CLIMEWORKS

Motivating scope extension to include Carbon Dioxide Removals via Direct Air Capture and Storage

17.08.2020

Content

Executive summary

In response to the Gold Standard consultation on operationalizing and scaling the post-2020 voluntary carbon market, Climeworks advocates for a scope extension to include Direct Air Capture and permanent storage (DACS), a technology-based Carbon Dioxide Removal (CDR) solution. In particular, a distinct technically readily available DACS technology with further reduced impacts and simplified monitoring is presented: the combination of Direct Air Capture and rapid in-situ carbon mineralisation (DACM). This contribution to the consultation shows that DACS activities implement the Gold Standard's vision and mission towards averting climate emergency and achieving the Sustainable Development Goals in practice.

Climate science, a key guidance for the Gold Standard, urges the need for large-scale CDR as a complementary tool to large-scale emission reductions in order to balance residual emissions and to avoid overspending the global Greenhouse Gas (GHG) emissions budget. DACS represents a scalable and inherently transparent CDR solution with minimal environmental impact. The amount of CO_2 removed can be metered as a physical stream and the determination of project emissions is straightforward as they predominantly stem from material and energy consumption.

A key co-benefit of DACS solutions is the location independence of the capture step due to the ubiquitous availability of air as the primary feedstock. In combination with the large and well-distributed potential for CO_2 storage globally, DACS implementations can be located in regions with prime renewable energy potentials with limited economic development and create synergies with the development of renewable energy generation. Furthermore, as a scalable

CDR option, DACS provides a realistic, low- impact avenue for negative emissions and, unlike geoengineering techniques and their potentially unpredictable effects, it does not alter natural systems. It is an invaluable and complementing solution to avoid using nature-based CDR solutions beyond sustainable limits generally avoiding competition with land, water and nutrients needed for the production of food and preserving ecosystems and biodiversity.

DACS is technically feasible as demonstrated by long-standing geological CO_2 storage and a growing number of DAC plants, as well as by an integrated solution demonstrated by Climeworks and Carbfix in Iceland. Here, geothermal energy provides electricity and heat to power a DAC unit and the CO_2 is stored in the geothermal reservoir applying the Carbfix method for rapid in-situ carbon mineralisation. Prior experience allows regulating remaining risks to lowest levels and corresponding standards and legislation exist, e.g. the EU CCS Directive.

DAC offers potential for further and substantial cost reductions through technological improvements and through economies of scale. A rapid scale-up is needed if the technology is to reach indispensable scales of several gigatons of CO_2 by 2050, allowing for a significant contribution to the large amount of CDR required by most climate models in order to enable a 1.5–2°C warming path. The installed capacity should grow by 55% per year starting today. While market demand for DAC-based CDR exists through individuals and organizations, who are looking for a transparent and metered approach to CDR, certification through the Gold Standard will ensure that implementations to meet this demand will be realized in the most sustainable way.

1 Introduction

To halt climate change, the world must cut emissions drastically *and* actively remove CO_2 from the air

The challenge: Limiting global warming is one of the major challenges humanity faces in the years and decades to come. It is now apparent that conventional emission reduction alone will not be enough to reach necessary international climate goals. The reason is, that we have already emitted too much CO_2 to be able to decarbonize fast enough. In order to reach net-zero emissions, residual emissions need to be balanced by negative emissions, as shown by Figure 1.

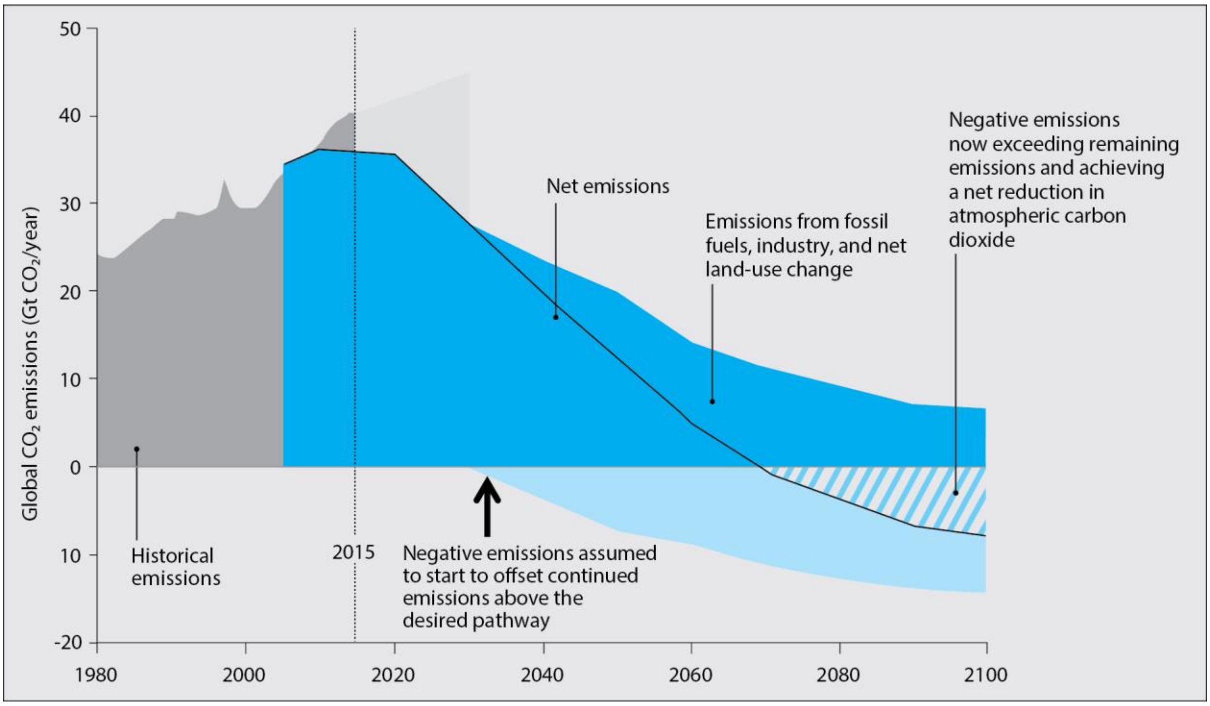

Figure 1: Exemplary emission pathway in accordance with the 2°C target (black line). In order to reach net-zero emissions, residual emissions need to be balanced by negative emissions, i.e. CDR. Towards the end of the century, the negative emissions exceed the residual emissions and a net-removal of CO_2 from the atmosphere is achieved. Figure adapted from EASAC.[1]

All integrated assessment models (IAMs) that reach the 1.5°C target in the corresponding IPCC special report consider approaches that remove CO_2 from the atmosphere, i.e. Carbon Dioxide Removal (CDR).[2] The extent at which the different models apply CDR depends on the pace and extent of emission reductions and reaches values ranging from 100 to 1000 Gt of CO_2 by the end of the century. As a minimum, CDR is required to balance residual emissions in the long term.

