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Sewage Treatment for the Skies

Mobilising carbon dioxide removal through public policies and private financing

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Disclaimer

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perspectives climate research

Climate Strategies

MÄLARDALENS HÖGSKOLA ESKILSTUNA VÄSTERÅS

Sewage Treatment for the Skies

Mobilising carbon dioxide removal through public policies and private financing

A Perspectives report on the public policy challenge of meeting short- and long-term funding needs for carbon dioxide removal.

Key messages and recommendations

The mitigation of climate change to limit global warming to well below 2°C, as specified in the Paris Agreement, builds on two pillars. The first pillar — supported by most stakeholders, but facing implementation challenges — is rapid and deep reduction of greenhouse gas (GHG) emissions from burning of fossil fuels and destruction of forests and other types of biomass. The second pillar — contested by many but increasingly seen as crucial — is carbon dioxide removal (CDR), i.e. the practice of actively removing CO_2 from the atmosphere and durably storing it[1]. Both pillars complement each other in the quest to achieve greenhouse gas-neutrality, a balance of emissions and removals.

Many forms of CDR exist; some based on accumulation of carbon through natural processes, others through chemical-physical absorption and sequestration technologies. Generally, the nature-based options are currently cheap but face permanence challenges, whereas the technological options tend to be very expensive but come with high permanence. In contrast to many emission reduction technologies such as renewable energy or energy efficiency, most approaches to CDR do not generate any goods and services that can be sold and thus generate revenues. Exceptions are afforestation, reforestation and ecosystem restoration where revenues accrue from non-timber forest products and recreational amenities. But here the revenues need to accrue in the long term to prevent reversal.

Given that most CDR approaches do not offer a valid business case in the absence of dedicated policies that create climate change mitigation related revenues, conventional commercial and concessional finance has to date largely by-passed CDR. The metaphor 'sewage treatment of the skies' expresses this characteristic of CDR as a public service for cleaning up the atmosphere. Ensuring that this public service is provided thus seems the unequivocal responsibility of the state: Policymakers thus need to not only mobilise funding to cover up-front capital costs but also long-term operational cost, which can be very high for technological absorption and underground sequestration. Likewise, CDR-related research, design, development and demonstration (piloting) (RDD&D) requires public funding in the near-term. The key challenge will be to bring down costs of non-nature-based CDR, and to prevent rent-seeking by technology providers. This can only be achieved if allocation of public funding is done in a transparent and competitive way, and continuously reassessed. The state will not be able to 'pick winners' once and for all. Initially, a differentiation by technology type will be needed given the massive cost differences between technologies.

1 See the glossary definition of «carbon dioxide removal» in IPCC (2018 and later reports).

In the long term, public policies should generate an increasingly universal carbon price — sufficiently credible to generate investment in CDR that contributes to a substantial decrease in CDR costs comparable to the cost decrease witnessed for solar and wind power such that CDR can become a regularly-provided public service across the planet.

To facilitate scaling-up of CDR, governments and public entities should:

— ensure that accounting in the context of the Paris Agreement's Enhanced Transparency Framework is sufficiently robust to address the challenges of CDR.

— eliminate regulatory barriers to CDR domestically (e.g. streamlining underground storage permitting processes or supporting storage site screenings) and internationally (e.g. acting on the amendment of the London Protocol allowing for transboundary CO_2 transport).

— consider specific absolute volume targets for CDR, e.g. in the Nationally Determined Contribution (NDC), potentially differentiated into technology categories, to cater for the strongly differing characteristics of the technologies with regards to costs and technological maturity.

— ensure proper monitoring, reporting and verification (MRV) and accounting of CDR in national GHG inventories and NDCs.

— include CDR in subsidy schemes for GHG mitigation as well as carbon pricing systems such as emissions trading (ETS) and baseline and credit schemes. Here, a differentiation between CDR with storage in biological systems and that in geologic reservoirs needs to be made due to the different levels of permanence. The incentives should incentivise cost reduction and prevent subsidy 'waterbeds'.

— enable CDR to access international public climate finance, through appropriate terminology and selection criteria.

— provide clear 'guardrails' to private sector statements for use of CDR in mitigation pledges. Here governments should set minimum standards for removal credits.

To facilitate the scaling-up of the carbon markets for CDR in particular, we recommend:

— actors negotiating, piloting and operationalising international market-based cooperation under Article 6 of the Paris Agreement to consider the particularities of CDR concerning, inter alia, permanence, leakage, additionality, baseline setting, MRV, and accounting, including corresponding adjustments. A crucial period for this is the workplan once Article 6 rules have been agreed.

— development cooperation agencies, public and private sector climate finance actors to support MRV methodology development for CDR, aligned with requirements under Article 6 and striving for high environmental integrity while keeping transaction costs manageable.

— voluntary carbon market actors to pursue CDR and removal credits based on sufficiently stringent MRV approaches appropriate to the respective use-cases for acquired units, ideally through clear guidelines by private sector initiatives such as the Science Based Target Initiative (SBTi). For this, private sector entities should set up an institution providing services to identify high quality removal credits.

A virtuous cycle of careful yet deliberate applied learning in technological and nature-based CDR approaches leading to cost reductions and another round of learning should be the aim of this policy package. Here, stakeholders' concerns that have in the past thwarted efforts to scale up carbon capture and storage need to be addressed in a credible manner by the policymakers through participatory deliberation and planning processes from the beginning.

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Abbreviations

A/R	Afforestation/Reforestation
BECCS	Bio-energy with carbon capture and storage
Capex	Capital expenditures
CBD	Convention on Biological Diversity
CCS	Carbon capture and storage
CCU	Carbon capture and use
CDM	Clean development mechanism
CDR	Carbon dioxide removal
CO_2	Carbon dioxide
DACCS	Direct air carbon capture and storage
EGR	Enhanced gas recovery
EOR	Enhanced oil recovery
ETS	Emissions trading system
GGR	Greenhouse gas removal
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
LCFS	Low carbon fuel standard
LTS-LEDS	Long-term low greenhouse gas emission development strategies
LULUCF	Land use, land-use change and forestry
MRV	Monitoring, reporting and verification
NDC	Nationally determined contribution
NET	Negative emission technology
Opex	Operating expenses
PES	Payments for ecosystem services
RDD&D	Research, design, development and demonstration
REDD+	Reducing Emissions from Deforestation and Forest Degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries
SBTi	Science Based Target Initiative
TRL	Technology readiness level
UNFCCC	United Nations Framework Convention on Climate Change

SDM	Sustainable Development Mechanism (the mechanism established under Article 6.4 of the PA)
SLCFs	Short-Lived Climate-Forcing agents
SRM	Solar Radiation Modification
UN	United Nations
UNCLOS	United Nations Convention on the Law of the Sea
UNEA	United Nations Environment Assembly
UNFCCC	United Nations Framework Convention on Climate Change

01

Introduction

In his recent Bloomberg column, science fiction author Kim Stanley Robinson (2020) refers to the removal of CO_2 from the atmosphere as 'sewage treatment of the skies'. An analogy which might do more to advance our comprehension of the carbon dioxide removal (CDR) challenge than much of the previous ten years of academic literature on the subject. The main problem seems to be that CO_2 does not smell and is no cause for eyesore as it — so to speak — piles up in the streets. These factors appear to have been relevant in the justification of public efforts and spending on waste disposal to date, which have evolved rather consistently in increasingly dense human settlements. There are more and more encouraging signs, however, that public policy will no longer be able to ignore the pollution of the atmosphere — even if the pollutant in question is an odourless and invisible gas that causes harm not directly but only through its accumulation in the medium-term.

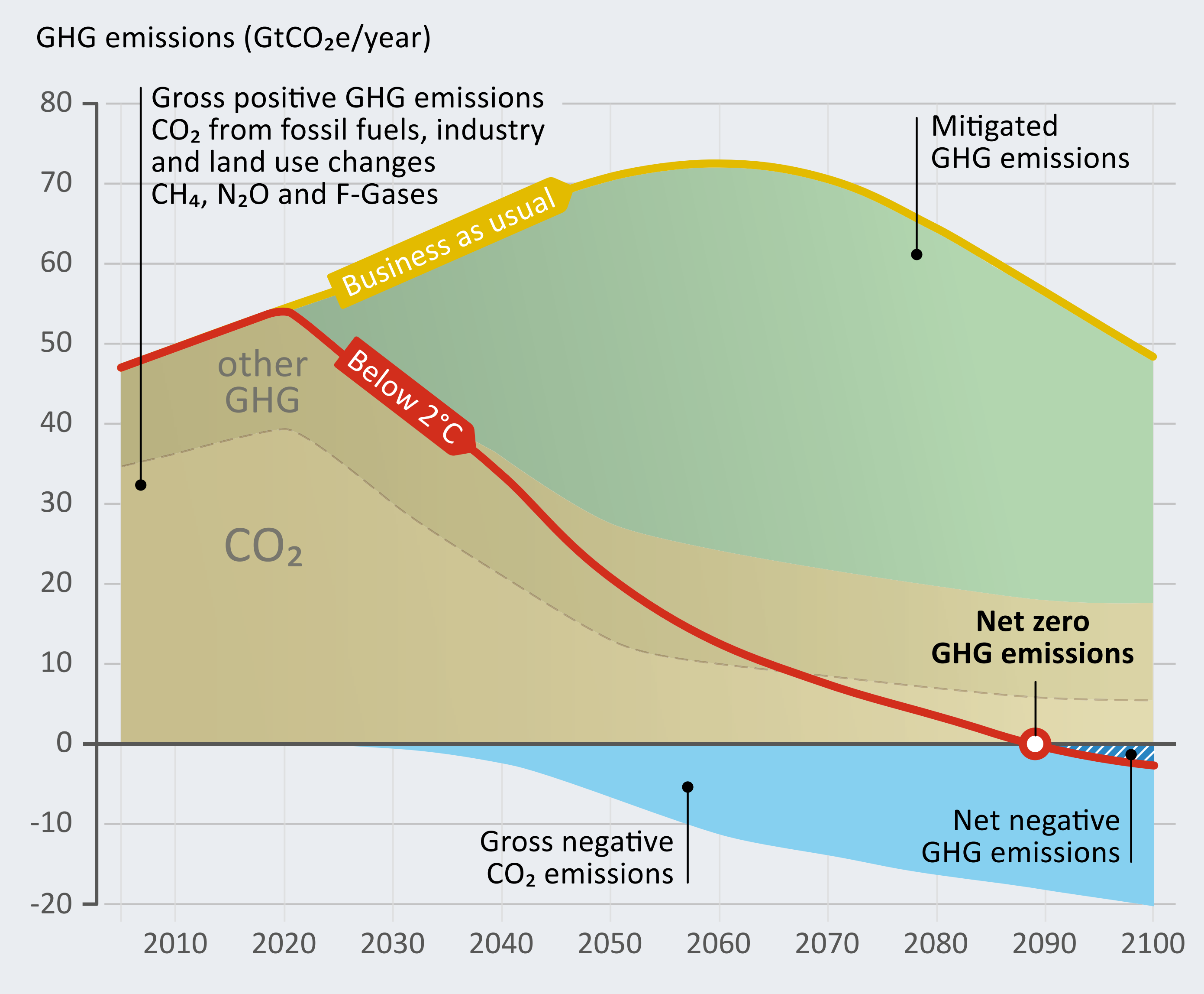
1.1 Greenhouse gas removals are necessary to achieve climate stabilisation

The Paris Agreement (UNFCCC 2015) set out to limit global temperature increase to well below 2°C and if possible 1.5°C, by achieving a balance of emissions and removals of greenhouse gases (GHGs) in the second half of the century. Measures across all sectors of the economy are needed to meet this goal including drastic emissions reductions (including a transition to zero-carbon energy, energy efficiency improvements, avoiding further deforestation) as well as GHG removal through natural and technological processes (see Figure 1).[2]

2 While technologies could in principle be developed to remove and store other GHGs — via negative emissions technologies (NETs) also referred to as greenhouse gas removal (GGR) — the overwhelming focus is on CO_2.

FIGURE 1

The role of GHG removal in mitigation scenarios



Source: UNEP (2017)

The Intergovernmental Panel on Climate Change (IPCC) projects very substantial amounts of 100-1000 billion tCO_2e to be removed during this century for keeping global warming near 1.5°C (IPCC 2014, 2018). To date there is an enormous gap between projected volumes of GHG removal and actual plans and policies for implementation of such removals.

