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Who Is Paying for Carbon Dioxide Removal? Designing Policy Instruments for Mobilizing Negative Emissions Technologies

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Carbon dioxide removal (CDR) poses a significant and complex public policy challenge in the long-term. Presently treated as a marginal aspect of climate policy, addressing CDR as a public good is quickly becoming essential for limiting warming to well below 2 or 1.5°C by achieving net-zero emissions in time – including by mobilization of public and private finance. In this policy and practice review, we develop six functions jointly needed for policy mixes mobilizing CDR in a manner compatible with the Paris Agreement's objectives. We discuss the emerging CDR financing efforts in light of these functions, and we chart a path to a meaningful long-term structuring of policies and financing instruments. CDR characteristics point to the need for up-front capital, continuous funding for scaling, and long-term operating funding streams, as well as differentiation based on permanence of storage and should influence the design of policy instruments. Transparency and early public deliberation are essential for charting a politically stable course of action on CDR, while specific policy designs are being developed in a way that ensures effectiveness, prevents rent-seeking at public expense, and allows for iterative course corrections. We propose a stepwise approach whereby various CDR approaches initially need differentiated treatment based on their differing maturity and cost through R&D pilot activity subsidies. In the longer term, CDR increasingly ought to be funded through mitigation results-oriented financing and included in broader policy instruments. We conclude that CDR needs to become a regularly-provided public service like public waste management has become over the last century.

Keywords: mitigation policy instruments, climate finance, carbon markets, negative emissions, Paris Agreement, net-zero emissions, nationally determined contributions, carbon dioxide removal

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INTRODUCTION

The ultimate objective of international climate policy is to stabilize atmospheric greenhouse gas (GHG) concentrations at levels that prevent dangerous interference with the climate system, according to the UN Framework Convention on Climate Change (United Nations Framework Convention on Climate Change, 2015). The Paris Agreement's long-term goal is to limit warming well below 2°C and pursue efforts to limit warming to 1.5°C by achieving a peak on global GHG emissions as soon as possible and achieving net-zero emissions globally in the second half of this century. The Paris Agreement sets a collective quantitative constraint on cumulative net emissions of GHGs at the global level. The Agreement furthermore provides qualitative indications (with room for interpretation) regarding the respective contributions of countries, sectors or of emissions reductions vs. carbon dioxide removal (CDR) therein (Honegger et al., 2021). In recent years, net-zero emission targets have emerged as an organizing principle of climate policy on various levels (Schenuit et al., 2021). While offering a long-term perspective and potential alignment with the Paris Agreement's collective goals, such targets are not sufficient on their own. They need to be operationalized on the level of specific decision-makers in all economic sectors and underpinned by specific policy instruments. In this paper, we address characteristics such policy instruments should (jointly) have and develop a set of necessary conditions for Paris-alignment with regard to CDR policy instrument mixes.

The Possible Roles of CDR

While afforestation and restoration projects have long served to remove and store carbon dioxide (CO_2) (Kupfer and Karimanzira, 1990), the idea of combining biomass energy generation with carbon capture and storage (BECCS) (Möllersten et al., 2003) was included in integrated assessment models (IAM) only in the late 2000s (Van Vuren et al., 2011). Direct air capture and storage (DACCS) (Keith et al., 2006) was added even later. Initially met by climate change scholars with skepticism, such CDR is increasingly viewed as essential for meeting net-zero emissions targets at national and regional as well as the global level. The readiness of, and support for CDR approaches varies widely from already implemented and low-regret (e.g., restoring mangrove vegetation) to low or unknown (in particular open-ocean-based) approaches [see Honegger et al. (2020) for an assessment of the impacts of various CDR approaches on the Sustainable Development Goals, Gattuso et al. (2021)]. At least three rationales are frequently put forward for considering CDR in public policy (Geden and Schenuit, 2020; Morrow et al., 2020): (a) balancing out residual emissions from effectively-impossible-to-decarbonize sectors (like agriculture) for achieving a permanent steady state of net-zero emissions, (b) temporarily balancing out residual emissions from hard-to-decarbonize sectors (like construction, heavy industry, and heavy transport), while solutions for these sectors are being developed and just transformations with job-transitions are taking place (Buck et al., 2020), and/or (c) to return to historical CO_2 concentrations through a phase of global net-negative emissions after achievement of complete decarbonization. Additionally, there is d) a moral argument interpreting well-established principles of distributive justice such that countries with significant historical emissions and technological capacities ought to act as first movers and attempt to drive down the cost of CDR so that others have access to a larger set of mitigation options (Fyson et al., 2020; Pozo et al., 2020).

These reasons all characterize the continuous and large-scale removal of CO_2 into permanent storage as a public good, which in many cases requires a systematic long-term public intervention. Yet, to date governmental action – beyond early-stage research and development funding – appears to be lagging and causing a systematic "incentive gap" (Fridahl et al., 2020). Calls for examining and mobilizing various CDR potentials are growing (e.g., Bellamy, 2018; Geden et al., 2019) and an increasing number of private companies and philanthropies are starting to voluntarily mobilize CDR. Yet so far CDR has not commonly been established as a necessary public service of similar nature as the treatment of solid or liquid wastes. This is despite the increasingly well-evidenced public-good nature of CDR services – as would be the case for the public service of disposing of liquid or solid wastes, which without government intervention would pile up on the street or pollute water, soil and air. While such a narrative holds promise for framing and guiding public policy, its historical context suggests that the associated policies may face continuity challenges (Buck, 2020).

Operational CDR Definitions Needed for Funding and Public Policy Instruments

Only recently have scientific definitions of CDR (overnmental Panel on Cli, 2018, p. 544) been operationalized with greater clarity, which is a precondition for designing appropriate instruments for mobilizing it. Through four principles, Preston Aragonès et al. (2020) differentiate CDR from other mitigation activities roughly as follows: (1) atmospheric CO_2 is physically removed, (2) then permanently stored out of the atmosphere, (3) all up- and downstream GHG flows are considered in the calculations, and (4) the atmospheric net-CO_2 flow balance is negative.

The Paris Agreement obliges its Parties to pursue "mitigation of climate change," which includes both emissions reductions and CDR (Honegger et al., 2021). Parties are to furthermore communicate their planned "mitigation" efforts via regularly updated nationally determined contributions (NDCs), long-term low greenhouse gas emission development strategies (LTS-LEDS), and their actually observed emission and removals via GHG inventory reports. Parties' mitigation efforts are to become increasingly comprehensive (including all emission sources and sinks, all GHGs, and all economic sectors) and ambitious in line with the collective net-zero emissions goal. Consequently, governmental action is needed to pursue CDR in addition to rapidly cutting emissions and private sector actors are likely to play an important role in the execution.

Differentiation Needed Based on CDR Characteristics

A key feature – and challenge – of CDR is that the storage of CO_2 needs to be 'durable' (overnmental Panel on Cli, 2018, p. 544) or permanent. The innate permanence of CO_2 stored in biological systems (soil- and plant biomass or biochar) is much lower than the innate permanence of CO_2 stored deep underground and/or in mineralized form (Möllersten and Naqvi, 2020). While permanence may overall be achieved in both cases through suitable measures, permanence of chemically stable compositions is dramatically higher. Emission reductions are innately permanent and do not face a risk of reversal. Policy instruments need to account for such differences in order to be compatible with net-zero ambitions, by differentiating results based on their permanence levels [e.g., recognizing temporary removals without relying on them in the long term; Ruseva et al. (2020)] or limiting their role within mitigation targets by further enhancing the pace and scale of emissions reductions accordingly.

