Options for supporting Carbon Dioxide Removal

Discussion paper

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Summary

The special report on the 1.5°C temperature limit by the Intergovernmental Panel on Climate Change (IPCC, 2018) unambiguously states that meeting a 1.5°C warming scenario with no temperature overshoot will require significant carbon dioxide removal (CDR). While aggressive and expedient mitigation actions remain the first priority and absolutely critical, it is also imperative to simultaneously explore and develop CDR options so that they are available at the scale required to achieve global net-negative CO_2 emissions in the second half of the century. The challenge of upscaling CDR provokes many technical, societal, and governance questions and challenges.

In this paper we set out to examine the broad policy frameworks that can support the development and upscaling of CDR and, in particular, whether CDR can be supported by offsetting schemes.

Our analysis begins by characterising some of the most prominent and promising approaches to CDR in terms of the costs, technological maturity, removal and storage potential, as well as potential risks and co-benefits. We then examine the types of support that these approaches would need at different stages of development and collate examples of policies and activities currently in place. Finally, we explore the broader types of policy frameworks that are required to signal and financially support upscaling of CDR.

On the basis of the analysis we provide the following recommendations:

Support biological CDR options (afforestation, reforestation, biochar and soil carbon sequestration) through domestic, regulation-based policies. These biological CDR options have multiple benefits, including biodiversity and soil fertility, although careful policies are required to avoid risks to food security. They could be incentivised as much as possible through direct national regulation or international support, emphasising the co-benefits, and ensuring a supportive policy and governance framework. When using carbon markets and offsetting with biological CDR options, the risks outweigh the benefits due to the high risk of non-permanence, limited additionality to what should happen anyway, and complex interactions with other land-use needs. Furthermore, there are other means to support biological CDR options that do not carry these risks.

Provide long-term, secure support for the research and development stage of CDR technologies by targeting various CDR options individually (BECCS, DACCS, enhanced weathering and mineral carbonation). More research and application of BECCS, DACCS, mineral carbonation (all in demonstration phase) and enhanced weathering (in R&D phase), is necessary to bring costs down and better understand the risks and benefits.

Governments and businesses could support R&D, provide pilot support for individual technologies. As with any R&D or demonstration support, those providing the financial support would see themselves as frontrunners and take the initial risk. This support would be seen as a contribution to solve climate change, in addition to a potential commercial advantage.

Carbon market mechanisms or carbon pricing in other sectors could be a source of revenue to support these activities (e.g., revenues from auctioning of an emission trading system, ETS), following the polluter pays principle, but ensuring that careful consideration is given not to divert funds from other effective mitigation activities.

Develop stable, predictable, efficient and large support mechanisms for CDR when technologies are mature. BECCS, DACCS, enhanced weathering and mineral carbonation will need continuous support, even if the costs are lowered, because these technologies have limited benefits other than CDR. The scale of CDR likely required is only possible if governments set the rules under which companies and consumers implement CDR at their cost and as part of their responsibility. If government revenues alone would be used, they would have to be very substantial.

Keep emissions and removals separate: Separate targets for emissions (with dedicated support for emission reductions) and targets for removals (with dedicated support for CDR) have significant advantages over combined net-zero targets, where emissions are offset against removals and climate neutrality is claimed. For the combined approach, risks could outweigh the benefits. In particular the approach can divert attention from reducing emissions under the uncertain assumption that one could always rely on removals at a later date. The approach of two separate targets and no offsetting provides clear responsibility for reducing emissions *and* increasing removals. The risks are lower in the separated approach: The possibility that some of the captured CO_2 may be released at a later date and requirements on monitoring are less relevant because the reduction of fossil fuel emissions is already secured within the approach. The separated approach also prepares for the net-negative phase required later in the century, which is not necessarily achieved by combined targets or offsetting.

Continue research and policy experiments: Some open questions remain as to how such a framework can be implemented in practice:

- What are the most effective policies to implement this framework?
- At what level should companies or governments set the emission and removal targets, if they are separated?
- What are the most appropriate sources of revenue for governments to support CDR?
- How should companies or governments choose which CDR approaches to support?

These questions need to be explored through further research and thinking, but also through policy experimentation and reflection. The broad suite of policies already in place can be assessed in more detail in terms of their effectiveness and appropriateness, with the most successful providing good candidates for further testing and upscaling.

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Abbreviations

AFOLU	Agriculture, Forestry and Other Land Use
AR	Afforestation and Reforestation
BECCS	Bioenergy with Carbon Capture and Storage
CDM	Clean Development Mechanism
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CDR	Carbon Dioxide Removal
CER	Certified Emission Reduction
DAC	Direct Air Capture
DACCS	Direct Air Carbon Dioxide Capture and Storage
DSF	Deep Saline Formation
EOR	Enhanced Oil Recovery
ETS	Emissions Trading System
FUTURE Act	Furthering carbon capture, Utilization, Technology, Underground storage and Reduced Emissions Act
GGR	Greenhouse Gas Removal
GHG	Greenhouse gas(es)
IAM	Integrated Assessment Model
IPCC	Intergovernmental Panel on Climate Change
LCFS	Low-Carbon Fuel Standard
MRV	Monitoring, Reporting and Verification
NASEM	(US) National Academies of Sciences, Engineering, and Medicine
R&D	Research and Development
SCS	Soil Carbon Sequestration
tCER	Temporary Certified Emission Reduction
tCO_2	Ton of Carbon Dioxide
$GtCO_2$	Gigaton of Carbon Dioxide
TRL	Technological Readiness Level

1 Introduction

The special report on the 1.5°C temperature limit by the Intergovernmental Panel on Climate Change (IPCC) unambiguously states that meeting a 1.5°C warming scenario (IPCC, 2018) with no temperature overshoot will require significant carbon dioxide removal (CDR) in addition to mitigation. While aggressive and expedient mitigation actions remain absolutely critical, it is also imperative to simultaneously explore and develop CDR options so that they are available at the scale required to achieve global net-negative CO_2 emissions in the second half of the century. The longer sufficient mitigation action is delayed, the greater the amount of atmospheric CO_2 removal will be necessary to keep the Paris Agreement goals within reach.

CO_2 emissions scenarios identified by the IPCC as consistent with limiting warming to 1.5°C have three distinct characteristics (Figure 1). (1) An initial phase in which emissions from all sectors fall rapidly and deeply to reach (2) net-zero CO_2 emissions by 2050, followed by (3) sustained net-negative emissions in the second half of the century. These scenarios all imply substantial CDR before 2050 as difficult to reduce emissions, e.g., from the aviation and thermal process heating sectors, are likely to continue until at least 2050. These scenarios imply a need to scale-up CDR to substantial levels of 100 – 1000 $GtCO_2$ cumulatively over the century (IPCC, 2018). Thus, the questions for policy makers are now not whether CDR will be needed, but rather how soon and how much CDR will be required to remove CO_2 from the atmosphere to avoid exceeding 1.5°C of warming.

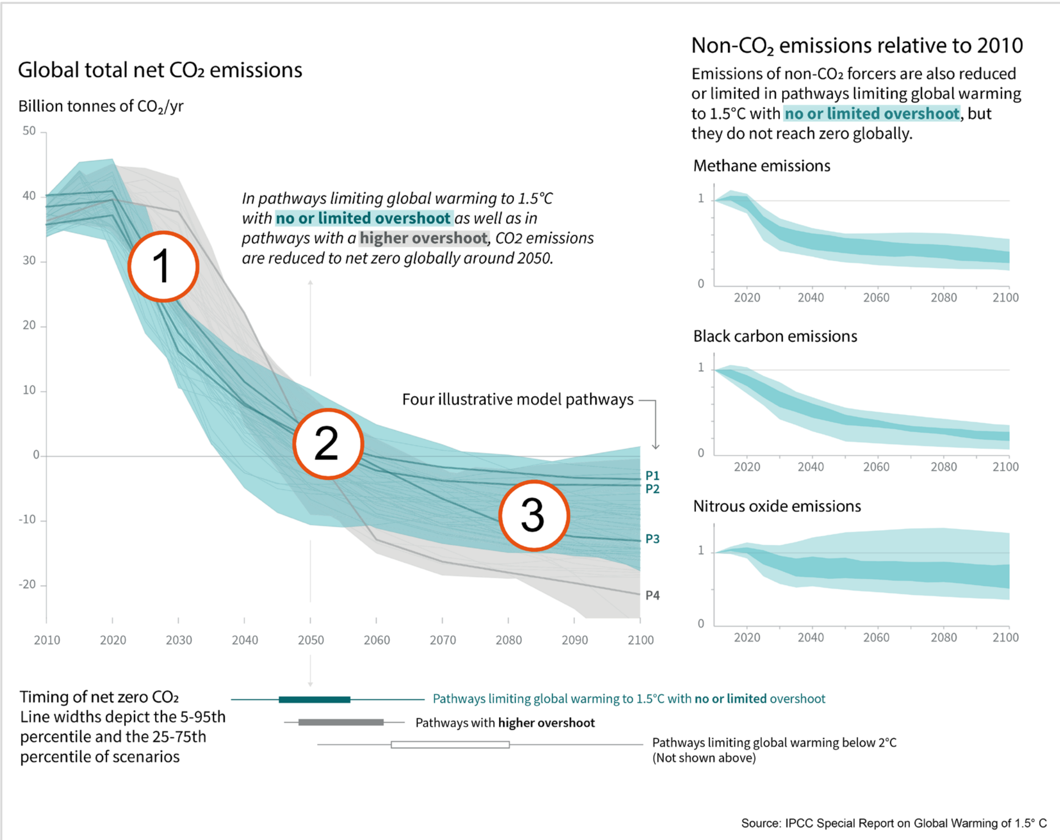

Figure 1: Emission scenarios towards 1.5°C and their characteristics (IPCC, 2018)