1.2 What is carbon dioxide removal (CDR) — a definition

While theoretically all GHGs can be removed from the atmosphere, to date attention has focused on the removal of CO_2, given that it is the most relevant GHG and also the technological approaches to remove other gases remain unexplored. The IPCC (2018, p. 544) refers to carbon dioxide removal (CDR) as follows:

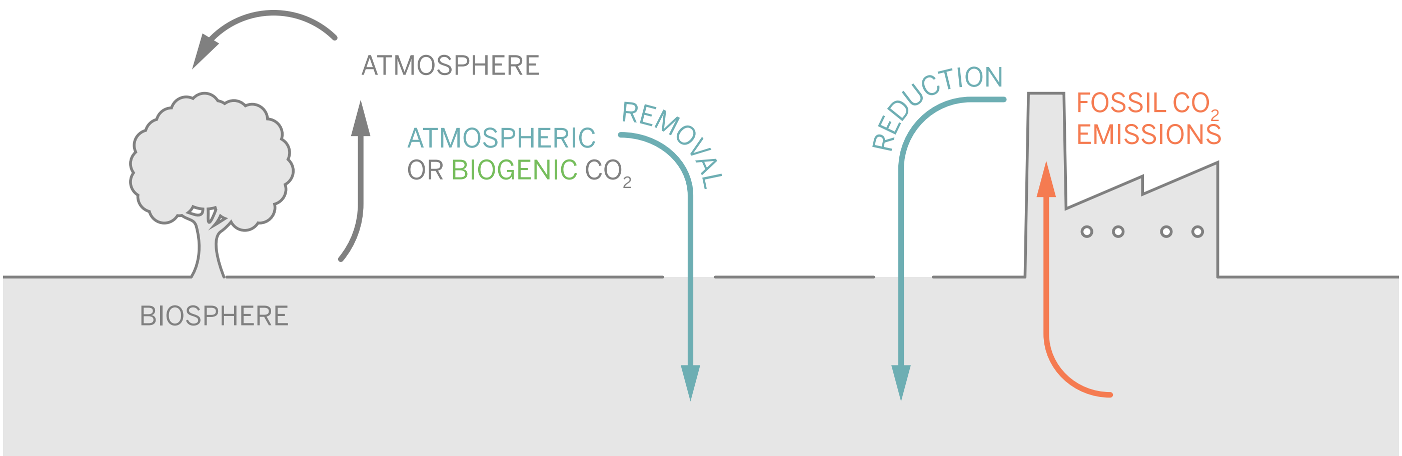
> *Anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities.*

Preston Aragonès and colleagues (2020) offer four necessary conditions that operationalise this definition and help delineate CDR from other mitigation activities:

1. CO_2 is physically removed from the atmosphere.
2. The removed CO_2 is stored out of the atmosphere in a manner intended to be permanent.
3. Upstream and downstream GHG emissions, associated with the removal and storage process, are comprehensively estimated and included in the emission balance.
4. The total quantity of atmospheric CO_2 removed and permanently stored is greater than the total quantity of CO_2 emitted to the atmosphere.

FIGURE 2

The difference between carbon dioxide removal and emissions reductions



Notes: Carbon dioxide removal is shown on the left, e.g. via CCS on biogenic or atmospheric CO_2 sources, and emissions reductions on the right, e.g. via CCS on fossil CO_2 sources.

Source: authors

Under both the United Nations Framework Convention on Climate Change (UNFCCC) and its Paris Agreement, Parties bear the substantive obligation to pursue 'mitigation of climate change', which includes both emissions reductions and CDR. Additionally, Parties are to communicate on their 'mitigation' efforts (amongst others via their nationally determined contributions (NDCs), long-term low greenhouse gas emission development strategies (LTS-LEDS), national GHG inventory reports and more). Parties' mitigation efforts are to become increasingly comprehensive (including all emissions and removals, all GHGs, and all economic sectors), and collectively ought to achieve a global peak and rapid reduction thereafter. All these stipulations suggest that Parties ought to more systematically pay attention to the various ways in which they may pursue CDR in addition to rapidly cutting their emissions.

1.3 Permanence

CDR activities need to be differentiated depending on the permanence of storage, which refers to the time horizons for which carbon is stored securely. Permanence of CO_2 storage needs to be carefully evaluated ex-ante and monitored ex-post. While the IPCC (2005) considers geologically stored CO_2 to be safe for over 1000 years provided careful site selection, storage in depleted oil and gas reservoirs or aquifers is reversible if there is leaking through boreholes or faults. Only fully mineralised carbon may fully be deemed permanently stored. Complex issues arise when considering the per se non-permanent storage of CO_2 through biomass. CO_2 in trees, other forms of living biomass or in soils can, in principle, be indefinitely stored, when the forests and soils are constantly maintained and any land use changes are closely monitored. Other forms of CO_2 stored in dead biomass are not, per definition, permanent, hence they should not be treated as a permanent storage of CO_2. Examples for these include long-lifetime harvested wood products, e.g. wood in construction buildings.

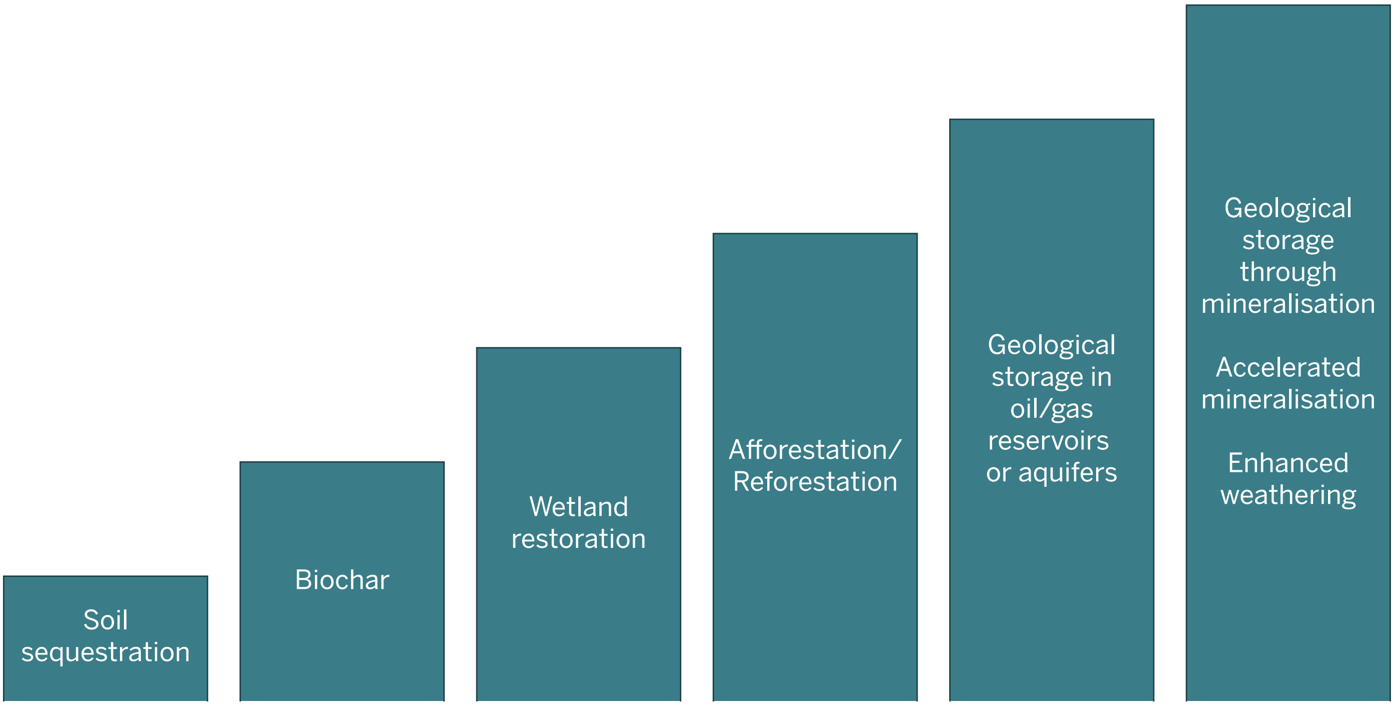
CDR can thus be grouped into different permanence categories[3] — depending on the reservoir in which CO_2 is stored (Möllersten et al. 2020). Geological storage in through mineralisation for bio-energy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS) as well as end products of accelerated mineralisation or enhanced weathering can be deemed as permanent without further monitoring. Geological storage in depleted oil and gas reservoirs and saline aquifers is highly likely to be permanent but requires monitoring. CO_2 stored in biomass can be released anytime through human or non-human disturbances. Afforestation and reforestation (A/R) can be reversed quickly through fire, pests, and vegetation clearing, wetland restoration through drainage or drought. For biochar applications, biological, chemical and mechanical processes and soil disturbances determine to which degree the full amount of biochar mass is retained in the soil and additional CO_2 is taken up by such treated soil, thus requiring careful monitoring. Soil carbon sequestration can be reversed rapidly through ploughing. The permanence of ocean fertilisation or alkalinisation practices remains deeply uncertain as more research is needed to fully assess both the efficacy and safety of such approaches. Monitoring is likely to be highly challenging.

While the permanence tends to be a function of the bio-physical properties of a storage site, there is a significant role for governance to account for and counteract limited permanence to ensure environmental integrity through specific policy measures (discussed later in sections 3 and 4).

3 Rather than via the popular but arbitrary differentiation into 'nature-based' or 'technological' CDR, we organise our analysis around the bio-physical properties of the involved steps (in particular the permanence of CO_2 storage) and the economic properties (whether an approach may generate sufficient revenue to be profitable or not).

FIGURE 3

'Permanence ladder' of different CDR types



Notes: Given the significant influence of human behavior, governance, as well as geographical factors this sequence is indicative only and the expected permanence of each specific application has to be judged individually against the backdrop of these factors. For a more detailed qualitative assessment of permanence categories of various CDR approaches see Möllersten et al. (2020).

Source: authors

1.4 The policy and funding gap for CDR

Even though science has highlighted the importance of CDR for several years, public efforts addressing technology development, finance, and implementation are still lacking. There is a massive implementation gap between CDR volumes used in projections and actual rollout, largely due to scarce funding and political hesitancy. While many reports and studies have to date examined cost and potential projections of different CDR this has been done on a very narrow empirical basis (Fuss et al. 2018; Schäfer et al. 2015).

This report therefore starts with an empirical assessment of existing policy instruments as well as public and private financial streams and initiatives, which either already do or could mobilise CDR. We start with a mapping of the landscape of actors relevant to mobilising and financing of CDR. Then we identify drivers for CDR-related financing, including various binding and voluntary mitigation targets by different government entities, companies, and consumers. We subsequently highlight gaps and overlaps regarding different types of financing and CDR technology development stages.

On this basis, we identify opportunities to address such gaps and overlaps in the financing landscape through dedicated policy instruments within a wider context of synergies and trade-offs regarding CDR activities including with regard to necessary technical work on methodologies for accounting of CDR.[4]

1.5 Outline

Chapter 2 gives a brief overview of the cost structures of various CDR technologies to reveal their financing needs and outlines requirements and possible structures for CDR finance (crediting and other financing streams). Chapter 3 categorises and discusses different types of financing for CDR including from public and private sector sources. Existing and emerging policy instruments and private initiatives potentially relevant to CDR are presented in chapter 4. Chapters 5 and 6 sum up and offer recommendations for the medium to long term.

4 A subsequent report will showcase various existing elements that could be leveraged toward a comprehensive, consistent and environmentally integer ensemble of monitoring, reporting and verification (MRV) methodologies and accounting rules enabling sound and credible CDR activities to contribute to overall mitigation and achievement of global GHG neutrality.

02

CDR financing requirements: revenue potential, cost differentials and cost-reduction potential

2.1 Revenue generation potential of different CDR types

Just as is the case for emissions reduction technologies, CDR technologies fall broadly into three groups regarding their financial characteristics: I) those that cannot generate revenues without policy instrument intervention, II) those which might generate some (but not sufficient) revenues or cost savings from co-benefits, and III) those that are profitable even in the absence of any dedicated regulatory, market-making or fiscal policy instruments or voluntary private sector mitigation engagement.

Group I technologies can be called 'pure climate technologies', the sole purpose of which is to limit the rise in atmospheric CO_2 concentrations. This includes most certainly the direct capture of CO_2 from ambient air with subsequent underground storage (except for the questionable purpose of enhanced oil or gas recovery (EOR or EGR)). But also CDR through retrofitting capture and storage technology to existing biomass-energy plants, as well as some other CDR approaches, where the value-chain necessary to achieving removals into long-term storage is solely dedicated to that purpose and does not by itself generate revenue.

Group II / III technologies include A/R with revenue streams from tourism (e.g. through entrance fees or ancillary tourist services) or the sale of non-timber forest products. Biochar and mineral weathering could generate financial returns for famers by reducing fertiliser requirements and increasing yields (Ye et al. 2019; Cornelissen et al. 2018; Kätterer et al. 2019). Even marine CDR based on ocean fertilisation or alkalinisation (with iron, phosphorus or limestone respectively) could conceivably be linked to yield increases of fish stocks (CBD Secretariat 2009).

