent to the capacity of Climeworks' Mammoth project. In other words, by 2050, each individual on the planet should 'own' a corresponding DAC unit capable of removing hundreds of kilograms of CO_2 per year (IEA-NetZero).

Comparatively, when we examine the provision of clean electricity, the projected 50,000 terawatt-hours per year required by 2050 will not be fulfilled by a single technology, but rather through a combination of various energy conversion routes and technology designs (IEA-NetZero). Similarly, the gigaton-scale deployment of DAC will necessitate the use of diverse technologies.

Considering the time aspect, the gigaton-scale DAC infrastructure must be operational by the net-zero target date, which makes early deployment of commercial DAC technologies essential.

The fundamentals of DAC technology

Looking at different DAC technologies

Looking at the current portfolio of DAC technologies, only a few examples have advanced to an early commercial phase. These solutions have effectively leveraged decades of experience in gas separation processes to optimize the removal of CO_2 from low-concentration sources, while minimizing energy requirements and maximizing productivity. It is not surprising that these solutions predominantly utilize solid sorbents or liquid solvents for the separation process. However, there are two notable differences compared to their use in traditional gas separations. Firstly, the design of contactors has been tailored to handle large flow rates at ambient conditions with minimal pressure losses. Conventional packed columns have been replaced by thin, flat sorbent sheets, monoliths, or cooling towers-like scrubbers in both adsorption and absorption-based concepts. Secondly, the sorbents and solvents employed in DAC separation are either newly developed, such as amine-functionalized solid sorbents, or they utilize multiple loops, as in the K-Ca solvents cycle. Moreover, as the scale of DAC deployment increases, a third key difference becomes more important: the provision of energy for regeneration. Solutions such as electricity-based regeneration and electrochemical-based separations are gaining significant interest as viable methods for providing the necessary energy.

Different DAC commercial technologies come with their own pros and cons. We can say that, unfortunately, there is no one-size-fits-all solution. Liquid-solvent processes, while benefiting from well-established technology suitable for large-scale plants, suffer from the challenge of high-temperature regeneration, particularly in the case of $CaCO_3$ calcination in the K-Ca cycle. Solid sorbent processes benefit of low-temperature regeneration (i.e. higher second-law separation efficiency), enabling CO_2-neutral regeneration through direct coupling with renewables using heat pumps, geothermal energy, or nuclear-based low-temperature heat. However, solid sorbent processes for DAC require further development and consolidation of the industrial ecosystem to provide components and, most importantly, sorbents at scale. Additionally, sorbent degradation remains a significant challenge that needs to be addressed. From a CO_2 productivity perspective, both processes are limited in their outputs, which is inevitable when targeting the capture of CO_2 at parts per million (ppm) levels. However, the solid sorbent route is inherently better positioned to benefit from new sorbents and simple reactor configurations.

In both liquid-solvent and solid sorbent approaches, there is potential for the development of new sorbents and solvents that, when combined with enhanced contactor design, can significantly enhance the performance of CO_2 separation from air. Just as with other modular industrial processes, it is expected that current commercial technologies will continue to evolve and improve in the coming decades. After all, we no longer drive the same automobiles that Bertha Benz used on her first trip to Pforzheim.

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DAC and storage within a portfolio of different CDR solutions

Samantha Tanzer

CDR Research & Technology Manager, Bellona

What distinguishes direct air capture & storage (DAC+S) within a portfolio of different carbon dioxide removal (CDR) solutions?

The purpose of any CDR system is to reduce atmospheric greenhouse gas concentrations by permanently removing more CO_2 than greenhouse gases it emits — and all CDR systems both remove and emit greenhouse gases. Therefore, the critical metric for a CDR system is “net removal”: the amount of atmospheric CO_2 permanently stored minus the amount of greenhouse gases emitted in its processes and their associated supply chains. Estimating net removal, requires life cycle assessment, which becomes more complex as supply chains get longer. DAC+S and afforestation both have the potential to be “small” systems that reduce the complexity of monitoring and verifying their net CDR. In contrast, supply chains for bioCCS can be very complex and cross territorial boundaries, thus complicating monitoring and accounting. But this is only part of the story; all CDR options have their trade-offs.

> “The critical metric for a CDR system is ‘net removal’.”