Given the amount of historical emissions to date, and continued high emissions rates, most emissions scenarios foresee that the remaining carbon budget will be exhausted in the coming decades and all excess emissions will need to be compensated through net-negative emissions, including carbon dioxide removal. Unless emissions are mitigated at a rate faster than that currently anticipated in the models, simply compensating one tonne of emitted CO_2 with one tonne of removals will therefore be inadequate to achieve the net-negative CO_2 emissions required around mid-century to meet the Paris Agreement goals and risks undermining policies to drive decarbonisation. CDR therefore needs to be incentivised not only to compensate current emissions but also to be able to push towards global net-negative emissions in support of Paris Agreement goals.

CDR technologies and techniques cover a broad range of biological, geological and technological methods, some of which are discussed in detail in this report. At the outset, it is critical to narrow the universe of potential CDR technologies to those that can plausibly claim to be net negative in the long run.

- First, and most critically, CDR must result in a net overall reduction in atmospheric CO_2. Thus, while using carbon capture and sequestration (CCS) on a natural gas fired power plant can reduce the plant's CO_2 emissions by 90-95%, there is still a net increase in overall atmospheric CO_2.
- Second, CDR technologies must store or sequester the captured CO_2, rather than use the captured carbon (i.e. carbon capture and use or CCU) for some purpose such as beverage carbonation, plastic production, cement, enhanced oil recovery (EOR) or synthetic fuels where it would be rereleased. Most, if not all, examples of utilisation do not have long enough timescales to be considered permanent.
- Third, to be net negative, a CDR technology must be paired with a storage or sequestration technique that prevents, with an extremely high degree of certainty, future unintentional releases of the captured CO_2.

We begin by outlining the various different potential CDR options available and outline their characteristics in terms of risk, commercial viability and potential, possible co-benefits or negative impacts, environmental integrity, monitoring and verification challenges, and the maturity and current commercial potential of the technology (Section 2). The maturity of any given option is important in determining what kind of support it needs in the near-term, be that upscaling or basic research and development. In the following section (Section 3) we characterise the type of support that is needed for different stages of development and survey the policy instruments already in place.

One of the challenges of CDR technologies is the prohibition on commercial re-use of the captured CO_2, if it leads to emissions at a later date, eliminating a number of potentially lucrative commercial income streams (e.g. EOR, synthetic fuels and some building material). Such re-use can stimulate the development of the technology, but in the long run will not lead to net negative emissions. Thus, different types of financial and policy support is needed relative to, for example, renewable energy or energy storage. In this paper, we examine what that support could look like and where it might come from for a range of CDR approaches.

Building on this knowledge we consider the broad policy frameworks that have been proposed for scaling up CDR over the coming decades to the levels required by 1.5°C consistent scenarios (Section 4). In particular, we assess the opportunities, challenges and risks of trading CDR credits in a market mechanism.

This study looks at CDR only and not other approaches considered as 'geoengineering' in some of the literature. Geoengineering options, such as solar radiation modification, carry different risks to CDR and are not discussed further here.

We examine and refer to removals of CO_2 (CDR) and not Greenhouse Gas Removal (GGR). CO_2 removal is a much more developed technology than removal of any other GHG, although some research has gone into the removal of methane, nitrous oxide and halocarbons. No comprehensive reviews into their sustainability, feasibility or costs have however been conducted to date (IPCC, 2018). Because of CO_2's long lifetime in the atmosphere and high abundance, it's much more important to remove CO_2 from the atmosphere than other greenhouse gases.

2 Characterising potential CDR approaches

Many different approaches for Carbon Dioxide Removal have been identified and are well summarised in scientific literature (Fuss *et al.*, 2018; Nemet *et al.*, 2018). Here we select and describe some of the different approaches, or combination of approaches, that have the potential to develop at a scale relevant for global efforts against climate change (Figure 2). We further identify some of the key characteristics of these options in terms of their total CDR potential, costs, maturity, permanence of storage, and any possible co-benefits or negative side-effects (Table 1). This characterisation will then be used to help identify which types of policy instruments are most appropriate for each type of CDR technology in the following sections.

Carbon dioxide removal involves first capturing the CO_2 from the atmosphere and second storing it. Biological options use plants to collect the CO_2 through photosynthesis; the CO_2 is stored in the biomass. CO_2 can also be removed from the atmosphere with technical options and stored, e.g., underground. Biological options for collection can also be combined with technical storage. Storage options have varying degrees of permanence (Figure 2).

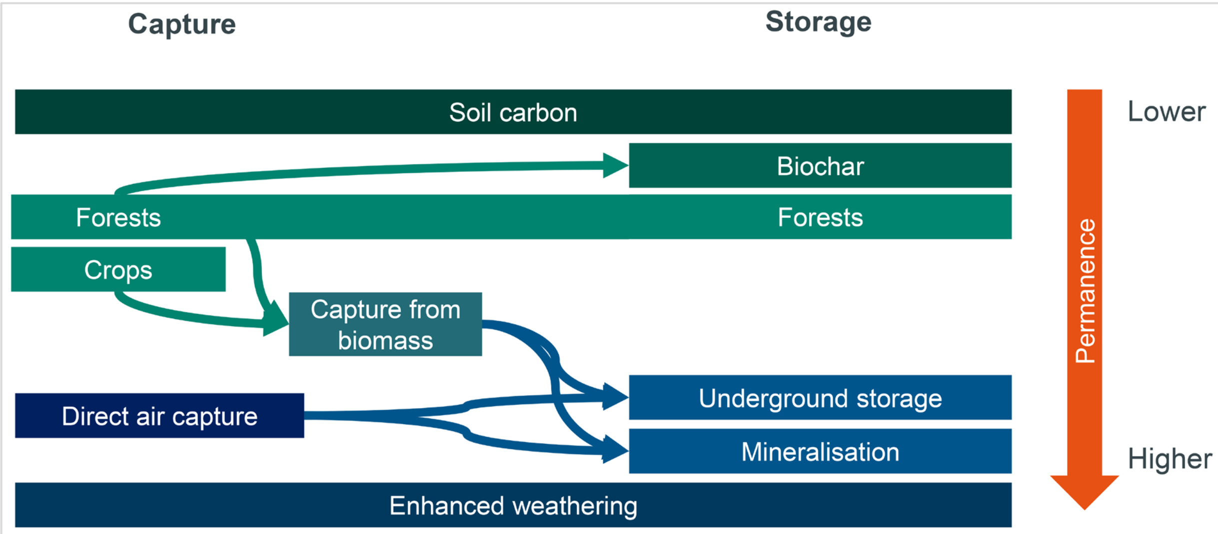

Figure 2: Capture and storage options for Carbon Dioxide Removal

The permanence of storage of different storage options is dependent on the vulnerability of the storage mechanism to disturbance and CO_2 release. The likelihood of underground or mineral storage to be permanent is much higher than that of biological options that are vulnerable to disturbances such as fires or deforestation.

For the remainder of the paper, we distinguish between the broad categories of 'biological capture and storage', 'underground storage' and 'mineral storage' approaches, acknowledging that some of the approaches in these categories are combinations.

2.1 Approaches for CDR

2.1.1 'Biological capture and storage'

Soil carbon sequestration results from land management measures enhancing the soil carbon content and leading to a net removal of CO_2 (Fuss *et al.*, 2018). Practices that either increase the soil carbon input (such as manure or plant roots) or reduce carbon losses through respiration or soil disturbance can facilitate soil carbon sequestration (The Royal Society and Royal Academy of Engineering, 2018).

Soil carbon sequestration measures are technologically ready to be implemented and are already practiced to some extent. Some soil carbon sequestration practices can be implemented at low or even negative cost (Fuss *et al.*, 2018; The Royal Society and Royal Academy of Engineering, 2018). Soil carbon sequestration is, however, very challenging to quantify, has historically likely been overestimated because of sampling bias (Baker *et al.*, 2007), and is limited in permanence and scalability. Soils are vulnerable to disturbance and typically reach their carbon saturation point after around twenty years (Kane, 2015; The Royal Society and Royal Academy of Engineering, 2018).