Another important difference between CDR approaches is their present and projected future financial structure, where few approaches are already – or may be in the future – benefiting from non-carbon revenue sources, while most may largely or exclusively have to rely on continuous carbon-related revenues. Policy instruments need to account for differences in long-term funding needs. Several reports and studies have examined cost projections of various CDR types, yet the empirical basis remains very narrow and comparability between projections of future CDR costs is limited (Fuss et al., 2018; Lehtveer and Emanuelsson, 2021).

Policy, furthermore, needs to be based on an encompassing and long-term view of the results: In some cases, the same type of activity can have widely different mitigation results, ranging from a net increase in emissions, a reduction in net emissions, all the way to varying degrees of net-negative emissions. It is therefore not sufficient to create generic categories of CDR activities whose effects can robustly be predicted by standardized calculation methodologies, but carbon flows need to be projected on a case-by-case basis and appropriately measured ex-post.

Outline and Approach

In this policy and practice review, we first identify a set of CDR-specific policy design needs emerging from the particularities of CDR (in contrast to conventional mitigation through emissions reductions activities). Building on those needs and situated within the emerging CDR policy literature, we then identify a set of six necessary functions for CDR policy mixes to fully aligned with the objectives of the Paris Agreement. Against the backdrop of these functions, we examine prominent examples of current policy elements at international and national levels as well as private sector initiatives which may offer (partial) steps toward fulfilling the identified functions in the way they contribute to mobilizing and financing CDR. Finding shortfalls – even among the perhaps best case approaches toward individual policy functions – we observe a near-universal lack of a systematic approach to fulfilling these functions jointly. Based on relevant lessons from climate change mitigation policy, we then offer actionable recommendations to start addressing the gaps and risks identified, and to transparently advance a set of dedicated policy instruments in collaborative fashion. Our recommendations target international climate negotiators, national mitigation planners, and private sector actors engaged in voluntary CDR efforts. We propose a stepwise approach that allows both the necessary differentiation between CDR approaches in the short-term and an increasingly level playing field for all kinds of CDR in the long-term. The objective would be that CDR efforts and mitigation efforts overall are enabled to credibly achieve Paris-aligned net-zero emissions targets at national and global levels.

CDR FINANCING NEEDS AND PROJECTIONS

Differentiating Cost-Revenue Projections

For design of efficient mitigation policy instruments a distinction has to be made between those mitigation options that require full-, partial-, or no public funding to be implemented. As a first differentiation we therefore suggest three categories of CDR approaches: (I) those that cannot generate revenues in the absence of dedicated financial support, (II) those which might generate some (but not sufficient) revenues or cost savings from co-benefits, and (III) those that may be profitable even in the absence of dedicated interventions (regulatory, market-making or fiscal policy instruments or voluntary efforts). **Table 1** offers an overview of potential revenue streams and marginal-cost categorization of various CDR approaches.

Technologies in group I – "pure climate technologies" – do not come with significant (or any) monetizable co-benefits: their sole purpose is to limit the rise in atmospheric CO_2 concentrations. The direct capture of CO_2 from ambient air and subsequent underground storage (DACCS) is the clearest example. Retrofitting capture technology to existing biomass-energy plants combined with underground storage (BECCS) (and some other CDR approaches) are further examples, where at least some necessary elements in the value-chain are solely dedicated to the purpose of CDR and thus do not generate revenue.

Group II and III technologies are not always as clearly identifiable; their separation requires a case-by-case examination for the determination of their so-called "additionality" – as has been done under the Clean Development Mechanism (CDM) of the Kyoto Protocol (Michaelowa et al., 2019a). While some (Cames et al., 2016) questioned the additionality of the majority of CDM activities. Others, however, contested their results, given that Cames et al. chose a very narrow definition of additionality based on the degree of increase of attractiveness of the activity induced by the carbon credits. Moreover, Cames et al. (2016) did not take the international regulation for treatment of host country mitigation policies under the CDM into account (Federal Ministry of the Environment, Nature Conservation, Housing, and Reactor Safety (BMUB), 2017). Afforestation and reforestation activities (A/R) can generate some revenue streams associated with co-benefits (e.g., tourism or the sale of (non-timber) forest products. Biochar and enhanced weathering can generate returns by lowering fertilizer spending and increasing yields (Cornelissen et al., 2018; Kätterer et al., 2019; Ye et al., 2019). Marine CDR via ocean fertilization or alkalinization (with iron, phosphorus or limestone) could potentially result in fisheries yield increases, yet these are highly uncertain and their overall desirability is unclear (Cox et al., 2021). Some forms of carbon capture and use (CCU) may also result in revenue and in CDR: binding CO_2 permanently in long-lived materials (e.g.,

TABLE 1 | Cost-revenue projections and technology readiness based on Poralla et al., 2021.

CDR type	(Potential) non-carbon revenue streams[a]	Financial projection group	Technology readiness level (TRL)[b] Möllersten and Naqvi, 2020
Afforestation and reforestation	• Monetizable 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	Mostly II, some III	7–9
Bioenergy with carbon capture and storage (BECCS)	• Electricity sales • Heat sales (district heat) • Waste treatment (if biomass is sourced from waste)	II	BE: 6–9 CCS: 4–7
Biochar as soil additive	• Agricultural productivity enhancement • District heat sales • Electricity sales	Mostly III, some II	3–7
Direct air carbon capture and storage (DACCS)	• Uptake of power when priced negatively	I	3–6
Direct air carbon capture and durable materials production (construction materials)	• Sale of pure CO_2 as a feedstock for carbon-based materials	II	5–7
Wetland restoration	• Monetizable ecosystem services, e.g., through PES • Water supply services • Reduced risk of flooding and soil erosion • Ancillary tourism and leisure (if non-consumptive)	II	3–5
Enhanced weathering	• Sale as replacement of conventional sand or pebbles • Sale of formed carbonates to paper producers (replacement of lime) • Sale as replacement of fertilize	Mostly II, some III	4–7
Accelerated mineralization (in reactor)	• Heat production (at large scale) • Sale of substitute for clinker in blended cement	II	5–7
Soil carbon sequestration	• Soil quality improvement services • Enhanced agricultural productivity	II	2–5
Ocean fertilization	• Fisheries yield increase services	II	

[a]Monetizable non-carbon revenue streams and co-benefits may need distinction. 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 monetizable.

[b]Technology readiness levels defined in line with 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).

cement, steel or alternative materials), or if enhanced oil or gas recovery (EOR/EGR) were done in a way that maximizes 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).

Technologies in group III are non-additional, which means that they could go ahead without any dedicated financial incentive. While some may be financially viable, they may be held back by other non-monetary barriers, which could render them additional nonetheless.

Overall, while transparently determining additionality will also be important for CDR project proposals overall, additionality of many CDR types will be obvious from the outset given their significant cost and their frequent lack of a business case (generation of revenues other than from the sale of carbon credits).

Costs – and in some cases revenue potentials – are evolving. With technology learning and scaling through an s-curve adoption, some CDR approaches may move from one group to another. While the actual pace of cost-reduction and revenue discovery is highly uncertain, it is very likely that to enable rapid learning and scaling, dedicated near-term interventions are a prerequisite. Therefore, policies are needed to pick a basket of "potential winners" including those activities with the best scaling and cost-reduction prospects.