Even IAMs that limit global warming to below 2°C assume CDR capacities of 2 to 10 Gt/year by 2050, corresponding to 5-25% of the 2010 CO_2 emissions.[3] This means that in addition to the exploitation of conventional mitigation strategies, the fast development of reliable large-scale CDR approaches is vital to achieving the climate target set forth under the Paris Agreement.[4]

The European Commission[5] as well as the US authorities[6] recognize CDR, or negative emissions, as a prerequisite to achieve their strategic long-term vision of a carbon-neutral Europe and a deeply de-carbonised US, respectively, by 2050. Five out of nine scenarios and

notably all of the 1.5°C scenarios in the European long-term strategic vision include large-scale Direct Air Capture (DAC). The DAC contribution is quantified at between 83 and 264 million tons of CO_2 per year by 2050.[5] As discussed in Section 3, DAC technologies extract CO_2 directly from the ambient air. Associated with CO_2 storage, then also known as DACS or DAC-based CDR, it provides a realistic, low-impact avenue for negative emissions and, unlike geoengineering techniques and their potentially unpredictable effects, it does not alter natural systems.

CO_2 storage via mineral carbonation aims to accelerate a natural process – the vast storage of carbon in rocks over millions of years – at a rate fast enough to contribute to climate-change mitigation. With this approach, the captured carbon is stored through its dissolution and injection into reactive rocks, such as mafic or ultramafic formations, for rapid mineralisation of the injected CO_2 to stable carbonate minerals.[7] This has already been developed and demonstrated within Carbfix on the scale of kt per year.[8]

While it is acknowledged that progressive industrialized economies may have to demonstrate CDR technologies at scale,[9] future implementations will increasingly rely on the local availability of renewable energy and CO_2 storage, resulting in opportunities for developing economies. DAC, in particular, profits from the ubiquitous availability of its central feedstock – i.e. air – which allows to make use of local opportunities for low-carbon energy supply, for example from solar, wind or geothermal energy. Large-scale CDR implementation will foster investments in local energy infrastructure and provide jobs and education with a long-term perspective. The geological CO_2 storage potential via carbon mineralisation exceeds the projected requirements by orders of magnitude and is distributed across the world within mafic and ultra-mafic formations, such as basalts and peridodites, which make up most of the oceanic floor and about 5% of the continents in addition to the CO_2 storage potential present in sedimentary basins.[10,11]

The time is right: Society and public debate, economy, and politics benefit from a demonstrated solution for scalable DAC-based CDR

Recently, climate change is rapidly gaining attention worldwide as the consequences of global warming become increasingly evident. Widespread and frequent extreme weather events, withdrawing and disappearing glaciers, frequent coral bleaching, record-low sea ice levels and ever-increasing average temperatures have sensitized large parts of the global population. Especially the younger generations make their voices heard, as demonstrated by the worldwide “Fridays for Future” movement. Climate change now heavily impacts people’s decisions as voters and customers. Politicians and corporations are struggling to present solutions that demonstrate their serious will to mitigate climate change while avoiding disruptive effects on price levels and unbearable consequences for less well-off societal segments.

Figure 2: The time is right. Climate change is rapidly gaining attention, as demonstrated by the worldwide "Fridays for Future" movement. Picture: Michael Kappeler/DPA.

The Gold Standard acknowledges climate science as the 'north star' for its development of rules and principles for carbon markets.[12] Climate science clearly states the need for CDR at a scale of gigatons of CO_2 per year, as described above. The argument that unrealistic hopes in future CDR technologies will postpone emission reductions today is backward-looking in the sense that these hopes have already been created. There is scientific evidence that large-scale CDR will be needed to at least balance residual emissions in the long term – even under the more and more unrealistic assumption that determined mitigation policies are set forth early and rapidly enough to avoid exceeding the emission budget. Additionally, thermodynamics dictate that separating CO_2 from the extremely dilute concentration in the air is energetically costly. It is definitely more costly than separating it from concentrated sources and – in the majority of cases – more costly than avoiding the generation of the CO_2 in the first place. CDR technologies are therefore not a substitute for rapid emissions reductions but necessary complementary solutions.

In this sense, adding a scalable CDR technology to the portfolio of climate change mitigation options facilitates the public and policy debate by adding an indicative price tag to further delaying determined emission reduction actions. It extends the climate change mitigation responsibility to organizations, countries and individuals claiming to cause "unavoidable emissions" by providing a readily available solution for balancing or reversing such emissions. Promoting such developments through the carbon markets would provide organizations with a transparent and metered tool to fully address their production-related emissions and offer carbon-neutral products whilst contributing to the achievement of sustainable development goals – an opportunity for differentiation in the market. It may even help to address questions of equity stemming from historical carbon debts. Investments in the development of DAC technologies are urgent, if they are to reach the projected scale of several gigatons of CO_2 per year. To achieve such scale-up in three decades, the required growth rate is 55% per year starting today. A delay until 2025 would increase the required growth rate to 80% per year.[13]

In the following, we demonstrate why DAC-based removals should be part of the portfolio of CDR solutions considered by the Gold Standard. In particular, we propose a subset of DAC-based removals with minimized risks, increased transparency and a range of co-benefits for inclusion in the Gold Standards' scope: the combination of solid-sorbent-based DAC and carbon mineralisation via the Carbfix method for save and permanent CO_2 storage.

2 CDR overview

There are different approaches that have the potential for net removals of CO_2 from the air. The most prominent ones are:

- **Forestry:** Large-scale tree plantations (afforestation/reforestation) to increase carbon storage in biomass and soil.
- **Soil organic carbon:** Improved agricultural practices lead to higher soil organic carbon stocks.
- **Blue Carbon:** Ocean / Water based practices to remove carbon from the atmosphere (e.g. mangroves / algae).
- **BECCS:** Bioenergy in combination with CO_2 capture and permanent storage
- **Enhanced weathering:** Distribution of silicate rocks on soil surfaces to bind CO_2 chemically
- **DACS:** Direct Air Capture of CO_2 and permanent storage

Figure 3 schematically outlines a comparative assessment of prominent CDR solutions using the criteria land requirement, water requirement, estimated costs, and impacts on the environment beyond effects on the greenhouse gas inventory. Due to the inherently different nature and the early stage of development of these CDR methods, the comparison has to rely on simplifying assumptions. Hence, the quantitative results admittedly contain significant uncertainty. Nevertheless, the analysis highlights key differences and important trends that are rooted in fundamental differences and are robust with respect to quantitative changes in the assumptions.

