Net-Zero Emissions

The role of Carbon Dioxide Removal in the Paris Agreement

Perspectives extended briefing report on the practicalities of net-zero emissions targets and the role of carbon dioxide removal in (sub-)national mitigation action

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Executive Summary

Achieving the Paris Agreement goal of limiting warming to well below 2°C or even 1.5°C requires a dramatic increase in the collective greenhouse gas mitigation ambition pursued by the international community: The implementation of Nationally Determined Contributions (NDCs) that are revised over time ought to eventually lead to a global balance of CO_2 emissions and removals (negative emissions). In 2020, Parties to the Agreement are to communicate their long-term aspirations in the form of Low Emissions Development Strategies (LEDS) outlining their vision for national climate action by 2050 in alignment with the Agreements' global temperature target. A growing number of Parties are putting forward net-zero emissions targets, yet credible strategies for their implementation, in particular for the large-scale continued removal of CO_2 are missing. The lack of experience with planning for net-zero emissions is an enormous challenge in particularly regarding the contributions of different possible approaches to carbon dioxide removal (or "negative emissions"). Here we analyze relevant provisions for CO_2 removal under the Paris Agreement in regard to NDCs, international cooperation, transparency, accounting and MRV as well as practical, sometimes highly political challenges policymakers are facing when seeking to implement CDR. Furthermore, we offer a vision of a net-zero world and how it may be achieved. The briefing report seeks to offer practical insights for experts and decisionmakers involved in planning the implementation of net zero-emissions targets as well as for researchers and technology developers studying or developing potential negative emissions approaches.

Contents

Abbreviations

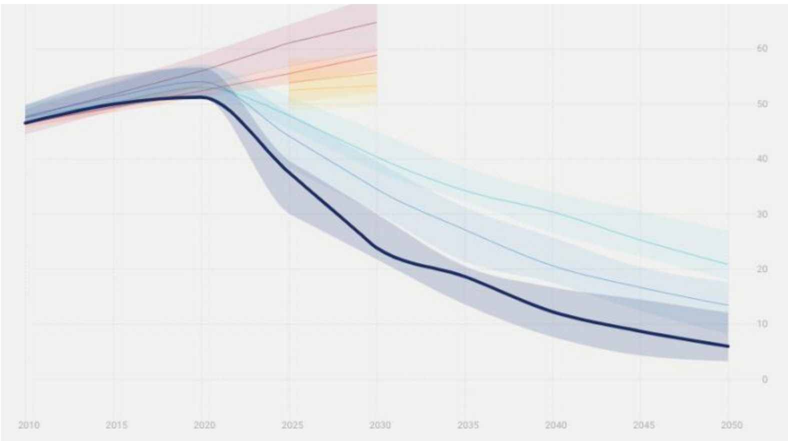
BECCS	Bioenergy with Carbon Capture and Storage
CBD	Convention on Biological Diversity
CCD	Convention to Combat Desertification
CCS	Carbon Capture and Storage
CDM	Clean Development Mechanism
CDR	Carbon Dioxide Removal (also see NETs)
CMA	Conference of the Parties serving as the meeting of the Parties to the Paris Agreement
COP	Conference of the Parties
CO_2	Carbon Dioxide
CSU	Carbon Storage Unit
DACS	Direct Air Capture and Storage
GHG	Greenhouse gas
GTP	Global Temperature change Potential
GWP	Global Warming Potential
IAM	Integrated Assessment Model
IPCC	Intergovernmental Panel on Climate Change
ITMO	Internationally Transferred Mitigation Outcome
LC/LP	London Convention/Protocol on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter
LEDS	Low Emissions Development Strategy
LULUCF	Land Use, Land-Use Change and Forestry
NAMA	Nationally Appropriate Mitigation Action
NDC	Nationally Determined Contribution
NETs	Negative Emissions Technologies
NMAs	Non-Market based Approaches
PA	Paris Agreement
REDD+	Reducing Emissions from Deforestation and Forest Degradation, Conservation of Forest Carbon Stocks, Sustainable Management of Forests, and Enhancement of Forest Carbon Stocks
RDD&D	Research, Development, Demonstration, and Deployment
SBI	Subsidiary Body for Implementation
SBSTA	Subsidiary Body for Scientific and Technological Advice

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

1. Introduction

Compared to the preindustrial period, global temperature has already increased by over 1°C due to anthropogenic climate change. In the Paris Agreement (PA) the international community has set out to keep global average warming to well below 2°C in order to limit the impacts from climate change on people and the planet to manageable levels. A target of 1.5° is envisaged under the PA and IPCC (2018) has assessed the possibilities to reach such a target in detail. In order to limit warming to any temperature, the laws of physics demand a stabilization of greenhouse gas (GHG) concentrations in the atmosphere. Stabilization of GHG concentrations is achieved when the sources and sinks of those gases are equal. Present scenarios to limiting warming to well below 2°C assume the removal of billions of tonnes of carbon dioxide from the atmosphere in addition to slashing greenhouse gas emissions by up to 90% within three decades[1]. Pledged mitigation policies are neither promising to cut emissions fast enough nor do they include dedicated measures to implement Carbon Dioxide Removal (CDR). As a result, mitigation pledges globally amount to a mere third of the necessary mitigation ambition to limit warming to well below 2°C – or a fifth of the effort needed for 1.5°C (Figure 1: Global greenhouse gas emissions until 2030 and their gap to 1.5°C, 1.8°C or 2°C emissions paths. Furthermore, only few jurisdictions have to date put in place effective mitigation policies that would actually put economies on the respective mitigation paths. If the PA targets are to be reached, governments need to both accelerate the implementation of existing mitigation pledges through introduction of effective mitigation policy instruments including regulation and incentives, as well as urgently enhance the ambition of their NDCs. As we will show in the following, this includes putting in place targets and measures that specifically mobilize CDR.

Figure 1: Global greenhouse gas emissions until 2030 and their gap to 1.5°C, 1.8°C or 2°C emissions paths.



Source: UNEP (2018).

Note on the 2030 scenarios: Baseline scenario (dark red), current policy scenario (light red), full implementation of unconditional NDCs (orange), Conditional NDCs (yellow). Note on the 2050 scenarios: Emissions pathways for

[1] Refer to section 2.2 for a detailed explanation of the difference between emissions reductions and removals (CDR) incl. the role that carbon capture and storage (CCS) can play.

2°C (light blue), 1.8°C (medium blue) or 1.5°C (dark blue) temperature stabilization. The curves depict CO_2eq net-emissions pathways (not specifying particular amounts of removals contributing to the downward path).

1.1 Implementing the Paris Agreement requires CO_2 removal

As discussed above, CDR has to be a relevant component of strategies to reach the PA targets, complementing emissions cuts, and needs to be developed and deployed rapidly. CDR can principally be done either by enhancing natural sinks of CO_2 (e.g. via afforestation or other high-carbon ecosystem restoration, enhanced weathering of rocks or ocean fertilization), by technological processes such as direct air capture and storage (DACS), or by combined natural and technical processes such as bioenergy with carbon capture and storage (BECCS).[2] The respective potentials of various CDR approaches are constrained by their economics (comparatively high mitigation costs per tonne of CO_2), local resource availability (biomass, land, water, and electric power) as well as societal and political dynamics. Furthermore, many CDR approaches have barely been tested at pilot-plant scale, which limits the understanding of real-world potentials including the risk – at larger scales of application – of triggering conflicts with sustainable development in various regional contexts (Honegger et al., 2018; Fuss et al., 2018).

1.2 Governance of Carbon Dioxide Removal under the Paris Agreement

This report seeks to identify already existing (but insufficiently utilized) governance routes through which challenges to the implementation of CDR in the context of the PA can be addressed in the near- to long-term. In so doing, the report is to serve as a guidebook for those involved in the rule-setting and implementation of climate change mitigation action, including UNFCCC Party negotiators and observers, (sub-)national legislators as well as private sector practitioners who might already now or in the near future be tasked with the design or implementation of climate policies. It provides insights on policy and implementation levers relevant on various timescales (e.g. the very short term regarding the negotiations on the rulebook for market mechanisms under Article 6 of the PA at the forthcoming twenty-fifth Conference of the Parties, COP25 in December 2019, and the long term in the context of defining credible emission strategies for the 2050 time horizon).

While showcasing that CDR approaches can trigger conflicts between different policy targets including concerning various aspects of sustainable development[3], the report does not present arguments in favour or against the implementation of particular approaches, or geoengineering techniques in general, but focuses on current key governance aspects regarding CDR.