Some forms of carbon capture and use (CCU) might also fall under this category depending on their design: if CO_2 is bound permanently in long-lived materials (e.g. cement or steel), or if enhanced oil or gas recovery (EOR/EGR) were done in a way that maximises CO_2 storage (resulting in a net-removal of CO_2, despite emissions associated with the production and later consumption of oil and gas) (Zakkour et al. 2020; IEA 2015).

Some CDR types are combinations of actions under different groups: The production of power and/or heat from biomass (waste products, plantations or algae) whereby resulting CO_2 emissions are captured at source and stored (BECCS) represents an example where a revenue generating and commonly applied process (biomass-for-energy), a Group II/III activity, is to be coupled with CCS that belongs to Group I. In some cases, revenue-generation potential may yet to be discovered, such that CDR types may occasionally move between revenue-groups.

TABLE 1

Overview of potential revenue sources for different CDR types

CDR type	(Potential) non-carbon revenue streams*	Characteristics of revenue	Group type
Afforestation and reforestation	• Monetisable ecosystem services, e.g., through forest-related Payments for Ecosystem Services (PES) schemes • Flood risk reduction and regulation benefits • Ancillary tourism and leisure (if non-consumptive) • New income opportunities generated by forests-based ecotourism • Sale of non-timber forest products	• Strongly depends on local circumstances, socio-economic trends, as well as physical, chemical or biological properties of ecosystems • PES are conditional upon delivery of certain services or activities • Value of ecosystem services likely to change due to climate change	Mostly II, some III
Bioenergy with carbon capture and storage (BECCS)	• Electricity sales • Heat sales (district heat) • Waste treatment (if biomass is sourced from waste)	• Depends on electricity market	II
Biochar as soil additive	• Agricultural productivity enhancement • District heat sales • Electricity sales	• Revenues accrue to different entities	Mostly III, some II
Direct air carbon capture and storage (DACCS)	• Uptake of power when priced negatively	• Minimal scale	I
Direct air carbon capture and durable materials production (construction materials)	• Sale of pure CO_2 as a feedstock for carbon-based materials	• Demand may be limited	II

* One can distinguish between monetisable non-carbon revenue streams and co-benefits (such as biodiversity protection and ecosystem services). While both sometimes overlap, some revenue streams (e.g., revenue from selling power or heat) do not necessarily constitute a co-benefit in the classical sense (accruing broadly to society) and some co-benefits are not readily monetisable.

CDR type	(Potential) non-carbon revenue streams*	Characteristics of revenue	Group type
Wetland restoration	• Monetisable ecosystem services, e.g., through PES • Water supply services • Reduced risk of flooding and soil erosion • Ancillary tourism and leisure (if non-consumptive)	• Demand may be limited	II
Enhanced weathering	• Sale as replacement of conventional sand or pebbles • Sale of formed carbonates to paper producers (replacement of lime) • Sale as replacement of fertiliser	• Products need to compete with conventional alternatives • Significant time-lag to revenue	Mostly II, some III
Accelerated mineralisation (in reactor)	• Heat production (at large scale) • Sale of substitute for clinker in blended cement	• Minor revenue sources	II
Soil carbon sequestration	• Soil quality improvement services	• Demand may be limited	II
Ocean fertilisation	• Fisheries yield increase services	• Demand may be limited	II

Note: The projected non-carbon revenue streams are indicative only (based on pioneering examples of successful execution of such removal activities under particular circumstances). In some cases, novel non-carbon revenue sources may be found or small-scale activities may be funded for various CSR purposes.

Source: authors

Group III technologies do not fulfil the principle of additionality, as they would go ahead without any public policy or incentive. Technologies which belong either to Group II or III require a dedicated additionality assessment as has been applied under the Clean Development Mechanism (CDM) of the Kyoto Protocol. In the context of novel technologies such as biochar, non-monetary barriers need to be taken into account.

2.2 Marginal abatement costs of different CDR types

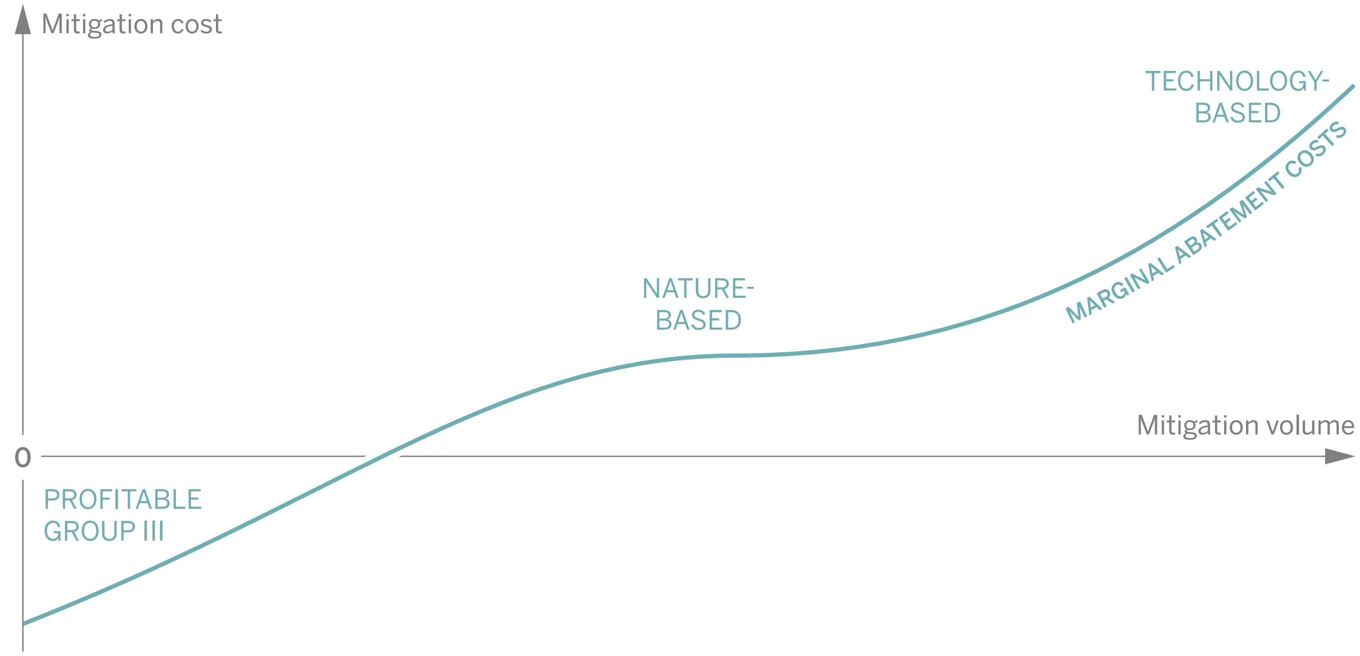
Group III technologies have negative marginal abatement costs, Group I and II positive marginal abatement costs (see Figure 4). Möllersten et al. (2020) and IPCC (2018) have collected cost estimates of different CDR types.

Approaches at an early stage of development and adoption often have higher mitigation costs compared to mature technologies — sometimes by several orders of magnitude. Some technology-based approaches currently have costs of over USD 1000/tCO_2 in the absence of other revenues. They are clearly not competitive with any emission reduction technology.

Therefore, below we discuss technology readiness levels, the relationship between technology adoption and cost as well as the projected long-term cost levels of CDR approaches.

FIGURE 4

Marginal abatement cost curve of different CDR types



Source: authors

2.3 Technology readiness levels of different CDR types

The technology readiness level (TRL), which expresses the maturity of a technology, varies significantly between CDR types (Möllersten et al. 2020). While A/R and BECCS[5] reach scores of up to TRL 9 with some BECCS systems operational at the moment, the vast majority of CDR technologies are situated between TRLs 3 and 7, i.e. ranging from experimental proof of concept (TRL 3) to system prototype demonstration in operational environment (TRL 7). Some marine CDR approaches such as ocean fertilisation have not yet reached proof-of-concept, hence only reaching TRL 2, while some reach TRL 5 (technology validated in relevant environment). In addition to the variation among CDR approaches, specific CDR types differ within their own respective group of technology, typically ranging across three or four TRLs. While this span is the smallest for A/R, the technology readiness levels of biochar applications remain relatively heterogenous with TRL scores of 3 to 7. Furthermore, there are specific approaches within a conceptual CDR approach that have different (often lower) TRLs, such as the use of biomass in sewage sludge treatment for energy generation with carbon capture and storage — an approach which fits within the conceptual approach of BECCS, but represents a distinct set of technological and financial challenges.

2.4 Cost-reduction potentials over time

Cost reduction potentials through upscaling are expected to vary between approaches: projections of technology learning curves are indicative of expected cost-reductions in case of a successful progression through various steps from early research, development to demonstration and upscaled application.

5 Möllersten et al. (2020) distinguish between the bioenergy component (TRL 6-9) and the CCS component (TRL 4-7).

But such learning curves remain highly uncertain and might often entail some degree of strategic or wishful thinking on behalf of technology providers. For technologies constrained by physical parameters, learning curves may end relatively quickly.

Assuming relatively conducive environments, innovation studies suggest technologic scale-up and learning leads to adoption pathways according to logistic growth curves (s-curves), in which adoption and rapid cost-reductions are mutually conditional and reinforcing. Initial phases of such s-curve growth are characterised by very small volumes and seemingly slow learning, whereby — viewed ex-post relatively little change can be discerned over long periods of time. Solar photovoltaic technology underwent that phase from the 1990's to the mid 2010's and only recently has its cost become truly competitive and uptake has been soaring. However, such a seemingly stagnant phase often sees crucial technological breakthroughs and thus a necessary foundation for the subsequent exponential growth phase. While costs remain higher than those of competing technologies, the continued scaling effects generate significant cost reductions, primarily in production and dissemination where significant expertise is gained in a fairly short amount of time so that in some cases within a few more years cost-competitiveness is reached. For electric cars and motorbikes, such cost-competitiveness is in reach and already partially achieved, which explains their rapid adoption. In the third and last stage markets are being saturated, the adoption curve flattens and eventually reaches a plateau, any more learnings and cost-reductions at this point may only cement the market domination and drive financial margins. Hardly any major mitigation technology other than hydropower appears to as of yet have reached that saturation point.

While s-curve adoption represents successful new products and their uptake, it is far from certain that CDR activities would follow such a path and it is virtually certain that without dedicated mitigation funding targeting CDR, most CDR approaches will not advance at all. This is because in most cases — contrary to e.g. renewable energy generation — there are no sufficient revenue streams. The service of atmospheric sewage-removal – that is the removal of CO_2 as a waste-product of human civilisation – thus requires dedicated funding. Furthermore, some CDR types might reach their growth limits regionally earlier than expected, mainly due to resource and space constraints. Hence, sound policies are needed to pick a basket of 'potential winners' including those activities with the best scaling and cost-reduction prospects.

2.5 Projected long-term marginal abatement costs

Turning to estimates of long-term marginal abatement costs (expressed in USD/tCO_2), both previous observations apply: On the one side, projected cost estimates for different CDR types vary considerably with the lowest costs typically associated with nature-based solutions around A/R, enhanced weathering, accelerated mineralisation and soil carbon sequestration techniques. Technological and hybrid solution like DACCS and BECCS, but also biochar applications are estimated to have higher ongoing costs associated with the transportation and underground storage of CO_2 and in case of DACCS and BECCS high operational energy requirements. On the other hand, costs do vary not only between different CDR types but also within each type as storage, energy and biomass resource cost and related revenue streams vary — as well as costs associated with planning and construction.

TABLE 2

Technology readiness levels and long-term cost estimates of different CDR types

CDR type	Technology readiness level (TRL)* (Möllersten et al. 2020)	Cost estimates per tCO_2 (in USD) (Möllersten et al. 2020)	Cost estimates per tCO_2 (in USD) (IPCC 2018)
A/R	7-9	0-100	5-50
BECCS	BE: 6-9 CCS: 4-7	20-100+	<200
Biochar as soil additive	3-7	40-130	-45-100
DACCS	3-6	40-600	20-1000
Wetland restoration	5-7	Uncertain	n/a
Enhanced weathering	3-5	20-40 (50-200)	15-40
Accelerated mineralisation	4-7	20-40 (50-130)	n/a
Soil carbon sequestration	5-7	20 (0-100)	n/a
Ocean fertilisation	2-5	Uncertain	2-457

* The technology readiness levels are defined according to the Horizon 2020 – Work Programme 2018-2020 (European Commission 2019): TRL 1 – basic principles observed; TRL 2 – technology concept formulated; TRL 3 – experimental proof of concept; TRL 4 – technology validated in lab; TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies); TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies); TRL 7 – system prototype demonstration in operational environment; TRL 8 – system complete and qualified; TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space).

