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Taking stock of carbon dioxide removal policy in emerging economies: developments in Brazil, China, and India

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ABSTRACT

Deliberately removing carbon dioxide from the atmosphere is an important element of bringing mitigation pathways in line with the climate goals of the Paris Agreement. To reach global net-zero CO_2 emissions and limit global warming to 1.5°C with no or limited overshoot, global mitigation pathways assessed by IPCC's Sixth Assessment Report require some world regions to achieve net-negative CO_2 emissions with large-scale carbon dioxide removal (CDR) deployment. This raises important questions about the availability and feasibility of CDR deployment in different societal and political contexts.

This paper therefore combines an analysis of CDR deployment in a sample of scenarios from the IPCC AR6 database with a bottom-up analysis of the state of CDR governance and policy in countries considered key in scaling up CDR capacity and not yet covered by existing research. In particular, the paper focuses on Brazil, China, and India as important emerging economies and large emitters. We highlight the expected use of CDR methods in those regions in scenarios and systematically assess and compare the level of CDR regulation and innovation across these countries. This comparative perspective has the potential to broaden the understanding of existing and emerging CDR policies and politics.

The synthesis of the case studies provides three key contributions to existing literature: First, we explore the state of CDR governance and policymaking in key emerging economies. As in OECD countries, there is a notable lack of CDR regulation and innovation to enable the scale of CDR required in the short- and medium term. Second, we identify that *repurposing policies* is a key type of emerging CDR policymaking in these countries targeting CDR methods in the land use, land use change and forestry (LULUCF) sector. We find that the repurposing efforts strengthen the level of regulation and innovation for this group of methods. Third, we explore three building blocks (regional differentiation, delay of upscaling, sustainability thresholds) of plausible CDR deployment narratives that could help bridge integrated assessment models and comparative case studies in future research.

Key policy insights:

- As in OECD countries, there is a notable lack of CDR regulation and innovation to enable CDR scale-up in Brazil, China, and India, questioning the political feasibility

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of existing scenarios.
- CDR policy is not starting from scratch, existing policy instruments – especially in the LULUCF sector – can be repurposed to strengthen the level of CDR regulation and innovation.
- While policies and regulations for CCS-based CDR are lacking in China, Brazil and India, the level of regulation for LULUCF-based CDR is higher.
- Comparative case studies can inform emerging CDR policy and governance at national and international levels, as well as exogenous CDR deployment narratives for future integrated assessment modelling.

1. Introduction

Achieving the climate change mitigation targets of the Paris Agreement requires unprecedented changes in all aspects of society (IPCC, 2022). In recent years, it has become increasingly clear in climate science and acknowledged in the climate policy debate that emissions reductions alone will not suffice to achieve the Paris Agreement goal of 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels' (Fuss et al., 2020; Riahi et al., 2021; Rogelj et al., 2018). Carbon dioxide removal (CDR) will be unavoidable to counterbalance residual emissions for achieving net-zero CO_2 emissions and reaching net-negative emissions in some sectors and countries (Babiker et al., 2022).

In the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (AR6) Working Group III (WGIII) report, modelled mitigation pathways that limit warming to 1.5°C (>50%) include net-negative CO_2 emissions from the Agriculture, Forestry and Other Land Use (AFOLU) sector that range between 20–400 $GtCO_2$ and gross removals by Bioenergy with Carbon Capture and Storage (BECCS) (30-780 $GtCO_2$) and Direct Air Capture and Carbon Storage (DACCS) (0-310 $GtCO_2$) (IPCC, 2022). Conceptually, the IPCC AR6 WGIII report identifies three functions for CDR in ambitious mitigation pathways: (1) accelerating near-term mitigation, (2) counter-balancing residual emissions for 'net-zero', and (3) achieving net-negative emissions. Whether and how these functions in climate policy are already materializing in practice, and whether the large amounts of CDR are plausible and feasible, will be a key question in future research on CDR. The existing research on CDR governance and policymaking highlights the substantial differences across countries in their way of addressing CDR and points to deficits in the regulatory environment for facilitating large-scale CDR deployment as an element of climate policy (Schenuit et al., 2021; Smith et al., 2023).