Biochar involves sequestering carbon in charcoal by interrupting the natural plant decay carbon cycle using pyrolysis and, typically, burying the biochar in soil. Pyrolysis involves combusting organic material (*e.g.* wood or agricultural biproducts) in a low- or oxygen-free environment, creating two biproducts: synthetic gas and charcoal (*i.e.* biochar). Rather than combusting the charcoal for energy or heat, it is buried in soil. Biochar stores the carbon contained in the biomass in stable chemical reaction that can store carbon for hundreds or thousands of years. Once added to soils, biochar can improve soil quality – notably water retention and fertility. The method is well-established but the use of biochar remains limited due to costs and the lack of pyrolysis facilities (The Royal Society and Royal Academy of Engineering, 2018). Biochar is related to soil carbon sequestration, but requires a substantially different intervention to collect, burn, and distribute the biomass.

Afforestation and reforestation are mature and widely used CDR options. These techniques remove carbon from the atmosphere by planting trees in previously unforested areas (afforestation) or by replanting trees in deforested areas (reforestation). After planting, trees continue to take up carbon over decades in contrast to the comparatively instantaneous capture and storage of the technological options below, or the release of carbon from burning fossil fuels.

The carbon sequestered in trees can be stored over long periods of time but can be re-released through deforestation or damage due to natural disturbances such as fires, insects, or droughts (The Royal Society and Royal Academy of Engineering, 2018).

2.1.2 'Underground storage'

Bioenergy with carbon capture and storage (BECCS) is a hybrid system combing biological capture and technical sequestration techniques in which biomass is combusted to produce energy and the carbon emitted in this process is separated or captured and then stored. The rationale of BECCS as a CDR technology rests on the assumption that bioenergy is carbon neutral, meaning that as much carbon is taken up from the atmosphere to grow biomass as is then released during combustion. This assumption can be questioned, as bioenergy production can also cause deforestation elsewhere or cause other emissions through e.g. fertilisers, production, and transport.

Once the carbon is captured and stored, the process should result in net CO_2 removal (Fuss *et al.*, 2018). BECCS is, together with measures in the Agriculture, Forestry and Land Use (AFOLU) sector, the main CDR technology used in IPCC modelling. In the IPCC Special Report on 1.5°C report, three out of four emission pathways rely on BECCS, ranging from 150 to 1190 $GtCO_2$ of cumulative CDR through BECCS by 2100 (IPCC, 2018).

Direct air carbon dioxide capture and storage (DACCS) involves capturing CO_2 directly from the air using chemical solvents and sorbents and storing it away (IPCC, 2018). The processes to capture CO_2 from the air are typically very energy intensive, and therefore coupling these plants with cheap renewable energy is important for bringing down the associated costs (Fuss *et al.*, 2018) and to ensure that no additional GHGs are emitted to produce electricity. Researchers and businesses have pioneered various technologies at different stages of maturity and some have already reached demonstration and semi-commercial phases (The Royal Society and Royal Academy of Engineering, 2018).

BECCS and DACCS require storage of CO_2 after capture to be counted as CDR. They are mostly understood to be combined with underground storage of the CO_2. A storage capacity of 900 $GtCO_2$ is estimated to be available if only depleted oil and gas fields are taken into account (The Royal Society and Royal Academy of Engineering, 2018). At the same time, risks linked to the permanence of storage and CO_2 transport are important (The Royal Society and Royal Academy of Engineering, 2018).

2.1.3 'Mineral storage'

Enhanced terrestrial weathering is a process which aims to accelerate the decomposition of reactive silicate rocks (e.g. basalt), calcium and magnesium rich silicate rocks. The natural breakdown of calcium and magnesium rich silicate rocks, or weathering, is a chemical reaction resulting in CO_2 removal from the atmosphere (The Royal Society and Royal Academy of Engineering, 2018). The atmospheric CO_2 removed is stored either as dissolved inorganic carbon in the oceans or in carbonate minerals on land.

Enhanced weathering describes grinding silicate rock to a powder that is spread over large areas, for example croplands to speed up the natural weathering process. Plant roots and micro-organisms facilitate the weathering of the rock dust and the high CO_2 levels in soil significantly speeds up this process.

Potential benefits of enhanced weathering include improved soil quality and fertility. There are however also potential risks such as deforestation if mining is required to source rocks (The Royal Society and Royal Academy of Engineering, 2018). Extraction and grinding of rocks also require large amounts of energy that would need to be accounted for if not supplied by renewable sources. Further, the effective rate of silicate weathering for CO_2 removal depends on temperature, rainfall, and the rate of the physical erosion of the rock.

Mineral carbonation accelerates the transformation of silicate rocks to carbonates. This process describes the storage component only and needs to be coupled with a source of carbon. Potential sources include the power sector and cement industry. Mineral carbonation may require high energy consumption, which can lower the net CO_2 benefits. According to the Royal Society (2018), carbonate minerals could provide one of the most secure forms of CO_2 storage.

2.1.4 Additional approaches

The list of CDR approaches included here is not exhaustive, but it includes some of the main technologies with potential to scale globally. Some other approaches worth mentioning include wetland, peatland and coastal habitat restoration, which has significant potential in some countries (The Royal Society and Royal Academy of Engineering, 2018) and ocean alkalinisation, which is based on a process similar to enhanced terrestrial weathering (Fuss *et al.*, 2018). In this paper we also do not address (other) marine-based CDR approaches. Some of these methods, including ocean fertilisation and macroalgae cultivation (coupled with BECCS or CCS), have been researched and trialled on smaller scales but they are not yet at a stage to deliver substantial CO_2 removal (C2G, 2019). Further research into these methods, including their risks and potentials, is needed.

2.2 Characterising CDR approaches

CDR options are very diverse in terms of their maturity, scalability, costs, permanence, environmental risk and storage profile. Some options have benefits that may go beyond carbon dioxide removal but also potential negative effects, which need to be taken into account when considering support for CDR measures. We have summarised some of these aspects in Table 1.

The **CDR storage potential** in terms of gigatons of CO_2 removed on a yearly basis ($GtCO_2$/y) varies significantly across the literature, as do associated **costs**. For CDR potential, we have chosen to present 2050 estimates from Fuss *et al.*, 2018 and the IPCC Special Report on 1.5°C (IPCC, 2018). The estimates from Fuss *et al.*, 2018 represent the authors' best estimates for sustainable global potential by 2050; the authors however note that cumulative potentials beyond 2050 vary. The IPCC potentials cover fewer technologies, as Integrated Assessment Models (IAMs) have tended to mostly include BECCS and, to a lesser extent, measures in the Agriculture, Forestry and Other Land Use (AFOLU) sector, such as afforestation and reforestation (IPCC, 2018). In terms of costs, we present values from across literature, as compiled in Fuss *et al.*, 2018.

Table 1: Overview of characteristics of Carbon Dioxide Removal approach

CDR Approach	2050 sustainable global potential[1] ($GtCO_2/y$)	2050 IPCC 1.5°C pathways[2] ($GtCO_2/y$)	Costs across literature[3] ($US\$/tCO_2$)	Maturity of technology (TRL in brackets)[4]	Duration of CO_2 storage	Benefits beyond CDR[5]	Potential negative effects[5]
Soil carbon sequestration	Up to 5	See AFOLU in AR	-45-100	Mature (8-9)	Short	Soil fertility, water, biodiversity	Possible increase of N_2O
Biochar	0.5-2	?	30-120	Demo (3-6)	Medium	Soil fertility, water	Food security, biodiversity, release of methane if used in rice paddy soils
Afforestation & reforestation	0.5-3.6	3.6 (afforestation) 1-11 (all AFOLU)	2-150	Mature (8-9)	Medium	Biodiversity	Food security, biodiversity
Bioenergy with carbon capture and storage (BECCS)	0.5-5	0-8	15–400	Demo (4-7 CCS) (7-9 Bioenergy)	Long	Energy, (CO_2 use)	Food security, biodiversity
Direct air carbon capture and storage (DACCS)	0.5-5 *with constraints* Up to 40 *without constraints*	?	30-1000	Demo (4-7)	Long	(CO_2 use)	Energy requirements
Enhanced weathering	2-4	?	Large variation	R&D (1-5)	Very long	Soil amelioration, nutrient source	Ground water, mining, air pollution
Mineral carbonation	?	?	?	Demo (3-8)	Very long		Ground water, mining, energy requirements

Evaluations in this table are based on Fuss *et al.*, 2018; IPCC, 2018b; Nemet *et al.*, 2018; The Royal Society and Royal Academy of Engineering, 2018
? = estimates not currently available in literature

[1] Authors' best estimate in Fuss *et al.*, 2018
[2] Scenarios with no or limited overshoot in IPCC, 2018
[3] Across all literature assessed by Fuss *et al.*, 2018
[4] Based on The Royal Society and Royal Academy of Engineering, 2018
[5] Based on Fuss *et al.*, 2018

The **'maturity of technology'** column distributes the CDR approaches across three broad stages of development, research and development (R&D), demonstration phase and mature technology based on the Technology Readiness Levels (TRL) categorisation

- In the **research and development (R&D) stage (TLR 1-4)**, technologies are in conceptual, prototype and experimental phases, requiring high upfront capital investments and presenting high risk profiles due to uncertain long-term technical feasibility and commercial viability.
- After initial technical feasibility and scalable commercial potential, technologies move to a **validation and demonstration stage (TLR 5-7)** to test their viability in the relevant application environments.
- Finally, CDR technologies reach a **mature stage (TLR 8-9)** at the point of real-world operation and full integration with existing systems.