Source: authors

While estimates for such reasons vary for every CDR type, the span for cost estimates of DACCS is by far the greatest one, with the lower limit at around USD 40/tCO_2 and the upper limit at around USD 600/tCO_2 (Möllersten et al. 2020). The IPCC (2018) includes even a wider range between USD 20/tCO_2 and USD 1000/tCO_2. DACCS technology providers have however indicated long-term operating costs to attain around 100 USD/tCO_2.

Cost and technological maturity gaps of most CDR approaches — as well as the necessary decadal lead-time for technological development and learning — clash with the projected magnitude of CDR in the vast majority of scenarios compatible with limiting warming to well below 2°C.

With some variation such pathways presume serious scale-up to start in the mid-2020’s and material (i.e. gigatons-scale) contributions to be available in the early 2030’s. Cumulative numbers do not allow to fully grasp the need for immediate action, yet their magnitude — McLaren and Jarvis (2018) find a range of 100-1000 $GtCO_2$ of removals needed within the 21st century — suggests reaching annual CDR rates of 5 to 20 $GtCO_2$ within two to three decades. Putting these numbers into perspective, Nemet et al. (2018) find that scaling up any CDR from 1 Mt in 2020 to 1 Gt in 2050 would require a consistent annual growth rate of close to 30%. Such growth rates can only be achieved under the best of circumstances and any single year of missed growth or any structural barrier would fundamentally undermine the prospect of such consistent growth.

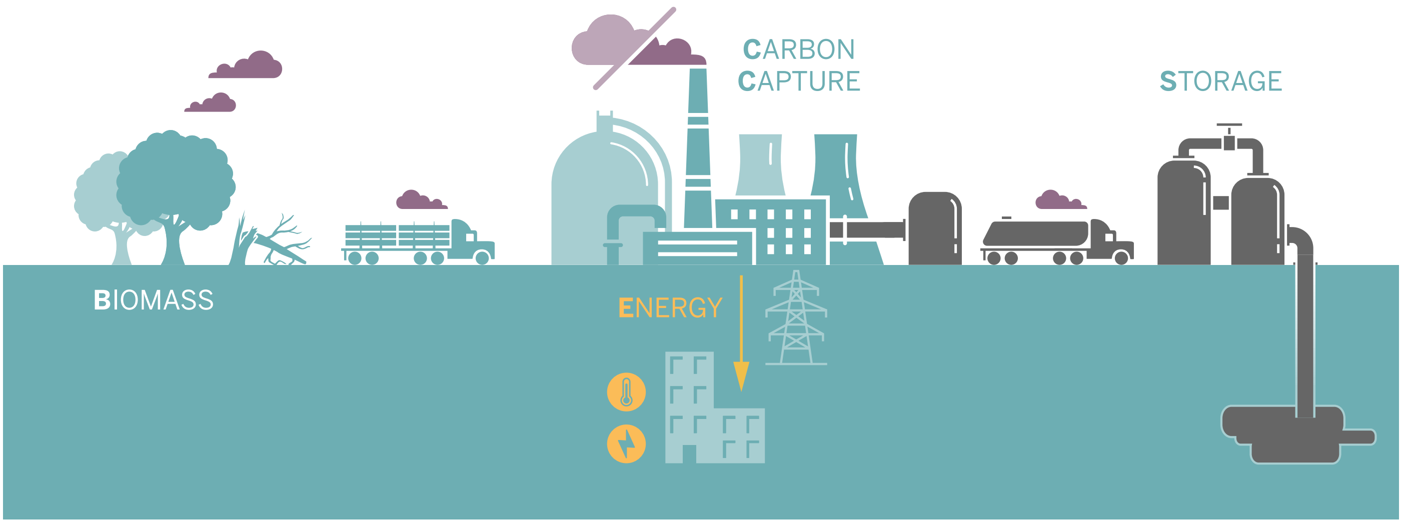
2.6 Actors at various stages of the CO_2 value chain and financing requirements

To analyse the public finance needs of CDR we first differentiate according to a CDR overall cost-benefit outlook (between those that solely rely on carbon-related revenues and those with other revenue streams as described above). In addition, each element in the value chain comes with a different need for financial resources. To illustrate this, we take BECCS as an example, for which one has to distinguish between three elements of the value chain, only the first of which represents a functioning business model in the absence of dedicated funding for CDR (see Figure 5): I) the harvesting and utilisation of biomass for energy production, II) the CO_2 capture at source, and III) the transport and underground storage of CO_2. Combining all three elements of the value chain, Fuss et al. (2018) indicate the total cost range for BECCS between USD 15-400/tCO_2.

For I) the benefit-cost balance is often positive, which explains why biomass-energy is a common form of power and heat production.[6] For II) cost of at-source CO_2 capture varies significantly by scale and composition of flue gas, as well as by the type of capture that can be embedded in the biomass processing: Budinis et al. (2018) and Irlam (2017) report the cost range of capturing CO_2 for a CCS plant in general, expressed as cost of CO_2 emissions reduced, from as little as USD 20/tCO_2 to as much as USD 124/tCO_2. Fuss et al.'s (2018) literature review specify the costs for the capture from ethanol fermentation at USD 20-175/tCO_2, while Sanchez and Callaway (2016) indicate the CO_2 emissions reductions cost between USD 60-110/tCO_2 for biomass-based integrated gasification combined cycles.

FIGURE 5

The value-chain elements of biomass-energy with CCS (BECCS)



Note: The elements in graphite colour represent costs that cannot be recouped other than through dedicated mitigation policy measures.

Source: authors

6 Variations of the same principle (BECCS) are not profitable to date or might be facing non-monetary barriers (e.g. biomass contained in municipal or industrial waste is sometimes not used for energy generation) and there are many decentralised small-scale bioenergy uses that are unlikely to become suitable for at-source CO_2-capture.

For III) cost estimates for transport and storage also vary significantly depending on distance and geologic conditions as well as the extent to which substantial deliberation processes are needed to ensure the regional populations' acceptance. Budinis et al. (2018) and Irlam (2017) have identified a possible range between USD 1.60-37/tCO_2. Given this wide range it would seem likely that if the stages in the value chain are undertaken by separate entities, the entity providing bioenergy requires less or no dedicated incentives, whereas entities providing the service of capturing, transporting or storing require a continuous results-based incentive. The flipside of this is the current situation whereby biomass-energy is common, but the full BECCS value chain is only implemented in a handful of small pilot plants[7].

For policy design or dedicated funding instruments (that are not merely offering an overall market-based incentive, but seek to advance a particular CDR activity in a particular country) a clear understanding of these different financial needs within the value chain of a CDR type is crucial to ensure proper allocation of resources. Where different process steps can be separated (in some cases the CO_2-capture at source is best embedded within the biomass processing) eligibility for funding needs to be closely tied the actual funding requirement associated with the specific activity (see Text box 1).

Furthermore, ill-defined 'CDR-policies' risk merely creating an incentive to reduce emissions (e.g. use biomass for energy production to replace fossil-fuel-based energy production) but to side-line actual CDR activities (e.g. steps II and III for a complete BECCS value chain). This seems to be the case for the US tax credit known as 45Q, which predominantly incentivises use of CO_2 for EOR (a practice which tends to represent a relative reduction in emissions but not an overall CO_2 removal).

TEXT BOX 1:

Significant differences in funding needs due to local circumstances

Given that the distance, mode of transportation (pipeline, ship, truck) and form of geological storage (onshore, offshore, depleted oil/gas fields, saline aquifers, shallow mineralisation) costs associated with CO_2 transport vary significantly. Funding instruments targeting the transport of the captured CO_2 to a geological storage site may need to adjust for particular circumstances. Longer transportation paths from land-locked countries without domestic geological storage potential will require a higher level of public incentives. For onshore pipeline transport costs could range from USD 1.5 to 11/tCO_2, for offshore pipeline transport costs could range between USD 2-15/tCO_2 (Budinis et al. 2018; Irlam 2017).

7 These exceptions include the Decatur bioethanol plant in the United States and the Drax power plant in the UK.

03

Public policy instruments and other drivers of financing for CDR

As shown above, most CDR cannot be implemented without public policy instruments providing financial incentives or mandating GHG emitters to use CDR. Below, we undertake a conceptual mapping of existing public policy instruments and private support measures.

FIGURE 6

Overview of public policy instruments and voluntary private support measures for CDR

Public policy instruments	Voluntary private support measures
MITIGATION TARGETS	EQUITY AND DEBT FINANCE
REGULATORY MANDATES	VOLUNTARY COMMITMENTS AND VOLUNTARY CARBON MARKET
SUBSIDIES FOR RDD&D	
CARBON PRICING INSTRUMENTS	
ANCILLARY POLICY INSTRUMENTS	

Note: Public policy instruments span overarching mitigation targets.

Source: authors

3.1 The hierarchy of policy instruments

One can broadly distinguish between five groups of policy instruments to mobilise CDR. The classification is closely linked to that of mitigation policies developed by the IPCC (Gupta et al. 2007).

Some of them establish a generic framework (which may be necessary but not sufficient), while others provide concrete support (Jeffery et al. 2020; Center for Carbon Removal 2017). They can be established at various levels ranging from the international to the subnational level:

- *Public mitigation targets* such as the target of the Paris Agreement to achieve a global balance of emissions and sinks in the second half of the century, and pledges by states and subnational entities to reach net-zero emissions in the next decades. Parties have to demonstrate their mitigation commitments align with the long-term goals of the Paris Agreement via their NDCs and LTS-LEDS. Targets are a necessary condition for mitigation action. However, they do not generate direct incentives for CDR but can play a key role in mobilising private action. Private actors may want to pre-empt other policy instruments that could burden them through setting their own net-zero targets.

- *Regulatory mandates* for public and/or private actors to pursue CDR activities. For example, heavy emitters like cement and steel producers could have to satisfy an emissions intensity standard that cannot be attained by any currently available production technology. Companies in such sectors could then endeavour to either purchase CDR certificates to offset their residual emissions (if a market for credible certificates was available) or purchase CDR-assets (e.g. incorporate a CDR company as a subsidiary). Such mandates are powerful drivers for upscaling of CDR, but can generate significant costs for the entities subjected to the mandate. Lobbies will therefore try to prevent mandates; experience from other mitigation technologies has shown that generally only profitable technologies (Group III) are mandated.

- *Subsidies for CDR research, design, development and demonstration (RDD&D) as well as implementation* can be provided as direct grants, tax credits or concessional loans. They can also take the form of contracts for difference. In order to be efficient, subsidies can be allocated through reverse auction. Subsidies are particularly important for immature, not yet bankable technologies. They are also crucial to explore possible environmental impacts and social risks associated with CDR activities. Experience from renewable energy deployment shows that large-scale subsidy programmes such as feed in tariffs were crucial in achieving the scale from which cost reductions could be rapidly achieved.

- *Carbon pricing instruments* such as cap and trade, baseline and credit systems and carbon taxes. Explicit eligibility of CDR under such instruments needs to be ensured. Carbon pricing provides a direct incentive to reduce CDR costs in order to increase the profit from the sale of allowances or credits. Carbon pricing is highly appropriate for mature CDR technologies. Even if CDR is not directly covered by a system, eligibility to create carbon credits could be sufficient if the carbon price is sufficiently high and not overly volatile.

- *Ancillary policy instruments* such as permanence requirements, guarantees for long-term storage, a harmonised framework for liability, risks and associated costs as well as information campaigns aimed at generating stakeholder understanding regarding CDR. These instruments are critical to ensure that CDR technologies can become mature. Categorising CDR activities as consistent with sustainable finance taxonomies and similar guidance like the EU's unfolding sustainable finance taxonomy would be an important ancillary policy, especially if the CDR value chain could be covered fully.

Policy instruments and policy instrument mixes or ensembles should be chosen carefully in order to cater for the wide range in maturity of CDR types. Policies are to serve multiple functions, including accelerate technological maturity, societal learning as well as capacity building, and should allow for iterative improvements. For the yet immature technologies they should effectively contribute to a cost reduction by providing sufficient financial (but also regulatory) support for each RDD&D stage, while preventing an unlimited support for technologies unable to reach maturity. Both early research, design and development as well as pilot (plant) implementation requires subsidies, which is especially true for more capital-intensive CDR activities such as DACCS, BECCs or biochar applications. The later scale-up to and beyond demonstration then requires a 'long-term funding promise pull', ideally through contracts for difference that justify the ex-ante capital expenditures (capex) investment and ex-post operational costs (opex) continued operating expenses (Nemet et al. 2018; Honegger and Reiner 2018). A mix of technology-agnostic and technology-specific instruments is needed to fully incentivise the CDR landscape.