In this article, we therefore aim to contribute three elements to the existing literature: first, we highlight *when*, *where*, and *which* CDR methods are scaling up in different global mitigation pathways from the IPCC AR6 database. Second, we provide case studies on three high-emitting, emerging economies from world regions that provide large shares of CDR in existing IAM pathways and advance an existing set of idealized types of CDR policy. Third, we explore the way forward for interdisciplinary work linking quantitative modelling and non-quantified social science knowledge from case studies.

This combined analysis allows the exploration of the spatial heterogeneity of CDR deployment in ambitious global mitigation pathways. The identification of world regions that contribute large shares of CDR is a relevant aspect of equity considerations in integrated assessment models (IAM) (Lee et al., 2021; Lenzi et al., 2021; Strefler et al., 2021) as well as a policy-relevant and politically contested issue under the UNFCCC (Malyan & Chaturvedi, 2021a; Mohan et al., 2021). Regions in the Global South tend to account for a large share of global CDR deployment in global IAM mitigation pathways (see Section 3). Most research on CDR governance and policymaking, however, has so far been limited to Organisation for Economic Co-operation and Development (OECD) countries (Bellamy et al., 2021; Fridahl et al., 2020; Schenuit et al., 2021). Therefore, we aim to contribute the first comparative case studies of the key emerging economies of Brazil, China and India.

This interdisciplinary and comparative approach contributes to exploring ways to merge quantitative modelling with non-quantifying social science knowledge (Brutschin et al., 2021; Geels et al., 2016; Peng et al., 2021a; Pianta & Brutschin, 2022; Trutnevyte et al., 2019; Turnheim et al., 2015) and points to areas for future interdisciplinary work to improve the political robustness of global IAM mitigation pathways.

2. A short history of CDR in IAMs

The debate on the large-scale use of CDR as an element of mitigation strategies dates back to the late 1990s (Möllersten & Yan, 2001; Obersteiner et al., 2001; Williams, 1998). With the IPCC's AR5 and the large amount of CDR required in the assessed scenarios until 2100 to stay below the 2°C level (IPCC, 2014), the issue has gained traction and received criticism (Anderson & Peters, 2016; Fuss et al., 2014; Geden, 2015). In the run-up to the IPCC Special Reports on 1.5°C Global Warming (IPCC, 2018) and Climate Change and Land (IPCC, 2019), the research communities started working to refine the knowledge on the geophysical and techno-economic availability of CDR, including its limits when considering sustainability goals (e.g. Holz et al., 2018; Roe et al., 2021; Smith et al., 2019; van Vuuren et al., 2018).

The importance of CDR in IAMs has been continuously criticized in recent years (e.g. Hasegawa et al., 2021; Pedersen et al., 2021). Two main criticisms have been raised: first, the sustainability trade-offs, e.g. with biodiversity and food security (Anderson, 2015; Creutzig et al., 2021). Second, researchers have identified a moral hazard associated with CDR, raising the issue that the deployment of large-scale CDR could lead to an obstruction of emissions reductions (e.g. McLaren et al., 2019; Morrow, 2014). IAM-based studies have responded to this criticism in two ways: First, modellers have increased efforts to broaden the CDR portfolio in IAMs to reduce reliance on land-intensive BECCS, for example by improving DACCS and Enhanced Weathering (EW) representation (e.g. Bistline & Blanford, 2021; Fuhrman et al., 2021; Hanna et al., 2021; Strefler et al., 2021). Second, modellers tried to reduce the reliance on CDR. Riahi et al. (2021) presented scenarios that do not allow global net-negative CO_2 emissions and avoid temperature overshoots. Nevertheless, even these modelled pathways still assume CDR to counter-balance residual emissions from some sectors and in some world regions.