The **duration of storage** varies significantly, ranging from short term to very long term. Biological storage options, such as soil carbon or forests, reach saturation after 10 to 100 years and are vulnerable to reversal (The Royal Society and Royal Academy of Engineering, 2018). For methods with CCS, we classify the duration of storage as "long" because carbon can be stored safely for thousands of years if the approach is successful. However, there is a potential for leakage that will become important in our discussions regarding the permanence of CDR. Finally, we also present some of the **benefits** of the different approaches (beyond CDR, where applicable) and potential **negative impacts**.

There are wide differences in the technological readiness, carbon removal potentials, permanence of storage, costs and benefits of the different CDR approaches. When it comes to costs, there are also wide ranges of estimated costs within each of the CDR approaches. We however note that the two most mature approaches – afforestation and reforestation, and soil carbon sequestration – are also the lowest cost. Soil carbon sequestration is in fact the only approach that can, in some circumstances, be applied at negative costs.

At the same time, the permanence of storage for these approaches is on the lower end of our scale; both approaches are vulnerable to disturbance and reversal, and soil carbon sequestration requires regular maintenance for the storage to be kept. Both afforestation and reforestation, and soil carbon sequestration, could be implemented on a wider scale, wherever it makes sense to do so, but given the storage constraints (both in terms of duration and saturation), other approaches will also be needed. For biochar, BECCS and DACCS, wider scale deployment is foreseeable, but cost reductions would likely be necessary, particularly for the latter two technologies. Both enhanced weathering and mineral carbonation are attractive options thanks to permanence of the stored carbon, but further research is needed on costs and global potentials.

3 Characteristics of CDR support needs and currently implemented policies

3.1 Characteristics of CDR support at different stages of maturity

The CDR approaches described above are all at different stages of technical and commercial maturity (Table 1) and require different types of policy and financial support.

(1) Research and development stage

In the research and development stage, **stability** and **predictability** of policy and financial support is most important. The development of new technologies usually requires continuous funding for an extended period. Uncertain revenue sources risk that R&D efforts are stranded before commercialisation or larger scale deployment. Such stability also needs to be predictable; even if support turns out to be stable in the long run, investments will be difficult if that stability cannot be anticipated.

As there is a substantial **risk** that the technologies will not achieve viability or reach a mature stage, risk mitigation and absorption are critical. In particular, some CDR technologies require high initial investment (e.g. DACCS), necessitating upfront capital investment and risk tolerance.

Finally, in addition to financial support, broader policy incentives and supporting political environment to generate demand are important to advance technologies at this stage (Åhman, Skjaerseth and Eikeland, 2018).

(2) Demonstration stage

In the demonstration stage, **scale** becomes more important, but investments can still be risky as the approach is not yet fully proven. Political and social support can be critical at this stage to ensure continued investment and incentive support as well as early adoption and pilot testing.

(3) Mature stage

In the mature stage, **scale** becomes the dominant imperative. Revenue streams need to be sufficient to meet the needs of the specific CDR technology and market, as well as the unlocking of scaled efficiency and per unit cost reductions. Revenue could be procured through a mixture of larger and smaller public and private revenue streams tailored to support the different CDR options.

Cost-effectiveness is also important, particularly due to the large scale of the support needed. The support mechanisms for the mature stage should focus on supporting the most cost-effective options but should also consider other benefits or potential negative consequences of CDR options, if any.

Stability remains a key characteristic of good CDR support in the mature stage. Incentive mechanisms need to be ongoing and durable, and they need to move to self-sustaining approaches that are not only reliant on direct government support.

3.2 Existing support mechanisms for CDR development

Several support mechanisms for CDR are already implemented around the world by governments and businesses, or could be implemented in the future. We have collated a range of existing examples (Table 2 and Table 3) and categorised them depending on the type of support provided. For government support, we include three broad categories: investment in research and innovation; regulations and standards; and markets and incentives. Support for research and innovation is primarily needed for technologies in their early stages of development; as a technology becomes more advanced, regulations and/or incentives are needed to ensure its uptake. Private sector support has come in the form of voluntary commitments for CDR, seed funding for CDR start-ups, and participation in voluntary CDR markets.

International efforts and international governance will be instrumental to the deployment of CDR on the level required to meet the objectives of the Paris Agreement (not included in the tables below). This could include cooperation to establish Monitoring, Reporting and Verification (MRV) standards for CDR, to develop robust sustainability frameworks or to build cross-border CCS infrastructure (The Royal Society and Royal Academy of Engineering, 2018).

Table 2: Existing government policy support for CDR

Support options	Measure	Examples
Investment in research and innovation	Investment in basic and applied research	• UK: £8.7 million GHG Removal Research Programme (NERC, 2017) • US: Draft USE IT Act to support CDR research (proposed in 2018) (U.S. Senate, 2019) • EU: Research support for CDR technologies
	Investment in demonstration and pilot projects	• Japan: CCS demonstration plant with a capacity of min. 100K tCO_2 yearly (2012-2020) (Sawada *et al.*, 2018) • The US National Academies of Sciences, Engineering, and Medicine (NASEM) have recommended yearly RD&D funding for DAC of US$ 240 million per year for the next 10 years (Larsen *et al.*, 2019) • UK: £31.5 million GHG Removal Research Programme (UKRI, 2020) • EU Horizon 2020: the NER300 fund has issued funding to CCS demonstration projects • EU Climate KIC accelerator funding for Climeworks direct air capture 2012/2013
Regulation and standards	Adoption of a national MRV system for CDR	• To our knowledge, no country has yet adopted a national Monitoring, Reporting and Verification (MRV) system for CDR
	CDR obligations	• To our knowledge, no country has yet formulated direct obligations for CDR for companies or consumers
	Procurement rules	• Legislation in the US has been proposed that would require states to purchase a certain amount of fuels or building materials made with air-captured CO_2 (Friedmann, 2019)
Markets and incentives	Tax credits	• US 45Q tax credit for carbon capture and storage or utilisation (2008, amended in 2018)
	Emission reduction credits, results-based payments	• Afforestation and reforestation included in CDM with temporary Certified Emission Reductions (tCERs) under the UNFCCC • Reducing emissions from deforestation and degradation (REDD+) is supported with results-based payments under the UNFCCC • California Low-Carbon Fuels Standard (LCFS) (2006, amended in 2018) • Australia's Emissions Reduction Fund awards credits to projects that would classify as CDR
	Carbon pricing / carbon tax	• The carbon tax in Norway has directly supported CCS projects in the country (Zapantis, Townsend and Rassool, 2019)
Public GHG emission targets	International – Paris Agreement	• 1.5°C goal requires large-scale negative emissions technologies to be deployed by 2050
	National- and state-level emission targets	• At least 70 countries have committed to net-zero emissions targets that will almost certainly necessitate negative emissions from CDR
	Public utilities	• Consumers Energy's (USA) net-zero emissions by 2040 plan utilises CDR to compensate for two natural gas-fired plants

Information presented in this table is based on "Center for Carbon Removal, 2017; Friedmann, 2019; Larsen et al., 2019" and own research.

Table 3: Existing private sector support for CDR

Support options	Measure	Examples
Seed funding for CDR start-ups	Equity investments in innovative technologies and projects	• Start-ups include Climeworks (CarbFix project in Iceland), Carbon Engineering, Global Thermostat, Infinitree LLC and Skytree • Funding to date mostly comes from oil companies (some start-ups refuse to take it) and philanthropists
Voluntary Private Sector commitments	Voluntary funding of CDR (e.g. as part of company CSR strategy)	• Stripe: voluntary commitment of min. US$1 million/year to CDR (2019) • Shopify: voluntary commitment of min. US$1 million/year to CDR (2019) • Microsoft aims to be carbon negative by 2030 and to invest US$1 billion in innovation for carbon reduction, removal and storage (Smith, 2020) • Starbucks has indicated funding for negative emissions technologies as part of its supply chain emission reduction commitments • AstraZeneca's "Ambition Zero Carbon" plan calls for negative emissions across entire value chain by 2030
Voluntary markets	Creation or participation in voluntary markets for CDR	• Land-based options (afforestation & reforestation) are used in voluntary offset markets • Puro: voluntary market in Nordic countries launched in 2019 (Puro, 2019) • Nori: voluntary market to launch in 2020 focusing on agricultural CDR measures

Information presented in this table is based on "Center for Carbon Removal, 2017; Friedmann, 2019; Larsen et al., 2019" and own research.