DAC+S is energy intensive due to the low concentration of CO_2 in the atmosphere but has the flexibility to be located where low-carbon energy and CO_2 storage are co-available, reducing or eliminating the need for CO_2 transport. However, the technology is still in its infancy, and even with ambitious investment, possible scale-up to the gigatonne scale will be decades away.

Where there is available land, well-managed afforestation can provide a more immediate option for large-scale CDR that also has potential co-benefits, such as biodiversity and local cooling. However, the selection of site and species must respect the local availability of water and nutrients and the (changing) climatic conditions. Effective afforestation requires perpetual vigilance to prevent die-back, even after the forest is mature and no longer increasing its carbon stock.

DAC and storage within a portfolio of different CDR solutions

BioCCS is a more complex CDR system that allows grown biomass to be used to satisfy human demand for carbon-based products while also transferring the CO_2 stored by the biomass to more secure geologic storage. In particular, bioCCS on existing point-sources of (partially) biogenic CO_2 (e.g., ethanol production, paper mills, biogas production, waste incineration) can provide an option for near-term CDR that uses industrially available technologies while abating current emissions.

CDR competes with other demands on resources used both by current societal demands and needed by other decarbonisation modalities, including electricity, land, water, biomass, and geologic CO_2 storage space. This competition, paired with the uneven distribution of these resources means that regions will benefit from tailored CDR portfolios that take advantage of what resources are most available. For example, DAC+S would fit well in locations where geologic storage and renewable energy resources are co-located in areas that would be difficult to connect to energy and industry infrastructure, whereas bioCCS is an option for generating removals from pre-existing industrial uses of sustainable biomass.

DAC+S and bioCCS are both options for permanent storage of atmospheric CO_2, which is the only effective way to balance residual and historic emissions of fossil CO_2 and other permanent greenhouse gases.

“ Regions will benefit from tailored CDR portfolios that take advantage of what resources are most available. ”

Unlike bioCCS, the potentially compact nature of a DAC+S system can allow for simpler carbon accounting and higher certainty of net removals. However, any intended use of DAC+S in a CDR portfolio must consider the scaling needs of the technology and requires laying sufficient groundwork in the near-term. This includes investment in the technological learning of DAC technologies; better understanding of other environmental impacts of DAC+S and how to minimise them; the characterisation of geologic storage; and the strengthening and expansion of renewable energy systems.

Whether it includes DAC+S, bioCCS, and/or managed afforestation, any CDR portfolios must fit into a climate change mitigation portfolio that is primarily defined by rapid and drastic emission reduction that minimise their reliance on CDR.

Adobe Stock. Landmannalaugar, Iceland.

LCAs and the carbon removal potential of DAC

Christian Bauer

Scientist, life cycle and sustainability assessment, Paul Scherrer Institut

What is a Life Cycle Assessment (LCA)?

Environmental LCAs are the method of choice to quantify environmental burdens of products and services over their entire life cycle, which includes production, operation and end-of-life. LCAs can be used to quantify greenhouse gas emissions and associated impacts on climate change, but also other environmental burdens such as pollutant emissions and their impacts on human health and ecosystems, as well as consumption of resources such as water, land and metals. Covering the entire life cycle allows for a comprehensive evaluation of the environmental performance of products and services, taking into account emissions due to manufacturing of infrastructure, energy supply, transport services and resource extraction. Thus, it enables unbiased comparisons of alternative options fulfilling the same service.

Why are LCAs relevant in the context of DAC+S and CDR in general?

By quantifying direct and indirect greenhouse gas emissions over the entire direct air capture and storage (DAC+S) value chain with its associated energy supply and infrastructure, LCAs can be used to measure the "net effectiveness" of DAC+S in terms of permanent CO_2 removal from the atmosphere. This net effectiveness represents the "net carbon removal", which is defined as the (gross) amount of CO_2 permanently removed from the atmosphere via any carbon dioxide removal (CDR) method minus the (direct and indirect) GHG emissions associated with the life cycle of the CDR method. A net effectiveness of 100% would be equivalent to zero life cycle climate impacts of a CDR method and represents the theoretical maximum. The time period for which CO_2 actually needs to be removed from the atmosphere to be categorized as "permanently removed" is not clearly specified. While climate science would argue for at least several hundreds and ideally thousands of years, at least one hundred years appears to be common practice in LCAs. According to some regulations, even shorter periods are sufficient.