In this article, we argue that these efforts should be accompanied by the integration of CDR policy insights to further enhance the realism of IAMs. Enriching and calibrating CDR-related assumptions with policy contextualization is an important step towards providing politically robust mitigation pathways (Pianta & Brutschin, 2022). The need to integrate social science knowledge into IAMs has been articulated by many scholars (Cherp et al., 2018; Geels et al., 2016; Turnheim et al., 2015; Victor, 2015). A growing number of such 'bridging studies' (Hof et al., 2020) can be identified in the literature and efforts to apply, operationalize, and further develop such strategies have emerged (Brutschin et al., 2021; De Cian et al., 2020; Peng et al., 2021b; Pianta & Brutschin, 2022; Roelfsema et al., 2022; Stammer et al., 2021; van Sluisveld et al., 2020). Trutnevyte et al. (2019) summarize the existing efforts to bridge IAMs and social science knowledge by identifying three main strategies: *bridging*, *iterating*, and *merging,* with increasing degrees of integration. For this analysis, we follow an iterative strategy, aiming to take a first step by developing building blocks for social science-informed exogenous CDR deployment narratives that could be translated into quantified assumptions for new model runs in future research.

3. Current scenario generation and CDR

Across global IAMs, the representation of technologies and techno-economic parameters differ considerably. Besides the structural representation and the numerical parametrization, there are different rationales of projecting techno-economic parameters (Krey et al., 2019). As mentioned in Section 2, the technological representation of the different CDR methods has evolved rapidly since the integration of BECCS (Tavoni & Socolow, 2013). Most of the IAMs include BECCS, and are starting to model DACCS and EW (Fuhrman et al., 2021; Gidden et al., 2023a; Grant et al., 2021; Realmonte et al., 2019; Strefler et al., 2021).

Here we focus on the reported output variables from scenarios, but it is essential that future work explores what is 'under the hood' (Krey et al., 2019) and which assumptions different models make about the timing and rates of technology upscaling. In the following, we focus on a few selected C1 category scenarios from the AR6 database (Byers et al., 2022) that limit global warming to 1.5°C (>50%) with no or limited overshoot and some of which are illustrative pathways across the AR6 WG III Report (Riahi et al., 2022). The main rationale behind this scenario selection is to reflect a variety of stylized mitigation pathways that have been prominently discussed in the literature.

We focus on six C1 scenarios to ensure a higher level of comparability. All of the selected scenarios assume uniform carbon prices. We include the scenario 'CEMICS SSP2 1.5C full CDR' developed by REMIND-MAgPIE because it is one of the few scenarios in the C1 category that explicitly reports EW deployment rates (Strefler et al., 2018). The 'Low Energy Demand' (LED) (Grubler et al., 2018) is shown because it does not rely on CDR methods that require Carbon Capture and Storage (CCS) in the process chain (hereafter: CCS-based) and EW; the 'SusDev SDP' (SDP) (Soergel et al., 2021) is shown as it was developed to address many Sustainable Development Goals (SDGs), and three net-zero scenarios with a 500Gt carbon budget from the ENGAGE project from WITCH, REMIND and MESSAGE models are included for additional comparison to trace differences across models (Riahi et al., 2022).

In Figure 1, in the upper panels (A), we show the cumulative rates of direct carbon removal in the land sector, BECCS and DACCS, and, if explicitly reported by a model, EW in $GtCO_2$. The reported direct carbon removal in the land sector is based on Gidden et al. (2023b), who provide a reanalysis of existing models to specify gross direct carbon removal levels in the land sector. In the lower panel (B) we display annual deployment rates in $GtCO_2$. Despite the growing body of research, the level of uncertainty about CDR deployment that can be plausibly modelled remains high. In Figure 1, we explored the trends along key scenarios at the global level. However, in order to improve the realism of IAMs and to explore the feasibility of these existing pathways, higher granularity data on world regions, as well as more attention to the temporal dimension of feasibility are required (Brutschin et al., 2021). We thus also present regional level data for the selected scenarios in Figure 2.