Approaches involving underground storage such as DACCS and BECCS, as well as some others e.g., biochar applications may have ongoing costs associated with transportation and storage of CO_2 (Hughes, 2017) or operational energy requirements. Furthermore, costs also vary between different regions as storage, energy and biomass resource cost and revenue streams vary (as well as planning and construction costs).

Projections for long-term costs of DACCS operation vary greatly with a lower limit at around USD 40/tCO_2 and the upper limit at around USD 600/tCO_2 (Möllersten and Naqvi, 2020), or even between USD 20/tCO_2 and USD 1000/tCO_2 (overnmental Panel on Cli, 2018). DACCS technology providers envisage long-term operating costs to stabilize on the order of 100 USD/tCO_2.

Some cost differences may thus remain in place in the long-term and a price differentiation within or across funding instruments may be warranted also on a continuing basis. Certainly, where there are differences in the innate permanence of storage (e.g., between storage in biological systems vs. in mineralized form or underground) a difference in incentives would be warranted.

Differentiation of CDR Value-Chain Elements

CDR tend to result from a combination of various value-chain elements, each of which is may be executed by a different actor (or even industry) and with varying marginal cost-gaps. Also, some elements of the value chain may be undertaken in different countries, generating challenges regarding the accounting and incentivization of the removal. Taking a typical (already existing) BECCS process as an example, there are at least three distinct elements of the value-chain: (I) biomass production and harvesting (II) utilization of biomass for energy production with CO_2 capture at source, and (III) the transport and underground storage of CO_2. Only the first two elements without CO_2-capture presently holds a functioning business model in the absence of dedicated funding for CDR. Variants, in which individual pieces are altered, may access some monetizable revenue from co-benefits such as the combination of (solid- or liquid) waste-burning with CO_2 capture, transport, and underground storage, whereby such waste management already tends to be funded as a public service. Replacing underground storage with using CO_2 as a raw material for production of long-lived (construction) materials may offer another such possibility for co-benefits-based revenues, although in such cases the innate permanence is limited.

Given that the scalability (both pace and final potential) likely varies across these elements, and given the consequent need to mobilize a portfolio of approaches, disaggregation of value-chain elements is thus necessary such that policy instruments or voluntary measures may pick potential winners with large long-term potentials (and permanence) – even when they may not compete well in the short-term (e.g., for lack of revenues from co-benefits).

Differentiation According to Full Value-Chain Results

An important differentiation also needs to be made based on the full value-chain mitigation result: Most combinations may be pursued in a (relatively less costly) way that either results in a mere net-reduction of (positive) emissions, or only a small volume of negative-emission – well below the actual CDR potential, thus failing to fund the scale-up of key value-chain elements. An example for this is the somewhat controversial use of direct air capture technology for enhanced oil recovery (EOR) or for production of synfuels. Both approaches somewhat reduce net (positive) emissions. EOR could in theory also be done in an *a priori* uneconomical manner whereby CO_2 storage is maximized rather than oil output, thus potentially resulting in zero or perhaps even negative emissions i.e., CDR. However, policy instruments that do not differentiate according to the final result of the full value-chain, risk creating false incentives by side-lining CDR and instead funding non-transformational activities (such as nominally lower-CO_2 fossil fuels). The net result of such policies may be a fossil fuel subsidy and corresponding overall increase in emissions (Clean Air Task Force, 2020). This appeared to be the case for the US tax credit known as 45Q, which particularly at the outset almost exclusively incentivized use of atmospheric CO_2 for EOR: The differentiation offered in the 2018 update (35 USD/tCO_2 for EOR vs. 50 USD for CDR) would appear insufficient in light of present cost differentials (Larsen et al., 2019).

NECESSARY FUNCTIONS FOR GOAL-COHERENT CLIMATE CHANGE MITIGATION GOVERNANCE

CDR used to achieve net-zero emissions compatible with the Paris Agreement's long-term temperature goal may sometimes be viewed as a stop-gap measure [a temporary measure to mitigate immediate harm and buy time for a permanent solution; Buck et al. (2020)], but given that most governments are not expected to achieve full decarbonization within appropriate carbon budgets (if ever), CDR may need to be attributed a more permanent role (Morrow et al., 2020). The corresponding paradigm shift - requiring a novel understanding of climate change mitigation as the composite of both emissions reductions and removals - may require a reorientation and a strengthened political mandate for consequent public policy (Geden et al., 2019). Unfortunately, neither target-setting, individual research or pilot activities, nor public deliberation will achieve much on its own. Based on these observations regularly raised in the literature in this field, we identify six functions that CDR policy instrument mixes ought to jointly deliver in order to pursue the objectives that CDR may have to fulfill as part of long-term mitigation efforts that are compatible with the Paris Agreement objectives:

1. Provide clarity on the intended role of CDR for the mitigation of climate change (particularly regarding scale and fungibility) in a way that is compatible with the Paris Agreement's goals and countries' targets [particularly regarding cumulative carbon budgets; Fyson et al. (2020)].
2. Accelerate innovation, technology learning and associated cost reductions to unlock a sufficient range of affordable and reliable CDR options – appropriate to each country's circumstances (Morrow et al., 2020).
3. Ensure an appropriate public participation in decisions surrounding how CDR is to be implemented – in a way that is appropriate to each country's political context (Bellamy, 2018; Cox et al., 2018; Bellamy et al., 2021).

4. Transition from piloting to cost-efficient, effective, long-term, scaled operation of CDR that further drives down cost (within a timeframe that is compatible with the role identified in function 1.).
5. Ensure robust and comparable measuring, reporting, verification and accounting of results to track national, regional and global progress toward net-zero emissions (Brander et al., 2021).
6. Prevent adverse side-effects to sustainable development goals and maximize positive co-benefits (Honegger et al., 2020).

Policies that could target CDR can be grouped into different categories similar to GHG emissions reductions policies (Gupta et al., 2007). Some may offer a generic framework, while others provide specific support or regulation (Center for Carbon Removal 2017; Jeffery et al., 2020). Most will – individually – offer necessary, but not sufficient, contributions to fulfilling the above functions. Policy instrument mixes, therefore, ought to be designed to jointly fulfill the different functions needed to align with the Paris Agreement and its long-term objective.

Governmental Climate Change Mitigation Targets

The uppermost policy layer (after the Paris Agreement itself) is the definition of specific short- to medium-term mitigation targets (Nationally Determined Contributions, NDC) and the long-term (mid-century) mitigation strategies (Long-Term Low GHG Emission Development Strategies, LT-LEDS). Both often merely represent a generic framework, but should provide sufficient medium- to long-term orientation for various government departments and private sector actors to anticipate more specific steps. Increasingly, LT-LEDS and NDCs – particularly in industrialized countries – are expected to specify how net-zero or net-negative emissions will be achieved, thus potentially including specific targets for CDR as a category (McLaren et al., 2019) or even more specific (e.g., sectoral, see Kaya et al., 2019) CDR targets, thereby creating clarity on the intended role of CDR and opening up public participation in the setting and operationalization of CDR policy. Where targets become sufficiently concrete, private sector actors increasingly likely want to become active and front-run potentially emerging policies. Several multinational companies have already started, as discussed in section Voluntary Action – Challenges and Opportunities.