3.2 The role of voluntary private sector efforts

Voluntary private sector efforts are emerging on the backdrop of increasingly ambitious corporate GHG mitigation pledges triggered by the emergence of the 'Fridays for Future' movement and an increased willingness of governments to set net-zero targets. If these framework conditions persist after the end of the COVID-19 pandemic, such companies could become a substantial source of funding for CDR. Importantly, one has to differentiate between financial flows supporting capital expenditure related to setting up pilot plants and funding of operating expenses for ongoing CO_2-removal flows. Capital investments can be done on the basis of *equity finance* and *debt finance* (UNEP FI 2014). *Equity finance* refers to an investment strategy to acquire a share in the ownership of a company or project. Although there is no obligation to repay the capital acquired through it, the original owner has to give up control of the business to a certain extent and to pay dividends to the shareholder. *Debt finance* involves the borrowing of money through the sale of bonds or taking of loans. The lender does not get any shares of the company but receives interest on the debt. This means that revenues need to be sufficient to pay the interest as well as the dividends required by shareholders. In the case of CDR, this is only possible if there are credible public subsidies for CDR or a robust market for CDR credits. Here, *voluntary private sector commitments* and purchases on the *voluntary carbon markets* come in. Experience from the Kyoto Mechanisms (Clean Development Mechanism, CDM; Joint Implementation, JI) and voluntary markets to date shows that there is limited appetite for upfront investment that could finance capex, as buyers just want to pay for credits once they have accrued. This is due to the various risks that might prevent credits from accruing. In the international carbon markets, thus emission reduction purchase agreements with milestones for credit accrual were developed. While many companies want to achieve net-zero emissions through a combination of emission reduction efforts within the company's scope 1-3 emissions, and purchases of emissions reductions credits on the voluntary carbon market, a few frontrunners plan to offset their residual emissions with the purchase of removal credits generated by dedicated CDR activities. If this approach gathers steam, demand for CDR credits could significantly increase.

It should be noted that providers of CDR credits on the voluntary markets apply very diverse approaches with regard to the methodologies used for calculating the removal, as well as regarding monitoring, reporting and verification. This 'wild west' situation might damage the long-term prospect for the international market of CDR credits.

3.3 Conclusion

We find that most public mitigation policy instruments are presently underdeveloped regarding CDR and will need to be carefully designed to incentivise the cost reductions and learning needed for a medium-term scale-up of CDR. In order to ensure this, decisionmakers will need to carefully tailor and regularly adjust the instruments they put to work. Voluntary private sector initiatives can complement public mitigation policies if public framework policies are strict, but suffer from absence of regulation and the threat of a 'race to the bottom'.

04

Mapping of currently existing policy instruments and other drivers of financing for CDR

The following section maps current real-world examples for policy instruments and private sector financing to mobilise CDR. As shown in Figure 6, drivers for CDR financing in the public domain span from overarching, abstract policy instruments (mitigation targets) to concrete subsidy programmes. Many already existing or future carbon pricing instruments could, in principle, be used to mobilise resources for CDR deployment, however, most of the currently available funding instruments exclusively focus on either fossil-point-source CCS (without consideration for the specificities of CDR) or nature-based solutions.[8]

4.1 Public policy instruments and drivers

4.1.1 Public mitigation targets

Until the end of 2020, 126 countries (accounting for over 50% of global GHG emissions) have announced or considered net-zero goals (some even net-negative)[9]. However, at the same time, NDCs and their updates are found to be woefully inadequate; the projected 'emissions gap' in 2030 has not decreased significantly in the last decade (UNEP 2020). Most current NDCs do not explicitly mention CDR or negative emissions. Some countries state that nature-based solutions around A/R, wetland restoration and soil carbon sequestration will be taken into account.

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8 Most of the currently existing finance for CCS activities addresses emission reduction or CO_2 use (CCUS) concerns, rather than CDR, i.e. negative emission efforts. Although this difference between emissions reduction and negative emissions needs to be stressed, some of the underlying policy and finance instruments could, in principle, also work for CCS activities that result in negative emissions (e.g. BECCS and DACCS). Also, some of the available funding for nature-based solutions addresses broader climate (emissions reduction and adaptation) and biodiversity concerns, rather than exclusively focusing on actively removing emissions.

9 While most countries with pledged neutrality targets refer to carbon neutrality, others go further by aiming for greenhouse gas or even climate neutrality, i.e. not only focusing on CO_2 but also taking other GHG and aerosols into account as well. Other countries move even further than that by announcing net-negativity targets, i.e. removing more CO_2 or other GHG and aerosols from the atmosphere than they emit.

Only around a dozen countries, including China, South Africa and Saudi Arabia, explicitly refer to CCS as an emissions reductions option but not look at it as part of a CDR effort. Approximately 30 more Parties have made public communications that allow inferring they are considering CCS as a potential future technology (Zakkour and Heidug 2019; Mills-Novoa and Liverman 2019; GCCSI 2020; PIK 2017).

While the US, the UK, Germany, Norway, Sweden, and Switzerland, as well as the European Commission, have taken note of the potentials and challenges of CDR in parliamentary debates, House Committees or relevant domestic administrative agencies,[10] the majority of the political debates has not yet resulted in the consideration of specific policy instruments, let alone their implementation.

Sweden is a prominent exception, and a frontrunner in showing how ambitious national targets promote CDR. Sweden has set a carbon neutrality target for 2045 and publicly stated that BECCS shall play a key role in attaining it. In the UK, the carbon neutrality target for 2050 was recently accompanied with the revised NDC of cutting GHG emissions by 68% by 2030 (compared to 1990). The government and the Climate Change Committee also highlighted the prominent role of CCS applications as well as nature-based removals and BECCS for achieving the mitigation target.

4.1.2 Regulatory mandates

Demands for zero-emissions aviation through either synfuels or DACCS offsetting are emerging and airlines[11] as well as fuel producers are seeking to front-run regulatory mandates for zero-emissions fuel or for compensating residual emissions.[12]

4.1.3 Subsidies

The US federal 45Q tax credit provides funding for EOR and EGR activities. Prior to 45Q's update in 2018, the tax provided a tax credit between USD 10-20/tCO_2 for EOR and EGR activities. Since 2018, this narrow focus has been widened and 45Q now provides increased incentives between USD 35-50/tCO_2 depending on the eligible activity. It is noteworthy in this context, that the updated terms of 45Q are still applicable to EOR, EGR and geological storage, but also to other forms of CO_2 utilisation as well as DACCS projects (US Department of Energy 2019). In late 2020, the US Congress adopted an omnibus bill, that authorises almost USD 450 million over the next five years merely for RDD&D purposes of various CDR approaches including soil carbon sequestration as well as technological removals (Suarez 2021).

The Swedish government is considering a twofold approach for scaling-up BECCS by including BECCS in its carbon tax scheme as well as setting up a reverse auction system. The logic behind the latter system is that a public entity, in this case the government, commits to a long-term procurement of a certain amount of CDR.

10 As a result of these initial discussions, some agencies have also commissioned reports on CDR, e.g. the German Environment Agency, the US Government Accountability Office, the British Science and Technology Committee, the European Commission and the European Academies' Science Advisory Council or provided mandates for developing a roadmap for mitigation through CDR (Switzerland).

11 United Airlines is joining a joint venture for the deployment of a large-scale direct air capture plant using technology developed by Carbon Engineering. JetBlue announced to start offsetting all domestic US flights mid-2021. British Airways, Qantas, Etihad, Delta Airlines, and SAS as well as many European aviation stakeholders have pledged to become 'carbon neutral' but their commitments appear uncoordinated and lack detail to date. Air France is launching a zero-emissions airfreight route between Los Angeles and Amsterdam.

12 British Petroleum acquired a majority stake in forest carbon-management company Finite Carbon. Shell is supplying specific clients with waste-based alternative fuels (so-called sustainable aviation fuels, SAF, which are said to reduce CO_2-emissions by approximately 80%).

Any entity that can provide such a removal service is allowed to submit bids and those CDR providers with the lowest costs associated with the service would then win the auction (Olsson et al. 2020; Lund Christiansen 2020, p. 20ff).

The set-aside of 300 million EU allowances, worth roughly USD 2.4 billion, in the New Entrants' Reserve (NER300) was earmarked for innovative renewable energy technologies and CCS activities. The second round of allocation awarded funding to one CCS project (White Rose CCS project in the UK).

The EU Connecting Europe Facility (CEF) through its sub-entity, CEF Energy, has funded several projects on cross-border CO_2 networks in its third and fourth call, with USD 11.5 million, including feasibility and front end engineering design studies for CCS and CCU networks in the UK, the Netherlands and Norway (European Commission 2020).

The EU's Innovation Fund, one of the world's largest fund for innovative low-carbon technologies including CCS and CCU applications contains USD 12 billion. The first call for large-scale project proposals closed at the end of October 2020 and the full applications of successful proposal have to be submitted by June 2021. The first call for small-scale projects was launched at the end of 2020 (European Commission n.d.c).

The research framework programmes of the EU, Horizon 2020 and its successor Horizon Europe, have been active in the context of CDR. Under Horizon 2020, 17 CCS projects received funding for i.a. the demonstration of optimal carbon capture technologies for cement plants, the development of innovative separation and capture processes or the storage of CO_2 as carbonated minerals (INEA 2020).

In addition to the finance of CCS applications, Horizon 2020 also has strongly focussed on nature-based solutions with regards to their role for biodiversity, adaption efforts as well as mitigation action. Evolving from Horizon 2020, Horizon Europe will become an even bigger research framework, which will provide further finance incentives for CDR. The available documentation on Horizon Europe's scope indicate that besides the continuous support for CCS and nature-based solutions, one can also expect a more nuanced approach to full CDR activities including DACCS and soil management practices as well (European Commission n.d.b).

European countries with emerging political discussions on CDR are also developing RDD&D financing for CDR. At least the US, the UK, Norway, the Netherlands, Sweden and Germany have funded individual national research programs at universities and research organisations or have mandated their national research councils to conduct respective studies on e.g. the technological and economic feasibility or the social acceptance of certain CDR activities.[13]

4.1.4 Carbon pricing

At the international level, the baseline and credit mechanism CDM has in many ways served as a blueprint for generating incentives for CDR. While projects resulting in reduced emissions from deforestation and forest degradation as well as improved forest management (REDD+) were excluded due to issues linked to reporting and accounting, the CDM allowed A/R project types, and developed baseline and monitoring methodologies that can be applied (at least partly) for various CDR approaches.

13 Examples of national research programmes or commissioned studies include i.a. the SPP 1689 Climate Engineering (GER), the LOHAFEX experiment (GER), studies by NOAA and NASA (USA), the CLIMIT research program (NOR), or the GHG Removal Research Programme (UK). Sweden's Industrial Leap Fund, although various sectors and technologies with high BECCS potentials are currently not included, could eventually provide RDD&D funding for them (Hansson et al. 2018).

To date, a total of 66 A/R projects have been registered under the CDM with a wide range in costs and amount of removed emissions (UNFCCC 2020); the five projects with credit issuance have generated over 3 million (temporary) credits[14] to date. After a lengthy process, CCS activities were made eligible under the CDM. The CCS rules under the CDM provide detailed terminology and clear regulatory guidance on the selection, characterisation and development of geological storage sites, liabilities, risk and safety assessments as well as guidance on baseline methodology submission. However, yet no approved CCS baseline or monitoring methodology exists as credit prices have been too low to mobilise CCS.

At the national level, some state entities have also introduced incentives for CDR. For example, the New Zealand ETS covers A/R projects which receive allowances. Owners of forested land can receive emissions units for removals, with liabilities for future reversals. They are entitled to receive respective New Zealand Units for increases in carbon stocks and must pay units for decreases. This has already given an incentive to accelerate A/R efforts and limit deforestation (Leining et al. 2020). Chinese provincial ETSs allow the use of credits from A/R activities, to allow companies under the program to meet their emissions reduction requirements via using forest offsets. California allows A/R credits into its ETS, with the California Air Resources Board as its main regulator which has already approved reforestation, improved forest management and avoided conversion methodologies (Hamrick and Gallant 2017a).

Australia has a domestic crediting scheme including A/R. Through the Emissions Reduction Fund, Australia purchases offsets through a reverse auction. To date, mainly forestry and land-use projects have succeeded in the auctions. California's Low Carbon Fuel Standard (LCFS) is a sub-national baseline and credit instrument that aims to decrease the carbon intensity of the State's transportation. Besides a few transport-specific mitigation technologies, it also allows DACCS credits. The average price of LCFS credits in 2020 reached almost USD 200, being the highest carbon price in the world (Townsend and Havercroft 2019; CARB 2020; IEA 2020).

While not directly mobilising CDR, the Norwegian carbon tax on offshore oil and gas production was the main driver for capture and geological storage of CO_2 in the first global large-scale CCS facilities, the Sleipner and the Snøhvit projects (Gavenas et al. 2015).