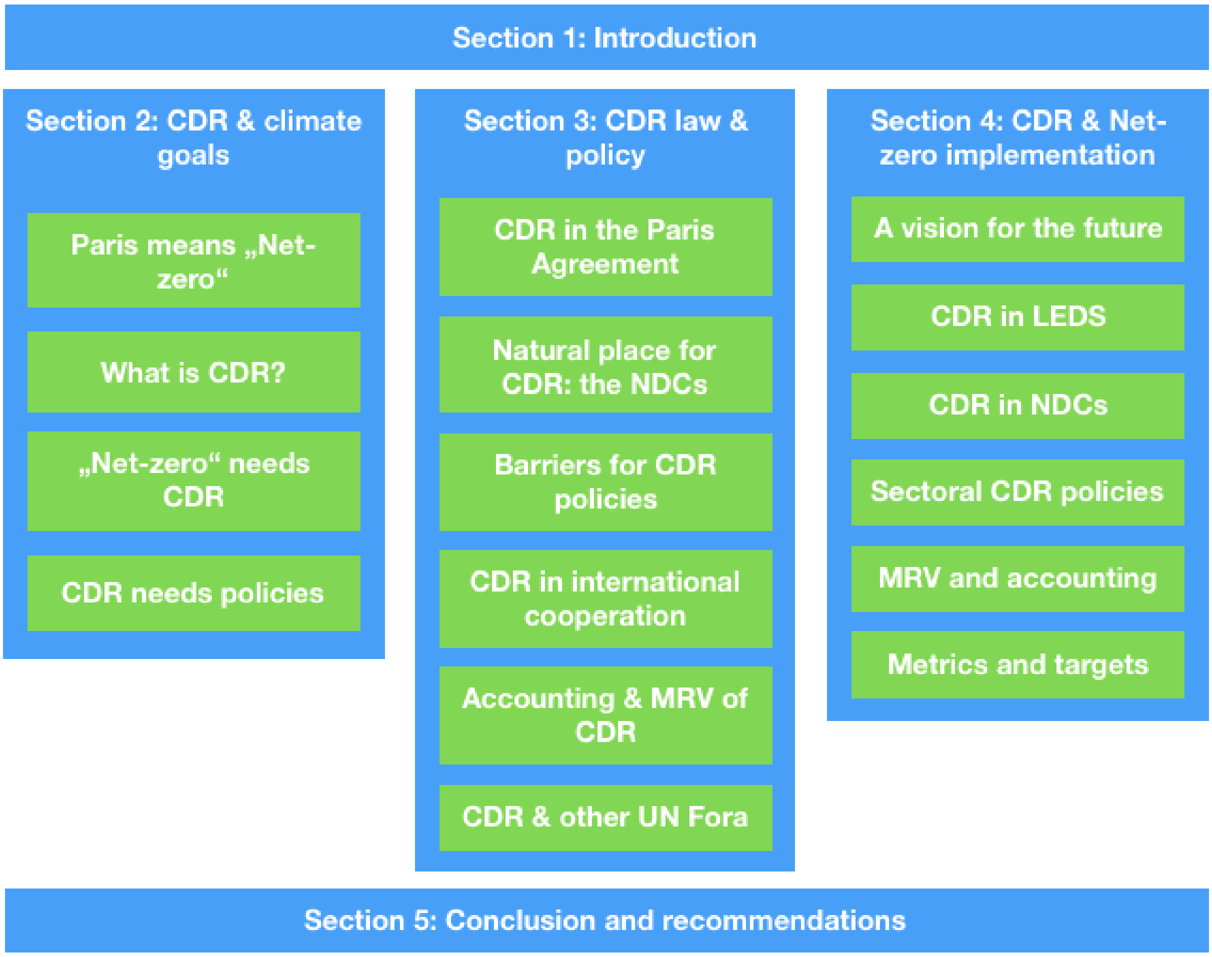
Hence, the report analyses existing avenues and institutional processes in context of the PA's architecture and corresponding national institutions and highlights their political, legal and

[2] For a comprehensive overview of different CDR options and their respective potentials and risks see Table 1 in the Annex.

[3] For an account of how particular CDR approaches might interact with the Sustainable Development Goals see Honegger et al. 2018.

economic links for a possible implementation of CDR. Besides legal issues concentrating on definitions and technical issues on accounting methodologies and MRV frameworks, the report also draws attention to questions related to international market mechanisms and other incentive schemes under PA Article 6.

Figure 2: The three main sections and their key contents.



The report consists of three main parts (Figure 2). Following this introduction, section 2 offers an overview of CDR, its role in stabilizing the climate system according to research and its main governance challenges. The third section takes stock of existing governance avenues under the PA by unpacking the articles of relevance to CDR. This aims at clarifying how exactly PA provisions relate to the implementation of CDR as for climate change mitigation. The fourth and final section offers a vision of how the different implementation processes and institutions under the PA – at (sub-)national and UN levels – are to interplay for robust implementation of CDR alongside emissions reduction in order to achieve the PA's objective of stabilizing the climate system.

2. Carbon Dioxide Removal and global goals for climate stabilization

2.1 Limiting warming to 2°C or 1.5°C means net-zero emissions

In the Paris Agreement the international community agreed to limit the increase of global average temperature to 1.5°C to 2°C above pre-industrial levels. Stabilization of the climate system at *any* temperature level requires counterbalancing every remaining single tonne of CO_2-emission by one tonne of CO_2-removal (CDR)[4]. For limiting warming to 1.5°C this ought to be achieved approximately by 2050, a 2°C target requires reaching net-zero emissions sometime in the 2070's.[5] Some jurisdictions have started to recognize this and are deliberating on or have set out to pursue net-zero (CO_2 or GHG, see section 4.7) emissions targets.

Textbox 1: Various jurisdictions that have set or are considering Net-Zero targets (based on Darby, 2019)

Net Zero target in place

Bhutan pledges continued carbon neutrality. Here it should be noted that over 80% of Bhutan's area is forested, meaning that its forest sink largely exceeds its emissions. Emissions can thus grow significantly from current levels without violating the target.

California, the fifth largest economy in the world, has a net-zero target set by executive order for 2045.

Copenhagen has pledged carbon neutrality by 2025

Costa Rica has an aspirational carbon neutrality goal for 2050 (the previous administrations announced Costa Rica would be carbon neutral by 2021, which shows that ambitious targets may not be robust over time).

Denmark set out a vision to build a climate-neutral society by 2050 including limitations for the sale of new petrol cars from 2030.

[4] From the present perspective it is obvious that the last few percentage points of decarbonization (especially in particular sectors like long-distance and heavy-duty transport, some industries or agriculture) are dramatically more expensive or for other reasons near-impossible to tackle. This is why most experts presently consider 5-10% of emissions (usually of e.g. 1990 levels) as unavoidable "residual" (Davis et al. 2018; Luderer et al. 2018).

[5] So, how much more CO_2 is the atmosphere able to absorb without raising its temperature above these values within the 21st century? To likely avoid (66% chance) exceeding 2°C the atmospheric concentration should remain below 450ppm CO_2eq (UBA, 2019). As of 2019, the remaining carbon budget for 2°C is therefore 1170 Gt CO_2 or 420 Gt CO_2 for 1.5°C. If emissions rates stayed at present levels (37-42 Gt CO_2/year) the 1.5°C budget would be overspent by the late 2020s or around mid-century for 2°C (IPCC 2014, 2018; Millar et al. 2017). If we were to assume a linear downward path, net-zero would have to be reached by mid-century (for 1.5°C) or by the 2070's for 2°C.

Fiji has formally pledged net-zero carbon emissions by 2050 in its NDC. Its "very high ambition" scenario even goes carbon negative, but is contingent on availability of new technologies and international support.

Finland has set a 2035 carbon neutrality goal.

France voted a net zero target by 2050 into law with different climate measures remained to be agreed. Despite this, France proposed postponing nuclear power plant closures and was urged by the High Council for the Climate to triple its pace of emission reductions.

Iceland has a climate change strategy with a carbon-neutral objective by 2040. The country already has virtually carbon-free electricity and heating from geothermal and hydroelectric sources.

Hawaii signed a bill to become carbon neutral by 2045 with carbon offsets dedicated for reforestation and carbon farming

Ireland, while not on track to meet its 2020 and 2030 targets, has a climate strategy with an intention for net-zero emissions by 2050.

The **Marshall Islands** have in their revised NDC formally pledged an aspirational goal of net zero GHG emissions by 2050 conditional on the availability of international support.

New York City announced a substantial climate program (OneNYC 2050) to become carbon neutral and achieve 100% clean energy by 2050.

Norway has one of the most ambitious legal net-zero target for 2030 worldwide. The major part will be achieved with carbon credits as well as electrification of road transport.

Portugal launched a roadmap for getting to net zero by 2050.

Sweden legally adopted its goal of GHG neutrality by 2045. 85% of the emissions cuts are to be achieved with domestic policies while the rest should be reserved for carbon credits.

Switzerland pledged to reach net-zero carbon emissions by 2050 with a considerable focus on DACS.

The **United Kingdom** amended its previous climate framework law lately with a dedicated net-zero target for 2050. Scotland aims at achieving net-zero by 2045 with the help of renewable energy sources and carbon storage. Wales expressed its ambition to reach net-zero by 2050.

The city of **Zurich**, Switzerland, has pledged net zero by 2030

Net Zero target under consideration

Chile aims at phasing out coal completely by 2040.