Beyond quantification of net carbon removal, LCAs can be used to quantify environmental co-benefits and potential trade-offs from CDR. There is a wide range of such side effects – for example, land use and associated impacts on soil carbon and biodiversity, change of agricultural yields, or impacts on water scarcity – and these often depend not only on the specific CDR method to be evaluated, but also on the

LCAs and the carbon removal potential of DAC

local boundary conditions and on the scale of CDR application. Important to note, however: LCA is not the method of choice for quantifying all kinds of side effects and not all of them can be integrated in the LCA framework for the time being.

> “Recent independent LCA studies have confirmed that DAC+S can be considered a very effective CO_2 removal solution.”

DAC+S from an LCA perspective

Recent independent LCA studies have confirmed that DAC+S can be considered a very effective CO_2 removal solution. This holds true for both sorbent-based and solvent-based CO_2 capture processes, if energy needed for CO_2 capture processes is associated with low GHG emissions, i.e. if electricity and heat requirements can be met by renewables. The type of energy supply for the CO_2 capture process determines the net effectiveness of CO_2 removal via DAC+S; other processes and their emissions, e.g. CO_2 transport and injection, are less important.

While sorbent-based processes operate at comparatively low temperatures around 100°C, which allows for the use of solar heat or heat pumps using renewable power, solvent-based processes require higher temperatures around 900°C. In a low-carbon fashion, these can be achieved by combustion of biomethane or by capturing CO_2 emission from natural gas combustion in addition to capturing CO_2 from the atmosphere. As renewables currently and in the foreseeable future are limited resources, renewable energy carriers including electricity used for CO_2 capture processes must not be diverted from other uses, but be supplied in addition. Which means that scaling up DAC+S will also require expansion of renewable energy supply. Thus, certain locations with large potentials for renewable energy are better suited for large-scale DAC+S implementation than others without such renewable potentials.

Compared to other frequently discussed CDR options such as afforestation and reforestation, bioenergy with carbon capture and storage or biochar-to-soil applications, DAC+S has the advantage of both real permanence of CO_2 removal, as it is geologically stored, and very minor environmental trade-offs. Further, it does not compete for agricultural land and biomass resources, which can be used for different purposes.

LCAs and the carbon removal potential of DAC

Sarah Deutz

Chair of Technical Thermodynamics (LTT), RWTH Aachen University

What can LCAs tell us about the potential of DAC as a CDR solution?

The carbon dioxide removal (CDR) potential of direct air capture and storage (DAC+S) depends on the amount of CO_2 captured from the atmosphere subsequently stored and greenhouse gas (GHG) emissions occurring due to energy and material requirements of the entire removal process (e.g., adsorbent production, plant construction, and energy provision for the capture and storage process). Furthermore, DAC+S may induce other environmental issues, in particular, when scaled to climate-relevant levels at the gigatonne scale. Herein, Life-Cycle Assessment (LCA) can contribute by identifying these additional GHG emissions and other environmental issues from all stages of the removal process containing the activities from cradle-to-grave: extraction of raw material, production, transportation, and product use, to recycling and disposal. However, DAC+S is still an emerging technology (currently operating at a pilot scale); thus, data availability remains challenging, e.g., for plant lifetime, potential recycling, future energy efficiency, and solvent/sorbent production and degradation. Thus, an exchange between sorbent producers and DAC experts from academia, industry, and policy is needed to fill these data gaps providing a solid basis to comprehensively consider the total CDR potential and potential side effects at a gigatonne level.

> “Maximizing the CDR potential of DAC+S means reducing GHG emissions in all supply chains.”

What conditions can maximize this potential from an LCA viewpoint (e.g. what role can geothermal energy play, compared to other renewable energy sources)?

Maximizing the CDR potential of DAC+S means reducing GHG emissions in all supply chains, e.g., plant construction and recycling, as well as solvent/sorbent production, use, regeneration, and treatment and, in particular, the energy supply as the main contributor to GHG emissions and most other environmental impacts. Thus, the energy supply should be matched with renewables. However, energy supply, particularly by renewables, will likewise be limited in the future. Further, the energy demand for DAC+S is in addition to actual global demand and competes with other technologies; thus, energy efficiency will remain a major issue in the future. In this context, suitable locations for DAC+S need to be identified with sufficient availability of renewables and appropriate ambient conditions such as temperature and humidity to minimize the GHG emissions and other environmental issues of DAC+S.

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DAC and scalability

A scientific perspective

Christian Breyer

Professor for Solar Economy, LUT University

What features make DAC particularly suitable for scaling?