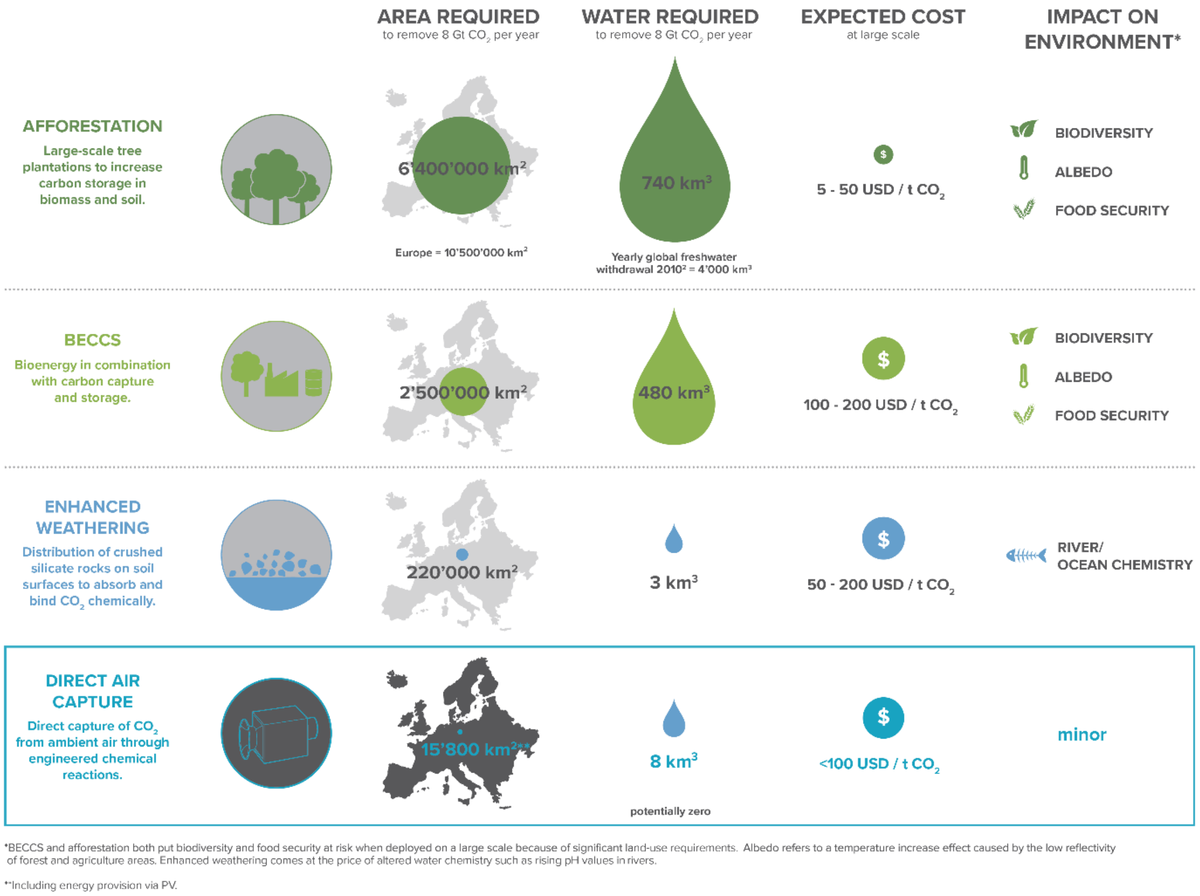

Figure 3: Comparison of CDR approaches removing 8 Gt of CO_2 per year. DACS shows inherent advantages as regards area[14] and water[15] requirements and only minimal impacts on the environment. DAC water requirements are based on conservative estimate of 1 t per t of CO_2.Cost estimates are based on scientific literature[16] and Climeworks' cost target for large-scale plants.

Already today, forests capture large amounts of anthropogenic CO_2 emissions from the air. Increasing this carbon storage through afforestation is a cheap and available solution. Nevertheless, its potential is limited, because just like BECCS it competes with land, water and nutrients needed for the production of food. DACS is able to provide important CDR capacities in addition to these biogenic alternatives.

DACS' water consumption is orders of magnitude smaller than that of biomass-based solutions and is not part of the physical working principle of the method, contrary to what is the case for enhanced weathering. Furthermore, DACS does not depend on arable land, has a minimal physical footprint and can hence be scaled to capture gigatons of CO_2. Biodiversity or ecosystems are not affected and there is no possible reverse effect on climate change once the CO_2 is permanently removed from the atmosphere through underground mineralisation.[4]

DAC-based CO_2 removal provides a realistic perspective towards fulfilling the net-zero emission ambition beyond biomass-based solutions. The availability of scalable technology-based alternatives helps to avoid the use of biomass, land and water resources beyond sustainable limits and thus helps preserving and restoring ecosystems and biodiversity.

3 DACS is a key component in the portfolio of solutions

DAC technology is able to capture CO_2 directly from the air. The process selectively captures CO_2 molecules, while all other constituents of air pass through. There are important technological differences compared to capture processes for concentrated sources due to the relatively low concentration of CO_2 in air (about 400 ppm or 0.04% compared to typically 3-20% for concentrated sources).

In order to bind CO_2 effectively, despite the low concentration, active materials with a strong affinity for CO_2 are required. Two fundamentally different designs have been developed. Both follow a cyclic approach, where the active material is loaded with CO_2 in a first step and regenerated in a second step in which the CO_2 is released.

- **Absorption** processes use strongly alkaline *liquid solutions* to bind CO_2. In a second step, the resulting CO_2-rich solution has to be treated to recover the solvent, which can then be reused, and CO_2 at high purity.
- **Adsorption** processes use functionalized, *solid sorbent materials* with high surface area to which the CO_2 binds. In a second step, the sorbent is regenerated and the CO_2 is released at high purity.

Energy is required (i) to bring the active material into contact with large volumes of air – typically in the form of electric energy that drives a fan – and (ii) in the regeneration step – typically in the form of heat.[17] In order to enable net removals of CO_2 within a life-cycle perspective, the specific CO_2 intensity of the energy must be low. The electricity demand can be covered by renewable electricity directly, e.g. from wind or solar sources. Adsorption processes can be designed to work with low-temperature heat as the main energy input. This characteristic makes them ideal candidates for an integration with geothermal energy, which can cover the heat demand through highly efficient direct use of the geothermal heat, as well as the electricity demand with continuous availability.[18] Low-temperature heat can also be sourced from solar thermal technologies, from renewable electricity via heat pumps, or as excess heat from existing industrial plants.