Two of the most significant government policy support mechanisms for CDR in terms of the price incentive given by a government are the United States' 45Q tax credit and California's Low-Carbon Fuel Standard (LCFS). According to analysts, these two policies will likely soon be combinable, leading to levels that could be sufficient to incentivise the development of Direct Air Capture projects (Larsen *et al.*, 2019; Townsend and Havercroft, 2019).

The 45Q tax credit

This 45Q tax credit was first created in 2008 but was subsequently amended in 2018 when the US Congress passed the FUTURE (Furthering carbon capture, Utilization, Technology, Underground storage and Reduced Emissions) Act. Some noteworthy changes include explicitly allowing for Direct Air Capture (DAC) with storage or use of CO_2 to qualify for the tax credit and increasing the incentive given to CCUS projects (see Table 4) and removing the 75 million tCO_2 cap on credits that existed previously (and which was close to being reached by the time of the amendment) (Friedmann, 2019). Eligible projects include CO_2 captured and securely stored underground, Enhanced Oil Recovery (EOR) and other CO_2 use projects (Martin, 2018).

Table 4: 45Q tax credit value progression in US$ per ton of captured CO_2 used or stored

	Enhanced Oil Recovery and other uses	Storage
2019	17.8	28.7
[…]	[…]	[…]
2026	35	50
Post 2026	Indexed to inflation	Indexed to inflation

Data from Nagabhushan and Thompson, 2019

For a project to be eligible for a tax credit, it needs to comply with minimum yearly carbon capture thresholds, which vary depending on the type of project (see Table 5). The US Clean Air Task Force estimates the policy could lead to 49 million tCO_2 captured and stored from the power sector per year by 2030 (Nagabhushan and Thompson, 2019). In June 2020, Proposed Regulations detailing updates to the tax credits and providing details on eligible projects were released.

Table 5: Carbon capture thresholds in the amended 45Q tax credit

Type of project	Beneficial use project other than EOR	All other industrial facilities (excl. power plants, incl. DAC)	Power plants
Annual carbon capture threshold	25 000 – 50 000 tCO_2	Minimum 100 000 tCO_2	Minimum 500 000 tCO_2

Data from Christensen, 2019

California's LCFS

In addition to the federal 45Q tax credit policy, California passed the Low-Carbon Fuel Standard (LCFS), first issued as part of the Global Warming Act in 2006 (Friedmann, 2019). The LCFS' primary objective is to reduce the carbon intensity of transportation fuels by 20% or more by 2030. The LCFS was later modified in 2018 to add provisions making two CO_2 capture measures eligible for carbon credits: synthetic fuels made from air-captured CO_2 and plants capturing CO_2 from the air and securely storing it (anywhere in the world) (Townsend and Havercroft, 2019). These changes came into effect in January 2019.

The carbon credit prices are determined by the market. Throughout 2019 the credits were traded at close to 200 US$/$tCO_2$: between January and November 2019, the average monthly credit price was between US$ 180 and 195 (California Air Resources Board, 2019). According to research by the Rhodium Group, the 30-year "break even" costs of a DAC project currently stand at close to US$ 240 per tonne of CO_2 (Larsen *et al.*, 2019). However, the Canadian firm Carbon Engineering published an estimate of US$ 94 to US$ 232 per metric ton of capture carbon for their industrial scale DAC systems (Keith *et al.*, 2018).

This means the current levels of the LCFS, despite being high, may not be sufficient to support DAC projects despite the policy's intent to do so. As mentioned previously, the LCFS could however be combined with the federal 45Q tax credit, with the incentives being close to levels required for DAC projects. This is however contingent on the US Treasury issuing guidance for new projects to be able to receive support under the 45Q tax credit until the US Treasury issues further guidance.

4 An alternative to offsetting as CDR support

We have established that substantial CDR will be required to meet the Paris Agreement goals (chapter 1) and that there are several possible approaches for CDR but that major scaling up is required (chapter 2). A few initiatives to support this scaling up are already underway (chapter 3) but will need to be more extensive to achieve the levels of CDR required in the latter half of the century.

In the following section we examine whether and how offsetting and climate neutrality claims can support CDR or if there are alternatives. We outline the risks and opportunities under different circumstances.

4.1 Offsetting mechanisms and carbon neutrality claims

Section 3.2 identified some programmes in which CDR technologies are considered as potential options for generating carbon credits to offset GHG emissions on compliance and voluntary markets. The purchase and use of offset credits to claim carbon neutrality is an increasingly popular approach for organisations to attempt to address their climate impact, as well as for governments to claim compliance with emission reduction targets. Some domestic and regional carbon pricing and trading instruments allow market participants to buy credits from CDR projects to offset emissions that are not covered by the participant's emission allowances. For example, Australia's Emissions Reduction Fund awards credits to projects that would classify as CDR, while some CDR outcomes are also eligible for compensation compliance under the California Low-Carbon Fuels Standard (LCFS). Likewise, some countries may wish to meet their GHG emission targets by purchasing carbon credits from other countries, including potentially from CDR projects.

Despite the popularity of offsetting approaches, carbon neutrality claims delivered through offsetting face a number of limitations and risks under the global governance framework of the Paris Agreement.

The suitability of any climate change mitigation project for offsetting should be a very critical consideration. When carbon credits are used to offset actually occurring GHG emissions to meet targets, instead of reducing one's own emissions directly, any issues related to the integrity of those credits can lead to the offsetting activity having a detrimental impact in terms of net GHG emissions.

The following sections give an overview of these challenges and the stringent criteria needed to overcome them, in order to indicate whether offsetting would be a suitable form of support for CDR activities.

We find that the CDR technologies and practices assessed in this paper are not currently able to provide a guarantee against all of these stringent criteria needed to overcome the challenges associated with offsetting in the context of the Paris Agreement, and that offsetting mechanisms are not the most appropriate policy framework for their of support.

4.1.1 Challenges of offsetting in general in the context of the Paris Agreement

While offsetting mechanisms can provide opportunities for the implementation of additional emission reduction projects, the Paris Agreement sets a new framework for international cooperation in which offsetting mechanisms also have some limitations. Without those limitations being recognised and addressed, such mechanisms could even pose a risk of undermining ambition of the Paris Agreement.

A thorough understanding of these challenges and the opportunities to overcome them is needed to determine whether offsetting mechanisms may be suitable support options for some CDR technologies and practices, and for other emission reduction projects (NewClimate Institute, 2018).

Carbon neutrality claims delivered through offsetting could detract from the transparent dialogue that is needed to reach zero GHG emissions worldwide. Claiming carbon neutrality through offsetting may divert attention from the fact that, to meet the objectives of the Paris Agreement, we need to reach zero GHG emissions worldwide and net-negative emissions thereafter. The Paris Agreement highlights the importance of transparency and facilitative dialogue for ambition raising to support full decarbonisation. Using offsets to claim carbon neutrality does not necessarily support efforts to decarbonise one's own activities, nor to engage in transparent dialogue on the actual occurring GHG emissions and solutions to reduce them.

Financial support should positively reinforce ambition raising, while offsetting activities have the potential to present perverse incentives that undermine this. The Paris Agreement requires all countries to set self-determined emission reduction targets (Nationally Determined Contributions – NDCs), which are to be revised at least every five years to reflect each country's highest possible ambition level. Without stringent safeguards put in place, the prospect of potential revenues from emission reduction or removal credits associated with offsetting programmes may present countries with a perverse incentive to restrict the extent to which they ratchet-up the ambition of their unilateral action during NDC revision cycles, so that more of their mitigation potential can be tapped by international offsetting mechanisms.

The integrity of offsetting credits for buyers is increasingly uncertain. The potential conflict between offsetting and host country ambition, addressed above, also entails a risk for buyers of offset credits related to the integrity of those credits. A key condition for determining the integrity of offset credits is the *additionality* of the emissions reduction project; that is, the guarantee that credited emission reductions or removals are additional to what could be achieved without the offsetting programme. In historical offsetting mechanisms, such as the CDM, additionality could be proven by showing that the activity was not required by local legislation or that local regulations were not enforced and that offsetting revenues could help overcome barriers that would otherwise prevent implementation. Since, under the Paris Agreement, all countries now have their own emission reduction targets and the requirement to regularly ratchet-up their ambition levels, this situation calls for the re-definition of the concept of additionality: additionality should imply complete certainty that the project supported could not realistically have been implemented otherwise, through unilateral ambition enhancements on the part of the host country.

Stringent safeguards are required for climate change activities to overcome these challenges and be suitable for offsetting mechanisms. To address the challenges identified above, stringent safeguards would be needed to ensure additionality against a revised definition that is in line with the context of the Paris Agreement, to avoid or reduce the effects of such perverse incentives and to ensure additionality. Offsetting programmes would need to ensure that they only tap highly ambitious mitigation options, which are beyond the reasonable reach of the host country's unilateral action and which do not represent a conflict with the country's own mitigation targets.