The **European Union** is internally negotiating over a bloc-wide 2050 net-zero target. Lately, the EU has promised to set its current goal of an emissions reduction of 80-95% from 1990 levels into law.

Germany, while failing to meet its 2020 target and at risk of failing to meet its 2030 target, is considering a net-zero target by 2050.

Japan is considering a carbon neutral goal by the second half of the century largely by means of CCS and hydrogen energy. The country lacks a phase out plan for coal, expected to still hold a 25% share of its electricity mix in 2030.

New Zealand has drafted a bill that sets a net-zero goal for all GHG (except biogenic methane, which is to be cut more moderately) by 2050.

While governments often pledge ambitious climate targets for the far future, they also often fail to put in place costly or unpopular measures to actually reduce emissions or implement CDR. This context helps to understand why CDR on the one hand is seen essential to achieving climate stabilization (IPCC 2018), while on the other hand countries have not yet put in the corresponding work across the spectrum toward implementation: from initial research, technology development to pilot activities to costly policy implementation.

2.2. Net-zero emissions require Carbon Dioxide Removal

Carbon Dioxide Removal (CDR) is a term that describes processes that result in a net-flow of CO_2 from the atmosphere into permanent storage over their entire lifecycle. The term is independent on how such flux is achieved (e.g. via biological processes, technological and/or chemical processes or combined ones). Carbon Capture and Storage (CCS) is a technology which could be used in different ways: Either for emissions reductions (by capturing CO_2 at a fossil fuel point source such as a powerplant) or for CDR (by capturing climate-neutral CO_2 from a biological source or from direct air capture).

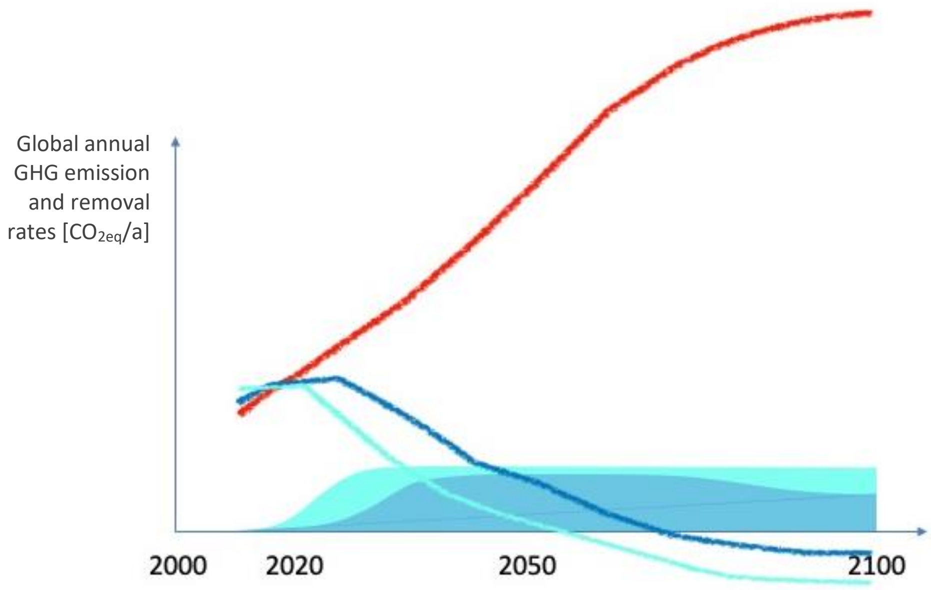
All model scenarios considered in the IPCC Special Report on the 1.5°C target (IPCC 2018) and numerous scenarios for 2°C (IPCC 2014) rely on CDR (generally in the form of biomass power generation with CCS, or BECCS). For 1.5°C the cumulative volume of such removals in scenarios is between 100-1000 Gt CO_2 over the remainder of the century (McLaren and Jarvis 2018 p. 10). This translates to annual CDR rates of anywhere between 5 and 20 Gt CO_2, which is anywhere between 10% to 45% of total global current annual CO_2 emissions from all human activity (or 2.5 to 10 times current global steel production rates).

As it is extremely uncertain that full decarbonization is achieved in time without overspending the 1.5°C budget (Michaelowa et al. 2018) or even the 2°C budget, many studies even go one step further and describe a so-called overshoot-and-return scenario taking place in the second half of the century: When carbon budgets attributed to particular temperature targets are overspent, these targets could within the laws of physics only be achieved by achieving *global net-negative emissions*. This is the case when the rate of removals exceeds the rate of all residual emissions, which would imply even greater rates of CDR post-2050 (Figure 3). It is questionable whether such scales of CDR could be achieved within a few decades, but – as is the case with emissions reductions – every bit counts.

The less rapid and deep emissions reductions, the greater the CDR challenge. The larger the theoretical CDR requirement, the higher the risk of *CDR failure*. CDR failure could arise both out of a lack of (political) feasibility or due to serious problems and adverse side-effects being caused. Due to the emissions residual discussed above, net-zero emissions targets require continued CDR even once emissions have been brought down drastically (to e.g. -90 to -95%).

And the steep downward path of net-emissions required can only be achieved with all options being tested and used at their full potential.

Figure 3: Idealized ramping up of global CDR deployment for 2°C (dark blue) or 1.5°C (light blue).



Note: Areas correspond to hypothetical, highly optimistic rates of removals designed for complementing rapid emissions cuts for achieving the necessary steep net-emissions reductions depicted by the similarly coloured lines. Technology applications generally grow (if successful) in an s-shaped growth curve. For meeting removal rates required within 2°C or 1.5°C pathways a discernible volume of CDR needs to appear already in the early 2020's and maximum removal rates ought to be achieved as early as possible for achieving a steep net-emissions drop. For 2°C removal rates may decline slightly toward the end of the century, but are expected to counteract unavoidable emissions beyond 2100.

2.3 CDR implementation requires dedicated policies

As indicated in the previous sections, CDR is to play a central part in climate policy measures to reach the PA goals. However, the economics of most CDR options fall into the same category as emissions reductions measures which have costs and are thus not implemented in the absence of financial incentives or mandatory regulation. So CDR will not happen without government intervention. Moreover, CDR approaches suffer from various obstacles including potential environmental side effects and challenging mainstreaming into various industry sectors. The following analysis of linkages between the PA and CDR will provide a starting point for identifying ways to overcome these barriers.

Furthermore, a lack of attention to governance issues of CDR at the international level beyond the PA is further slowing any meaningful action at national levels. Although there are some international norms in place concerning CDR in various regimes, including the Convention on Biological Diversity (CBD), the London Convention/Protocol on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (LC/LP) or the United Nations Convention on the Law of the Sea (UNCLOS), they lack a holistic governance approach and by consequence end up restricting rather than advancing CDR implementation as part of climate policy. Moreover, these regimes treat CDR primarily as a category of geoengineering and secondarily (at best) as a mitigation policy (C2G2 2019; Mace et al. 2018).

A lack of incentives and clarity of vision regarding the role of CDR as part of climate policy appears to also have stifled public and private spending on research, development, demonstration, and deployment (RDD&D). Attempts at strengthening governance of research via non-binding principles and codes of conduct have generally also portrayed CDR as a category of geoengineering and do not seem to have overcome the lack of RDD&D efforts.[6]

3. Carbon Dioxide Removal in law and policy

The achievement of the PA's objectives depends entirely on the policies put in place by (sub-)national governments for achieving their respective NDCs. One key component to mobilize such policies is the "ratcheting-up mechanism" for raising the ambition of NDCs. Another important element is the relatively far-reaching "enhanced transparency framework" setting out the requirements for Parties to communicate on their efforts. The following sections will outline the governance opportunities offered by key elements of the PA for the implementation of CDR policies.

3.1 "Mitigation" means emissions reductions and CDR

Mitigation is perhaps the most critical term in international climate policy: The UN Framework Convention on Climate Change (UNFCCC) characterizes a Party's measures on the *mitigation of climate change* as "limiting its anthropogenic emissions of greenhouse gases and protecting and enhancing its greenhouse gas sinks and reservoirs" (UNFCCC, 1992, Art. 4.2.a). *Sinks* are defined as "any process, activity or mechanism which removes a greenhouse gas (...) from the atmosphere" (UNFCCC, 1992, Art. 1.8). In Article 4.1 the PA specifies that to achieve its long-term temperature goal, Parties ought to:

"… achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century."

Accordingly, CDR (and removal of other greenhouse gases) for all intents and purposes under the Paris Agreement is *mitigation* (along with emissions reductions).[7]

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[6] Existing non-binding principles and forums aiming at regulating at least parts of CDR include e. g. the precautionary principle, the Oxford Principles, the Asilomar Principles, the Code of Conduct developed by the Geoengineering Research Governance (GRGP) project or the Carnegie Climate Geoengineering Governance Initiative (C2G) (GESAMP 2019, p. 85ff.).