In adsorption-based DAC processes, most sorbent materials co-adsorb water from air humidity, and hence, provide the theoretical potential to co-produce water. Further research is required to demonstrate that DAC processes can provide water as a resource effectively, which is why we present a conservative view in this text. In fact, current research aims at minimizing water adsorption for energetic reasons. In some implementations, process consumptions of water exceed the co-produced amount of water. Stringent reporting requirements for water consumption in corresponding DACS methodologies for Gold Standard certification should suffice to avoid overutilization of water resources.

Geological CO_2 storage

The storage of CO_2 in climate-relevant amounts requires vast volumes that are durable in geological timescales and effectively keep the CO_2 separated from the atmosphere. Geological formations provide such volumes in the form of microscopic pore structures in various types of rock. The techniques that enable the storage of CO_2 deep underground have been developed and used for decades in geothermal energy and, although for very different purposes, in the oil and gas industry. CO_2 storage has been proven to be technologically feasible and can also be economically viable.[10,19] The most common approach is to inject pure CO_2 in the liquid or supercritical aggregate state into natural reservoirs in sedimentary basins at depths exceeding 700 m. In such systems, the CO_2 is initially physically trapped below an impermeable cap rock, some of which becomes trapped in small pores and, over time, dissolves in the saline formation water and reacts with the subsurface rocks to form stable carbonate minerals. As the storage progresses, the CO_2 becomes more immobile, increasing the security of storage and decreasing the reliance on the efficacy of the cap rock.[19,20] While proper characterization of the geological reservoir prior to CO_2 injection is mandatory to ensure containment by the cap rock, it is conceptually wrong to assume a typical and steady leakage rate. Geological CO_2 storage is meant to be permanent by design, leakage only occurs in the case of unexpected failure. The (low) risk of leakage occurs mainly while CO_2 is injected and further decreases with time.[19,21] Where the mineralogy of the reservoir allows for complete mineralisation, the CO_2 will eventually be fully immobilized as precipitated carbonate rock material.

In-situ mineral carbonation aims to accelerate the mineralisation process. With this approach, the CO_2 is stored via injection into reactive rocks, such as mafic or ultramafic rocks, which contain high concentrations of divalent cations. Carbon mineralisation can be further promoted by the dissolution of CO_2 into water before or during its injection, such as the Carbfix method, achieving solubility trapping immediately and mineral trapping within years.[7] Injection of dissolved CO_2 into reactive rocks for mineral carbonation results in a negligible risk of the CO_2 migrating back to the atmosphere both i) over the short term, due to the dissolution of CO_2 and the density-related inhibition of surface migration, and ii) the long term, due to the conversion of the CO_2 into carbonate minerals.

Detailed regulations and standards that aim at guaranteeing sufficient site characterization, leakage detection and remediation plans, as well as the avoidance of conceivable induced seismicity exist and can guide the development of appropriate methodologies for the Gold Standard.[22–25]

4 DACM – Direct Air Capture and carbon mineralisation

The EU Horizon 2020 project Carbfix2 demonstrated the combination of Climeworks' DAC technology and the Carbfix method for rapid in-situ carbon mineralisation[11] realizing DACS in a highly efficient and especially safe way.

How the Climeworks DAC technology works: The DAC plant captures atmospheric CO_2 applying a temperature-vacuum swing adsorption process. Air is drawn into the plant using fans and the CO_2 within the air is chemically bound to the solid sorbent material. CO_2-free air is released back into the atmosphere. Once the sorbent is saturated with CO_2, it is heated to around 100°C using low-grade heat as an energy source. The CO_2 is then released from the filter and collected as concentrated gas. This continuous cycle (see Figure 4) is then ready to start again. The sorbent is reusable and lasts for several thousand cycles (approx. 2-3 years).

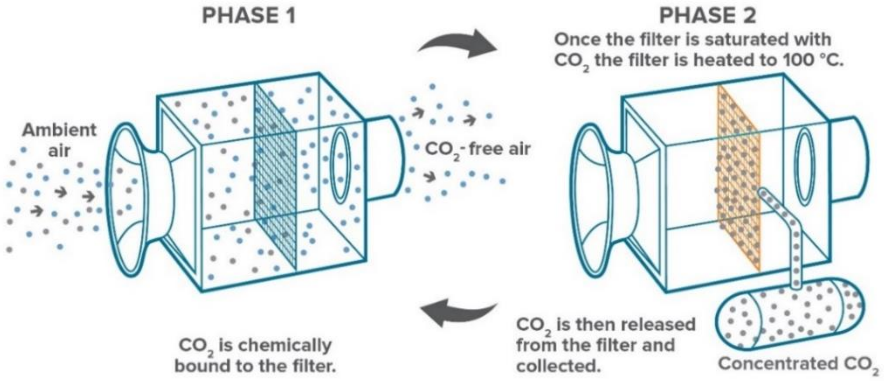

Figure 4: Working principle of the Climeworks DAC technology: Phase 1 produces CO_2-free air and binds the CO_2 on the filter. Phase 2 produces pure CO_2 and regenerates the filter.

The technology is based on a decade of R&D activities, largely in collaboration with world-leading Swiss research institutes at ETH Zurich (Swiss Federal Institute of Technology) and at the Swiss Federal Laboratories for Materials Science and Technology (Empa).[26–28] A key characteristic of the modular Climeworks filter structures is that they can be used with different sorbent materials.

One plant consists of several so-called "Collectors", of which one is shown schematically in Figure 4. This modular concept makes the plants scalable through numbering-up. The Collectors are designed for mass-production, enabling deployment on the large scale required for climate change mitigation.

How the Carbfix method works: The Carbfix method was developed over the past decade by Reykjavik Energy and several academic partners.[7,8,29] When applied in combination with a CO_2 capture step, the Carbfix method involves the release of the captured CO_2 as fine bubbles into a stream of co-injected water at depth within injection wells (alternatively, for gas streams with high initial CO_2 concentration, the dissolution of CO_2 in water can take place in a scrubbing tower, essentially replacing the capture step). The gas completely dissolves into the water before entering the porous reservoir rocks (see Figure 5). The water is typically sourced from the same underground reservoir. With this storage approach, which has been applied at depths between 400-2200 meters underground at temperatures between 30 and 260°C it is proven that after two years, already 95% of the CO_2 is converted into stable carbonate minerals.[7,30] Once mineralized, the CO_2 is permanently bound to the subsurface rocks and cannot be released. We refer to this particular combination of technologies as **Direct Air**

Capture and mineralisation (DACM), in order to emphasize the focus on mineralisation as the dominant storage mechanism.