The suitability of any climate change mitigation project for offsetting should be a very critical consideration. When carbon credits are used to offset actually occurring GHG emissions to meet targets, instead of reducing one's own emissions directly, any issues related to the integrity of those credits can lead to the offsetting activity having a detrimental impact in terms of net GHG emissions. Responsible offsetting requires a high degree of certainty in the integrity of the carbon credit; in order for the outcomes of any climate change mitigation activity to result in carbon credits that could be counted to offset a GHG emissions balance, those outcomes need to be directly equivalent to the actually occurring GHG emissions and their effect on the atmosphere, both in the short- and long-term. This direct equivalence refers not only to the volume of GHG emission reductions from a specific project activity, but also the certainty of the measurement, and the permanence of the impact in terms of their effect on the atmosphere.

These stringent criteria put in doubt the suitability of many climate change mitigation activities for offsetting. Most, if not all, climate change mitigation projects entail at least some degree of uncertainty related to the integrity of the measured GHG emission reduction outcomes. In recognition of the difficulties to identify projects that represent the level of certainty required for offsetting to be a responsible practice, some organisations forego the offsetting approach and associated carbon neutrality claims, although they may still use the existing structures and processes of carbon crediting mechanisms as a form of results-based finance (more see Section 4.2).

4.1.2 Suitability of CDR outcomes for offsetting mechanisms

While the suitability of outcomes for offsetting is an issue that requires particularly critical consideration for many climate change mitigation activities, this is also true for the outcomes of CDR projects, where an assessment of the equivalence of emission reduction outcomes is particularly nuanced. We look here into the integrity and equivalence of CDR outcomes against GHG emission with regards to the *permanence* of the outcome, the *additionality* of the CDR activity, the potential for *leakage* of outcomes beyond the project boundaries, and the degree of *methodological certainty related to measurement* of the outcomes.

Table 6, and the following sub-sections, give an overview of the selected CDR measures from section 2 with regards to these factors, showing that none of the CDR measures can provide a complete guarantee regarding the certainty of the project outcome across *all* of those factors.

Table 6: Overview of the factors affecting suitability of CDR technologies for offsetting

	Approach	Factors affecting suitability for offsetting			
		Permanence	Additionality+	Leakage (displacement of emissions)	MRV methods
Biological capture and storage	Soil carbon sequestration	Vulnerable	Low to medium probability	Vulnerable	High complexity
	Biochar	Vulnerable	Low to medium probability	Vulnerable	High complexity
	Afforestation & reforestation (AR)	Vulnerable	Low to medium probability	Vulnerable	High complexity
Underground storage	Bioenergy with carbon capture and storage (BECCS)	Possible but not guaranteed	Medium to high probability	No issue	Uncertain for storage
	Direct air carbon capture and storage (DACCS)	Possible but not guaranteed	Medium to high probability	No issue	Uncertain for storage
Mineral storage	Enhanced weathering	Likely	Medium to high probability	No issue	Uncertain and high complexity
	Mineral carbonation	Likely	Medium to high probability	No issue	Uncertain and high complexity

The table is the authors' simplifying summary that provides an overview of the analysis of the following sub-sections.

+ *The probability of additionality is indicated in the table to be low to high, but in all cases depends on national circumstances (see text below).*

Permanence of carbon dioxide removal

The *permanence* of a CDR outcome refers to the degree of certainty that the previously sequestered carbon will not be released at a later point in time. Permanence is a very important issue when considering the relevance of CDR outcomes for offsetting GHG emission balances, since the release of previously sequestered carbon at any point in the future negates the benefits of the sequestration for the long-term mitigation of climate change. At the point at which the carbon dioxide is released, the atmospheric concentration of carbon dioxide is restored to the same value that it would have been had the CDR activity never taken place. The removal of carbon dioxide from measures without permanence is only a delay in emissions, and therefore should not be used to offset carbon dioxide emissions, which have a higher permanence.

The only CDR measures in this analysis with an established likelihood of permanency are *enhanced weathering* and *mineral carbonation* (Table 6). Here the CO_2 is transformed into stable solid matter.

Sequestration in forests or soils is vulnerable to reversal at any point in time, due to disturbances such as tilling, floods, droughts, fires, pest outbreaks, poor management or incentives for land-use change (IPCC, 2019). Although some of the sequestered carbon may end up in more permanent applications – such as the use of wood for building – there can be no reliable guarantee for any specific project that all of the sequestered carbon will find its way to such applications.

The permanence of bioenergy or DAC combined with underground storage is tested and functional in demonstration plants, but still entails a degree of uncertainty; it is reliant on the choice and permanently continued operation and management of the storage technologies, as well as uncertain geological factors unless fully mineralised (see Annex I). Permanence of storage in 'technical' approaches is therefore not necessarily guaranteed, though far more likely than permanence from 'biological' sequestration measures.

The non-permanence of some CDR approaches is reflected in the methodologies of some crediting mechanisms, for example the Clean Development Mechanism (CDM). Here, projects from forestry and land-use were not issued Certified Emission Reduction credits (CERs); rather, a temporary unit (tCER) was established to recognise that CDR outcomes could not be considered equivalent to the outcomes of the avoidance of emissions through emission reduction activities. However, this led to little use of this in practice. Other approaches, especially used for forestry projects including afforestation and reforestation, include "buffer accounts" which attempt to estimate the future likelihood of reversals and set aside a corresponding number of credits. Some programmes have suggested making either project developers or credit buyers liable for any future reversals. All of these approaches face important challenges in terms of medium- and long-term monitoring and governance such as for hundreds of years (Schneider *et al.*, 2018).

Additionality of the CDR activity

The *additionality* of an emission reduction activity in the context of carbon market mechanisms requires that those outcomes result from a project that would not take place in the absence of the incentives provided through the existence of carbon market mechanisms, e.g. revenues from carbon credits.

Additionality in international market mechanisms in the context of the Paris Agreement should not only be a measurement of deviation from the business as usual baseline, but also an assessment of whether or not the activity is within reasonable reach for unilateral domestic action (see Section 4.1.1). Only technologies and practices that are extremely ambitious and which are otherwise "inaccessible" to the host country government – sometimes referred to as the "high-hanging fruits" – should be considered *additional* in this context.

Due to the maturity, the relatively low cost, or the relatively high co-benefits associated with CDR measures related to land use, the *additionality* of those measures is questionable in most country contexts, when considered against this definition of additionality. In contrast, the measures involving underground and mineral storage may be considered relatively inaccessible technologies in some country contexts due to their early stage of development and potentially prohibitively high costs.

Leakage of project outcomes across project boundaries

Leakage (in relation to offsetting) is the shifting of emission reduction outcomes from inside the project boundary to outside of the project boundary, i.e. the displacement of emission activity. If emissions "leak", the emissions reductions or removals achieved inside the project boundary are not necessarily real reductions on the global level, as they still occur, just in a different location.

This is a particularly troublesome issue for land-use change projects, including projects that result in carbon sequestration in forests or soils, where conflicting potential land uses may lead to high-emitting land-use activities to simply shift outside the managed project boundary (Schneider *et al.*, 2018). For example, if non-forested land used for soy cultivation is then reforested, the soy cultivation may simply move elsewhere, potentially driving deforestation in another location – this is a particular challenge for globally traded commodities. Likewise, projects that resist pressure for land-use change on protected soils, including biochar, can also lead to such land-use changes to simply occur elsewhere.

For measures involving underground and mineral storage, where there is not an existing carbon reservoir that requires protection in the face of competing resource demands, leakage of project outcomes is unlikely to represent a significant issue.

Methodological uncertainties related to monitoring, reporting and verification

Methodological uncertainties related to MRV are issues that can affect the environmental integrity of any climate change mitigation project inadvertently or purposefully. Climate change mitigation projects where the emissions impact cannot be directly observed and measured may require a large number of assumptions to estimate those impacts, and advanced technology may be required for accurate measurements. In CDM methodologies for emission reduction projects, this has been partially addressed through the use of assumptions and baselines that are believed to be conservative, but there are many cases of technologies where further research has cast doubt on those methodological decisions and the real impact of projects.

These uncertainties are particularly pertinent for many CDR technologies; where removals cannot be measured directly, project developers must use complex methodologies or advanced remote sensing technologies (Schneider *et al.*, 2018). As mentioned above, for soil carbon sequestration estimation through sampling has yielded conflicting estimates (Gross and Harrison, 2018).

Direct air capture and capture through biomass in BECCS can be measured during the capture process; the challenge here is the verification. For underground and mineral storage, it is challenging to monitor and verify the permanence of the storage (see Annex).

Suitability of CDR measures for offsetting

Given the stringent criteria, which should be applied to the consideration of suitability for offsetting, none of the CDR measures assessed in this paper provide the suitable level of guarantee that they can be considered directly equivalent to emission reductions (Table 6).

Nevertheless, the analysis indicates that the suitability is nuanced across the different CDR options. While biological capture and storage entail serious issues for permanence and several other environmental integrity factors, the other CDR measures face fewer issues, which may be addressed over time as technologies and practices mature.