[7] While the English version of this paragraph is a bit ambiguous (does it refer to natural "removals by sinks" and/or anthropogenic removals?), an analysis taking other language versions into account makes it clear that the scope taken here is the broadest possible, meaning an atmospheric balance of all in- and outgoing greenhouse gases – i.e. "greenhouse gas neutrality" (Fuglestvedt et al. 2018).

Other areas in which *mitigation* is characterized affirm this: The temperature goal defined in the Agreement's Article 2 refers to the objective of the UNFCCC, which is characterised as

"stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC, 1992, Art. 2).

Articles 4 and 5 of the PA make direct reference to CDR in characterizing actions expected from its Parties: While the following paragraphs in Article 4 provide detail on the required balance between anthropogenic emissions by sources and removals by sinks, Article 5 specifically states a need for dedicated action to protecting and enhancing sinks and reservoirs.

Textbox 2: CDR and the term "geoengineering" / "climate engineering"

While in principle some CDR types – applied to remove CO_2 at large scale – might also fall under the definition of "geoengineering" / "climate engineering", such characterization is unhelpful as it covers very different ideas and approaches to climate intervention Solar radiation modification (SRM) – the key, controversial type of "geoengineering" – requires fundamentally different governance measures than does CDR. It is therefore paramount that CDR is addressed specifically within the context of the PA, rather than as part of an imaginary ensemble of "geoengineering" ideas.

While the PA does not suggest any quantified target regarding the exact timing and share of residual emissions versus removals, it does however specify that the balance should be achieved "(...) on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty (...)" (Art. 4.1 PA).

While some are emphasizing differences between what may be considered natural removals or nature-based solutions versus technology-based ones, such differences are not always clear-cut. There is furthermore no general implication that one of these categories is per se more or less desirable than the other one, but desirability of each approach has to be judged case-by-case for the respective circumstances in which it could be applied. The broader governance landscape also looks different for the various types of activities. For afforestation and reforestation there are for instance already established policy instruments and lessons from the past, whereas for many technological removals, only some policy building blocks are available (e.g. around CCS for both BECCS or DACS).

Article 4's first paragraph offers another qualification that seems relevant for CDR: After global peaking of GHG emissions, rapid reductions ought to take place "in accordance with the best available science". This emphasizes the troubling insights from IPCC findings (in particular IPCC 2018) that the mitigation pathway for 1.5°C or even for 2°C is so steep that there is essentially no historical precedent for the corresponding transformation of the global economy. Accordingly, efforts ought to be dramatically accelerated across the entire spectrum of potential options (Michaelowa et al. 2018). This qualification of the envisaged global mitigation pathway can furthermore be read to mean that scientific knowledge of potential adverse effects of mitigation action may not be disregarded but utilized to ensure the best possible policy design. With regard to CDR, this has furthermore implications regarding the *permanence* of CO_2 removed*,* which can be a key determinant of environmental integrity (also see Art. 4.13.). Safe and long-term storage of CO_2 (be it in organic form or in geological formations) therefore needs to be ensured and the possibility of shorter-than-expected storage durations (e.g. in case of biological or soil-based storage) ought to be anticipated and – when they occur – accounted for.

3.2 CDR to become an integral part of NDCs

Any reference to "mitigation" by extension not only applies to emissions reductions, but also to CDR. This includes crucially all stipulations pertaining to the NDCs. Such stipulations e.g. characterize how Parties ought to communicate on their mitigation activities and how the same ought to align with the global temperature goals.

By consequence activities that result in CO_2 removal are subject to Parties' NDCs. Accordingly, any calls to raise the ambition of NDCs in order to align with the global temperature goals also extend to Parties' efforts in the realm of CDR.

While there is presently hardly any explicit expectation or diplomatic pressure to undertake CDR as part of NDCs, this is likely to change once awareness of the necessity of CDR for net-zero targets is growing. Furthermore, Parties are to update and strengthen their NDCs every five years which will likely result in pressure to put in place dedicated targets for CDR and install CDR policies for their achievement, with the first revision due until 2020. Given that all target setting, policy planning and implementation is within the authority of individual states, the processes will be rather heterogenous. Nonetheless all jurisdictions will be facing similar challenges.

Of the current NDCs, however, none seem to be building a basis for potential CDR applications. A few countries are working towards operationalizing CCS capacities, which is a building block for some CDR approaches, but progress falls short of IPCC projections for the use of CCS due to lacklustre political support.[8]

3.3 Barriers facing CDR policies

Several aspects might prevent individual countries and the international community as a whole from incorporating CDR in their NDCs. First, current NDCs have a limited time horizon, extending just to 2030. This rather short time horizon leaves little to no time for countries to scale-up RDD&D in a way that CDR might be operational on a large-scale. Second, socio-technological obstacles are omnipresent ranging from a lack of familiarity and public acceptance to insufficient technological maturity and economic readiness. Third, the relatively vague requirements provided by the UNFCCC for designing NDCs pose challenges for some countries. On the one hand, especially countries without sufficient human and financial capacities claim that international guidance on critically important substantive and methodological issues like monitoring, reporting and verification (MRV) are missing.

[8] China, Saudi Arabia and South Africa refer to CCS as part of their mitigation efforts. 30 more Parties refer to CCS technology as a potential future addition under their NDC, yet not defining potential rates of deployment (PIK 2017; Zakkour and Heidug 2019).

As Figure 4 shows, some CDR technologies are at rather early stages of development or face other implementation barriers (IPCC, 2018).

Figure 4: Feasibility dimensions of CDR

System	Mitigation Option	Evidence	Agreement	EC	Tec	Inst	Soc	Env	Geo	Context
Carbon Dioxide Removal	BECCS	Robust	Medium							Depends on biomass availability, CO_2 storage capacity, legal framework, economic status and social acceptance
	DACS	Medium	Medium							Depends on CO_2-free energy, CO_2 storage capacity, legal framework, economic status and social acceptance
	Afforesta-tion & Reforesta-tion	Robust	High							Depends on location, mode of implementation and economic and institutional factors
	Soil carbon sequestra-tion & biochar	Robust	High							Depends on location, soil properties and time span
	Enhanced weather-ing	Medium	Low							Depends on CO_2-free energy, economic and social acceptance

Green shading signifies that no particular barriers have been identified in the particular feasibility dimension, orange shading indicates that, on average, the dimension does not have a positive or negative effect on the feasibility of the option, or the evidence is mixed, and red shading indicates presence of potentially blocking barriers. Grey shading means that the literature found was not sufficient to make an assessment. Abbreviations for various dimensions of feasibility:
Ec: Economic- Tec:Technological- Inst:Institutional- Soc:Socio-cultural- Env: Environmental/Ecological- Geo: Geophysical

3.4 International cooperation through market and non-market mechanisms could accelerate CDR deployment

As pointed out in the previous section CDR is part of mitigation and hence ought to be considered in context of NDCs. So what questions does this pose for international cooperation between Parties in context of the implementation of their NDCs? International cooperation as foreseen by the Agreement's Article 6 could provide for an avenue to creating necessary incentives for CDR deployment and provide a crucial opportunity to mobilise mitigation wherever and however it is the most cost-efficient and effective (Honegger and Reiner 2018). Second-order benefits of such international cooperation includes spill-over of practical experience and resulting capacity building effects regarding the appropriate use of CDR. But there are also significant challenges associated with the pursuit of CDR via international cooperation, which are discussed in some detail in section 4.5.

3.5 Accounting, transparency and MRV for CDR

Accounting, transparency and MRV of mitigation action is essential to ensuring the objectives of the Paris Agreement are met. Therefore, it is critically important that the corresponding provisions for mitigation – including CDR – are reliably operationalized from the beginning.[9] As to date most attention has been paid to already established emissions reductions activity types and only a small number of CDR types it is important to pay more attention to specific questions around accounting, transparency and MRV for CDR. In doing so, some lessons can be learned from experiences made with previous approaches under the UNFCCC and the Kyoto Protocol that might at least partially be applicable to the case of various CDR types.

The activity-based approach to the land sector of the Kyoto Protocol is of special interest because of the various implications for land-based CDR techniques. One of the main criticisms of this approach was that – aside from delivering limited incentives for forest- and land-related activities and challenging environmental integrity – it supported asymmetric accounting. Since its installation, this has been a door opener for accounting only beneficial activities while neglecting activities which actually release emissions.

Besides the activity-based approach the Kyoto Protocol also established project-based mechanisms, namely the Clean Development Mechanism (CDM) and the Joint Implementation (JI) with their respective transferable emission units, the certified emission reductions (CERs) and emission reduction units (ERUs). On top of that, methodologies for afforestation and reforestation and CCS projects were developed as well, although few (forestry) to none (CCS) actual activities have been approved due to the crash in CER prices after 2011. Some stakeholders complained about high transaction costs for accounting under the CDM and JI.