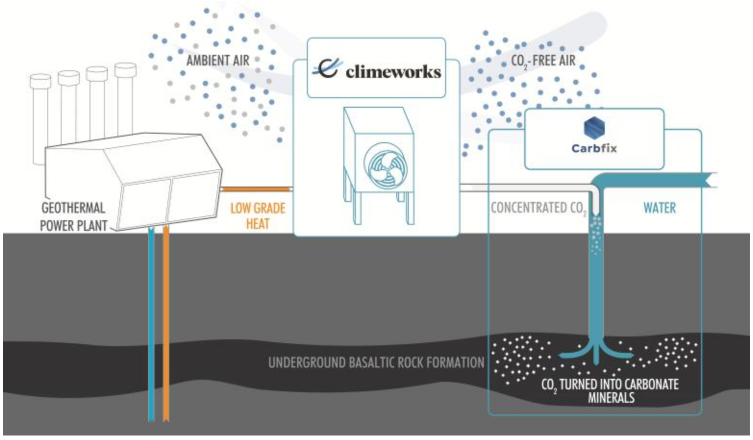

Figure 5: DACM captures CO_2 from air with renewable energy (here, geothermal heat and electricity) and stores it permanently underground.

In the Carbfix2 project, the DACM activity is fully integrated into the operation of a geothermal power plant (i.e. Reykjavik Energy's plant at Hellisheiði, Iceland), further reducing the environmental footprint. The DAC plant is powered by geothermal electricity and by low-grade geothermal heat that is difficult to utilize in the power plant. Furthermore, the CO_2 is co-injected with the geothermal recycle stream, i.e. the geothermal water that has been cooled by the power plant and is re-injected into the geothermal reservoir anyway. The CO_2 dissolves in the geothermal recycle and mineralizes in the basaltic geothermal reservoir.

Conventional CCS technologies capture CO_2 from large point sources that burn fossil fuels such as coal-fired power plants and – contrary to the Carbfix method – store the CO_2 as a pure phase in saline aquifers. Dissolution and mineralisation of the CO_2 then require hundreds to thousands of years. An additional difference is that conventionally, CO_2 capture has to be co-located with a point source from where the CO_2 is then transported to a storage site. Thanks to the uniform distribution of CO_2 in the air, DAC adds a degree of freedom to the siting of the capture plant, which can be co-located with a storage site or with renewable energy generation capacity, or ideally with both. Furthermore, conventional CCS is carbon-neutral at best, whereas the novel DACM approach actively removes CO_2 from the atmosphere and is therefore *carbon negative*. The life cycle emissions of Climeworks DAC amount to between 30 and 100 kg CO_2-eq. per 1'000 kg of CO_2 captured from the air if powered by renewable energy, according to recent studies by RWTH Aachen and by the Paul Scherrer Institute.[31,32]

The Climeworks DAC technology and the Carbfix method for geological mineralisation guarantee permanent and safe CO_2 removal

From the perspective of an expert risk assessment, the risk of leakage and perceptible induced seismicity are small for conventional CO_2 storage, as both the probability and consequence of such happenings are small.[21] In the specific case of the Carbfix method for geological CO_2 storage, the risks are significantly further decreased or even excluded.[33]

Contrary to the conventional method of injecting pure CO_2, Carbfix dissolves the CO_2 in water *prior to injection*. The resulting fluid has a higher density than the water present in the reservoir, such that the dissolved CO_2 is negatively buoyant. Hence, the risk of upward leakage through the caprock is physically impossible. Furthermore, the highly reactive nature of the basaltic

rock formations at the storage site enables rapid mineralisation of the CO_2, i.e. the dissolved CO_2 reacts with rock minerals to form solid carbonates, such as $CaCO_3$ (calcite). Carbfix has demonstrated the mineralisation of 95% of the injected CO_2 within two years.[7,30] In conventional CO_2 storage, dissolution and mineralisation of the CO_2 require hundreds to thousands of years. Thermodynamically, carbonates represent the lowest-possible energy level a carbon atom can attain and consequently, carbonate rocks are hardly reactive and environmentally benign. Leakage of CO_2 back into the atmosphere requires unusual conditions – e.g. direct contact with magma during the birth of a new volcano – and is highly unlikely. Should it occur against all odds, the released CO_2 is likely to be dissolved in the formation waters before being re-mineralised following reactions with the formation rocks.

In the past, CDR has sometimes been conflated with Solar Radiation Management (SRM) in the popular term «geoengineering». This conflation is misleading[34] for several reasons. In particular, CDR acts against the physical root cause of climate change, i.e. the excessive concentration of greenhouse gases in the atmosphere, whereas SRM masks the primary effect, i.e. global warming, by changing the planet's radiation balance in other ways.[35] This fundamental difference has consequences on the durability of the achieved effects. CDR with permanent CO_2 storage copies the natural processes that have controlled the CO_2 concentration in the atmosphere for millions of years, such that the effects are durable in terms of geological time scales. In contrast, the effect of SRM methods, such as aerosol spraying, diminishes rapidly once their continuous application is stopped. SRM also fails to address consequences of CO_2 accumulation in the atmosphere other than temperature increase, in particular, ocean acidification. Furthermore, the risks associated to SRM are largely unknown and – contrary to geological CO_2 storage – cannot be confined to defined volumes of the natural system.[34,35] Aerosols in the atmosphere are dispersed by wind and precipitation with uncontrollable dynamics and their side effects, such as altered precipitation patterns that are yet to be understood. For an overview of general differences between CDR and SRM, the reader is referred to a report by the U.S. National Research Council (Table S.1, p.4).[35] Therefore, instead of conflating SRM and CDR and in line with the most recent IPCC literature, we see a need to stress the inherent differences and to highlight that the use of CDR methods may – alongside rapid emission reductions – reduce the potential urge for applying SRM techniques in the future.

5 Co-benefits

Climeworks' technology has the potential to reverse climate change: direct air capture can help to prevent inconceivable ecological, economical and social damages that would be the consequences without climate action.

The **broader impact** of making a scalable solution for CO_2 removal available is the elimination of the most extreme future burden for the society, as shown by integrated assessment models. On the way to a net-zero or net-negative emissions economy, these models typically have to rely on disruptive and extreme measures (e.g. unsustainable use of natural carbon sinks, extreme CO_2 pricing) to mitigate the last bit of CO_2 emissions, if CDR technologies are unavailable.[2,36]

Due to its interdisciplinary nature, DAC-based **CDR creates jobs in a broad range of professions**[37] including chemistry and material science, engineering, earth science, manufacturing, business and marketing, as well as communications. The technology can

contribute to a fair and equitable transition of workers from fossil to clean industries where many of the skills required in e.g. oil and gas operation are also required for underground carbon sequestration.