We can detect some patterns across regions in the selected model results: For BECCS, several scenarios assume an early deployment of the technology in the Asia, Latin America, and OECD regions in this decade. There are also some interesting model differences. For example, the WITCH-based scenario assumes a slower BECCS scale-up in Asia and Latin America compared to the REMIND-MAgPIE-based scenarios 'CEMICS SSP2 1.5C full CDR' and 'NPi2020_500'. Overall, there is a considerable degree of uncertainty. A wide range is also reported for direct carbon removal in the land sector. However, despite these differences, it is worth noting that direct removals begin to increase immediately, especially in the world regions Asia, Latin America, and Middle East and Africa . The variable 'Carbon Removal-Land Direct' shown here also suggests that after this rapid increase, gross direct carbon removal levels peak and decrease throughout the second half of the century.

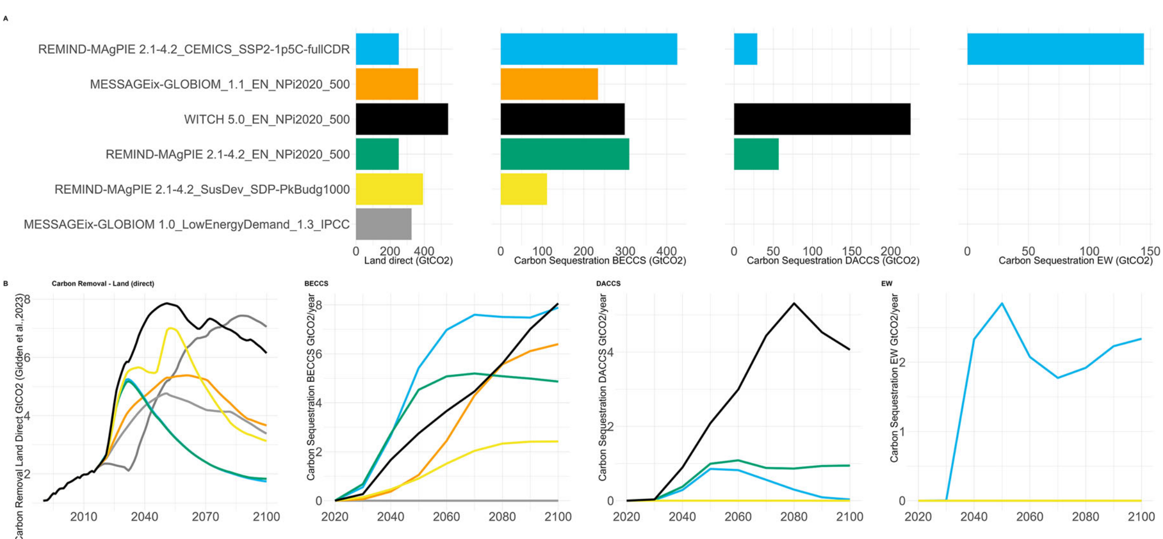


Figure 1. Panel A reports cumulative carbon removals in $GtCO_2$ across different technologies for the select C1 scenarios, for BECCS, DACCS and EW from the AR6 database (Byers et al., 2022), and for direct removals in the land sector from a reanalysis (Gidden et al., 2023b), variable Carbon Removal – Land (direct). In Panel B annual deployment rates in $GtCO_2$ are displayed for each respective technology from the same sources as in Panel A.

Figure 2. Values for the select C1 scenarios from the AR6 database (Byers et al., 2022) for BECCS, DACCS and EW from the AR6 database (Byers et al., 2022), and for direct removals in the land sector from a reanalysis (Gidden et al., 2023b), variable Carbon Removal – Land (direct) for five key IAM regions Asia (R5ASIA), Latin America (R5LAM), Middle East and Africa (R5MAF), OECD90 and EU (R5OCECD90 + EU), Reforming Economies of the Former Soviet Union (R5REF) (see Supplementary Material 1 for regional definitions)

Overall, the pathways show that the regions of Latin America and Asia typically contribute large amounts of CDR. They point to a rapid upscaling of both Land Use, Land-Use Change, and Forestry (LULUCF) and CCS-based CDR in the current and next decade, raising questions about the state of CDR policy in these regions and whether these amounts are politically feasible. Since the social science literature lacks comparative case studies on countries in these regions, the knowledge about the credibility and political feasibility of these pathways is very limited. As a starting point for exploring plausible developments of CDR deployment, we conducted case studies on key countries in these regions: Brazil, China, and India. We see this study as a first step in comparative work across these countries and regions, with the aim of stimulating future work.