The EU ETS stands out as the currently world's largest ETS. In term of accounting, the EU ETS treats CO_2 that has been captured and safely stored underground as not emitted. For the second phase of the EU ETS (2008-2012) CCS installations were allowed to be opted in while CCS application during the third phase (since 2013) are explicitly included (European Commission n.d.a). An important and curious limitation is that only CCS applications that use a pipeline infrastructure for transporting CO_2 from the capture to the storage facility are rewarded under the current EU ETS set-up. CCS applications that solely involve other modes of CO_2 transportation, such as ships, trucks or trains cannot benefit from revenues generated under the ETS (IOGP 2019). However, the EU ETS does explicitly not cover CDR and only highly creative interpretations requiring government intervention could allow for including BECCS activities. For CDR to be fully eligible to benefit from the ETS, all ETS-related rules would need to be modified (Hansson et al. 2018; Rickels et al. 2020a, 2020b).

14 The achievements of A/R activities are measured in terms of the quantity of carbon removed from the atmosphere and the period of time during which it remains sequestrated. Therefore, credits would ideally be quantified in tonne-years. However, the CDM rules provide for a less complex accounting approach: credits can be either time-sliced (temporary Certified Emission Reductions, tCERs), measured as different tonnage valid through fixed time-chunks) or tonne-sliced (long-term Certified Emission Reductions, lCERs), measured as fixed tonnage spanning across different periods) (UNFCCC 2013).

Nature-based removal projects have been financed by various public climate finance vehicles including the Global Environment Facility and the Green Climate Fund. Especially A/R as well as wetland restoration projects, but also individual soil carbon and biochar practices have benefitted from such resources, while it must be noted that these projects are mainly seen as adaptation and resilience-building efforts and mostly do not follow mitigation targets. Besides the support of nature-based solutions, the Global Environment Facility has also provided finance for some technological solutions as well, namely methane capture applications and one BECCS activity (GEF 2021; GCF 2021).

4.1.5 Ancillary policy instruments

Legal responsibility for the permanence of storage when multiple actors are involved in CDR value-chains has been addressed in various countries. The EU CCS Directive provides legal guidance on the issues of responsibility and liability between the host country of the storage and the entity managing the underground storage facility. In the US, CCS operators must similarly adhere to EPA's Reporting Program, which regulates the geological storage of CO_2.

Regarding nature-based CDR activities, the integration of the land use, land use change and forestry (LULUCF) sector into the EU 2030 Climate and Energy Framework marks an important regularly development. Covering GHG emissions and removals that are not regulated under the EU ETS and the Effort Sharing Regulation, the LULUCF Regulation forms the third legal pillar of the EU's efforts to reduce overall GHG emissions. Most importantly, the Regulation sets a specific target for the LULUCF sector — the so-called 'no debit rule': for the accounting periods 2021 to 2025 and 2026 to 2030 Member States must ensure that accounted GHG emissions ('debits') in the LULUCF sector are compensated by an equivalent amount of removals ('credits') through action in the sector (Hansson et al. 2018; Grimault et al. 2018).

The EU Commission is currently developing a 'Carbon Removal Certification Mechanism', that is to become operational in 2023 and could serve — if not as the basis of a systematic inclusion of CDR activities into the EU ETS — at the very least as an instrument enhancing transparency for domestic policies targeting various forms of CDR toward the respective member states burden sharing responsibilities.

An example for an information campaign is the French government's *4% Initiative: soils for food security and climate* launched in 2015 which aims at raising awareness for the critical role of soils in storing carbon.

TEXT BOX 2

International policies acting as barriers to implementation of CDR

Several policies — domestic and international — hinder the mobilisation of CDR, particularly underground storage of CO_2.

The Convention on Biological Diversity (CBD) addresses 'geoengineering' (a term which includes the 'large-scale' removal of CO_2 from the atmosphere), inviting Parties to 'Ensure […] that no climate-related geoengineering activities that may affect biodiversity take place, until there is an adequate scientific basis […] with the exception of small scale scientific research studies that would be conducted in a controlled setting' (CBD 2017). Yet the CBD remains ominously silent on the question of what constitutes 'large-scale' CO_2-removal and it has failed to put in place operational processes through which to judge when an activity may affect biodiversity, what constitutes 'an adequate scientific basis', 'small scale scientific research', or a 'controlled setting'.

The cross-border export of CO_2 for geological storage in sub-seabed geological formation is regulated and constrained within the London Convention/London Protocol. As of today, the necessary amendment has not been ratified by the required number of Parties, hence it is not legally binding (UBA 2019), but nonetheless its existence has created sufficient uncertainty to pose a barrier.

For marine CDR activities, the United Nations Convention on the Law of the Sea (UNCLOS) (1982) also asks its Parties to refrain from any activities that might be harmful for the environment. However, similarly to the case of the CBD, the scope of this guidance is ill-defined. The OSPAR Convention furthermore allows CO_2 storage in the seabed under certain conditions as defined in its Annexes II and III (Doelle 2015), although these annexes have not yet been fully ratified.

Domestic policies and frequent lack of domestic regulatory clarity also often get in the way of investments into CDR, particularly where such lack of clarity intersects and enhances local popular opposition. Geological storage has only been developed in countries, where the national government took a serious interest and active role in their development. Similar challenges face the use of biochar in agricultural or forest soils, where standards ensuring the high quality of materials used need to become widely adopted and recognised as well as where there may in some instances be other questions as to the permissibility of such distribution from a soil preservation perspective. Building codes may often conflict with the use of novel cement compositions as well as with the enhanced use of wood as construction material.

And standards or regulations regarding the dispersal of mineral dust (for enhanced weathering) on agricultural land may furthermore be missing.

4.2 Voluntary private sector activities driving CDR

Private sector pledges and efforts toward CDR have grown dramatically recently. While the absolute majority of the recently emerged finance pledges are regarded as voluntary commitments or activities on the voluntary carbon market and will be discussed in the following chapter, some private actors and CDR providers are active in the field of equity and debt finance as well.

4.2.1 Equity and debt finance

DACCS technology providers like Climeworks and Carbon Engineering are at the forefront of successfully attracting private capital from individuals, philanthropists, corporations or other (institutional) investors — mostly to cover capex of their incremental scale-up of pilot plants.[15]

— Climeworks has raised almost USD 150 million over six funding rounds since its foundation in 2009. Venture Kick and Zürcher Kantonalbank acted as lead investors providing grants, pre seed investments and series B investments. In the most recent venture rounds, Climeworks attracted capital from private investors and family offices. Besides these funding rounds, Climeworks also offers subscription programs for removal credits for everyone, which are priced at over USD $1000/tCO_2$.

— Carbon Engineering has received over USD 107 million over five funding rounds.

15 The list of private investments into the two DACCS companies is based on the publicly available information on each company profile on Crunchbase (2020) and on their own websites.

Building upon an initial convertible note, the company also successfully attracted funding through a venture round, corporate round, private equity round and grants with the federal government, BHP and Chevron amongst the leading investors.

While DACCS companies are successful in attracting equity finance allowing them to build some pilot plants, no actor — public nor private — has yet committed to continuously funding CDR through DACCS over several years (at a cost of several hundreds of dollars per tonne CO_2). In the absence of such commitments, any equity finance going into DACCS has to be viewed as a one-off philanthropic gesture, rather than an investment into a reliable business model.

4.2.2 Voluntary private sector commitments and the voluntary carbon market

There are hardly any public funding flows targeting operating expenses, i.e. the actual CDR process; this is left to a handful of private actors via bilateral voluntary commitments and participation in the voluntary carbon market. Both strategies can work independently from each other but overlap in many instances. Various private actors have announced voluntary commitments to support different types of CDR during 2019-2020 (the details are available in the Annex).

Commitments to CDR fall into three groups. The first group encompasses those companies that support CDR and their providers because they see potential for a future market opportunity. Major oil and gas companies as well as energy- and CO_2-intensive industries seeking to pivot toward new business models sometimes fall into this group. Such industries either possess relevant expertise (e.g. in EOR and EGR), or face pressure to reduce the carbon footprint of their products or to reuse CO_2 in the spirit of circular economy strategies. The number of companies in this group is fairly modest and it is often unclear to which degree strategies are genuine attempts at pivoting to zero-carbon business models or rather serve as short-term public relations strategies. If efforts in this group become more credible, the carbon footprints and financial relevance for potential scale-up should not be underestimated. The Norwegian Northern Lights project can serve as an example: In early 2020, the project partners, Equinor, Shell, and Total, have reached an investment agreement, worth USD 680 million for initial investment, and handed over the development and operation plans to the Norwegian government (NS Energy 2020).

The second group is the use of CDR commitments within broader corporate environmental, social, and governance (ESG) commitments. With growing numbers of private actors, companies and other organisations pledging carbon-, greenhouse gas- or climate neutrality, the relevance of and commitment to support CDR has grown considerably. An initial mapping of strategies put forward (see the list of examples below), suggests a need for greater clarity and transparency: First, a lot of companies merely refer to an overarching goal of *becoming neutral* or *reaching net-zero emissions* and use the terms of carbon, greenhouse gas and climate neutrality interchangeably without clearly distinguishing between them. Each of these concepts is different, however, particularly regarding necessary efforts toward emissions reductions. Secondly and closely related to the first point, companies often do not provide information on how they consider to become neutral, respectively which activities they focus on.

Only a minority of neutrality pledges clearly introduces system boundaries, and defines which emissions will be targeted (including sometimes whether the target includes scope 1, scope 2 and scope 3 emissions).[16] Thirdly, in accordance with the missing demarcation, many of the identified neutrality pledges refer to a combination of emission reduction efforts and the purchase of conventional emissions reductions credits on voluntary markets to offset residual emissions.

This strategy represents a weak form of climate-neutrality, which is not compatible with global net-zero emissions (in the long-term, only offsetting based on carbon removal units should be permitted).

Finally, the third group of net-zero commitments includes both ambitious emission reduction plans across the company's entire reach of influence and additionally identifies the need and plans to mobilise CDR to reach neutrality. Most companies in this group refer to nature-based solutions such as A/R and wetland restoration. Others, particularly North American companies, also include soil management practices, yet only a small minority includes technological CDR activities with high permanence such as BECCS and DACCS, or enhanced weathering as part of their strategy.

Some examples of mitigation strategies referring to CDR include the following companies, which can be grouped according to scale and boldness into frontrunners and secondary players:[17]

As frontrunners, we see the following companies:

— Microsoft targets carbon negativity by 2030 and will have removed all the carbon the company has ever emitted by 2050. It established the Climate Innovation Fund with a budget of USD 1 billion to support nature-based solutions, soil carbon sequestration as well as novel technological removal technologies. Most recently, Microsoft has announced that its Fund will make a substantial investment into Climeworks.

— Shopify has announced becoming carbon neutral and even negative in the future and will also spend at least USD 1 million/year for carbon sequestration projects. The pledge is especially noteworthy because Shopify announced that they will buy these credits at any price.

— Stripe claims having reached carbon neutrality already in 2019 and pledged to invest USD 1 million/year into forestation initiatives, soil management reforms, enhanced weathering, and direct-air capture technologies. In May 2020, it announced that Climeworks, Project Vesta, CarbonCure and Charm Industrial have been selected to receive funding. In addition to its own commitment, Stripe launched its own app Stripe Climate, through which clients can direct a fraction of their revenue to support scaling up CDR.

— Swiss Re will achieve net-zero emissions of its operations by 2030. In parallel with reduction efforts, Swiss Re will increase its internal carbon levy from USD 100/tCO_2 in 2021 to USD 200/tCO_2 in 2030. This strategy allows the company to enter long-term agreements with carbon removal service providers and boosting the removal business.

16 Scope 1 emissions refer to direct GHG emissions from owned or controlled sources, scope 2 emissions refer to indirect GHG emissions from the consumption of purchased energy and scope 3 emissions refer to other indirect GHG emissions that occur in the value chain of the company (WBCSD and WRI 2004).

17 The information for this initial and non-exhaustive mapping of mitigation strategies referring to CDR are obtained from ICRLP (2020) and the respective companies' websites.

As secondary players, we see the following companies:

- Amazon intends to become carbon neutral by 2040 and established the Right Now Climate Fund (USD 100 million) and the Climate Pledge Fund (USD 2 billion) to support climate action around the world. Amazon focusses on nature-based solutions around restoring and protecting forests, wetlands, and peatlands.
- Apple has pledged to reach net-zero CO_2 emission across its entire portfolio by 2030. This will be done with a deep emission reduction effort which is paired with a nature-based solutions strategy to restore and protect forest mangroves and natural ecosystems.
- The Boston Consulting Group announced plans to reach climate neutrality by 2030 with a combination of nature-based and technological solutions. The Group is expecting to spend USD 35/tCO_2 in 2025 on reductions and removals, rising up to USD 80/tCO_2 for removals in 2030.
- Oil and gas majors BP and Royal Dutch Shell have pledged to become carbon neutral by 2050 and refer to nature-based solutions as well as measures to capture and sequester CO_2.
- British Airways and its parent company IAG intend to become carbon neutral by 2050 by partnering up with capture technology provider Mosaic Materials, which develops an innovative adsorbent material to take out CO_2 from the air.
- Danone has announced its intent to become carbon neutral across its full value chain by 2050. In order to reach net-zero emissions, Danone North America commits up to USD 6 million to research ways to help regenerate soils and increase soil carbon sequestration.
- Delta Airlines will commit USD 1 billion over the next 10 years to become the world's first carbon neutral airline. Besides emission reduction, Delta also will invest into innovative projects and technologies to remove carbon from the atmosphere including nature-based solutions, soil capture and other CDR technologies.
- Ikea aims for carbon negativity by 2030 by storing carbon in land, plants and products. Thus, it will explore ways to ensure that carbon remains stored in IKEA products for a longer time through circular economy efforts.