With suitable storage sites all over the world, the technology further allows for a global implementation in several countries, also in the developing world. It allows for possible **collaborations between the northern and southern hemisphere** and makes for a sustainable economic sector in social and biophysical dimensions, in any location with suitable geological formations.

Besides CDR, DAC technology can supply CO_2 for the **production of renewable synthetic fuels**, which are derived from CO_2 and H_2O using renewable energy. Such fuels are essential for enabling a carbon-neutral transportation sector in the future, in light of the various limitations associated with the use of biofuels derived from biomass, such as competition with arable land for food production.

Hence, renewable synthetic fuels made from air-captured CO_2 are considered a major factor in achieving the EU's emission reduction targets by 2050 (80% below 1990's level) – although they currently remain an emerging innovation and production at scale remains to be demonstrated. Even with the widespread use of electric vehicles, hydrocarbon fuels seem irreplaceable for major transport applications (e.g. aviation and maritime cargo) which are responsible for a significant share of the final energy demand in the mobility sector.[38] Air-captured CO_2 provides the potential for these fuels to become carbon-neutral (see Figure 6).

More importantly, synthetic fuels are chemical energy carriers that enable the long-term (i.e. seasonal) and **large-scale storage of renewable electricity**. Furthermore, they allow for sector coupling between the electricity sector, where renewable energy has achieved the largest penetration already, and applications in mobility, chemistry and industrial heat. As such, synthetic fuels support the further increase of renewable energy generation capacity beyond the current receptivity of the electric grid.

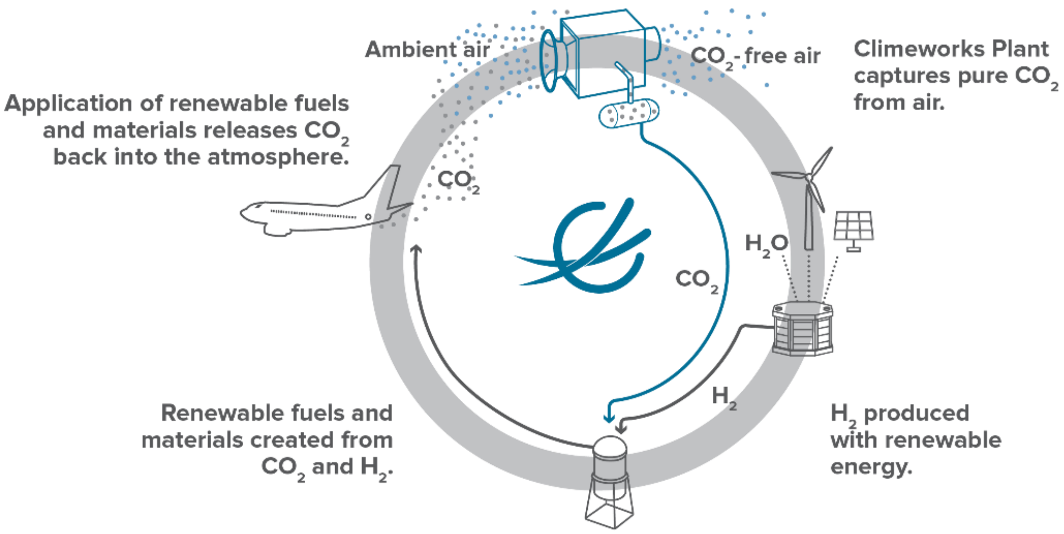

Figure 6: DAC enabling a truly circular carbon economy.

6 Feasibility and risk mitigation

Technologically, all elements required to build, install and operate a DAC-CDR plant are available. Small-scale DAC plants with a capacity of up to several thousand tons have already been built for purposes other than CDR.[39,40] A minimum-scale DAC-based CDR demonstration plant has been operated in Iceland to generate know-how about required adaptations to the local environment and for the integration with geothermal energy. Currently, Climeworks is realizing a scaled-up implementation of DAC-based CDR in Iceland with a nominal capacity of 4000 t/year, which will bring the learnings from different plant scales, applications and locations together in a practical installation – the world's first industrial-scale DAC-based CDR operation.

Solid-sorbent-based DAC technologies profit from the opportunity of using a modular design, which enables early demonstration at small scales.[18] Climeworks consequently exploits the modular design route, which allowed the installation of multiple pilot plants early in the company's history – 14 plants have been built, installed and maintained. Consequently, the organizational structure of the company has proven its suitability. Internal procedures and tools are clearly documented and communicated (ISO certified) and the engineering as well as the operative parts of the company are used to delivering according to strict timelines and quality requirements. Hence, despite its technological novelty, there is a small DAC industry that is capable of implementing projects transparently and reliably.

The feasibility of geological CO_2 mineralisation applying the Carbfix method has been proven in the projects Carbfix (2011–2014) and Carbfix2 (2017–2021) in two different geological reservoirs. The process has also been confirmed by similar projects in the United States.[41,42] Within another Horizon 2020 project called GECO (2019-2022), Carbfix and partners are currently preparing the widespread implementation of the technology outside Iceland and under different geological conditions. Besides this comprehensive practical experience, the Carbfix method as well as the reservoir characterization and the monitoring applying specifically developed tools and measurements to quantify the mineralisation have been comprehensively described and discussed in the scientific literature (see Section 4). The resulting know-how provides a sound basis for the development of a methodology that ensures safe and permanent CO_2 mineralisation with the Carbfix method.

Economically, Climeworks' market research and actual sales already confirm sufficient demand for carbon dioxide removal from individuals and organizations. The visibility of the planned industrial-scale project together with third-party certification of the entire CDR value chain will allow to increase the awareness around carbon dioxide removal as an important measure to maintain a healthy balance of carbon dioxide in the air and ultimately help mitigate climate change among the public and policymakers.

Risks that result from the operation of DACM plants can relate to both the DAC or to the mineralisation part. Projects need to present detailed risk assessment and risk management plans including as regards the construction, operation and deconstruction phase as well as the long-term behaviour of the stored CO_2. A methodology for certification of carbon removals within the carbon market therefore needs to address the risks along the entire value chain.

The construction of a **DAC plant** mainly entails the assembly and installation of pre-fabricated modules on site. Ecosystem effects are in general limited to the footprint of the plant and the need to prepare the ground, e.g. with foundations and access roads. In addition, a limited

amount of earthworks is required to provide media connections, e.g. for electricity and heat and for the transport of CO_2 to the mineralisation site. The risks for the workers on site and for the local community correspond to the risks of typical industrial construction sites and are well covered by existing health, safety and environment regulations. For installations in developing countries, the methodology shall include best-practice guidelines.