Recognizing the shortcomings of previous regimes, the PA did make some adjustments and specified that the accounting for NDCs "(...) shall promote environmental integrity, transparency, accuracy, completeness, comparability and consistency, and ensure the avoidance of double counting (...)" (Art. 4.13). Additionally, the PA refers to the use of scientifically established methodologies and metrics assessed by the IPCC (Art. 13.7) and the accompanying decision (para 32c) emphasizes that once a source, sink or activity is being introduced in the NDC it should continuously be included.

Apart from the methodological challenge of establishing a robust and reliable accounting and MRV scheme the same is true for the establishment of GHG inventories. Under the previous Kyoto regime reporting requirements for developed and developing countries differed quite substantially: Developed countries are/were obliged to report their GHG inventories annually, using the 2006 IPCC Guidelines, as well as the Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories, and the IPCC Good Practice Guidance for Land Use, Land-use Change and Forestry. The inventory reports is/was further accompanied by Biennial Reports, highlighting the progress of meeting the reduction targets. In contrast to that, developing countries have/had to report their inventories every four years using the 1996 IPCC Guidelines and the Good Practice Guidance for Land Use, Land-use

[9] E. g. see Decisions 31 and 36 as well as Articles 4.13, 4.14 and 13.7 (UNFCCC, 2016, 2015).

Change and Forestry, with Biennial Update Reports (BURs) indicating the updated inventory (Mace et al., 2018, p. 15ff.). Compliance with these requirements was very patchy, with only a minority of developing countries actually submitting BURs to date

As one of the surprises of COP 24, the enhanced transparency framework under the PA now requires all countries to submit detailed Biennial Transparency Reports (BTRs) from 2024, applying 2006 IPCC guidelines and following a detailed set of guidance. However, there is still an "escape clause" as developing countries can claim the need for flexibility and least developed countries (LDCs) and Small Island Developing States (SIDS) can report "at their discretion. Nevertheless, these rules aim at allowing a comprehensive overview of a Party's current emissions and removals. Challenges for reporting range from insufficiently robust inventories, which do not cover all emissions, to differences in how NDC are being presented and communicated to significant capacity asymmetries (Mace et al. 2018, p. 18ff.).

3.6 Other multilateral processes

A number of processes and institutions provide the backdrop for action to implement CDR.

The central decision-making authority and supreme body under the PA is the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement (CMA). Decisions in the CMA are made by consensus, which can complicate coordination between countries especially if there is no unifying paradigm for CDR (in contrast to emissions reductions activities). This could be problematic in the contested context of CDR, insofar as that some countries are somewhat interested in CDR as a mitigation option, whereas other countries reject CDR as dangerous "geoengineering". Overcoming such divide will require avoiding ideologically charged debates and shifting concerns into more practical conversations around governance including avoidance of negative impacts on sustainable development.

A relevant side-venue to this is the Convention on Biological Diversity (CBD). Parties to the CBD have taken non-binding decisions on issues relating to CDR ultimately allowing to work toward guidance on permissible activities (Craik and Burns 2016, p. 12). This shows that constructive governance steps on CDR are possible as long as CDR is addressed as a group of potential mitigation activities (rather than a generic type of "geoengineering"). Cross-regime coordination between the UNFCCC and the CBD as well as the Convention to Combat Desertification (CCD) might be fruitful for designing guidance to Parties seeking to pursue some CDR activities. A respective Joint Liaison Group of the mentioned regimes is already in place and could serve to work out specific co-benefits and synergies of policy measures.

In addition to the placing/location of CDR in the CMA and the Joint Liaison Group, respective dialogues could also be initiated and moderated within the subsidiary bodies of the UNFCCC: the Subsidiary Body for Implementation (SBI) and the Subsidiary Body for Scientific and Technological Advice (SBSTA). Both bodies provide crucial assistance to countries in designing, implementing and communicating their mitigation and adaptation measures. As for other content-related issues, the SBI and SBSTA could organize workshops to serve as a forum for CDR-related information and experience exchange and provide the relevant political and technical guidance for countries.

4. A way forward: Implementing CDR to achieve the Paris Agreement

This section presents a vision of a future in which CDR plays – what the authors would characterize as – an appropriate role to achieving the PA's targets. For that, the following sections outline how that future would look like and what the policy measures might be that would lead there.

4.1 A vision for the future

Let us imagine it is the year 2049, the international community is gearing up to a special stocktake on the collective climate change mitigation achievements, which on aggregate are expected to amount to a 90 to 95% cut in global GHG emissions and a near-corresponding rate of CO_2-removals. Although warming above pre-industrial has surpassed 1.5°C in the early 2040s and weather extremes have increased by nearly 50% compared to 2019 with serious impacts on populations, ecosystems and economies across the globe, the international community is readying itself to celebrate a substantial achievement: For the first time in human history since the early days of the industrial revolution, GHG emissions and removals are cancelling each other out; the UNFCCC's objective of stabilization of GHG concentrations in the atmosphere is (finally) achieved.

What did it take for the international community to arrive at this point, in spite of starting with dramatically insufficient ambition in 2015? Back then, Parties put forward national mitigation targets that amounted to a mere fifth (1/5) of what 1.5°C pathways demanded. Additionally, many organizations made strong claims about which technologies might or might not be regarded as appropriate "solutions" to achieving the enormous challenge of eliminating humanity's impact on the climate system, thereby effectively ruling out a substantial number of low-carbon technologies and CDR approaches from political consideration. For several years after the adoption of the PA only few people were paying attention to the fundamental problem that cutting emissions "as much as possible" would have to be expected to fall short of climate stabilization insofar that some emission sources were likely to remain and that furthermore, narrowing down the portfolio of approaches rather than expanding it, would render its achievement even harder than it already was. Although the IPCC had already in 2014 highlighted that the large-scale implementation of CCS was essential to address industry emissions, most of the political focus was on expanding renewable energy capacities and advancing energy efficiency and some jurisdictions had effectively rendered the use of CCS an impossibility. However, as more and more countries pledged to pursue net-zero emissions targets, the question of their implementation became more and more pressing, and it became apparent, that active removal of CO_2 would not only be necessary for the end-game of countering any residual emissions, but also to help bend the net-emissions curve downwards, thereby preventing dramatic overspending of the 1.5°C carbon budget.

While substantial mitigation achievements of the 2020s were due to the transformation of energy systems and the electrification of transport, the ground for medium-term action was being prepared in the area of CDR: A handful of Parties were willing to look past the immature and expensive technology ideas put forward by academics and innovative start-ups and created incentives for such ventures to develop, pilot and gradually scale-up their CDR plants. While for over a decade the removal of CO_2 resulting from those investments remained extremely low by comparison to the challenge at hand, an increasingly mature range of industrial processes and agricultural practices emerged. Of those that eventually proved capable of reaching industrial scales, some were bought up by longstanding carbon-intensive industries enabling their respective decarbonization. Other start-ups remained separate entities, offering their carbon removal services to entities that were seeking to go beyond the already achieved emissions cuts to achieve carbon neutrality.

In the mid 2030s, industrialized countries had more or less completed their energy transition to a near-zero carbon renewable energy mix. Other sectors, however proved harder to decarbonize and the economics of CDR were increasingly becoming competitive to those of conventional mitigation measures e.g. in construction and agriculture (Honegger 2018). This was made possible by the visionary thinking of a few actors back in the early 2020s, who had been willing to overlook the initially extremely unattractive economics of some of the nascent CDR technologies and to dedicate substantial amounts of R&D investments into their advancement. The successful CDR approaches underwent three stages to full-scale deployment: Initial research on a theoretically feasible removal process in the lab, first pilot plant construction demonstrating the feasibility with annual removal rates of up to one million t CO_2 and finally the construction and operation of small industrial scale plants with an increasing potential for scale and replicability. The three stages each benefited from a dedicated regulatory and financial environment resulting from substantial rethinking and redesigning of existing climate policy measures as well as the introduction of some policies specifically designed to advance one or several different CDR types. As a result of conducive economic and regulatory environments, the private sector engaged heavily in researching and developing CDR technologies and practices, which was essential in bringing down costs. Furthermore, regulation and guidance on public engagement focussed on proactively engaging with the concerns and hopes of civil society both on the local level where pilot plants were planned and at the global level of international climate policy, which allowed to not only develop hardware, but also an entire socio-technical system around it effectively allowing to maintain a high and growing level of political support both locally and globally.

4.2 Imminent action: Inclusion of CDR in LEDS

Parties are called to formulate and communicate low emission development strategies (LEDS) with a time horizon of 2050.

To be compatible with net-zero emissions targets, Parties ought to present how they envisage mobilizing their respective mitigation potential of CDR in their LEDS. Specific steps toward CDR readiness should be outlined in the LEDS with some clarity of key milestones e.g. in 2035, 2040 and 2050 including any dedicated R&D programs, key sectors, and deliberation processes toward the implementation of specific policies.