DAC fulfills the same fundamental criteria as solar PV, batteries and electrolyzers. It is a modular technology that can be manufactured in a highly automated process with acceptable (low) technological barriers. Learning rates of such technologies are typically between 15-25%; thus, fast cost scaling is possible, while highly standardized technical specifications can be achieved. Industrial scaling of such modular technologies is even accelerated, as the industrial manufacturing excellence from solar PV was partly transferred to battery manufacturing but also to electrolyzer manufacturing, and it is highly likely that major industrial players will do so with DAC. There is also an industrial tendency for one-stop shopping, for instance offered by Longi, with expanding the core business from solar PV to electrolyzers to offer green e-hydrogen. It is highly likely that sooner rather than later this will be expanded to green e-methanol and e-kerosene jet fuel value chains, then including DAC. The window of opportunity for start-up players may be closing soon, before huge and extremely powerful renewable technology players will enter the market.

This is a consequence of scalability and the high level of existing manufacturing excellence of highly modular renewable technologies. Thus, start-ups have to accelerate the pace, in particular in identifying profitable niches and growing with these niches for accelerated scaling [2,3].

> “DAC fulfills the same fundamental criteria as solar PV, batteries and electrolyzers.”

Are there limitations to scaling and how can they be overcome?

Yes. There are almost no technical limitations and no manufacturing limitations. The real limitations are lacking policies for enforced CCU quotas using sustainable CO_2 as raw material, as that would push DAC+U, and there are no relevant negative CO_2 emission policies in place. Without clear demand side regulation, markets will not be ramped and thus scaling is blocked. Substantial investments are required for policy advice to ramp the markets now, and, for European players with closed value chains in Europe to avoid repeating industry policy failures of the past, such as for solar PV and batteries with massive value destruction in Europe due to failed industry policy. Such failures have to be avoided right from the beginning.

DAC and scalability

A scientific perspective

> “It is a modular technology that can be manufactured in a highly automated process with acceptable (low) technological barriers.”

How does this compare to other CDR solutions?

First, one needs to distinguish between CO_2 extraction and CO_2 storage, which is too often mixed up. In Integrated Asssessment Models, the entire CDR discussion is handled rather superficially: IAMs bet on simple rainfall-based afforestation, bioenergy CCS, and DAC+S. One model further assumes enhanced weathering, and, they are quite weak in explaining the CO_2 storage, which is too low of a standard. Rainfall-based afforestation is a high risk option given the increasing wildfires around the world (see Mediterranean, US West Coast, Canada, Siberia, Australia, to name just a few), thus, a high risk option. BECCS is in conflict with arable land and global food supply (while the arable land in the world is shrinking since 10+ years) and biodiversity, requires large amounts of water, and is area inefficient as the photosynthesis efficiency is 0.5% at best, last but not least, it is expensive.

Enhanced weathering is limited in volume. Given this, DAC+S remains as a highly scalable option, very area efficient, affordable in the long-term (around 100 €/t CO_2 in 2050), and it does not necessarily need water, while it can be placed in barren land. The geologic storage of CO_2 has to be taken into account, too. Carbon mineralization as done in Iceland is one of the most promising ways forward and we know that the storage potential is higher than 30,000 $GtCO_2$ globally, thus almost abundantly available, in comparison to the less than 2,000 $GtCO_2$ needed for all CDR for a 1.0°C path[4]. In addition, desalination-based afforestation may be also quite attractive, as it can be done in barren land, and it has a bunch of co-benefits, while the cost is around 100-200 €/tCO_2, finally a nice complementary approach to DAC+S.[4 5 6]

DAC and scalability

A policy perspective

Giana Amador

Executive Director, Carbon Removal Alliance

From a policy perspective, how would you describe the scale-up potential of DAC technology (especially in the U.S. context)? Based on this, what role will DAC play in future policy making? How can policy support the further scale-up of DAC?

The scale potential of direct air capture will undoubtedly be proven in the next few years. Today, a large part of delivered, permanent carbon removal comes from direct air capture facilities. These early projects have captured the hearts and minds of US Federal policymakers and have set an example for what high-quality carbon removal can look like for the rest of the field. Major policies passed in the last few years by the US Federal Government, including the updated 45Q tax credit in the Inflation Reduction Act and the $3.5B for the Regional Direct Air Capture Hubs Program at the US Department of Energy, have spurred the development of the world's first million-ton facilities. As these projects come online, they will answer core questions about the technological viability and cost potential of direct air capture, as well as give us critical information on the local community, economic, jobs and environmental benefits and risks of these projects. These projects will also define the public and policymaker perception of direct air capture for years to come.