The identified neutrality and CDR claims build on different finance instruments. While some companies will establish their own funds and direct money to individual projects or CDR providers, others will purchase CDR credits on the voluntary carbon market. The voluntary carbon market has seen some action in A/R. Over the last years, forestry and land use has become the leading category both in terms of transactions and issuances. Volumes generated between 2017-2019 have reached over 105 MtCO_2 amounting up to a value of over USD 390 million (Donofrio et al. 2020). The leadership position of forestry and land use is based on a significant increase in volume from REDD+ projects (from 10.6 MtCO_2e in 2016 to 30.5 MtCO_2e in 2018) and A/R projects (from less than 2 MtCO_2e in 2016 to 8.4 MtCO_2e in 2018) (Donofrio et al. 2019). Forestry and land use credits are predominantly purchased from projects in Latin America and Africa, and by buyers concerned with community benefits and biodiversity (Hamrick and Gallant 2017a, 2017b). Similar to the average price, prices for these credits fell significantly over the last years: from USD 4.4 in 2016 to USD 2.4 in 2018 for REDD+ credits, and from USD 8.1 in 2016 to USD 5.7 in 2018 for A/R credits (Donofrio et al. 2019).

Donofrio et al. (2019) argue the increasing popularity of nature-based credits on the voluntary carbon market is based on (i) research showing that the mitigation potential of nature-based solutions has been vastly underestimated; (ii) awareness-raising campaigns launched by the United Nations in response to the 2018 IPCC Special Report on Land (which identified carbon sinks as critical to meeting the goals of the Paris Agreement); and (iii) media outlets ratcheting up their coverage of tree-planting projects.

A/R activities are certified by standard setting organisations like Verra, Gold Standard (GS) and Plan Vivo who have long thrived in the voluntary carbon market and offer various standards. Examples of such standards include the Verified Carbon Standard (VCS) Program and the Climate, Community & Biodiversity Standards (CCBS) (managed both by Verra), Gold Standard Verified Emission Reductions and Plan Vivo Certificates (PVCs). The standard setting organisations have developed different approaches to manage non-permanence risk: Verra requires a risk assessment that is used to determine the amount of credits that cannot be traded but must be deposited a pooled buffer account. This pool is intended to cover unforeseen losses in carbon stocks (Verra 2018). Meanwhile, the Gold Standard has designed five backstop elements: (i) specific requirements to assess the design of each activity; (ii) frequent monitoring, reporting and verification (MRV); (iii) a compliance pathway that lays out how activities that have high permanence risks get back on track; (iv) the liability of underperformance remains with the project owner; and (v) the Gold Standard Compliance Buffer, which requires that every project reserves 20% of its issuances in the event that carbon is no longer sequestered (Gold Standard 2020).

A national level semi-voluntary standard is the UK Woodland Carbon Code (and its new and related programme, the Woodland Carbon Guarantee) which is a voluntary standard to accelerate A/R activities in the UK and to develop a domestic market for woodland carbon. The Code provides individuals and landowners implementing A/R activities with the option to sell their captured carbon in form of Woodland Carbon Units. The Guarantee builds upon the experiences made with the Code and, as a long-term incentive scheme, provides long-term payments for carbon sequestration projects. It also provides the option to sell the Units to the government for a guaranteed price every 5 or 10 years up to the mid-2050s. If sold to the government, these credits are then used to contribute directly to the UK's mitigation targets.

Recently, providers of CDR credits have entered the voluntary carbon market sphere. For examples, Puro earth (Finland), Nori (US), MoorFutures (Germany) and max.moor (Switzerland) focus on different CDR activities for which MRV methodologies were developed. Most of these relate to biological CDR. There is no consistent approach to addressing key issues such as permanence of removed CO_2 or additionality and many lessons from the CDM were simply disregarded in their design. While MoorFutures and max.moor exclusively focus on wetland and peatland restoration projects, whose credits are priced at around USD 78-92/tCO_2, Nori offers removal credits from agricultural carbon sequestration projects worth around USD 15/tCO_2. Puro earth, a start-up of Finnish energy company Fortum, takes a different CDR approach by offering removal credits for biochar, wooden building materials and carbonated building materials, which cost between USD 23-180/tCO_2.

05

Discussion and conclusion

CDR is a crucial part of any strategy to reach the Paris Agreement's long-term target but is currently treated as an afterthought instead of a necessary public service. Many CDR types represent a pure public good as they do not generate sufficient revenues to be viable without direct payment, government subsidies or incentives from carbon pricing schemes. This would not be a problem in and of itself, given that we have managed to put in place reliable financial flows to resolve pure public goods (such as solid or liquid waste treatment) in the past. While more and more countries specify long-term net-zero targets between 2035 and 2060 that cannot be reached in the absence of CDR, short-term NDCs for 2030 show an increasing 'mitigation gap' and do not feature CDR other than low-cost A/R with no innate permanence. Existing and planned policies similarly almost exclusively address A/R to date, while instruments mobilising CDR tied to permanent underground storage are largely missing.

Somewhat surprising, some private sector actors have become frontrunners in the past two years in pledging voluntary CDR activities – either directly funding and deploying CDR or purchasing CDR credits on emerging voluntary carbon markets specialised for CDR. Most, however still focus on A/R and biological CDR. With several high profile forest fires and growing awareness of losses in carbon stocks, attention for underground permanent storage may increase.

To unlock policies that systematically advance CDR more clarity is needed regarding the necessary functions of policy: It needs to be clear why removals are needed for achieving specific climate objectives, why permanence of storage matters, how removals differ from emissions reductions and what (inter-)national rules, governance objectives, and best-practice approaches apply so that actions start to match the communicated ambitions.

For this, robust MRV methodologies and accounting approaches need to ensure environmental integrity including by properly addressing permanence, additionality and avoiding double counting or double claiming of the same efforts.

Policy instruments need to walk the tightrope between unduly favouring one specific CDR type, and ‘letting 100 flowers bloom’. An overly early ‘picking of winners’ risks overlooking promising but ‘invisible’ CDR approaches or actors. An illustrative example relates to enhanced weathering, which albeit may prove a highly synergetic and permanent long-term carbon removal option has been largely ignored to date for perhaps being too unspectacular or slow. At present it takes proactive organisations such as the Dutch Olivine Foundation or the Stripe CDR initiative to prevent such approaches remain entirely ignored. At the same time, efficiency of public funding requires that at the appropriate time ‘dead ends’ are eventually identified and discontinued and thus do not deviate funding from more promising approaches.

5.1 Short- and medium-term policy and financing instruments (2030)

In the short- to medium-term, the focus should be especially on issues related to research and development activities as well as capex financing needs. However, short-term finance measures cannot succeed in triggering the vast investments needed for large capex investments unless there are clear long-term commitments that accompany them. Given the high costs of many CDR options, combinations of various forms of finance should be envisaged, e.g. revenues from carbon markets with public climate finance.

5.1.1 International

First, internationally negotiated regulations currently restricting CDR deployment should be continuously checked – whether they are still in accordance with the latest scientific findings – and revised where needed.

The three Paris Agreements’ Article 6 mechanisms (in paragraphs 6.2, 6.4 and 6.8) should be leveraged strategically to advance CDR approaches in their respectively most appropriate form — considering the different degrees of international oversight and stringency (Michaelowa et al. 2020): the less stringent Article 6.2 may serve as an entry point for bilateral piloting activities that allows pre-testing elements of market instruments that may later be put to work within larger regional emissions trading or under the more stringent Article 6.4 market mechanism. Doing so will serve not only as a proof of concept of such international cooperation on CDR, but also help CDR technology providers overcome the valley of death between early pilot plants and at-scale installations.

Article 6.4’s more stringent rulebook and UN oversight makes it perfect to advance cooperative CDR efforts that are to be counted toward NDCs in a way that enhances trust and credibility of CDR. Article 6.4 might be especially relevant for mobilising private finance alongside public resources (Michaelowa et al. 2019) yet for many CDR approaches the prices achieved in such a market might for a long time remain insufficient as stand-alone incentives (Honegger and Reiner 2018).

Article 6.8 — the placeholder for so-called non-market mechanisms — comes with little guidance. But it offers a general catch-all context for advancing capacity building, technology transfer, regulatory or financial incentives or cooperative RDD&D (Honegger et al. 2019). Article 9 furthermore offers guidance on financial transfers from developed to developing Parties and Articles 10 and 11 address technology transfer and respective capacity building efforts.

Parties seeking to engage in any of these activities (that do not offer a quantifiable mitigation contribution toward their NDCs) may get creative and commence various forms of collaborative effort to advance CDR — as they have been in the broader context of climate change mitigation for years.

5.1.2 National

At the national level, two distinct dynamics are possible: On the one side, progress at multilateral level regarding rulesets for CDR could accelerate pressure for advances at national levels. Such a dynamic would suggest that multilateral negotiations shape the expectations for domestic CDR policy implementation via the rules and guidance provided under the Paris Agreement. In the very near-term this does not appear very likely, given that negotiations, e.g. on Article 6 rules and guidance, do not appear to have considered the particularities of CDR to date and guidance for new NDC iterations remains rudimentary. The alternative — a bottom-up scenario — seems more likely, in which front-runner countries such as Sweden and the UK move forward and demonstrate how they translate their net-zero ambitions into various specific CDR targets and policies, thereby providing a process and decision template and indirectly shame others into following. Given that presently several countries appear to pursue — or in their own perception retain — the status of a climate leader, such a dynamic appears quite plausible. In our observation the list of countries with such declared ambition heading into 2021 includes (in no particular order): the UK, Switzerland, Germany, the entirety of the EU, the US, Finland, Norway, Japan and China.

Regardless of international dynamic(s) national governments on their own have broad leeway to support and accelerate CDR also in the medium term. Given that price levels under Article 6.4 are expected to remain insufficient for many CDR types there is considerable need for support in tackling the large upfront capital expenses and near-term operating expense hurdles for the more capital-intensive high-permanence approaches. Progressive countries could offer a premium on top of market prices that would account for the elevated cost levels of technologies which have not yet made their way down the cost curves.

National COVID-19 recovery funds with often very sizeable near-term budgets are of particular interest. They could — if well designed — become a strong driver channelling resources towards CDR in the next few years. UNEP (2020) highlights the importance of using the recovery measures to accelerate a green and net-zero transition. Recovery funds could also be used to pave the way for more structural reorientation to ensure long-term funding for CDR by altering the political economy of climate finance. So far nearly all CDR funding went to nature-based approaches given their low cost despite their uncertain permanence. COVID-19 recovery funding – if properly targeting the relevant RDD&D stages of high-permanence CDR activities – could play a key role in driving down cost reductions. Allocation of funding in the near-term is likely to shape the political economy with effects for the long term: For example, the agriculture and forestry sector, in which many of the identified removal activities such as biochar applications, enhanced weathering, soil carbon sequestration activities or biomass production and harvesting for BECCS could take place, is represented by a powerful lobby in many countries that has been able to keep the sector out of any mitigation policies. Hence, interventions in that sector may both leverage these forces to ensure long-term commitments, but they also need to be very careful to not create entrenched perverse incentives which will be very hard to eliminate later.

5.2 Long-term policy and financing instruments (2050)

Simultaneously guiding and building upon the short- to medium-term policy instruments, the long-term perspective needs to be closely interwoven with them.

5.2.1 International

At the international level, policymakers and practitioners can take various actions and address the need for scaling up CDR.

The public and private sectors need to establish more effective cooperation modes. These modes must address the existing finance gap of CDR by mobilising public and private capital. But they should also establish a forum for an exchange of ideas and experiences between state and non-state stakeholders. In addition, new cooperation modes around public-private partnerships, risk sharing agreements between entities capturing CO_2 and entities transporting and storing CO_2 as well as insurance schemes covering such activities need to be developed or further stressed.

Second, international market mechanisms and climate finance to date have largely focussed on emission reduction activities. In the long-term, CDR will dominate international cooperation as baselines for emission reduction activities will converge to zero.