As of the end of 2020, 126 countries (accounting for over 50% of global GHG emissions) have announced or considered net-zero goals[1]. Yet, on aggregate, NDCs had not significantly decreased the projected 2030 mitigation gap (United Nations Environment Programme (UNEP), 2020) before the end of 2020 and the vast majority of NDCs and LT-LEDS do not specify a cumulative net emissions volume (i.e., carbon budget), nor do they detail the relative contribution expected from emissions reductions vs. CDR. Information needed to judge the contributions' adequacy is thus missing. The latest government announcements interpreted optimistically suggest a reduction in the median global projected temperature increase by 0.5°C (from 2.6 to 2.1°C), yet still comprising a 16% chance of exceeding 2.7°C (Climate Action Tracker, 2020). Even the optimistic median (50:50 chance) value of 2.1 would still be far from "well below 2°C" and 1.5°C. And even this (insufficient) level of ambition is at risk, given that the commitment to specific sets of mitigation policies that would be likely to deliver on these targets remains highly inadequate.

Further, the approach to planning remains unsystematic: LT-LEDS that mention CDR focus strongly on nature-based solutions including A/R, wetland restoration and various other soil carbon sequestration approaches without offering a strategy to dealing with the lack of innate permanence of these approaches. A dozen countries include plans for using CCS to achieve emissions reductions (but so far not toward mobilizing CDR to achieve net-negative emissions). Approximately 30 further Parties have made public announcements that they might be considering CCS in the future, often without specifying the expected respective contributions (Potsdam Institute for Climate Impact Research (PIK), 2017; Mills-Novoa and Liverman, 2019; Zakkour and Heidug, 2019; Global CCS Institute (GCCSI), 2020).

In light of the above, national commitments in NDCs and LT-LEDS to date largely fail to adequately advance all six necessary functions (regarding clarity, innovation, participation, transition to cost-effective long-term operation, monitoring and accounting, and side-effects).

Domestic Mitigation Policy Instruments

Policy instruments introduce a regulatory or financial alteration of market and behavioral dynamics targeting a specific range of actors, sectors, activities, products, or services. We identify five types of instruments that – by way of a policy mix – may allow mobilizing CDR activities: (a) R&D activity-oriented subsidies, (b) mitigation results-oriented subsidies, (c) regulatory mandates (d) fully-fledged carbon pricing, and (e) ancillary instruments.

a) *R&D activity-oriented subsidies* enable or accelerate CDR research, design, development, or demonstration (RDD&D). Given that this type of subsidy is to target technology advancements at various stages of development, funding volumes and envisaged results have to be adapted individually to allow each technology to progress to its respective next maturity level. Such funding is not constrained to considering near-term cost-effectiveness, but can take a long-view and attempt picking potential future winners, thus unlocking early-stage technology learning. The EU Innovation Fund is an example of such an approach. Activity-oriented subsidies are not intended (and suitable) for funding scaled operations beyond an initial piloting phase and therefore are necessary, but not sufficient to CDR scale-up. Past experience with such subsidies shows that governments need to be bold to prevent emergence of "bottomless pits" swallowing public money (Haapanen et al., 2014).

[1]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 like Finland and Sweden 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.

b) *Mitigation results-oriented subsidies* for scaled implementation and initial operation may be provided as direct grants, tax credits, concessional loans or contracts for difference. Contrary to activity-oriented (R&D, piloting) subsidies these are allocated on the basis of expected or achieved tons of CO_2 removed. In order to be efficient, such subsidies could e.g., be allocated through reverse auction in order to ensure that the most cost-competitive CDR provider is funded (Olsson et al., 2020). Mitigation results-oriented subsidies can have a bridging-function for near-mature activities, which cannot yet access permanent instruments or themselves serve as longer-term instruments. Given that such subsidies can serve to enable larger-scale piloting they also offer crucial opportunities to test and explore possible environmental and social implications of scaled CDR activities in a particular geographical context. The US' tax break 45Q is an example of a mitigation-oriented subsidy, yet it has to date largely failed to meaningfully advance CDR, due to lack of focus (Larsen et al., 2019). Experience from renewable energy deployment evidence the importance of large-scale subsidy programs for achieving operation-scales that rapidly unlock further cost reductions.

c) *Regulatory mandates* could require specific actors (public or private) to pursue or fund CDR activities. If targeting particular sectors, regulations could e.g., require heavy emitters such as power, cement, or steel producers to satisfy an emissions intensity standard, which may be unattainable without CDR. Companies in such sectors could then either develop in-house CDR capacities, purchase CDR-assets (e.g., incorporate a CDR company as a subsidiary), or pool (net) emissions with other companies that overachieve requirements. In all cases, such regulatory mandates could be highly effective at upscaling CDR, but generate significant near-term uncertainty and costs for entities subjected to the mandate. If proposed, certain interest groups and lobbies will therefore try shaping or even preventing them; broader mitigation policy experience suggests that the resulting instruments may end up being limited in scope to already profitable technologies (Michaelowa et al., 2018). Various *carbon pricing instruments* such as cap-and-trade, baseline-and-credit systems or carbon taxes with or without a revolving fund for CDR may seek to enable the long-term continuous operation of efficient mitigation activities. Long-term reliability and explicit eligibility of CDR under such instruments needs to be ensured, given that long-term revenue security is a prerequisite for meaningful private sector investment. Ideally, carbon pricing can act to further incentivize technology learning (including for CDR), and lower overall cost while expanding efforts. If it achieves long-term increases in price levels, as part of a credible, long-term governmental commitment to ambitious climate policy on a path to e.g., net-zero or net-negative domestic emissions, carbon pricing can be suitable for mature CDR technologies. It is also a very useful mechanism to drive continued innovation and thereby bring down the costs of competing technologies. Even where industries or specific CDR activities are not directly covered by a carbon pricing system, they could be made eligible to create removal credits that could be sold into the system. A credible prospect for such possibility could offer a sufficient incentive to build-up CDR activities (if the carbon price in that system is sufficiently high and not overly volatile). Given that such eligibility would affect supply-and-demand it would have to be offered in such a way that the carbon pricing objectives (the overall resulting mitigation) are advanced rather than undermined: Caps may for example be adjusted downwards or credits may be retired into a market reserve in order to reflect for the greater ambition levels that CDR eligibility might unlock in the medium-term.

d) *Ancillary policy instruments* serve to enhance consistency and alignment with overarching objectives, by creating regulatory boundaries and operational guidance to key actors. For CDR this could entail establishing permanence requirements, a system of long-term storage guarantees or reserves, a harmonized framework for liability, as well as public engagement processes that feed into policy design and enable building broad-based support for CDR policy mixes. Ancillary policy instruments are critical to ensure that CDR can become a mature element of consistent national and international climate policy rather than being pursued haphazardly, limited to pilot projects and never actually fulfilling any meaningful role in climate change mitigation. Clearly establishing all relevant CDR value-chain elements within financial guidance and regulations – such as the EU sustainable finance taxonomy – would be another type of ancillary policy instrument, which could be essential for aligning public and private efforts toward a common goal.