Moving forward, federal policy can continue to support the future scale-up of direct air capture in a few ways:

1. Continued investments in Research, Development and Demonstration to test new approaches and support technological breakthroughs, bringing DAC down the cost curve,
2. Improved regulatory clarity to ensure that DAC facilities can come online quickly, with strong safeguards and protections in place,
3. Robust first markets created through government procurement and other market incentives,
4. Dedicated support for community education and engagement, as well as funding to drive local job creation and community wellbeing.

Together, these types of policies can serve as a launchpad for a thriving, gigaton-scale direct air capture industry that serves the climate and communities across the globe. Direct air capture is one powerful tool in a full portfolio of carbon removal solutions that is needed to meet our climate goals.

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Integrity through measurability

The view of a verification body

Edwin Alders

Senior Principal Scientist, Low Carbon Technology, DNV

Sam Dresner Barnes

Sustainability Consultant, DNV

> “For technologies such as DAC, additionality is relatively straightforward as a business-as-usual case would simply be not removing carbon dioxide from the atmosphere in the first place.”

DAC is often described as being measurable and additional – can you explain what this means?

Additionality and measurability are two of the five principles which underpin any carbon dioxide removal (CDR) programme wishing to generate and sell credits within the voluntary carbon market. These principles exist as a mechanism to make certain that all carbon credits represent genuine, quantifiable GHG emissions reductions or removals.

Additionality is a defining concept in CDR, it seeks to ensure that emissions removals or reductions exceed a business-as-usual case. In other words, reductions or removals which would have happened even in the absence of the activity, such as those that are mandated by regulation or those which occur through mechanisms that are common-practice.

In some projects, additionality can be hard to prove due to its counter-factual concepts and principles, as such of variety of tools have been developed which market participants can use to demonstrate that their project is additional. However, for technologies such as direct air capture (DAC), additionality is relatively straightforward as a business-as-usual case would simply be “not removing carbon dioxide from the atmosphere in the first place”. Also, due to DAC’s energy demand, energy balances must be considered as a project must ensure that it is removing more emissions than those that are created through its operation process. In order for DAC processes to be impactful, its energy demand should principally be covered by renewable sources.

Integrity through measurability

The view of a verification body

Another way in which CDR projects seek to create genuine carbon credits is to make sure the removal or reduction can be quantified (i.e., be measurable and real). DAC is underpinned by known, clearly defined chemical processes, occurring within a relatively closed environment where processes can be contained and controlled, thereby reducing the variables that may influence the outcome. It is the cumulation of these factors that make DAC measurable, evidenced further by the fact that the process contains different monitoring events which utilize calibrated measurement devices, that provide records of adsorption, injection, and other parameters essential to assure the efficiency and performance of the process.

Why and how are measurability & additionality relevant to a verification body such as DNV?

It is the role of auditors and third-party verifiers to ensure that DAC projects follow these principles, in order to verify an emission reduction or removal has occurred and subsequently a carbon credit can be generated. These principles are subsumed within standards which ensure that CDR programmes deliver environmental benefits and can demonstrate quantifiable results. Both DAC operators and third-party verifiers rely on clearly documented criteria within project methodologies, whereby the criteria are transparent, and accurate. Existence of these clear criteria both help the DAC operator to efficiently document its operations and the third-party verifier to implement an efficient and transparent verification.

> “DAC is underpinned by known, clearly defined chemical processes, occurring within a relatively closed environment where processes can be contained and controlled.”

Integrity through measurability

A policy perspective

Chris Sherwood

Secretary General, Negative Emissions Platform

The measurability of DAC is essential for the monitoring, reporting and verification (MRV) of CDR produced by the technology. How do you view the role of MRV for DAC developers?

In the short time I have spent at the Negative Emissions Platform (NEP), I have already noticed some key differences separating the carbon dioxide removal industry from that of the technology sector, where I worked for the last 13 years.