4. Assessing the state of CDR regulation and innovation: towards an analytical framework

The emerging literature on CDR governance and policymaking provides an increasingly fine-grained understanding of frontrunners in regulating and incentivizing CDR (e.g. Bellamy et al., 2019; Boettcher et al., 2023; Buck et al., 2023; Buylova et al., 2021; Fridahl et al., 2020; Geden et al., 2019; Honegger et al., 2021; Nemet et al., 2018; Thoni et al., 2020). While there is a growing body of empirical case studies (Bellamy et al., 2021; Boettcher, 2020; Fridahl et al., 2020; Fuss & Johnsson, 2021; Schenuit et al., 2021), not all world regions have been covered.

Building on the analytical framework first presented in Schenuit et al. (2021), we develop a taxonomy of different levels of regulation and innovation to advance comparative research and explore the current state of CDR policymaking (see Figure 3). A first pillar assesses the level of CDR-related regulation based on six key building blocks of CDR policymaking. To allow for systematic and comparative analysis across countries, we conceptualize this as an ascending ranking. It should be noted that the ranking is a conceptual distinction and simplification to allow for comparisons across countries. The hierarchy inscribed in the ranking reflects the degree to which CDR is integrated into climate policy, but we acknowledge that CDR policymaking is more complex in the real world. It is important to note that the ranks are not mutually exclusive, nor are certain lower rankings necessarily a prerequisite for the higher ones. Used as a strategy for structuring and coding the empirical material, this analytical heuristic helps to identify commonalities and differences across cases through systematic coding (see Table 1, Supplementary Material 2). In the second pillar, we capture the stages of CDR innovation. This conceptualization draws on Nemet et al. (2018). In this taxonomy, we do not include the sixth stage, 'public acceptance', because public acceptance data for CDR specifically is scarce for the countries we focus on here.

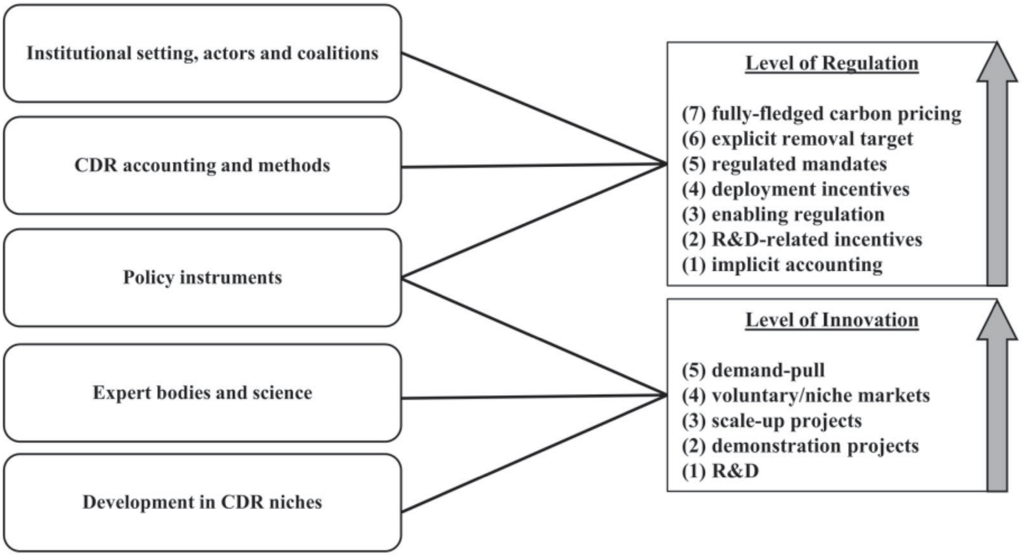
We conducted a three-stage research process. First, together with country experts, we collected empirical observations of the state of CDR policy based on the five key dimensions (Figure 3). Through an iterative process of desk research and exchange with country experts, key observations were identified and documented (see Supplementary Material 2). This material is the backbone of the comparative approach and the resource for the second step: coding and assessing what level of regulation and innovation can be identified in the different cases, separately for LULUCF-based and CCS-based CDR. In a third step, we synthesized the findings and linked them to the broader CDR policy and governance literature.