Policy instruments can thus be differentiated by their objectives (to offer short-term support for R&D, piloting, bridging or a long-term framework). For credibly transitioning to cost-efficient, effective and long-term continuous operation, long-term instruments (regulatory mandates, tax- and subsidy-based incentives, or market-based incentives) need to be evaluated against challenges and opportunities that affect their feasibility, effectiveness, and long-term efficiency and stability. These often depend on country-specific political economies and thus require nationally rooted evaluation. For adopting nationally appropriate policy instruments, governments would do well to proactively identify in particular the factors that may challenge the long-term stability of instruments and resulting incentives (including in countries with frequently changing administrations) alongside their expected efficiency and effectiveness in their respective national contexts.

So far, purely regulatory mandates for inducing CDR activities do not appear to play an important role among (at least) OECD countries' deliberations on mitigation policies (Schenuit et al., 2021). Arguably US EPA emissions standards for the energy sector could be viewed as a template – including for other sectors – for a regulatory approach that might ultimately incentivize the use of CDR for reductions in company- or sector-wide net-emissions.

While there already are several domestic (market-based) policy instruments in place for A/R activities (New Zealand's ETS, Chinese provincial ETSs, California's ETS, Australia's domestic crediting scheme), other CDR approaches – notably those with higher innate permanence – have largely been neglected.

Parliaments, and administrative agencies in the US, the UK, Germany, Norway, Sweden, and Switzerland, as well as the European Commission, are taking note of the need to develop policy instruments suitable to advance high-permanence CDR[2] but in most cases specific policy instruments have not yet been implemented. Sweden is a notable exception: it has set a net-zero emissions target for 2045, with net-negative emissions thereafter, and publicly emphasized that various types of CDR, including BECCS, will be mobilized to contribute to this target. Furthermore, Sweden is developing concrete plans to include BECCS in its carbon tax scheme and – in committee and public debate – appears to be moving fast toward an additional policy instrument where the government (through the Swedish Energy Agency) purchases CDR services through a system of reverse auctions (Lund Christiansen, 2020, p. 20ff). While clearly not as far advanced, the UK may become a runner-up. The UK has set a carbon neutrality target for 2050, its revised NDC introduces an intermediary emission reduction target of 68% by 2030 (compared to 1990), and government communications consistently highlight the prominent role of CCS applications as well as nature-based removals. However, given that specific policy instruments appear to still be missing, it is not yet possible to judge the adequacy of their overall policy instrument mix (e.g., in dealing with permanence issues of nature-based removals) and by consequence the overall merits of the UK's approach.

Among the sub-national actors, California is a notable frontrunner: its low-carbon fuel standard (LCFS) – a baseline-and-credit instrument for mitigating transportation emissions – allows for external credits from DACCS activities. In 2020, LCFS credits reached a world-record high of USD 200/tCO_2 [California Air Resources Board (CARB), 2020; International Energy Agency (IEA), 2020].

International Policy Toolset

International carbon markets have existed for the last 20 years, first under the Kyoto Protocol [Clean Development Mechanism (CDM) and Joint Implementation (JI)] and now under the Paris Agreement (Article 6). As negotiations on international cooperation under the Paris Agreement are still ongoing to conclude the rulebook of Article 6 (at COP26), we look to the past for insights on how mitigation transfers might be designed in the future: The Kyoto Protocol's CDM, which has already been discussed in section Differentiating Cost-Revenue Projections (regarding the demonstration of additionality), in many ways has served as key reference for baseline-and-credit mechanisms for mitigation and offers several lessons for CDR. The CDM included A/R activities – of the over 7,800 registered CDM projects, 66 were A/R projects (UNEP DTU Partnership, 2021). The CDM offers several baseline and monitoring methodologies to quantify removals for this activity type. After a long process, CCS activities were made eligible under the CDM in 2010; the CCS rules under the CDM provide detailed terminology and clear regulatory guidance on the selection, characterization and development of geological storage sites, liabilities, risk and safety assessments as well as guidance on baseline methodology submission. So far, however, no approved CCS baseline or monitoring methodology exists given that credit prices have been too low and uncertain to mobilize CCS.

The role of international cooperation and transfer of mitigation outcomes is expected to change under the Paris Agreement – given its long-term objective of global net-zero (or even net-negative) emissions and requirement for all countries to set national mitigation targets. Over time, with the pace reflecting the countries' "common but differentiated responsibilities and respective capabilities," national mitigation targets will need to balance out any residual emissions through CDR. As global emissions approach zero, international market-based cooperation, based on the international transfer of mitigation outcomes under Article 6 of the Paris Agreement will by consequence increasingly shift focus from emissions reduction activities to mitigation outcomes from CDR activities. The CDM's lessons regarding additionality assessment need to be carefully considered when applying market-based cooperation to CDR, especially regarding the separation of Group II and III technologies, as discussed in section Differentiating Cost-Revenue Projections above.

VOLUNTARY ACTION–CHALLENGES AND OPPORTUNITIES

With governments slowly moving toward the operationalization of net-zero targets, some private sector actors have, somewhat unexpectedly, become first movers in mobilizing various types of CDR. There is, however, a strong divergence in the quality and ambition of these efforts (**Table 1**). While some attempt a quick-fix corporate social responsibility (CSR) strategy and pursue the lowest-hanging fruit without a credible long-term strategy (purchasing the lowest-cost carbon credits offered on the voluntary market or announcing tree-planting campaigns with questionable permanence and additionality), others have adopted a leadership approach by seeking to enable technology learning through investment in high-cost, high-permanence CDR approaches. Some of the most ambitious efforts include to date the plans of Microsoft, Shopify, Stripe, and SwissRe (see **Box 1**). It should, however, be noted that none of these approaches addresses the challenge of double-counting of removals at the company and national level. This means that the mitigation outcomes of widely advertised voluntary private sector mitigation activities automatically show up as lower emission levels in the national GHG inventory of the government where the activity takes place (thereby contributing to its claimed progress toward NDC achievement). The double-claiming of the same mitigation

[2]Some agencies have 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. Switzerland has provided a mandate for developing a policy roadmap for mitigation through CDR.

BOX 1 | Private sector leadership in mobilizing CDR with a long-term view.

Microsoft aims to achieve "carbon negativity" by 2030 and to have removed all of the company's past CO_2 emissions by 2050. It has 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 CDR technologies. Most recently, Microsoft has announced that its fund will make a substantial investment into the DACCS technology provider Climeworks.

Shopify has announced becoming carbon neutral and even net negative in the future and will 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 to have reached carbon neutrality in 2019 and has pledged to invest USD 1 million/year into forestation initiatives, soil management reforms, enhanced weathering, and DACCS 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 app Stripe Climate, through which clients can direct a fraction of their revenue to support scaling up CDR.

Swiss Re aims to achieve net-zero emissions of its operations by 2030. To drive and finance mitigation, 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 into long-term agreements with carbon removal service providers to boost the CDR markets.

outcome toward both the private sector actor's carbon neutrality target and the host country's NDC would effectively render the private sector actor's carbon neutrality claim untrue. This is because, in case of mitigation outcomes counted toward the host country's NDC, the private sector actor effectively subsidizes the achievement of mitigation levels that the country was committed to achieving anyway. Double-claiming can be avoided if the host country agrees to "uncount" such mitigation outcomes in its NDC-related reporting to the Paris Agreement.