One of the most visible differences is in the importance that carbon removal founders and CEOs understand public policy has for their business. While the first policy-focused role for a tech company would likely be advertised after several funding rounds and an existing headcount of thousands of employees, CDR companies often cover policy work with their very first hires. This is because tech company leaders see regulation as friction and a cost that does not add direct value to their business. “MRV,” for instance (Measuring, Reporting and Verification within the CDR industry) within a tech context would typically be investor-focused and consist of monthly unique user numbers and related business metrics.

By contrast, CDR founders can see that MRV is foundational to their business. This is because it addresses three critically important stakeholder communities.

The first is government. CDR is an activity that does not lend itself to individual or community action – it is of interest to governments because of the global nature of the problem it helps tackle. Therefore, it is states, and not just consumers, who are going to drive the growth of the industry. Of course, there are two sides to this coin; states are going to be both producing the rules and regulations that define the industry, as well as offering the subsidies that will make large-scale CDR possible. Government’s interest in MRV is ultimately based on its need for budget and political accountability.

A second key stakeholder community is investors. Many investors in CDR are looking for long-term profits, with the expectation that the industry will grow to an enormous size in the next 25 years. All investors in CDR can see that climate impact is the product. Both drivers point towards MRV as a key proof point for investment into a CDR business idea.

The third is civil society, in its broadest sense. Whether it is local communities affected by the construction of CDR facilities, environmental NGOs looking at biodiversity and climate impact, investigative journalists looking to unearth greenwashing, or members of the public who want to understand how they can contribute to the resolution of our climate emergency, MRV that is easy to understand, scientifically sound, and communicated clearly will be the most important condition for credibility.

Lack of accountability, of awareness of societal impact, and moral credibility are weaknesses that are existential threats to tech giants today. MRV is our tool to ensure that they are not the undoing of CDR tomorrow.

Giana Amador

Executive Director, Carbon Removal Alliance

Giana Amador is the Executive Director of the Carbon Removal Alliance (CRA). CRA unites carbon removal innovators to advance policies that support a diverse set of permanent carbon removal technologies. In 2015, Giana co-founded the first dedicated carbon removal organization, Carbon180. At Carbon180, Giana wore many hats — from guiding the team's strategy and communications to ultimately leading its policy program. During her time as policy director, Giana advocated for landmark carbon removal policies, including the $3.5 billion for direct air capture hubs in the Bipartisan Infrastructure Law and the first-ever dedicated carbon removal research program in the Energy Act of 2020. Giana has provided testimony before the House Natural Resources Committee and advised presidential campaigns on carbon removal.

Her past research focused on the political economy of renewable energy, with an emphasis on green industrial policy and coalition building. Giana was named to the Forbes 30 under 30 list in 2022 and one of Entrepreneur's 100 Most Influential Women. She holds a degree in Environmental Economics & Policy from UC Berkeley.

Edwin Aalders

Senior Principal Scientist, Low Carbon Technology, DNV

Mr Aalders is the Senior Principal Consultant within DNV Research group with over 20 years of experience in International Climate Change negotiations & Carbon markets mechanisms working with key multilateral organisations such as the UNFCCC, UNEP, Green Climate Fund, European Commission, World Bank & Climate Technology Centre & Network (CTCN) and national and international companies.

Mr Aalders has lived and worked in Europe, Africa, Asia Pacific, Latin America and is member in variety of advisory boards and steering committees of organisations that aim to develop new programmes under the umbrella of Climate Change and the UN SDGs.

Christian Bauer

Scientist, life cycle and sustainability assessment, Paul Scherrer Institut

Christian Bauer is researcher in PSI's Technology Assessment group and manages LCA related activities of the group. He has more than 20 years of professional experience in LCA, mainly focused on energy supply and systems, low-carbon fuels, mobility, energy storage and carbon dioxide removal. His group develops methods and tools for advanced prospective LCA and linking LCA with Integrated Assessment and energy system models. He is the principal investigator on several Swiss and EU funded research projects, including CDR related ones. He is also member of the board of the ecoinvent association, which develops and operates the world's leading LCA database.

Christian Breyer

Professor for Solar Economy, LUT University

Christian Breyer is Professor for Solar Economy at LUT University, Finland. His major expertise is the integrated research of technological and economic characteristics of renewable energy systems specialising in energy system modeling for 100% renewable energy, on a local but also global scale. Publications cover integrated sector analyses with power, heat, transport, desalination, industry. The Power-to-X Economy comprises most of his research and 1.0ºC pathways are increasingly investigated in addition to the 1.5ºC standard.