Despite the conclusion that the outcomes of CDR measures do not represent a high enough degree of certainty in order to be responsibly used in offsetting programmes, this does not detract from the high importance of all of these measures for the achievement of the Paris Agreement objectives, and the need to channel more finance and support to them. However, other support options should be pursued to avoid any potential negative impacts associated with incommensurate offsetting.

4.1.3 Examples of existing CDR support delivered through offsetting mechanisms

The previous section found that CDR measures generally to not represent the suitable degree of certainty in their environmental integrity for use in offsetting mechanisms. This finding can be further illustrated with examples from existing programmes that do pursue such an option.

Some companies and governments have already started to offset emissions through the use of forestry credits, to claim carbon neutrality. For example, the Australian Emission Reduction Fund and the Californian emissions trading system both allow offsetting of fossil fuel emissions with forestry activities.

The key **advantage** of such an approach it supports the expansion of forest sinks. However, care must be taken in how that support is given, and these examples have several **drawbacks**:

- The approach gives the false impression that fuel emissions were neutralised, by indicating equivalence of emission reductions from fuels with emission recovery in forests. Forests grow slowly over decades capturing carbon over an extended period of time, whereas emissions from fossil fuel burning occur instantaneously. Given that captured CO_2 in forests may be released in the near future, the fuel emissions are not neutralised.

- The Paris Agreement goals require that forests are enhanced while fuel emissions *also* need to be reduced to zero; one should not be accomplished at the expense of the other.
- The ability to sell forestry credits may cause countries to face perverse incentives with regards to the level of national ambition to unilaterally support forestry projects, in order to maximise the potential for foreign investment. Some developing countries in particular may need more financial support to ramp up and maintain their action in forestry projects, but an environment in which this finance positively reinforces ambition raising efforts, rather than providing perverse incentives, would be more constructive.

A similar example is that a company or a country could offset fuel emissions through more technical solutions, such as a direct air capture with CCS project. This is considered by some to be more appropriate than the example of offsetting with forestry activities, since removals through direct air capture are currently significantly more expensive per tonne of CO_2 compared to forestry projects. The Californian low carbon fuel standard is an example where a government has chosen this approach. The EU ETS also allows CCS removals to be counted against emissions, regardless of whether they were from direct air capture or not.

The advantage of this example is that it supports a currently expensive technology that may be needed in the future and that is currently getting little attention. However, the drawbacks of the previous example remain; the approach also gives the false impression that fuel emissions were neutralised. Although the permanence of storage with CCS is longer and more likely than in forests, the captured CO_2 may be released at a later date and cannot be fully guaranteed. As with the forestry example, this approach does not take account of the fact that both fuel emissions need to be reduced to zero *and* removals need to be enhanced in the long run; one should not be accomplished at the expense of the other.

4.2 Alternative support frameworks with a ‘contribution claim’

In section 4.1.1 we specifically examined whether offsetting schemes are appropriate for supporting CDR activities and outlined that some developments would first be needed against important criteria for environmental integrity, in order for this to support rather than undermine ambition within the framework of the Paris Agreement. Hence, alternative support options are needed to meet the important challenge of scaling up the support provided to CDR activities.

In light of the general limitations of offsetting in the context of the Paris Agreement and the increasing consumer awareness on the uncertainty of some carbon neutrality claims, an increasing number of organisations are opting for an alternative approach in which they provide financial support for climate change mitigation action *without* claiming the outcomes of those actions as their own[6]. This may take the form of results-based finance, in which credited project outcomes might still be procured, or it might come in the form of more flexible climate finance without a stringent quantification and crediting process. Organisations and governments that provide such support may still externally communicate the details of the support they have provided – we refer to this as a *contribution claim* – but they do not need to transfer ownership of the GHG mitigation outcomes away from the project and host country, and do not assume a *carbon neutrality claim*.

Such a support option is already in use by companies and governments and can easily be replicated and scaled up. Stripe and Shopify provide a voluntary commitment of min. US$ 1 million/year to GHG removal, and Microsoft aims for US$ 1 billion in support for innovation in reduction, removal and storage. Several

[6] See, for example, NewClimate Institute’s *Climate Responsibility* approach: newclimate.org/climateresponsibility

countries including the United Kingdom, the United States, Japan and the European Union provide research funding as part of their regular research budgets (Section 3.2).

A contribution claim approach for CDR technologies has multiple **advantages**:

- A contribution claim approach can provide support for important, yet currently expensive technologies that may be needed in the future. It can address the needs of early stage CDR support with higher costs per tonne reduced, because it doesn't require a one-for-one offset.
- Since a contribution claim does not necessarily require certainty in immediately quantifiable emission reduction results, it might also be more appropriate for supporting technologies that remain less mature or unproven, although representing significant transformation potential. This does not mean that the effectiveness of such support should not be considered: as approaches are further developed and MRV methods improved, the total effectiveness of the support in terms of tons of CO_2 removed should be monitored.
- A contribution claim approach for CDR technologies also ensures that both emissions reductions and removals can be targeted at the same time, as would be required to meet the objectives of the Paris Agreement.

A potential **drawback** of the contribution claim approach for CDR activity support may be that, from a marketing perspective, this claim is more difficult to communicate than carbon neutrality claims delivered through offsetting. As such, it may be less attractive for companies or countries whose marketing approach may also be important in justifying additional expenses. Verification of the usefulness and effectiveness of the investment still needs to be proven. It could be expected that these potential disadvantages will be mitigated over time, as consumers and investors become increasingly conscious, and even demanding, regarding the nuances associated with climate change support claims.

Aspects of historical carbon market mechanisms might still be useful for channelling and monitoring the results of finance under the contribution claim. For example, a CDR support approach based on a contribution claim could be provided through results-based finance, in which credited CDR outcomes are procured by the support provider. Such credited outcomes could be awarded not only for carbon dioxide removal, but also for other sustainable development benefits. This may have the advantage that the provision of finance is made easier for the support provider, since the credit procurement market might provide a means of more easily identifying projects in need of support. The crediting of outcomes can help the support provider to outsource the task of monitoring the effectiveness of that finance flow. Such an arrangement could still make use of several aspects of existing crediting mechanisms, such as project registration protocols and registries, established monitoring and reporting processes, as well as credit verification and issuance procedures.

5 Target setting with CDR outcomes

In line with the requirements of the Paris Agreement to achieve net-zero global CO_2 emissions by 2050 (see Section 1), an increasing number of countries and companies have committed to achieve net-zero emissions (sometimes also referred to as carbon neutrality) by that time or earlier. Such a target is achieved if CO_2 removals exceed CO_2 emissions. Such targets provide the framework for detailed policies and incentives to achieve them (e.g. through offsets, as discussed above). Some companies and governments also count investments in emission *reductions* (not removals) outside of their operations / country towards their targets, though the suitability of this type of offsetting for net-zero targets is not a focus of this paper.

As CO_2 emissions in some sectors are more challenging to reduce (e.g. aviation) than in others, collectively reaching net-zero emissions fast enough can likely only be achieved with CO_2 removals to balance any residual emissions from difficult-to-reduce sectors. Furthermore, most 1.5°C consistent emissions scenarios include net CO_2 removals in the second half of the century, which can only be achieved through CDR.

In the following, we discuss two options for how companies and governments can set targets in a manner that incentivises CDR, which is closely related to the offsetting or contribution claim discussed in the previous section. As in the previous sections, the consideration is about whether or not counting removals against emissions would be an appropriate and effective option for upscaling CDR support.

5.1 Targeting net-zero with a *combined* reduction and removal target

A country or company could set a net-zero emissions target with combined reduction and removal approaches. All countries that have set themselves net-zero emissions targets to date, including for example, Norway, Sweden, and the United Kingdom, have explicitly stated that they will have to rely on carbon removal of some sort to reach it.

The approach of combining emission reductions and removals aims for the most cost-efficient solution to zero emissions. In theory, removals should only be relied upon if they are cheaper than the reduction of emissions. Since some CDR activities can be expensive, there should be an incentive for reductions in emissions from fossil fuel consumption.

However, the disadvantages and risks of a combined net-zero target are considerable. The approach can divert attention from reducing emissions under the uncertain assumption that one could always rely on removals at a later date; worse still, optimistic assumptions related to potential cost reductions of CDR technologies in the future may lead to delayed action for both emission reductions and removals. If such removal technologies are not incentivised at an early date, they may well not reach the maturity required to perform the necessary role. In addition, this approach allows for residual emissions that could be problematic later in the century when emissions need to move towards net negative. This approach carries similar drawbacks and uncertainties as offsetting, in the sense that it assumes direct equivalence of emission reductions and removals and neglects the risk that captured CO_2 may be re-released.

5.2 Targeting net-zero with *separate* reduction and removal targets

Another option would be that a country or company sets a zero (or very low) emissions target for fossil fuel emissions *and* a separate carbon removal target (McLaren *et al.*, 2019). Both targets would have to be accomplished separately.

Many near- and medium-term national GHG emission targets have already gone through this evolution; many of the recent national GHG emission reduction targets of developed countries exclude forestry, or targets for the forestry sector are set separately. In the accounting under the Kyoto Protocol, forests are accounted separately with special rules (Höhne *et al.*, 2007).