What makes the voluntary efforts highlighted in textbox 1 stand out from other voluntary efforts is their willingness to tackle high up-front costs of some CDR types that potentially have high innate permanence, rather than simply purchase ready-made, often low-cost and sometimes low-permanence credits from voluntary carbon markets to claim carbon neutrality. Their efforts can thus help accelerate innovation and piloting of CDR activities and raise public interest. This development represents a noteworthy deviation from the experience under the CDM and JI as well as voluntary markets to date: In the past appetite for up-front investment for capital expenditures of novel projects was very limited, reflecting the buyers' interest in making immediate mitigation claims through credits that represent already achieved and verified mitigation outcomes (Michaelowa et al., 2019b). Furthermore, up-front investments face various risks and uncertainties as to whether these activities ever lead to the expected mitigation outcomes that investing companies can claim to count toward their pledges.

Conventional voluntary offsetting through the purchase and cancellation of credits in the voluntary carbon markets may promote those CDR activities that can already be competitively implemented with results-based funding. So far, A/R has been the dominant CDR activity type in voluntary carbon markets (Donofrio et al., 2020), with a roughly 400% growth in A/R credits between 2016 to 2018 (Donofrio et al., 2019), mostly stemming from projects in Latin America and Africa (Hamrick and Gallant, 2017).

Private standard-setting organizations such as Verra, Gold Standard Foundation, and Plan Vivo issue carbon credits against verified mitigation outcomes from eligible activities, including A/R, that meet their standards. There is no unified approach to managing non-permanence risk of eligible CDR activities: Verra's approach includes a risk assessment to determine a share of credits that may not be traded or claimed, but are instead deposited into a pooled buffer account. In case of unforeseen reversals (re-emission of carbon), a corresponding volume of credits will have to be canceled from the buffer account (Verra, 2018). The Gold Standard approach includes five elements: (i) specific requirements to assess the innate risk of each activity; (ii) frequent monitoring, reporting and verification (MRV) of outcomes; (iii) a compliance pathway adapted to each activity type with high permanence risks; (iv) attribution of liability for underperformance to project owners; and (v) an overarching buffer fed by 20% of all activities' issuances (Gold Standard, 2020).

New voluntary market platforms and service providers specifically focussed on CDR units have emerged in the past 2 years, including Puro.earth (Finland), Nori (US), MoorFutures (Germany), and max.moor (Switzerland). These also predominantly focus on CDR with storage in biological systems (with limited innate permanence) and they come with widely different approaches to addressing fundamental issues such as the additionality of activities as well as the permanence of removed carbon. Many lessons from past baseline-and-credit systems, most notably the CDM, appear to have been ignored in their design. MoorFutures and max.moor exclusively focus on wetland and peatland restoration projects (with credits priced around USD 78-92/tCO_2), Nori focusses on agricultural carbon removals (priced on the order of USD 15/tCO_2), and Puro.earth offers credits from biochar production as well as the use of wooden and carbonated building materials (prices ranging USD 23-180/tCO_2).

While the purchase of carbon credits through voluntary carbon markets can deliver near-term reduction in net emissions, it does not necessarily ensure long-term mitigation in line with net-zero global emissions. The introduction of NDCs by all countries under the Paris Agreement expands the challenge of double claiming for voluntary actions given that virtually all mitigation is now also counted toward a country's NDC achievements. Private actors can make Paris-aligned carbon neutrality claims only with mitigation outcomes that are not counted toward an NDC. It is important that private sector support for CDR is recognized as complementary to public CDR policy, rather than a substitute or justification for postponing public action.

REQUIREMENTS FOR ALIGNING POLICY INSTRUMENT MIXES AND PRIVATE SECTOR EFFORTS WITH THE PARIS AGREEMENT

In the following, we discuss how the different instruments may all be necessary but not sufficient for fulfilling the six functions for achieving alignment with the Paris Agreement laid out in section Necessary Functions for Goal-Coherent Climate Change Mitigation Governance.

National (medium-term) targets and (long-term) strategies are necessary to provide clarity on the intended role of CDR for the mitigation of climate change, to allocate public funding for innovation and research as well as for pilot-scale subsidies. As such, the definition and later operationalization of strategies and targets provides opportunities for public engagement and deliberation on the appropriate role and implementation of CDR as part of national mitigation efforts. Targets that are consistent with global pathways and national responsibilities and offer sufficient detail are thus a precondition to the development of domestic and international long-term carbon pricing and regulation instruments for mobilizing CDR alongside emissions reductions. At the same time, targets alone are not sufficient to fulfill the stated objectives as they have to rely on more specific and operational instruments for implementation.

Public innovation and research funding is another necessary (but not sufficient) element to achieve alignment with the stated objectives, given that a broad ensemble of approaches needs to be nurtured in order to prevent running out of options. Some approaches still have a long technology learning path ahead of themselves – particularly approaches involving geological storage or mineralization with high innate permanence. Activity-focused public funding is on its own not sufficient and as per its defined scope often does not entail funding longer-term operation of pilot plants in a results-based manner.

Therefore, to fund operating cost of pilot plants and initial projects at scale (e.g., in a period in which long-term instruments are not yet ready) mitigation-oriented temporary subsidies are needed to avoid a valley-of-death for actors that run out of innovation and research funding before they can access permanent carbon pricing instruments or benefit from regulation. Yet such funding may per its stated objective be limited in time and scale of activity and has thus to pave the way for inclusion of the funded activities in a pricing or regulatory regime that is intended to be operational indefinitely (or for as long as gross positive emissions make CDR necessary).

True long-term alignment with net-zero mitigation pathways ultimately requires carbon pricing or regulatory instruments that effectively ensure covering long-term marginal operating cost of a nationally appropriate set of CDR approaches that will remain in place indefinitely. This has to be the objective of any national or regional climate target that cannot with absolute certainty achieve 100% emissions-reductions based decarbonization (within the stated time-horizon). This arguably applies to virtually all Paris Agreement Parties, perhaps with the exception of countries such as Bhutan that presently already boast a negative emissions balance due to extensive and stable forest cover and very minor industrial activity.

Given the potential for significant side-effects – both harmful and positive – largely depending on CDR policy design (Honegger et al., 2020) and scale (Cox et al., 2018) as well as the importance of climate change mitigation for achieving long-term sustainable development (Nerini et al., 2019), it is essential that both domestic policy instruments and international (market and non-market) cooperation efforts are based on sound understandings of potential negative side-effects and positive co-benefits arising from every specific intervention. While the rulebook for Article 6 itself may require host countries to assess such effects on their sustainable development priorities, this minimal requirement may not be sufficiently stringent. It would seem advisable that – particularly early movers – put in place a far-reaching and transparent process through which to judge possible sustainable development implications that take all involved countries' SDG strategies into consideration. International certification (e.g., for biomass sourcing and biochar quality) could, furthermore, help create transparency and a trustworthy basis for broader efforts (Cox and Edwards, 2019).

While we observe some steps toward fulfilling individual functions (see **Table 2**), we find each to be falling short even taken on their own. Given that all six functions are necessary conditions, we submit that urgent action at multiple levels is needed in order to move toward comprehensive and overall sufficient policy mixes.

We notably observe the following shortfalls – even among what we consider to be the best-practice approaches and much more so in others' (see also **Table 2**): 1. lacking specificity on the role of CDR (even in the highly advanced plans of Sweden), 2. absence of a systematic approach to R&D and piloting activity-based support for CDR (even among the well-endowed EU-funded innovation support instruments), 3. lack of proactive invitations for public engagement and deliberation by public administrations developing policy mixes for CDR (including in countries with well-established deliberation processes on mitigation policy such as Germany, the UK, and France), 4. lack of clear steps to transition to a cost-efficient long-term CDR policy framework, 5. gaps regarding provisions on accounting of (trans-boundary) CDR and CDR-specific MRV under the Paris Agreement's transparency framework and Article 6 (a study on a European carbon removal crediting mechanism may offer an opening only by 2023), and 6. no systematic approach to anticipating and managing potential negative and/or positive side-effects of CDR applications.