5. Governing CDR in Brazil, China, and India: A bottom-up assessment

The following section summarizes the main observations derived from the analysis and provides summaries for each country (for details and a systematic coding following the framework outlined above, see Table 1 in Section 5.4 and Supplementary Material 3). It is important to note that while the comparison conducted here aims at addressing a knowledge gap on CDR policy and governance in emerging economies, it can only provide a snapshot of the current status quo and is thus a starting point for future research.

5.1 Brazil

Since the early days of multilateral climate governance, Brazil has been perceived as a key actor (Franchini & Viola, 2019). This is related to both the risks for climate through deforestation and the mitigation potentials of forest conversation, reforestation, and afforestation (Rochedo et al., 2018). Given the importance of the agriculture and forestry sectors, AFOLU-related policies have always been important in Brazilian climate policy (Brazilian Government, 2008). The vast Brazilian tropical territory is often included in the climate change debate, and many in the country view the AFOLU sector as Brazil's 'silver bullet' to compensate for hard-to-abate emissions. Land-based mitigation is expected to contribute significantly to meeting the 2050 climate target and is also perceived as a possible revenue stream through international cooperation (Baptista et al., 2022). President Lula de Silva's administration has promised that mitigation in general and combating deforestation in particular will be among the government's top priorities (Rodrigues, 2023). It has re-established the Amazon Fund, as well as the programme of deforestation control (Brazilian Government, 2023), and announced new initiatives at



Level of regulation	Description
Implicit accounting	'Net'-targets established, CDR methods could theoretically be accounted towards mitigation targets.
R&D-related incentives	Incentive structures for CDR-related research and development projects, e.g. through public co-funding.
Enabling regulation	Regulation that enables and allows all elements of CDR process chains, e.g. monitoring, reporting and verification, or transport and storage of CO_2.
Deployment incentives	Financial remuneration for removing carbon from the atmosphere (e.g. direct payment, tax credit, etc.).
Regulated mandates	Mandates or obligations to remove a certain amount of CO_2 from the atmosphere by specific actors or sectors.
Explicit removal target	A quantified removal target as part of mitigation strategies; in addition to and separated from an emissions reduction target.
Fully-fledged carbon pricing	Carbon pricing instruments that cover CDR, e.g. through integration into emissions trading systems.
Level of innovation	**Description**
Research and Development	Public, private, or joint research and development funding dedicated to CDR methods.
Demonstration projects	Public, private, or joint funding and implementation of CDR demonstration projects.
Scale-up projects	Initiatives and projects to scale up deployment of specific CDR methods.
Voluntary/niche markets	Markets for trading credits generated through CDR deployment.
Demand pull	Established demand-pulls, e.g., through voluntary corporate commitments or legally binding climate targets.

Figure 3. Analytical framework to study the level of CDR regulation and innovation, based on and further developed from Schenuit et al. (2021).

COP28, including the 'Restoration Arc Fund' aimed at ecological restoration and storing carbon (Agência BNDES de Notícias, 2023).

5.1.1 Level of CDR-relevant regulation

In 2022, the Brazilian Government pledged to achieve net-zero GHG emissions by 2050 in its updated NDC (Brazilian Government, 2022). The role of *LULUCF-based* CDR became less specified in the updated NDC (Brazilian Government, 2022; den Elzen et al., 2022). However, the new government, re-committed to restoring 12 million hectares until 2030 (MMA, 2023). In terms of collectively binding policies, the Climate Change Law 12187/2009, and its regulation Decree n 7390/2010 (replaced by Decree n 9.578/2018), included CDR actions in its target (including 15 million hectares of degraded pasture, the expansion of 4 million hectares of crop-livestock-forestry integrated systems, and the expansion of 3 million hectares of planted forest area). Furthermore, the Low-carbon Agriculture Program (ABC+), which aims to develop revenue streams for ecosystem services by farmers, is linked to instruments for trading carbon credits. In addition, the Floresta + programme aims to increase the payments for environmental services related to forest conservation and restoration. Programs such as the National Alcohol Program (Maroun & Schaeffer, 2012), the National Biodiesel Program (Rathmann et al., 2012), and the RenovaBio Program (Köberle et al., 2022), all encourage the production and use of biofuels. These programmes are not directly related to CDR, but the governance and industry infrastructure built in the context of these programmes could be relevant for BECCS deployment. Efforts exist to use the RenovaBio programme as an instrument to encourage the development of BECCS in the country (Silveira et al., 2023).