One of the first steps could entail to commit or aspire to explicit targets for rates of CDR that are to be reached by e.g. 2035, 2040 and 2050. The LEDS would be the most appropriate location to communicate such targets, insofar that it represents a less binding document that allows to elaborate a country's vision in comparison to the binding NDC. While any removals achieved toward these targets would also count toward net-emissions reductions targets (as is already the case for countries with CDR thanks to e.g. forest sinks) there are several advantages to presenting explicit CDR targets (rather than merely presenting net-emissions targets). A dedicated CDR target would significantly strengthen transparency allowing the international community to check progress on removals and by extension whether Parties collectively are on track toward the Paris targets of achieving balance of emissions and removals (McLaren et al. 2019). It would also allow for continuous reflection on the appropriateness and achievability of respective emissions reductions and removals targets. This would help prevent the lure of hidden large CDR promises in the distant future that cannot be kept.

Exploration and modelling of natural sinks and projections on technical removals would allow to specify and revise over time the respective rates aimed for by each CDR type crucially informing policy design. Policymakers need to be aware of the character of natural sinks like forests to eventually saturate, they therefore cannot extrapolate uptake indefinitely into the future. Strategic planning processes established under the LEDS ought to ensure cross-sectoral coordination that allows assessing the respective needs and potential conflicts over common resource requirements (notably geological CO_2 storage).

Also under the LEDS, a dedicated longer-term dialogue process could be established that – comprising of a diverse range of mitigation (incl. CDR) experts as well as other stakeholders from the private sector and civil society organizations – could allow for continuous deliberation and reality checks especially with regard to potential trade-offs and side-effects that CDR applications (as well as conventional mitigation actions) could pose. Such a committee could be modelled after the positive example of the UK's Committee on Climate Change (CCC) and potentially play an important role informing policy instrument design for CDR and emissions reductions.

4.3 National CDR targets in revised NDCs

While current NDCs largely gloss over any potential contribution of CDR besides forest sinks, revisions of NDCs increasingly ought to address the question how CDR can complement emissions reductions: Parties' obligation to update NDCs regularly with increasing ambition can be expected to increasingly put pressure to consider more and more potential mitigation options including CDR.

A first step for CDR inclusion could be a pledge to accelerate research, development and testing of various CDR approaches via a dedicated publicly funded R&D program encouraging competitive development for various options meeting their R&D needs according to their respective development stage. It would be important that such efforts then are pursued with strong consideration of sustainable development implications to allow for holistic ecological and societal assessment of potentials and risks upon scaling up such approaches under particular local circumstances. Crucially, such efforts would allow Parties to refine cost projections of CDR options and understand the cost-influencing accompanying factors (e.g. regulatory environment), with significant implications for deployment policy planning. Present cost projections of CDR approaches ought to be taken with a grain of salt as they are based on a very limited set of academic studies and lack real-world data due to the private sector technology developers' intellectual property considerations. Projections offered by such developers on the other hand might have to be adjusted to various geographical circumstances taking into account local resource constraints or in some cases lacking acceptance by local populations (as observed in case of CCS in the past).

Integrating a specific CDR target in NDCs would represent a stronger commitment to pursuing CDR implementation. Developing countries, most of which make implementation of an ambitious NDC target conditional on international support, would be likely to situate any CDR activities going beyond the most basic forestry as part of their conditional NDC target.

Crucially – as in case of emissions reductions – inclusion in NDCs should be done as much as possible in a sector-specific manner, credibly demonstrating what steps are undertaken to implement the respective actions within particular sectors of the economy. Naturally, forestry, agriculture, ecosystem preservation and other related land-use sectors would lend themselves in particular for nature-based CDR. However, CDR should increasingly also be planned for in the energy sector (e.g. as BECCS). Even construction and housing could move toward implementation of some particular removals (wherein e.g. new materials would bind and store CO_2 in construction. All such planning should as best as possible aim to reduce net-emissions of each sector toward zero-. In a net-zero world, some sectors would likely be expected to deliver net-negative emissions (e.g. energy) in order to counteract inevitable residual emissions of another sector (e.g. agriculture). However, fungibility between residual emissions and CDR outcomes may need to be limited if permanence is not sufficient. In this regard, a Party needs to define – ideally in alignment with international standards (e.g. under Article 6 mechanisms) – what threshold of permanence can be considered sufficient. Moreover, particular attention should be paid by observers and decisionmakers alike to ensure that NDCs counting on CDR for achieving their ultimate target gradually build up the CDR capacity, while continuously checking that both emissions reductions and removals are on track.

In order to be socially robust and politically feasible, the definition of sector-specific CDR targets must be informed by the specific country specific socio-economic and political circumstances. This means that decision-making in each phase should be preceded and informed by stakeholder engagement processes involving government, private sector, environmental groups, scientists and other potentially concerned groups. In developing countries, such processes could also be undertaken in the planning phase for Nationally Appropriate Mitigation Actions (NAMAs) as outlined below.

4.4 Economywide or sectoral CDR policy implementation

CDR activities could contribute to achieving net-zero emissions for an entire sector. This needs to be driven by specific policy instruments. Generally, such instruments can include technical regulation or monetary incentives. The latter can be framed as "sticks" – like a carbon tax or an emissions trading scheme or "carrots" – like subsidies for CDR investment and operation.

"Carrots" could include:

- Direct RDD&D funding to advance the technological development and properly assess the potentials and risks related to CDR
- Allowing CDR to generate offsets for other policy instruments
- Tenders for the provision of public CDR infrastructure

- Direct investments by publicly held entities (e.g. state-owned utilities)
- Subsidies for concrete CDR activities (like the EU subsidies for CCS funded by the auctioning of the new entrant reserve in the EU ETS)

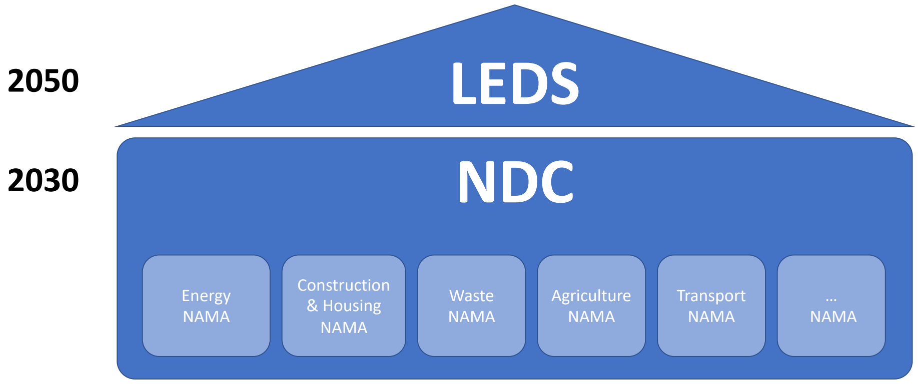
"Sticks" could include emissions trading or carbon taxes. Much of the recent research, development and piloting of CCS activities in the EU have been driven by the principal eligibility of CCS under the ETS and the corresponding financial incentive. Yet the price level generated by the ETS had in recent years not been sufficiently high and stable to accelerate CCS deployment at scale. To fully account for the specificities of CDR (in contrast to CCS with fossil fuel point source CO_2), ETS rules would need to adapted so that units could be issued specifically for removed CO_2 rather than for avoided emissions of CO_2 (Berg et al. 2017). Depending on the permanence of removed CO_2 (e.g. in case of CO_2 storage in timber constructions with limited lifetimes), CDR units would need to be issued with a discount factor to account to adjust to shortened storage durations. Unit generation would also be conditional on monitoring requirements that would allow for adjustments in case of unexpected changes in the lifetimes of products (see MRV section below).

As part of their national efforts to mitigating climate change, many developing countries already submitted Nationally Appropriate Mitigation Actions (NAMAs). These generally refer to sector wide mitigation activities (e.g. direct public investments) or policies (to incentivize or regulate particular low-carbon behaviour). NAMAs are generally understood to represent the building blocks on which developing country NDCs are defined and through which they are implemented. While to date there are no NAMAs targeting technology-based CDR, envisaging net-zero emissions targets this would easily be possible. This would both allow the active Party to showcase its particular efforts, potentially attract international support via climate finance and over time allow for mutual learning between Parties' regarding the pursuit of particular CDR approaches within particular sectors.

Although the requirements of NAMAs are not clear cut and leave room for interpretation, NAMAs need to be measurable, reportable and verifiable and also be in accordance with sustainable development strategies. CDR could be included in a Party's NAMA in various ways depending on which policy instrument will be chosen and what sectors will be targeted. The policy instruments relevant for mobilizing the adequate financial and technological resources for CDR in developing countries could be manifold and could use elements from existing and future international instruments like CDM methodologies, Article 6 mechanisms or REDD+.

Depending on the chosen instrument developing countries could initiate respective actions across different levels of governance, starting from generating support and economic incentives at the international level, to designing and coordinating them on the national level and finally implementing and assessing them on the subnational level with the involvement of local actors, as shown in Figure 4 below. But all this would at least in the short and medium term have to be contingent on international support.