Operational risks may include environmental pollution through spillage of media from the plant. For solid-sorbent-based DAC processes, such risk is mainly related to heat transfer media, e.g. aqueous glycol solutions, and CO_2. Established methods exist to minimize these risks, including the installation of leak trays and leakage sensors. The sorbent material, which is required in large quantities, may contain complex chemical structures that bind CO_2 during the adsorption step. However, as a fundamental requirement for economically viable DAC processes, these active sites on the sorbent need to be chemically stable for thousands of cycles and may not be removed from the sorbent. In fact, Climeworks' sorbent material is insoluble in water and nontoxic. In addition, the sorbent material is contained in the contactor structures, further reducing spillage risks. The risks for the workforce on site resulting from the handling of heat, electricity and CO_2 can be minimized by conventional design rules and, where necessary, corresponding sensors and alarms.

Other ecosystem risks that need to be considered are related to the fact that large volumes of air need to be passed through the contactor. Direct effects on flora and fauna are minimized by the slow movement of air through the contactor, which is a consequence of the need to limit the pressure drop through the DAC collector. In addition, a steel grid covering the collector opening prevents insects or birds from entering the collector. The reduced CO_2 concentration in the air leaving the collector does not provide health and safety risks. Effects on the environment are unlikely, as the mixing of air due to Brownian motion and wind-driven convection is very rapid. In addition, the cyclic nature of solid-sorbent-based DAC processes entails that only a subset of collectors is in adsorption mode at any given point in time. Hence, the reduced CO_2 concentration is limited to very limited volumes of air a few meters around the DAC plant, as computational fluid dynamic model results show. Besides GHG emissions, the life-cycle analysis for Climeworks' DAC technology assessed 15 further environmental impact categories to determine potential environmental trade-offs and to detect potential burden shifting (incl. ozone depletion, particulate matter, acidification, eutrophication freshwater) without raising major concerns.[32]

The main risks as regards the leakage of CO_2 from the reservoir are described above. In summary, the Carbfix method reduces these risks again significantly compared to conventional geological CO_2 storage, where they are already low. In the following, risks related to the operation of the surface installations for CO_2 transport and injection, to induced seismicity and to public perception are discussed.

Leakage of CO_2 from the transport and injection infrastructure presents health and safety risks. As described above, the natural dispersion of leaked CO_2 outside of closed rooms is rapid, making environmental effects unlikely.[21] Nevertheless, the monitoring strategy needs to be able to detect such leakage and (i) warn people in the direct vicinity that may suffer from the increased CO_2 concentration and (ii) guarantee a quick resolution of the leak including automatic shutdown of the plant in severe cases. Again, existing regulation and standards for the handling of concentrated CO_2 can be used to manage these risks appropriately.

The risk of inducing perceptible seismicity through underground operations has seen increasing media coverage in recent years. For example, there are more than 180,000 active or formerly active injection wells in the United States for both waste-water disposal and enhanced oil recovery. Induced seismic events have been associated with ~10% of these wells, with high injection rates being the dominant trigger for induced seismicity.[43] The current DACM demonstration co-injects the CO_2 with the recycle of a geothermal power plant. The risks concerning induced seismicity are put in perspective by the fact that the maximum CO_2 fraction in the injected water is approximately 3%-wt. Consequently, the co-injection of such small fractions of CO_2 do not alter the seismic risks of injecting water only. The consequences of water injection and production at Hellisheiđi in Iceland are expertly understood after more than a decade of geothermal operations and the monitoring system on site has validated that there is no increase of seismicity that could lead to significant earthquakes or rock failure. Three years prior to the scaled-up gas injection, the Carbfix target reservoir was taken into service as a reinjection zone for waste water from the power plant. Reinjection started on 1 September 2011 with a high flow rate of ~500 kg/s, resulting in an excess injection pressure of ~28 bar. Microseismicity increased immediately in the area north of the injection sites, with the largest seismic events being a sequence that included two magnitude 4 earthquakes on 15 October 2011. This has led to the introduction of a workflow through which preventive steps, including the adjustment of the injection rates, are taken to minimize the risk of induced seismicity.[44] The Carbfix project applies this framework and, following its implementation, the annual number of seismic events greater than magnitude 2 in the area has decreased from 96 in 2011 to one in 2018, which is considered satisfactory and demonstrates that the project is being operated within its regulatory boundaries. This experience and knowledge gained during demonstration in a highly fractured and seismically active system is being used when planning new Carbfix activities outside of geothermal systems, where the risk of induced seismicity is considerably lower than at Hellisheiđi.

On the one hand, experience demonstrates that the public perception of geological CO_2 storage can be negative. Social sciences report a low level of information and understanding of the physical, chemical, and geological context required to conceptualize the working principles of geological CO_2 storage in the public[45] and that misunderstandings and misconceptions tend to play an important role in the public dialogue.[46] Correspondingly, high “unknown” and “dread” factors in the psychometric paradigm indicate a likely overestimation of the corresponding risks.[47] On the other hand, multiple projects, and in particular those with a scientific background and a focus on knowledge transfer and communications, did not see public opposition but rather caused enthusiasm and attracted visitors and media locally and internationally. The carbon mineralisation projects Carbfix1 and Carbfix2 at Hellisheiđi, Iceland, as well as the conventional CO_2 storage demonstration in Ketzin, Germany serve as successful examples. Hence, strategies for adequate communication and early and continuous stakeholder dialogue are elemental requirements of any geological CO_2 storage activity, including DACM projects. In addition to the Gold Standards’ guidance on criteria and requirements regarding the engagement and consultation with stakeholders, specific guidelines and tools for geological CO_2 storage exist[48–51] and the combination of DAC and Carbfix carbon mineralisation provides good opportunities for positive perception, because of the “natural” origin of the CO_2[52] and the reassuring effect of rapid mineralisation.

Environmental effects of the CO_2 mineralisation are mainly limited to the drilling of wells for the characterization of the reservoir and for injection and monitoring. In addition, it is worth

mentioning that the injection of CO_2 may affect the microbial fauna in shallow underground reservoirs, where existing although the extent the CO_2 taken up by microbes compared to that being incorporated in carbonates is insignificant.[53] The microbes continue to grow, but the composition of species adapts to the changes in their environment, which suits some species more than others.[54]

7 Markets and customers

The future market for CDR is bound to be in the trillion-Euro-range if we are to meet the climate goals established in the Paris Agreement. Due to global markets' inherent inability of reflecting negative externalities related to CO_2 emissions, the CDR market is largely dependent on the implementation of more equitable market frameworks. Indeed, pressure applied by scientists and the public on political decision-makers is growing, as described above. The following is a summary market overview based on the current regulatory framework and demonstrate that significant growth of DAC-based CDR activities is already sustained by existing demand.