For *CCS-based CDR*, the level of regulation is much lower. The debate is mostly confined to expert circles (Machado et al., 2021). So far, CCS developments have been mostly limited to efforts by the fossil fuel industry: Petrobras has a natural gas processing plant in the Santos Basin Pre-Salt Oil Field with Carbon Capture, Utilization and Storage (CCUS), which has been operational since 2011 (Turan & Zapantis, 2021) and reinjected 10.6 million tons of CO_2 in 2022 and accumulated 40.8 million tons (Petrobras, 2023). The coal industry in the State of Santa Catarina has a research institution that works on understanding and investing in CCS (SATC, 2019). The lack of policy support, however, is perceived as a barrier for large-scale deployment of both fossil CCS and CDR (Machado et al., 2021).

5.1.2 Level of CDR innovation

The level of innovation of *LULUCF-based CDR* methods is high. The importance of voluntary trading schemes is increasing and incentive schemes are already established (e.g. ABC+). Although still incipient, there may be space for a demand-pull coming from the private sector for LULUCF-based CDR options in Brazil in the future.

The level of innovation of *CCS-based CDR* is low. Neither BECCS nor DACCS are part of substantial Research, Development and Demonstration (RD&D) policy initiatives. However, linked to the bioethanol sector, first demonstration projects are being announced (Bioenergy International, 2021), and the gas and oil company Repsol Sinopec Brazil announced the construction of experimental DAC plants to remove CO_2 from the atmosphere (Repsol Sinopec, 2022, 2023). In the future, biochar could be an option in Brazil. Biochar is being used in agriculture at different scales, including to understand how its use affects pasture recovery (Latawiec et al., 2019); moreover, scientists have identified large potentials for EW in Brazil (Goll et al., 2021).

5.2. China

China is currently the largest emitter of annual greenhouse gases emissions, and developments in its climate policy are therefore receiving considerable attention (Skjærseth et al., 2021). Its efforts have been described as an attempt to position itself as a 'climate leader for the Global South' (Qi & Dauvergne, 2022). The Chinese President's pledge in 2020 to peak emissions before 2030 and achieve carbon neutrality by 2060, along with the submission of an updated NDC (Chinese Government, 2021; Xinhua, 2020), were applauded by climate policymakers and experts worldwide. Nevertheless, the operationalization of the target into actual policymaking is limited (Climate Action Tracker, 2023), and the substantial challenges, including domestic politics, become apparent. In the context of the net-zero pledge, existing afforestation/reforestation measures and their repurposing as CDR policymaking are gaining increasing attention (Mal et al., 2024).

5.2.1 Level of regulation

In general, China's level of regulation of *LULUCF-based CDR* is high. Reforestation programmes have existed for a long time in China and pledges to enhance the carbon sink in the LULUCF sector are part of climate policy. In its NDC, China pledged to increase the forest stock volume by 6 billion m3 compared to 2005 levels. Additionally, the enhancement of carbon sinks capability is listed as one of 'Ten Key Actions for Carbon Emission Peaking' (Chinese Government, 2021, p. 34). The NDC pledges that nature-based solutions should keep consolidating and enhancing ecosystem carbon sinks, including 'blue carbon'. It also highlights that carbon sink trading will be integrated into the national carbon emissions trading market (Chinese Government, 2021). To a limited extent, 'sink trading' is already established through forestry credits in the voluntary emission trading scheme for China Certified Emissions Reductions (CCERs) (suspended in 2017, relaunched in October 2023) (Myllyvirta et al., 2022; Shrestha et al., 2022). Similar initiatives can be identified at the province level (e.g. The People's Government of Sichuan Province, 2021). However, as in other countries, securing the quality of certificates is a challenge (Li et al., 2022). Projects that enhance LULUCF removals are typically shaped by command-and-control policies (An et al., 2021). It is important to note that carbon sequestration is not the only motivation. Initiatives such as the Three-North Shelter Forest Program in the Gobi Desert, started in 1978, show that the Chinese Government has been pursuing other objectives (e.g. avoiding desertification).