Setting two separate targets provides clear responsibility for reducing emissions *and* increasing removals. As such, it is preparing the country for the net-negative phase required later in the century. The possibility that some of the captured CO_2 may be released at a later date is less relevant because the reduction of fossil fuel emissions is already secured within the approach.

However, the establishment and following of two separate targets is not without challenges. The target values need to be set in a way that provides clarity, certainty and balance. This is not straight forward and will lead to debates.

A separate governmental removal target would require a set of policies to be laid out for its achievement. For example, the government could directly purchase carbon dioxide removal from particular technologies directly from service providers.

Revenues from CO_2 pricing from other emissions could be one financial source. Depending on the CO_2 price, the total revenue generated by emissions in the latter half of the century may be insufficient to cover the full cost of CDR. Furthermore, those revenues could be used for other climate related measures, e.g. to support for climate adaptation.

Separate targets would give transparency to national targets in terms of the scale of the CDR challenge and would show more clearly the extent to which CDR could be met by biological approaches and to what extent more expensive approaches will be required. This transparency could also clarify the extent of investment requirements needed in the near-term.

Companies could adopt a similar approach for setting voluntary targets; one target for reducing one's own emissions and one target for supporting CDR. Again, this would bring clarity and transparency to how those companies are reducing their own emissions. Alternatively, the government could require companies of a certain size, level of revenue or energy use, to support CDR through the imposition of binding targets. The level of the requirement could be linked to a company's greenhouse gas emissions, but does not necessarily have to be. Service providers could help companies to fulfil the obligation in competition with each other.

6 Recommendations

Based on our consideration of needs and options for CDR support, we suggest the following:

Support biological CDR options (afforestation, reforestation, biochar and soil carbon sequestration) through domestic, regulation-based policies. These biological CDR options have multiple benefits, including biodiversity and soil fertility. They could be incentivised as much as possible through direct national regulation or international support, emphasising the co-benefits, and ensuring a supportive policy and governance framework. When using carbon markets and offsetting with biological CDR options, the risks outweigh the benefits due to the high risk of non-permanence, limited additionality to what should happen anyway, and complex interactions with other land-use needs. Furthermore, there are other means to support biological CDR options that do not carry these risks.

Provide long term, secure support for the research and development stage of CDR technologies by targeting various CDR options individually (BECCS, DACCS, enhanced weathering and mineral carbonation). More research and application of BECCS, DACCS, mineral carbonation (all in demonstration phase) and enhanced weathering (in R&D phase), is necessary to bring costs down and better understand the risks and benefits.

Governments and businesses could support R&D, provide pilot support for individual technologies. As with any R&D or demonstration support, those providing the financial support would see themselves as frontrunners and take the initial risk. This support would be seen as a contribution to solve climate change, in addition to a potential commercial advantage.

Carbon market mechanisms or carbon pricing in other sectors could be a source of revenue to support these activities (e.g. revenues from auctioning of an emission trading system, ETS), following the polluter pays principle, but ensuring that careful consideration is given not to divert funds from other effective mitigation activities.

Develop stable, predictable, efficient and large support mechanisms for CDR when technologies are mature. BECCS, DACCS, enhanced weathering and mineral carbonation will need continuous support, even if the costs are lowered, because these technologies have limited benefits other than CDR. The scale of CDR likely required is only possible if governments set the rules under which companies and consumers implement CDR at their cost and as part of their responsibility. If government revenues alone would be used, they would have to be very substantial.

Keep emissions and removals separate: Separate targets for emissions (with dedicated support for emission reductions) and targets for removals (with dedicated support for CDR) have significant advantages over combined net-zero targets, where emissions are offset against removals and climate neutrality is claimed. For the combined approach, risks could outweigh the benefits. In particular, the approach can divert attention from reducing emissions under the uncertain assumption that one could always rely on removals at a later date. The approach of two separate targets and no offsetting provides clear responsibility for reducing emissions *and* increasing removals. The risks are lower in the separated approach: The possibility that some of the captured CO_2 may be released at a later date and requirements on monitoring are less relevant because the reduction of fossil fuel emissions is already secured within the approach. The separated approach also prepares for the net-negative phase required later in the century, which is not necessarily achieved by combined targets or offsetting.

Continue research and policy experiments: Some open questions remain as to how such a framework can be implemented in practice:

- What are the most effective policies to implement this framework?
- At what level should companies or governments set the emission and removal targets, if they are separated?
- What are the most appropriate sources of revenue for governments to support CDR?
- How should companies or governments choose which CDR approaches to support?

These questions need to be explored through further research and thinking, but also through policy experimentation and reflection. The broad suite of policies already in place can be assessed in more detail in terms of their effectiveness and appropriateness, with the most successful providing good candidates for further testing and upscaling.

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8 Annex I - Geological sequestration & permanence

Geological sequestration techniques for the long-term sequestration of captured CO_2 using BECCS or DACCS capture methods can, on average, offer greater assurances of permanence than 'biological' techniques such as forest or soil carbon storage. Nevertheless, the permanence of geological sequestration is neither guaranteed nor absolutely certain. Rather, the permanence probability factor for any given geological sequestration project (i.e. the probability that the sequestered carbon remains sequestered for the defined period of time) depends considerably on the geological formation, technique used and on the pre-, mid- and post-injection operation and management of the storage facility (Anderson, 2017).

Geological sequestration includes a number of different storage techniques with varying degrees of technical and commercial viability. To date, possible methods can be grouped into two main categories.

- **Supercritical Subsurface Injection**. CO_2 is pressurised into a relatively dense fluid and injected into a subsurface formation that holds or previously held fluids. The two most widely available types of subsurface formation are Deep Saline Formations and Buoyancy Traps.
    - **Deep Saline Formation (DSF) Injection**. Captured CO_2 is injected into deep subsurface saline formations. The relatively buoyant CO_2 then migrates through the formation, becoming trapped in permeable and porous rock. DSF constitutes approximately 95% of CO_2 storage potential in the United States and the vast majority globally.
    - **Buoyancy Traps**. Natural subsurface geological "structural traps" with largely impermeable vertical cap rock and horizontal seals, typically associated with natural formations containing (or once containing) oil and gas (Núñez-López and Moskal, 2019).
- **Geological Mineralisation**. Utilises a geochemical method to induce carbonation reactions and form a stable carbonate rock. Storage can be *in situ* in existing surface or subsurface rocks or *ex situ* in industrial by-products such as mine tailings (Gislason *et al.*, 2016).

For the purposes of this Annex discussion, "permanence" consists of two related but independent factors. First, the *potential temporal duration* of the CO_2 sequestration under a theoretically ideal scenario and, second, the *environmental risk* that an intervening factor causes an escape or early release of the sequestered CO_2.[7] The theoretical temporal duration of geological sequestration is considerable. In theory, injected or mineralised CO_2 would be removed from the short-term carbon cycle in perpetuity (i.e. for thousands of years). Indeed, the IPCC estimated that DSFs could be "very likely" to retain 99% of injected CO_2 after 100 years and "likely" to still retain that same percentage even after 1000 years, or more, if certain assumptions are met (including adequate monitoring) (IPCC, 2005). Nevertheless, our understanding of potential temporal duration is still largely hypothetical as the behaviour of large quantities of injected CO_2 is still being modelled, and the assumptions regarding proper injection controls and post-injection monitoring in the IPCC estimate are significant.

The environmental risk that the sequestered CO_2 can escape is extant and dependent on geological and operational factors. First, reservoir specific qualities are hugely important, including porosity, permeability and leakage potential. Whether in a super critical fluid or gaseous states, injected CO_2 naturally tries to migrate vertically and horizontally and can dislodge existing fluids and gases in the process. A thorough understanding of the subsurface formation is necessary to have any degree of confidence that the CO_2 will not migrate to a release point. Further, subsurface injection can build pressure at the point of injection and at various points in the formation as the CO_2 or displaced pre-injection fluids and gases migrate. DSF are considerably less well studied than buoyancy trap formations, which are typically former or current oil and

[7] This Annex is focused solely on the risks of premature CO_2 release, but geological sequestration techniques, like biological techniques, present related but non-CO_2 environmental risks as well, including groundwater contamination and induced seismic activity.

natural gas well sites that have undergone extensive subsurface examination by oil companies. Further, DSFs are generally larger and thus the area of pre-injection examination and post-injection area of review and monitoring can range up to 100 km.

Second, environmental risk is heavily dependent on the technical and regulatory steps governing the pre-, mid- and post-injection phases of the sequestration. Risk of escape is highest during the injection phase, when the injected CO_2 increases pressure in the geological formation, potentially causing accelerated migration or induced seismicity. Escape risk remains extant for long periods of time as the CO_2 can remain mobile and pressure points can build within the formation, requiring post-injection pressure monitoring to avoid pressure build-up or decrease associated with migration. Thus, robust regulatory oversight to ensure proper techniques are used during injection and sufficient post-injection well management and monitoring are critical to decreasing long-term risk.

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