Sarah Deutz

Chair of Technical Thermodynamics (LTT), RWTH Aachen University

Sarah Deutz pursues her Ph. D. thesis at the Institute of Technical Thermodynamics from RWTH Aachen University on the life-cycle assessment of low-carbon technologies considering development and deployment scales. She uses modeling approaches from screening to an integrated energy system design. In this context, she focuses on low-carbon technologies such as Carbon Capture Utilization and Storage, Carbon Dioxide Removal, and Power-to-X, assessing their potential contribution to decarbonization strategies.

Since 2020, Sarah has led the Energy System Engineering - Life-Cycle Assessment research group. The research group focuses on method development for assessing and designing sustainable systems in energy and process engineering. Model-based and computer-aided methods are used to analyze and design such systems to be reliable, efficient, flexible, and sustainable. For mathematical method development, basic principles of thermodynamics are used to evaluate and improve energy systems on different levels: from molecules over industrial production processes to multi-regional energy systems. In addition, technologies and systems are evaluated based on life-cycle assessments to identify environmental tradeoffs and burden-shifting considering planetary boundaries.

Sam Dresner Barnes

Sustainability Consultant, DNV

Sam is a Sustainability Consultant at DNV specialising on the validation and verification of carbon dioxide removal and reduction programmes against the ISO 14064-2 Standard. Beyond this Sam works frequently on green finance projects with a focus on the EU Taxonomy, he also conducts life-cycle assessments and assurance of non-financial reporting data. Sam's background is in environmental biology and marine ecology, he holds a bachelor's degree with Honours from the Bournemouth University, and a Masters in Sustainability and Leadership from the University of Huddersfield.

Matteo Gazzani

Associate Professor, Utrecht University

Matteo Gazzani is associate professor at the Copernicus Institute of Sustainable Development, Utrecht University; he is also part-time faculty at Eindhoven Technical University, Faculty of Chemical Engineering and Chemistry. He received his B.Sc. and M.Sc. in Energy Engineering from Politecnico di Milano, where he also obtained his Ph.D. cum laude in Energy and Nuclear Sciences and Technologies. Prior joining Utrecht University, he was a postdoctoral fellow at ETH Zurich, where he started working on direct air capture. His overarching goal is to facilitate the transition to a climate neutral society via cutting-edge research and inspiring education. His research focuses on improving the design and understanding of new chemical and energy processes by bridging fundamental sciences to the process and system level analysis.

Shashank Samala

CEO, Heirloom

Shashank Samala is CEO of Heirloom, a company building Direct Air Capture technology to permanently remove a gigaton of carbon dioxide from the atmosphere by 2035. Prior to Heirloom, Shashank founded Tempo, a software-accelerated electronics manufacturer.

Chris Sherwood

Secretary General, Negative Emissions Platform

Chris Sherwood is Secretary General of the Negative Emissions Platform, the trade association for the carbon dioxide removal industry. After starting his career in IT systems implementations with PwC in London, he worked in a range of Brussels-based public policy roles for over 20 years. This includes stints in consultancy, the US government, and then 13 years in-house in the tech sector: first at Yahoo and then a series of e-commerce companies affiliated with Naspers, the South African tech investor, where he held global roles. Chris was one of the first tech sector policy professionals in Brussels, and when he joined NEP in November 2022, he was the longest-serving. He saw through landmark pieces of Internet regulation such as the GDPR, Digital Services Act, Digital Markets Act, as well as two major antitrust cases against Big Tech. Chris has UK, French, and US citizenship and holds Masters degrees in German and European Studies.