The above list demonstrates that key functions lay in the domain of public policy. Voluntary efforts by private sector actors can contribute to some of the objectives (e.g., mobilizing removals including by funding research and development of high-cost CDR types), these efforts cannot on their own fulfill the functions that public policy mixes need to provide. Functions that in particular cannot count on private efforts include most notably: Functions 1 and 3 (gaining clarity on the societally desirable role of CDR through proactive public deliberation), function 4 (as costly voluntary efforts cannot be maintained indefinitely on competitive markets), and functions 5 and 6 (as

TABLE 2 | Examples of government steps toward specific policy functions (and how they fall short).

Function	Example
1. Clarity on role of CDR (aligned with Paris targets)	Sweden specifies an 85% domestic emissions reductions target and maximum permitted use of so-called supplementary measures, consisting of CDR (increased carbon sink in forests and land, BECCS and other technological measures for negative emissions) and international verified mitigation outcomes, to compensate for the remaining 15% of emissions to reach net zero by 2045 and to go beyond net zero thereafter. Sweden has also set intermediary goals for 2030 and 2040. In its strategy and action plan for achieving negative GHG emissions after 2045, Sweden specifies preliminary contributions of different categories of supplementary measures, and their planned evolution over time, e.g., gradually shifting the source of international verified mitigation outcomes from emission reductions to CDR.
2. Accelerate CDR innovation, technology learning and cost reductions	The EU funds research and development of CCS (including some CCS-reliant CDR) as well as (separately) agricultural soil carbon based CDR. These instruments do not systematically target CDR (lacking focus), but instead broader technology/sector categories.
3. Public engagement	France, the UK and Germany (as well as others) have created deliberation processes dedicated to inviting a public conversation on desirable climate change mitigation policy mixes Federal Ministry of the Environment. Nature Conservation and Nuclear Safety (BMU), 2020; Convention Citoyenne pour le Climat (CCC), 2021a,b; Federal Ministry for Economic Affairs and Energy (BMWi), 2021; United Kingdom's Climate Change Committee (CCC), 2021. All three countries have failed to give adequate space to considerations regarding the role of CDR and corresponding policy design for reaching long-term mitigation objectives.
4. Transition to a cost-efficient long-term CDR policy framework	The European Commission has signaled intent to develop a carbon removal crediting (CRC) mechanism. The mechanism is currently designed by consultants and will only enter political consideration from 2023 onwards.
5. Consistent MRV and accounting	CDM and IPCC guidance offer indications for the future accounting of CDR. Such guidance may be interpreted in different ways (e.g., in case of transboundary CDR value-chains) and due to the novelty of many CDR approaches application to date has been limited.
6. Identifying and managing side-effects	Voluntary carbon credit certifiers have offered relevant standards for assessing side-effects of mitigation activities (e.g., the Gold Standard) and under the Kyoto Protocol national governments were tasked with determining the overall desirability of proposed activities. To date, equivalent standards and procedures have not been developed – neither for voluntary efforts nor for governmental CDR policies.

global comparability is required). Furthermore, private actors can only partially contribute to (costly) innovation. In the best case, they can complement or build upon public mitigation efforts – if these represent a stringent framework. Where the public policy ensemble, however, is incomplete or inconsistent, the absence of comparable approaches to fundamental pillars of mitigation can lead to a "race to the bottom." This risk is particularly large where voluntary activities are wrongly perceived to replace public policy and thereby alleviate pressure on governments to take on their responsibilities.

ACTIONABLE RECOMMENDATIONS

Against the backdrop of six functions that each appear necessary – but on their own not sufficient – for pursuing CDR in alignment with the Paris Agreement, we find a need for governments to start pursuing a systematic approach to multi-layered public policy instrument deployment targeting CDR as part of their mitigation efforts at the international and domestic level and with the private sector.

Our recommendations target three types of actors: those shaping international climate policy, those shaping national level climate policy and private sector (including philanthropic) actors.

International Climate Policy

International climate policy may have to undergo a paradigm shift (Geden et al., 2019) in order to overcome the present chasm between the abstract notion of CDR as relevant for Paris-aligned net-zero emissions targets and the widespread lack of operationalization in policy. This includes actors shaping expectations regarding revised NDCs and the outstanding parts of the Paris Agreement rulebook relating to the guidance and rules for international transfers of mitigation outcomes under Article 6. In the Article 6 work programme, methodological work on baseline setting and MRV should consider also CDR-specific issues so as to safeguard the environmental integrity also of CDR-based transfers.

In light of fundamental and unresolved questions associated with varying levels of innate permanence across CDR approaches, pilot activities that specifically examine these issues conceptually while testing them in practice can play a crucial role in highlighting and – through appropriate design and application choices – demonstrating how environmental integrity can be ensured while mobilizing CDR. International institutions should therefore support methodological work on baseline and MRV methodologies for various CDR types and advance conceptual work on instruments to ensure permanence and prevent transfers of removal credits for activities with a high risk of non-permanence. Moreover, a stringent yet operational approach to additionality assessment needs to be developed. This type of work will be essential for ensuring proper accounting of CDR in line with the spirit and provisions of the Paris Agreement and relevant IPCC inventory guidelines and practices.

Many actors in international climate policy also play a key role in creating expectations for and judging the ambition levels in countries' mitigation contributions and strategies (NDCs and LT-LEDS) as well as implementation plans and policies. For coherent planning regarding CDR in particular and mitigation in general, it is crucial that these judgments take a long-term view (Morrow et al., 2020) and anticipate the need to include both short- and long-term action to promote CDR. This could include, for example, recognizing particular efforts toward advancing high-cost CDR options, which may not provide significant short-term results in tons of CO_2 mitigated, but may be upscaled in the long-term while costs could be reduced, and thus be crucial for reaching net-zero emissions. Actors in international climate politics increasingly ought to establish the expectation that long-term targets ought to specify not only a net-zero year, but include commitment to a cumulative net-emissions constraint as precondition for judging the adequacy of contributions and to later adequately track progress.

Also, technical questions have to be resolved at the international level, which affect the setting of national targets: The operationalisation of the Paris Agreement's Enhanced Transparency Framework should address CDR specific challenges and offer accounting rules that are suited to deal with all variants of CDR. This includes also the possibility of CDR activities with transboundary CDR value-chains, which risk causing issues of double counting if not addressed properly.

In the context of the upcoming global stocktake, the role of CDR in reaching the long-term goal of the Paris Agreement should become a focus area that promotes public attention and debate relating to the transparent elaboration of CDR roadmaps – i.e., policy mandates for a particular role of CDR within long-term mitigation efforts. In this context negotiators in the international process as well as Parties' domestic climate policy planners and NDC developers should examine the operational pros and cons of specifying both net-emissions reduction pathways and how these are decomposed into separate gross emissions and CDR pathways. Separate targets can have the advantage of creating greater transparency and offer an opportunity to critically examine the adequacy of plans, yet they may also complicate definitions of climate finance or the use of carbon markets for international cooperation.