CDR for individuals: social sciences provide socio-demographic insight on the share of the population that can be attracted by DACM carbon certificates. A representative German survey[55] identifies three target groups (*critical-creative*, *young*, and *affluent*) that sum up to 46% of the population. Similarly, Metag et al.[56] found 42% of the German population to be *concerned activists* or *alarmed* regarding climate change. The latest "Six Americas" study found 58% of the US population in the same two categories (up from 51%).[57] In addition to concerns about climate change, we at Climeworks recognise the wish of being part of technological innovation as a secondary motivation for many of our CDR customers.

Market size: considering the population of the EU and US alone and assuming that 45% can potentially be attracted by Climeworks CDR, as a conservative average based on the surveys referred to above, this results in a Total Addressable Market (TAM) consisting of 380 million people.

CDR for organizations: Businesses are looking for opportunities for differentiation of their products and their brands from competition.[58,59] In addition, the worldwide climate demonstrations of the "Fridays for Future" movement and the corresponding attention for climate change mitigation may have marked a paradigm shift: facing unequivocal signs of climate change in their everyday life, people are demanding action, including from political and business leaders. In 2019, several elections as well as campaigns against emission-intensive business projects demonstrated that climate change is now affecting people's decisions as voters and customers. Furthermore, as people are looking for purpose in their jobs, an image as a frontrunner in sustainability becomes a crucial factor in recruiting. As a consequence, a large number of corporations, including global champions, are announcing net-zero emission strategies. Net zero is becoming the new standard as it demonstrates the acceptance of scientific evidence and the objectives of the Paris Agreement (limit warming to 2°C, ideally 1.5°C).

Simultaneously, CDR technologies are supported by the currently planned expansion to emission accounting by the World Resource Institute (WRI) led GHG Protocol. The stated goal of the expansion makes for possibilities of accounting carbon dioxide removals through both, natural and technology pathways. This expansion is timely and needed and should also provide further clarity and guidance to private sector companies setting net zero targets.

Market size: industry emissions alone account for approximately 20% of the global CO_2 emissions, i.e. approximately 8 Gt per year. Over the course of the coming 5 years, we expect a significant increase in demand through increased pressure for social responsibility.[59,60] A recent study identified 262 companies that have set science-based emissions targets in line with the 2°C objective[59] and the corporate group committed to 1.5°C (Business Ambition for 1.5°C) has grown 34% from 177 companies to 237 companies in less than a year.[61] Prominent examples include Microsoft, Swiss Re and Stripe.

- **Microsoft:** the company is on a path to remove, by 2050, all the carbon the company has emitted either directly or by electricity consumption since it was founded in 1975. The announced plan focuses on a portfolio of negative emission technologies explicitly including DAC. Microsoft's direct and indirect emissions currently sum up to 16 million tons per year. Its negative emission strategy continuously increases carbon removal activities to 7.5 million tons per year in 2030.[62]
- **Swiss Re**: in February 2020, Swiss Re announced a net-zero emission strategy for 2030. Swiss Re explicitly refer to CO_2 removal with permanent storage in addition to further increased efforts in cutting emissions.[63]
- **Stripe**: In addition to constantly reducing their own emissions, Stripe is actively removing carbon dioxide from the atmosphere. Stripe is investing USD 1 million annually to pay, at any price, for the direct removal of carbon dioxide from the air and its sequestration in secure long-term storage. One of the companies they purchased from in 2020 was Climeworks.[64]

Companies like these have the potential to become catalysts for others to take action. Broad implementation will likely lead to massive cost reductions and to making CDR more widely available, causing further increase of demand. We have seen repeatedly that an increase in demand leads to a better supply, for example in the solar energy industry.

stripe

May 18, 2020:
Stripe announces **purchase of 322 tons** of Climeworks CDR worth **EUR 230'000**.

Figure 7: Microsoft (left; copyright Microsoft Corporation) and Stripe both committed to buy carbon removal credits. This will put more pressure on political decision-makers for the implementation of more equitable market frameworks.

8 Conclusion

Carbon Dioxide Removal (CDR) technologies are not a substitute to emissions reductions but a necessary complementary solution. The fast development of reliable large-scale CDR technologies is vital to achieving the climate target set forth under the Paris Agreement.

Direct Air Capture (DAC) technology associated with CO_2 storage (Direct Air Capture and Storage, DACS) is a readily available, low-impact solution to facilitate negative emissions and, unlike geoengineering techniques, does not alter natural systems, and treats the cause of warming and not merely its symptoms.

Adding a scalable CDR technology such as DACS to the portfolio of climate change mitigation options facilitates the public and policy debate by adding an indicative price tag to delaying determined emission reduction actions. On a practical level, it extends the climate change mitigation responsibility to industries, countries and individuals claiming to cause "unavoidable emissions" by providing a readily available solution for balancing or reversing such emissions. In particular, organizations are exploring ways to remove their emissions within their own operations and value chains and are with some urgency evaluating novel and scalable solutions to address such "unavoidable" or hard-to-mitigate emissions (for example to report against committed targets under respective frameworks, such as the Science Based Targets Initiative, SBTi).

Business models built around such needs can trigger investments in the development of DAC technologies, which are urgent if they are to reach the projected scale of several gigatons of CO_2 per year. Promoting such developments through the carbon markets provides organizations with a transparent and metered tool to address in particular production or service related emissions.

In response to the Gold Standard consultation on operationalizing and scaling the post-2020 voluntary carbon market, and technology-based carbon removals in particular, and in light of the important role of CDR technologies – and DACS in particular – on the way to meeting the objectives of the Paris Agreement, we urge the Gold Standard Foundation to broaden the scope of the Gold Standard for Global Goals and to approve DACS as an eligible type of project activity. We would welcome for the Gold Standard Foundation to strengthen its pioneering role and provide guidance, especially now that the development of comprehensive CDR market regulation has been announced by the European Commission.[65] Allowing for DACS under the Gold Standard for the Global Goals (GS4GG) will set a precedent to incorporate social sustainability criteria (through the subordination to the Sustainable Development Goals) into the development of technology-based CDR approaches. Early involvement from the GS4GG allows for a high impact in the further development of the nascent DACS industry.

Should the Gold Standard Foundation decide to approve DACS as an eligible type of project activity, Climeworks stands ready to work towards the certification of removals under GS4GGs, specifically for Direct Air Capture and carbon mineralisation (DACM) as a technically readily available DACS technology. To that effect and in an anticipated move, we will be submitting a Methodology Concept Note for DACM activities to the Gold Standard Secretariat in due course, demonstrating our determination to contribute to the deployment of solutions delivering the needed negative emissions.

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