Samantha Eleanor Tanzer

CDR Research & Technology Manager, Bellona

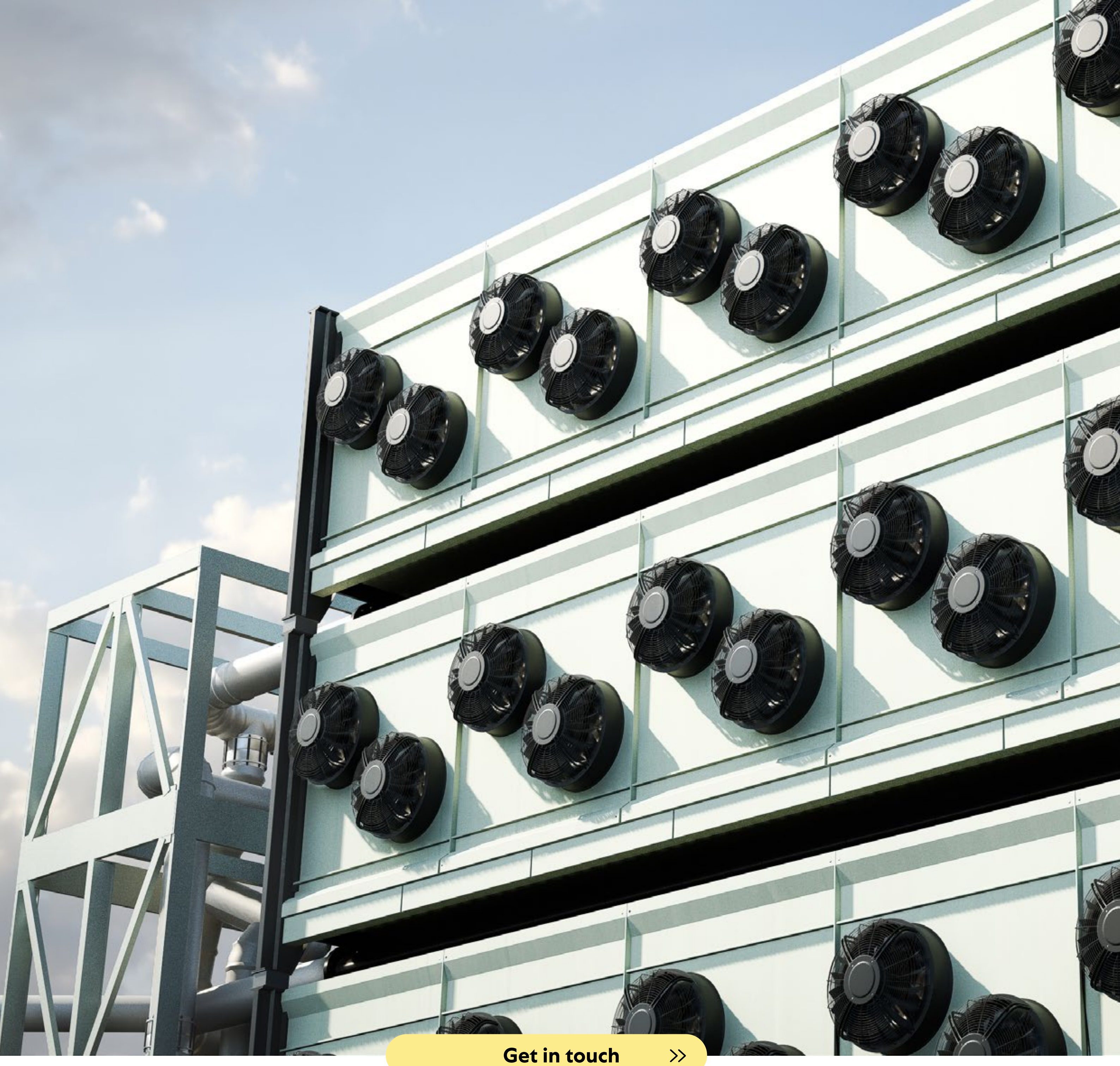
Dr.ir. Samantha Eleanor Tanzer is consulting as the CDR Research and Technology Manager at Bellona Europa, a solutions-oriented climate policy NGO in Brussels, where she advises policymakers on the complexities of CDR systems and greenhouse gas accounting. She also leads research on the governance of CDR for the NEGEM H2020 project, which seeks to identify realistic deployment pathways for negative emissions technologies and practices.

Dr. Tanzer received her PhD on "Negative Emissions in the Industrial Sector" from Delft University of Technology, where her researched focused on life cycle assessment, temporal issues, and cost metrics for the use of biomass and CCS across several industrial sectors. She holds a MSc in Industrial Ecology jointly from the Delft University of Technology and Leiden University and a BA in Economics from Swarthmore College.

Maxime Tornier

Head of R&D Programs and NPI, Climeworks

Maxime Tornier is the Head of R&D Programs and New Product Introduction at Climeworks. He received his M.Sc in Engineering from Ecole Centrale de Lille (France) and an M.Sc in Aerospace Engineering from Cranfield University (UK). Prior to joining Climeworks, Maxime worked at Airbus and Dyson in early research. In his current role at Climeworks, he manages the development of new technologies and products, ensuring the timely delivery of new innovations into the company's plant execution roadmap.



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