Figure 5: The relationship between Low-Emissions Development Strategies (LEDS), NDCs and sectoral mitigation policies (Nationally Appropriate Mitigation Actions, NAMAs in developing countries



Apart from the identification of relevant levels of governance, policies could also target specific sectors including in particular the Land-use and Land-use Change and Forestry (LULUCF) sector: Past experience here can become increasingly important also in the energy sector when considering BECCS policies. Existing LULUCF sector-specific approaches target natural CDR via afforestation, reforestation, peatland and blue carbon protection. The same methodologies for quantifying mitigation outcomes in the LULUCF sector which are comparatively well established under the REDD+ mechanism can serve either starting point for BECCS methodologies and on the ground policy experience (notably regarding sustainable development) offer relevant lessons learned for the future design of CDR NAMAs.

4.5 International cooperation on CDR under Article 6

The key pillar of international cooperation by market and non-market mechanisms in the PA is its Article 6. Despite Article 6 not explicitly referring to removals or sinks, the central insight – namely that CDR is "mitigation" and thus in principle fits the same structures as emissions reductions – applies here too. Focussing on Article 6 as the central avenue for coordinating international cooperation under the PA allows differentiating between three distinctive approaches, expressed in paragraphs 6.2, 6.4 and 6.8. While these mechanisms under Article 6 are novel there have been plenty of experiences made with previous market-based approaches under the Kyoto Protocol, namely the CDM and JI, on which negotiators and practitioners should build (Michaelowa et al. 2019a; Michaelowa and Butzengeiger 2017; Brescia et al. 2019). If designed correctly, market mechanisms can mobilize financial resources at scale and allow implementation of CDR in a cost-efficient manner across the world. In the following we provide just a glimpse of the issues surrounding CDR and Article 6 – a more detailed discussion can be found in our dedicated briefing report (Michaelowa et al., 2019c).

While CDR units could in principle be directly traded as internationally transferred mitigation outcomes (ITMOs), some scholars are proposing the establishment of further accounting entities like carbon storage units (CSUs)[10]. However, there are pros and cons as this could reduce liquidity and lead to a lower price.

First and foremost, Article 6.2 allows for bilateral voluntary cooperation via market mechanisms in the implementation of NDCs. Parties pursuing cooperative approaches under Article 6.2 "shall ensure environmental integrity and transparency", and follow guidance on "applying robust accounting to avoid inter alia double counting". This guidance is yet to be developed and adopted by the COP. To which degree the guidance will effectively prevent mitigation (emissions reductions and CDR) activities resulting in double counting remains to be seen. For the sake of credibility and long-term reliability it is highly advisable that Parties pursuing activities under Article 6.2 pursue the highest possible standards in avoiding double counting and generally ensuring environmental integrity.

The stringency of activities under Article 6.2 is expected to be lower than that of Article 6.4 dubbed the *Sustainable Development Mechanism* (SDM).

The SDM under paragraph 6.4 offers a second, potentially more credible instrument: With stronger wording, activities under the SDM are to "support sustainable development", to deliver an overall mitigation in global emissions and are subject to central oversight by a Supervisory Body under the UNFCCC. While due to fears of jeopardizing national sovereignty, it is unlikely that sustainability safeguards protecting the environmental, social and economic dimensions will be formally prescribed, the need to report activities according to common standards will enhance pressure to avoid negative side effects. The SDM could serve as a central avenue for involving non-state actors as well as leveraging private resources. Besides the participatory effect of broadening the debate by inviting actors from different constituencies and jurisdictions this could also be beneficial if allowing to mobilize both public and private finance to address the presently rather high price of CDR activities (Michaelowa et al. 2019b; Honegger 2018; Honegger and Reiner,2018).

Carbon units from CDR have a key difference to units generated by emissions reductions primarily due to issues related to permanence, which may require to limit fungibility of these two types of units, as done already under the CDM for forestry credits. However, there may also be issues in such a case as under the CDM, temporary credits were unattractive for credit buyers due to the risk of not being renewed; demand for these credits thus was negligible. International guidance on how to achieve environmental integrity without eliminating the incentives is required in this regard. Approaches to ensure permanence can use buffer stocks or apply discounting; such approaches are applied in a number of ETSs. Guaranteeing a full permanence going beyond decades requires elaborate responsibility systems ensuring that the founding and closing of companies does not lead to a vacuum regarding the responsibility. This may be one of the biggest challenges for incentivizing CDR activities.

The third possibility for enhancing the international cooperation on CDR could be through non-market approaches (NMAs) under paragraph 6.8. The PA text is very generic allowing for the consideration of a wide range of possibilities for international cooperation, yet further guidance could guide and narrow down the options. So far, non-market mechanisms relevant for CDR could include inter alia international support or capacity building for any policies or

[10] For more information on CSUs and their role within the Paris architecture see Zakkour and Heidug (2019).

projects implementing CDR projects or activities via regulations or financial incentives, technology transfer, direct cooperation on pilot plant implementation, cooperative R&D programs, and more.

4.6 MRV and accounting of CDR

The appropriateness of CDR under any “carrot” or “stick” policy instrument depends on the accuracy of monitoring, reporting and verification (MRV) of removals, which fundamentally need to build on appropriate assessments of the entire life-cycle emissions and sinks (cradle to grave). Continued MRV over very long periods is a necessary condition to ensure permanence. To advance CDR, Parties should seek to pursue pilot activities with a particular emphasis on working out high-quality MRV methodologies and accounting practices that provide reliable evidence of accrued removal results.

MRV systems are broadly designed as either sector- or project-based. Individual CDR projects and activities should follow a stringent project based MRV. For most CDR activities a clear and consistent system boundary can be outlined in regards to life cycle emissions and removals. In case of BECCS the lifecycle relevant for the CDR MRV would extend from the growing and harvesting of biomass (including any prior land-use change immediately related to the growing of biomass), transportation and processing (e.g. combustion), to capture and storage (Torvanger 2019, p. 331ff.). If power or heat produced from BECCS displaced power or heat sources with higher CO_2 intensity, the displaced CO_2 could be separately credited as emissions reductions. Similarly, in case of DACS, the process would likely include the power consumed by DAC facilities, transport, power needed for storage and the storage itself, as well as the lifecycle emissions of the associated infrastructure (from construction to decommissioning). Furthermore, topics that initially proved highly controversial for MRV of CCS (e.g. risk assessments of and liability questions regarding storage sites) have progressed significantly, thanks e. g. to the EU directive on geological storage (European Parliament and European Council 2009).

While there is a menu of established MRV methodologies under ETS or the CDM applicable to various CDR approaches from which CDR Parties choosing to cooperate internationally on CDR could draw, several CDR types would require novel MRV baseline and crediting methodologies or at least adaptations to existing MRV methodologies presently used in voluntary markets. Among the CDR types presently known, these likely include DACS, enhanced weathering, soil carbon enhancement, biochar, CO_2-negative concrete, timber used in construction with end-of-life storage, and more. Some of the more exotic and less understood approaches such as marine interventions (which presently lack a robust governance framework and therefore are not presently a deployment option for inclusion in NDCs) would require fundamentally new approaches to MRV.

Once MRV on a project level is dealt with properly, aggregation for consideration in the national inventory should be straightforward.

4.7 GHG metrics and net-zero targets

There are different interpretations of 'net-zero' due to the varying decay rates of GHGs[11] in the atmosphere; their half-life differs from thousands of years to just few decades. Therefore, the global warming potentials (GWPs) used to compare different GHGs have always to be linked to a specific time horizon. So far, the international community has applied a 100 year time horizon for the calculation of GWPs under the Kyoto Protocol and the PA. It should be noted that GWPs have changed considerably over time due to advances in scientific understanding. The transparency rules of the PA require all countries to use the same GWPs from the most recent IPCC Assessment Report from 2024 onwards.

Although the PA text requests Parties to list emissions and removals of all GHGs in their NDCs and account for all in their GHG inventories, the situation is not as clear-cut when it comes to net-zero targets: The Agreement's language on 'balance' is tightly associated with 'stabilization of the climate system'. A literal reading could mean 'balance' ought to be achieved across all GHGs – where e.g. a tonne of each GHG emitted is to be counteracted by another tonne of the same GHG removed elsewhere. Presently hardly any removal approaches are being discussed for GHGs other than CO_2, which could be for technical difficulties as well as for the reason that removal of CO_2 might just be more important for its relatively long lifetime in the atmosphere. Methane with its short lifetime would have to be treated differently from N_2O (which has a comparable lifetime to CO_2) or the industrial gases with lifetimes of many thousand years. In a slightly less narrow reading, one could agree that GWPs can be used to convert other GHGs into CO_2-eq – by consequence CO2 could e.g. be removed to counteract emissions of other GHGs. But the choice of a particular GWP time horizon would then impact on the physical warming result with changing effects over time.