National Level Climate Policy

While many issues necessitate international coordination thus requiring international and domestic actors work hand-in-hand (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), actors focussing on national climate policy face several specific challenges associated with CDR.

Perhaps most notably, governments need to establish long-term commitments and policies that ensure the delivery of emissions reductions and CDR for reaching net-zero emissions within the constraints of a fair, Paris-aligned carbon budget. Furthermore, they – particularly in developed countries – need to implement short- to medium-term efforts to tackle the R&D costs as well as the capital and operating cost of CDR activities. Unspecific targets (e.g., a single-year target for achieving net-zero emissions, without a carbon budget constraint) are ambiguous and could, in extreme cases, entail no transformation at all. Thus, NDCs and LEDS, or at least the related policy documents, ought to increasingly specify intermediary, sector-specific objectives, including for CDR-related action and elaborate a quantitative carbon budget that represents a fair share of the collective effort.

Such commitments, communicated via NDCs and LT-LEDSs, need to promptly be backed with specific policy instruments that can effectively deliver the stated short- or long-term objectives: Short-term activity-focussed funding (focussed on R&D- or pilot activities to accelerate innovation and technology learning) as well as long-term mitigation-focussed results-based instruments (market mechanisms or service contracts awarded to the most cost-effective CDR provider) are both necessary as a basis for – and to achieve the necessary transition to – efficient, effective, and long-term operation. For this purpose, forward-looking domestic climate policy has to include proactively advancing best-practice CDR pilot activities as well as gradually developing roadmaps, guidance, and where needed regulation not only to advance domestic policy, but also to offer other countries project templates and learning opportunities. While rooted in domestic climate policy, some governments may also choose to fund CDR activities elsewhere – either as climate finance (whereby the host country counts the mitigation outcomes toward its NDC through its GHG inventory) or by acquiring CDR-based mitigation outcomes under Article 6 (whereby the host country would have to "uncount" any internationally transferred mitigation outcomes).

Given the large potential for double counting between voluntary market activities (often involving grandiose claims) and public climate policy, regulation may become necessary to address also voluntary market activities by private sector actors. At a minimum, further concerted international efforts are needed to enhance the comparability of private sector actors' claims associated with mitigation outcomes to avoid a race to the bottom in voluntary mitigation activities, including by ensuring that they are additional, robustly designed and implemented, that the associated mitigation outcomes are robustly MRV'd and accounted for, and that leakage and non-permanence are appropriately addressed.

Particularly for large-scale nature-based removals, policy-makers may want to advance stronger environmental and social safeguards, based on host countries' sustainable development strategies. Given the public calls for strong scrutiny of CDR activities, this may not only be warranted for the sake of preventing adverse impacts and enabling co-benefits, but also necessary for alleviating public concerns and preventing a negative public perception of such (costly) publicly funded mitigation efforts and thereby ensure long-term feasibility.

Private Sector and Philanthropic Actors

While public authorities are responsible for ensuring coherence with Paris Agreement objectives and – where deemed as such – ensuring that CDR is being offered as a public service, private sector actors can, and in some cases, have already become frontrunners, demonstrating possible approaches and creating expectations. Under most circumstances it will be private actors who deliver CDR – be it as is currently the case in anticipation of future policy measures, as part of ESG efforts, or simply in executing upon a functioning business case enabled by policy incentives or regulation. Continuous learning and exchange of ideas between public and private actors is therefore important to identify barriers as well as opportunities – particularly at this early stage where public roadmaps, strategies and policies are to be developed.

Given the risk of undermining mitigation through badly executed actions causing adverse side-effects, eroding public support or proving ineffective or not permanent, the current flurry of private initiatives needs to be scrutinized and strengthened to enable a "race to the top" in the quality of activities instead of a temporary rush that risks to tarnish all CDR efforts. This is true not only for companies' internal efforts but all the rapidly emerging markets for CDR credits. Past lessons and experiences must be utilized to the fullest.

The limited innate permanence of carbon storage in the biosphere (challenging nature-based approaches), the inherent risk of reversals in these removal activities, and the risk of other side-effects is reminiscent of failures and scandals associated with forestry projects in the early days of in the CDM and in voluntary markets (Michaelowa et al., 2019b). These experiences should be a warning sign and lead us to approach "nature-based solutions" with great care. Further efforts are needed to enhance the certification of high-quality nature-based removals, building on and engaging with the extensive existing efforts.

Finally, more progressive actors in the private and philanthropic sector should follow with a willingness to address CDR with a long-term perspective and contribute to exploring high permanence approaches in which CO_2 is stored underground and/or mineralized. Together, we can hope that these efforts will be met by governments stepping up and putting in place the necessary policy infrastructure to create sustained and reliable long-term public demand for CDR.

DISCUSSION

While CDR has a long-contested history in climate policy (Carton et al., 2020) and – at large-scale – subsumed under "geoengineering" in biodiversity and waste policy (Brent et al., 2018), it can no longer be sidelined in international and domestic climate policy, given that such neglect further undermines the already drastic underachievement of collective mitigation (Michaelowa et al., 2018).

We set out to contribute to the emerging CDR-policy literature, in particular by offering a structure that operationalizes conditions, concerns, and expectations already voiced in the academic literature and rooting this structure in the governance architecture afforded by the international climate change regime. We believe to have succeeded in our approach, particularly in offering six necessary functions that allowed us to identify governance gaps and deduce actionable recommendations. Upon further examination the six functions may prove not exhaustive or warrant refinement. We are however confident that they, indeed, are necessary.

Our examination of CDR governance and funding needs and ongoing efforts highlights the enormous amount of work that lies ahead in order to embed CDR into climate policy in a manner that accelerates, rather than undermines the pursuit of overarching climate (and sustainability) objectives.

Action is needed at all levels to 1. gain clarity on the intended role of CDR for limiting warming, 2. accelerate innovation, 3. ensure participation, 4. transition to long-term cost-effective operation, 5. robustly measure, report and verify results as well as account for them properly and 6. manage side-implications. We were surprised by the currents' policy mixes' near-universal failure to address all six policy functions, although Sweden emerged as a clear leader and possible exception. We see possibilities to "anchor," adapt and develop existing policy tools into comprehensive policy mixes addressing these functions. In our view, this will, however, have to build on strong and high-level public engagement. In our view, future work needs to properly address the normative nature of questions regarding the appropriate role of CDR in public policy and should not shy away from the apparent divergence of views on these matters. We see an important research need on the way to design deliberation processes and to build them on a science-based manner that utilizes the rich experience in mitigation policy overall and with CDR-related practices in particular. To move away from the current state of conceptual reliance of net-zero pledges on CDR without actual policy planning to mobilize CDR at scale, we need to see stronger transdisciplinary engagement (Dowell et al., 2020) and broader alliances across research, CDR practitioners and industry partners, as well as across public policy domains (Fuss et al., 2020). Such alliances should aim at generating a sound understanding of how innovation can be accelerated, costs can be brought down, and costly "dead-end streets" can be avoided in the particular political economy of each country or region. The sense of urgency for such collaborative effort is growing in light of the time-constraint afforded by "well-below 2°C" or 1.5°C compatible net-emissions budgets. Therefore, we call on the entire community of policy-oriented research to overcome disciplinary barriers and to embark on the necessary collaborative work without delay.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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