Thus, future cooperation under Article 6 will increasingly relate to CDR activities and in the long-term, Article 6 cooperation might nearly exclusively focus on CDR activities.

5.2.2 National

States should use their LTS-LEDS as the ideal context in which to sketch out a path to net-zero emissions and, thus, to a credible and sustainable scale-up of domestic CDR capacities as well as plans for roll out of policy instruments.

Reaching net-zero emissions will require serious changes in hard-to-decarbonise sectors (such as agriculture, steel, cement, aviation or maritime transport). Even in the long-term, full decarbonisation may not be feasible for these sectors, thus raising the question whether they ought to build CDR capacities to balance such residual emissions. By defining stepwise sectoral targets or expanding the scope of carbon pricing instruments to include these hard-to-abate industries, countries can send the necessary signals well ahead such as to not cause major disruption.

States and non-state actors can also deepen their cooperation at national level. Through public-private partnerships, storage insurance policies as well as other new policy instruments (e.g. feed-in tariffs or contracts for difference to promote BECCS, and long-term public purchase agreements for any CDR type) countries may gradually ramp up capacities for domestic CDR in the medium- to long-term.

06

Recommendations

We address three groups of actors: International policymakers, national level policymakers and private sector actors.

6.1 International policymakers

International policy needs to facilitate and streamline CDR efforts rather than impede and obfuscate their relevance: UNFCCC negotiators should fully recognise CDR as a form of mitigation and operationalise the mitigation toolset for addressing the full value chain of the public good CDR. Moreover, regulatory barriers in other international regulatory contexts need to proactively be identified and overcome. International organisations should also share best-practice examples for early R&D collaborations and fiscal incentives.

Within the Paris rulebook, CDR needs to systematically be considered alongside emission reduction measures — particularly for the Article 6 rulebook. In the Article 6 work programme, methodological work for issues related to baseline setting and MRV needs to be prioritised. In the negotiations on the operationalisation of the Enhanced Transparency Framework, accounting rules for removals need to be sufficiently specified. International institutions should support methodological work for MRV of various CDR types and advancing conceptual work to ensure proper accounting for removals compatible with overall provisions of the Paris Agreement and IPCC inventory guidelines and practices.

In the context of the upcoming global stock take, the role of CDR to reach the ambitious long-term target of the Paris Agreement should become a focus area.

Negotiators and Parties' NDC developers should examine the pros and cons of specifying CDR targets alongside emissions reductions targets – including for the definition of climate finance.

International climate policy actors should engage with stakeholders from the political, economic, scientific and civil society on the above-mentioned issues to identify key concerns and desires, avoid misunderstandings, and lay the foundation for a broadly supported mobilisation of CDR. A clear-sighted discussion of the advantages and shortfalls of various CDR and CDR policy approaches would help preventing one-sided and short-lived support for fashionable but problematic approaches from spoiling the entire basked of mitigation efforts.

6.2 National level policymakers

National level actors ought to work hand-in-hand with international negotiators and institutions, notably regarding the implications of specifying CDR targets, piloting international CDR mitigation cooperation under Article 6 and advancing a consistent approach to properly accounting for CDR in national inventories.

Governments of developed countries need to create long-term commitments for the public good CDR, particularly for those CDR activities that are the most capital intensive. This can be done through subsidy programmes or mandates for private sector actors. Creative design of the latter would allow to link these with carbon market approaches, e.g. allowing companies facing a mandate to fulfil it by providing removal credits. Policies should aim at accelerating mobilisation of (potentially self-paying) co-benefits of individual CDR activities by deepening the communication with relevant stakeholders, identifying regulatory barriers and providing early fiscal incentives with a clear phase-out date when a CDR technology pays for itself. This could be achieved through reverse auctions for removal action. A similar approach could be implemented for (part of) bilateral mitigation finance.

In the longer run, governments could consider to include separate targets with specific time horizons for CDR deployment when updating their NDCs. A similar approach could be implemented for public climate finance as well.

When submitting and updating NDCs, national policymakers should consider to include separate targets with certain time horizons for CDR deployment. This would ensure that removal activities can be (politically and financially) addressed and monitored separately while not undermining emission reduction efforts. With an even longer time horizon, the potentials and necessary funding gaps of CDR should be highlighted in the LT-LEDS.

Furthermore, policymakers should advance best-practice pilots and gradually develop roadmaps, guidance and — where needed regulation — including for private-sector actors to ensure that voluntary CDR projects as well as CDR activities that are counted toward NDCs are properly designed, implemented, MRV'd and accounted for. Particularly for large-scale nature-based removals, policymakers may want to advance stronger environmental and social safeguards (including to ensure full respect for the rights of Indigenous Peoples as well as local communities, and the conservation of biodiversity). Similar issues also do apply to CDR with geological storage, although their permanence risks would be several orders of magnitude smaller. Therefore, transparent norms should address limited and uncertain permanence and correspondingly clarify liabilities for leakage or reversal.

6.3 Private sector actors

While public authorities are the responsible actor for setting up an appropriate political-regulatory and financial landscape that ultimately results in the continued provision of public goods, private sector actors can, and in a few instances, have already acted as frontrunners, aiming to demonstrate possible approaches that later become increasingly the norm. Active exchange of ideas between public and private actors therefore allows to identify barriers as well as opportunities for hands-on practices that may feed into public roadmaps, strategies and policies.

Given the important role of private sector action in mobilising removal through company-level targets, as well as the risk of tainting CDR through badly executed, cheap actions with negative impacts, initiatives need to be strengthened that lead to a 'race to the top' or virtuous spiral toward high quality. This applies both for company-internal action as well as the generation and acquisition of removal credits. As has been the case with emission reduction credits, private sector entities should set up an institution providing services to identify high quality removal credits. The established 'Gold Standard' Foundation for high quality emission reduction credits could be provided with the mandate and financing to systematically expand to include removals. Initiatives bringing together companies that set up ambitious climate change mitigation strategies like the Science Based Target Initiative (SBTi) could require minimum standards for removal credits.

A necessary condition for prevention of 'Wild West' removal action by the private sector would be regulatory oversight on the national level with regard to claims regarding removal credits. This oversight should focus on issues related to permanence and the quality of MRV. It should prevent the emergence of low-quality removal credit providers and the multiple claiming of the same activities' mitigation results.

Given the strong emphasis of many private sector actors on nature-based removals, and the inherent risk of such removal activities being non-permanent and having negative repercussions for local communities, an initiative for high-quality nature-based removals should be co-subscribed by the SBTi and other important interest groups like the International Emissions Trading Association (IETA). The experience with forestry projects in the early years of the CDM and the voluntary markets with a significant number of failures and scandals taken up by non-governmental organisation (NGOs) should be a warning sign to the 'nature-based solutions' community.

The frontrunners in the private sector with a high willingness to pay should explore high permanence approaches in which CO_2 is stored underground and/or mineralized (such as DACCS, enhanced weathering, (bio)waste-CCS and BECCS). However, to be upscaled, governments need to consistently work towards a high and sustained future public demand for removal – by treating removals as a necessary public service.

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Annex

TABLE 3

Private company net-zero strategies explicitly involving CDR

Private actor	Sector	Type and target date of neutrality	Vehicle	Funding sum	CDR option
Amazon	Retail	Carbon neutrality, 2040 Neutralise any remaining emissions with additional, quantifiable, real, permanent, and socially-beneficial offsets	Right Now Climate Fund Partner: The Nature Conservancy The Climate Pledge Fund	USD 100 million (total) USD 2 billion (total)	Nature-based solutions: restoring and protecting forests, wetlands, and peatlands
Apple	Tech	Carbon neutrality, 2030 For supply chain and products Emission reduction 75%, CDR 25%	Impact Accelerator that will focus on investing in minority-owned businesses Conservation International, Conservation Fund, World Wildlife Fund	Undefined share of USD 100 million	Nature-based solutions: restoring and protecting forests, mangroves and natural ecosystems
AstraZeneca	Pharmaceutical/ Chemical	Carbon negativity, 2030		USD 1 billion (total)	Nature-based solutions: 'AZ Forest', a 50-million tree reforestation initiative 2020-2025
Boston Consulting Group	Consulting	Climate negativity, 2030 Independently verified carbon credits, 100% from CDR		USD 35/tCO_2 in 2025, rising to USD 80/tCO_2 in 2030	Nature-based and technological solutions
BrewDog	Retail	Carbon negativity, 2020 Independently accredited carbon offsets	Woodlands Trust, Carbon Neutral, Ribble Rivers, The Nature Conservancy	Not disclosed	Nature-based solutions: Purchased 2,050 acres of land in Scotland to plant 1,500 acres of broadleaf native woodlands and do peatland restoration on 500 acres by 2022

Private actor	Sector	Type and target date of neutrality	Vehicle	Funding sum	CDR option
British Airways (and its parent company IAG)	Aviation	Carbon neutrality, 2050	Mosaic Materials	Not disclosed	Innovative adsorbent material to take out CO_2 emissions directly from the atmosphere
Consumers Energy	Energy	Carbon neutrality, 2040 Offset acquisition	2019 Clean Energy Plan	Not disclosed	Carbon sequestration, or large-scale tree planting
Danone	Retail	Carbon neutrality, 2050		Danone North America will commit up to USD 6 million to research ways to help regenerate soils and increase soil carbon sequestration. Danone France commits around USD 6 million to support farmers in transitioning to regeneration of soils	Transforming agricultural practices to sequester more carbon in the ground (member of the 4 per 1000 initiative)
Delta Airlines	Aviation	Carbon neutrality CDR offset purchase		USD 1 billion over the next 10 years	Forestry, wetland restoration, grassland conservation, marine and soil capture, and other CDR technologies
Easy Jet	Aviation	Carbon neutrality, 2020 Offset purchases, inter alia CDR		USD 32 million/year	Reforestation
Harvard	Finance	GHG neutrality, 2050 CDR offset purchase		Not disclosed	All
Heidelberg Cement	Heavy Industry (steel, cement)	Carbon neutrality, 2050		Not disclosed	New technologies for CO_2 sequestration and use in the cement-making process

Private actor	Sector	Type and target date of neutrality	Vehicle	Funding sum	CDR option
Horizon Organic (Danone)	Retail	Carbon negativity, 2025, full supply chain		USD 15 million Horizon Farmer Investment Fund to support its farmers with low- and no-cost loans for capital, training, technology and tools for sustainable practices.	Regenerative agriculture, soil sequestration, restoring prairie lands and forestlands, and evaluating and pursuing new technology
Ikea	Retail	Carbon negativity, 2030		Part of USD 237 million for forest planting	Storing carbon in land, plants and products
Microsoft	Tech	Carbon negativity, 2030	Climate Innovation Fund	USD 1 billion	A/R, soil carbon sequestration, BECCs, and DACCS
Nestle	Retail	Carbon neutrality, 2050		Not disclosed	A/R, restore land
Repsol	Energy	Carbon neutrality, 2050		Not disclosed	A/R
Royal Dutch Shell	Energy	Carbon neutrality, 2050, partially on products, reduce emissions by30% by 2035 and by 65% by 2050.		Not disclosed	A/R, other
Salesforce	Tech	Carbon neutrality, 2017		Not disclosed	A/R
Shopify	Tech	Carbon neutrality and negativity	Sustainability Fund	USD 5 million/year (total) Buying USD 1 million of sequestered carbon annually at any price	A/R, other
Smithfield Foods	Retail	Carbon negativity, 2030		Not disclosed	A/R, soil sequestration
Starbucks	Retail	Carbon negativity, 2050		Not disclosed	A/R

Private actor	Sector	Type and target date of neutrality	Vehicle	Funding sum	CDR option
Stripe	Tech	Carbon neutrality, 2019		USD 1 million/year for CDR at any available price	A/R, soil sequestration, enhanced weathering, and DACCS. In May 2020, Stripe announced their first four purchases: Climeworks, Project Vesta, CarbonCure, and Charm Industrial
Unilever	Retail	Carbon neutrality, 2039	Climate & Nature Fund	USD 1.2 billion (10 years)	Landscape restoration, reforestation

Source: authors, adapted from ICRLP (2020)

NET-RAPIDO:

Negative emission technologies readiness assessment, policy instrument design, options for governance and dialogue aims to create a clear understanding of the opportunities, challenges and risks of negative emission technologies (NETs) for climate action to enable an objective and pragmatic consideration of this approach in policymaking. Through informed analysis and dialogue amongst relevant stakeholders, NET-RAPIDO aims to break new ground on this topic through balanced recommendations on key elements of NETs, with focus on the economic feasibility and support needs.

NET-RAPIDO is a project implemented between 2018 and 2019 by Mälardalen University, Perspectives Climate Research and Climate Strategies.

MÄLARDALENS HÖGSKOLA ESKILSTUNA VÄSTERÅS

perspectives climate research

Climate Strategies

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