Global net-zero CO_2-equivalent emissions calculated using 100-year GWPs would result in a sustained decline in global temperature as residual emissions would likely include short-lived climate-forcing agents such as methane, and thus "overdo" mitigation. Other metrics, such as the global temperature change potential (GTP) or the CO_2-forcing-equivalent emissions (CO_2-fe have been proposed but for other reasons are so far not consistently viewed as favourable than the GWP. Using 100 year GTPs instead of GWPs would result in fairly constant global temperatures once net-zero CO_2-equivalent emissions are achieved (Pierrehumbert 2014; Fuglestvedt et al. 2017). It is however possible that choosing such metrics would affect emerging economies differently than highly industrialized economies due to different emissions profiles.[12]

The choice of metric, whether using the GWP or the GTP, and for which time horizon, has significant consequences for assessments of amounts and timing of CDR. It is imperative that policymakers address this issue early enough, fully understand the advantages and disadvantages of each metric and decide early enough on the metric to be used for net zero approaches. Otherwise, a serious conflict can be expected some decades from now.

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[11] The six Kyoto GHGs are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6) (UNFCCC, 1997, Annex A).

[12] Given the political, rather than the technical, nature of this report, the description of how such metrics are built is not included here. For a detailed examination see Fuglestvedt et al. (2017).

5. Conclusion and recommendations

In light of the need to achieve net-zero global emissions by the second half of the 21st century, Parties ought to put forward strategies for the implementation of Carbon Dioxide Removal (CDR), complementing drastic emissions cuts, detailing milestones to be reached in e.g. 2025, 2030, 2040 and 2050. This strategy should be part of the Low Emissions Development Strategy that Parties are to present in 2020 and include the following elements:

- Specific CDR deployment targets with intermediate milestones in 2030, 2040 and 2050
- Commitments to accelerate research and development efforts into CDR types that are promising for the respective country context
- Establishment of a committee comprising of mitigation (incl. CDR) experts and various sectoral stakeholders charged inter alia with continued deliberation on the potentials, costs, appropriateness, and potential implementation paths for various CDR pathways (alongside emission reduction pathways)
- An inter-ministerial planning process for elaborating sectoral CDR policies drawing on insights from the above expert-and-stakeholder committee
- Design of a stage-gate process to approval of CDR options and policies with specified near-term milestones the achievement of which would determine adjustments in other policy areas (e.g. failure to achieve particular CDR milestones would require ramping up efforts in emissions reductions efforts).
- Specify R&D targets for reaching specified levels of technology readiness across a range of preferred CDR options within a 5, 10 and 15 year time horizon in function of various CDR options' respective technology readiness.
- Setting in place a strategy for policy planning toward CDR implementation policies including public consultation process to anticipate for and avoid NIMBY and public backlash
- Design specific incentives for the prioritized CDR technologies, aiming to maximize cost reductions, and ensuring that CDR can also be used in the context of emissions trading systems or to offset carbon tax liabilities. Discuss to which extent specific "windows" for CDR can be provided given that costs of many CDR options are likely to remain higher than those of classical mitigation options for a considerable amount of time.

Furthermore, Parties should strive to gain clarity on a number of issues concerning the use of CDR within international cooperation frameworks (guidance for Article 6.2 and 6.8 as well as the rules, modalities and procedures for Article 6.4).[13] In the short term, it needs to be ensured that the rules for the market mechanisms under Article 6.2 and 6.4 do not exclude CDR nor allow for CDR without sufficient clarity on MRV, accounting and sustainability aspects. Parties should furthermore strive to achieve agreement on a common metric around which to define net-zero emissions targets given the shortcomings of the currently used global warming potentials in this respect.

[13] For detailed discussion of these questions of immediate relevance to negotiations on the Article 6 rulebook refer to Michaelowa and colleagues (2019c).

To achieve net-zero emissions, private sector companies also need to step up and start exploring all CDR options that could be developed within their activities. Investments into such internal evaluations would be in their own self-interest as these would prepare them for any potential future demands of reducing net-emissions toward or even below zero in the long term. As a consequence of increasing pressure, companies might increasingly want to invest into R&D on promising CDR options internally or in partnership with universities or even acquire CDR technology developers with a view to accelerate their development in order to hold a competitive advantage over laggards in a world increasingly defined by the need for drastic net-emissions cuts.

Civil society organizations, particularly environmental NGOs can also contribute to the challenge posed by the need for a net-zero emissions future by offering various alternative visions of the future and pathways to get there, which can crucially inform the challenging work of deliberation and planning toward such ambitious goals and thereby help render policies more productive by including additional perspectives and concerns.

Achieving net-zero emissions represents perhaps the grandest challenge of the 21st century and requires "all hands on deck".

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Annex

Table 1: Overview of key Carbon Removal technologies (Honegger, 2018; IPCC, 2018; UNEP, 2017; Akademien der Wissenschaften Schweiz, 2018; Fuss et al., 2018; Nemet et al., 2018; Minx et al., 2018; Schäfer et al., 2018)

Technology	Description	Removal potential[1]	Costs per tonne CO_2	Co-benefits vs. risks	Technological maturity
Afforestation and forest ecosystem restoration	Planting of forests and restoration of ecosystems that result in long-term storage of carbon in above- and below-ground biomass.	0.5 - 10 < 3.5 (2050) 1 - 7 (narrowed down to 0.5 - 3.6) (2050)	1 - 100 USD 5 - 50 USD (2050) 5-50 USD	Increases soil quality, water retention capacity and biodiversity vs. competition with food production; requires on-going management to maintain permanent carbon sinks	Techniques are known and already proven on a large scale
Renaturation	Restoration of ecosystems with high potentials of storing CO_2.	no data	no data	Increases the adaptive capacity of ecosystems; creates habitats for species; improves water balance vs. changes in energy balance and evaporation;	Techniques are known and already proven on a large scale

Technology	Description	Removal potential[1]	Costs per tonne CO_2	Co-benefits vs. risks	Technological maturity
				higher methane emissions	
Bioenergy with carbon capture and storage (BECCS)	Burning biomass for energy generation and capturing and permanently storing the resulting CO_2.	0.5 - 5 < 5 (2050) 1 - 85 (2050)	50 - 250 USD 100 - 200 USD (2050) < 200 USD	Business opportunity; economic diversification vs. competition with food production and biodiversity; air pollution; high energy demand	Limited demonstration activities and doubtful large-scale deployment
Enhancing soil carbon content with biochar	Biomass burning under low-oxygen conditions yields charcoal “biochar” which is then added to the soil to enhance soil carbon levels.	0.5 - 5 < 2 (2050) 0.5 - 11 (narrowed down to 2.3 – 5.3) (2050)	10 - 135 USD 30 - 120 USD (2050) -45 - 100 USD (negative costs relating to the multiple co-benefits of SCS, such as	Reduces N_2O and CH4 emissions; increases soil fertility vs. more heat absorption; worse CO_2 balance than BECCS	Limited production capacity

Technology	Description	Removal potential[1]	Costs per tonne CO_2	Co-benefits vs. risks	Technological maturity
			increased productivity and resilience of soils)		
Enhanced weathering or ocean alkalinisation	Enhancing natural weathering of rocks by extracting, grinding and dispersing carbon-binding minerals on land or by adding alkaline minerals to the ocean to enhance oceanic carbon uptake.	0.5 - 4 < 4 (2050) 0.72 - 95 (land application) & 1 - 6 (marine application) & 0.1 - 10 (ocean alkalinisation)	20 - 1000 USD 50- 200 USD (2050) 15 - 40 USD & 14 - >500 USD (ocean alkalinisation)	Decreases acidity; improved soil quality; crop yield increases; enhanced crop nutrition vs. impacts on terrestrial and marine ecosystems; high energy demand; negative local effects	Not tested
Direct air capture and storage (DACS)	Capturing CO_2 directly from ambient air by a chemical process, followed by permanent storage or use.	0.5 - 10 < 5 (2050)	40 - 1000 USD 100 - 300 USD (2050)	Business opportunity vs. high costs; increases the	Prototypes are under way; technology is rather immature

Technology	Description	Removal potential[1]	Costs per tonne CO_2	Co-benefits vs. risks	Technological maturity
		no IPCC data on potential	20 - 1000 USD	demand for energy and water	
Ocean fertilisation	Fertilising ocean ecosystems with nutrients to accelerate phytoplankton growth, which partly sinks to the seabed thus moving carbon from the atmosphere to the seabed.	1 - 4 15.2 $ktCO_2$ - 44 $GtCO_2$	50 - 500 USD 2 - 457 USD	Increases fishing and biomass vs. increases greenhouse gases; acidification in the deep ocean; alteration of local food webs and ecosystems; disruption of marine ecosystem	Small-scale projects under way, but no consensus on future deployment

Respective source of values: Black (Akademien der Wissenschaften Schweiz, 2018); red (Fuss et al., 2018; Nemet et al., 2018; Minx et al., 2018) and green (IPCC, 2018, p 342ff.)

[1] Projected mitigation potentials in gigatonnes (= 1 billion tonnes) CO_2 p. a.; societal, economic and political barriers are largely unaccounted for in these assessments.

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