CCS-based CDR methods are the subject of discussion among expert communities, and increasing attention is being paid to CCS-based CDR in national modelling (He et al., 2022; Liu et al., 2022). However, dedicated CDR policy initiatives do not yet exist. The government is gradually promoting the RD&D and application of CCU and CCS mainly by announcing pilot projects in the 14th Five Year Plan (FYP) (see Jiang et al., 2020; Ma et al., 2023). The NDC includes these technologies in a list of so-called 'carbon peak pilots' (Chinese Government, 2021, p. 38). However, so far, existing CCS projects are linked to fossil CO_2 point sources and in most projects CO_2 is reinjected for enhanced oil recovery (EOR) (Sun et al., 2018; Turan & Zapantis, 2021).

5.2.2 CDR innovation

The level of innovation of *LULUCF-based CDR* is high, it is already a well-established component of China's climate policy. Initial attempts of 'sink trading' indicate that voluntary markets will become increasingly important. New carbon intensity targets and the net-zero target will lead to rising demand for LULUCF-based CDR.

While no specific funds for *CCS-based CDR* demonstration plants have been identified, reports on CCUS in China show that innovation policy for DACCS and BECCS is receiving more attention and that the level of innovation is expected to increase (Bofeng & Qi, 2019; Cai et al., 2021; Liu et al., 2022; Ma et al., 2023). Studies on the development of CDR-related patents indicate that, after the US, China holds the most CDR-related patents, with a focus on BECCS, biochar, DAC, and soil carbon management (Kang et al., 2022). Moreover, small start-ups can be identified, such as Carbon Infinity (Izikowitz, 2021) and 'C4X' an applicant to the X-Prize on CDR.

5.3 India

India is the world's third largest emitter and has played an increasingly important role in multilateral negotiations in the past decade (Mohan, 2017). In recent years, issues related to climate policy have moved up the national political agenda (Dubash, 2019): At COP26, the Indian government announced a net-zero emissions target for 2070. In 2022, a net-zero bill was introduced in the Parliament (Rajya Sabha, 2022). In light of the rapidly depleting carbon budget for 1.5°C, India has recently called upon developed countries to go 'net-negative', in order to free up 'carbon space' for developing countries (Mohan et al., 2021).

5.3.1 Level of regulation

The level of regulation of *LULUCF-based CDR* is high in India. In its 2015 INDC, the government pledged to create a carbon sink of 2.5–3 billion tonnes of carbon dioxide, setting a dedicated and quantified removal target, which was reaffirmed in the NDC update (Government of India, 2022a). The promotion of forest restoration is firmly anchored in India's governance architecture. However, the potential for climate change mitigation was not always the main motivation for it (Roy & Fleischman, 2022). The National Action Plan for Climate Change (NAPCC), set up in 2008, lists the Green India Mission (GIM), which aims to increase forest cover and contribute to the aforementioned NDC targets. In 2018, the government planned to create a 140,000-km tree line on both sides of national highways, grow plantations along the river Ganga and reduce the consumption of wood or biomass as fuel. There are also several state-level afforestation schemes. While the government does have ambitious afforestation plans, the country still lacks well-defined policy instruments at various levels and faces problems with implementation and accountability. The potential for revenue generation through programmes such as REDD + shaped the debate and policy proposals in the post-Kyoto and pre-Paris phase (Dutta et al., 2013; Kishwan et al., 2009), leading to the formation of strong path dependencies.

The situation is different with regard to *CCS-based CDR*. India is perceived to have a strong interest in CCS given its large coal power fleet and the potential for CO_2 sequestration, which is the subject of ongoing research (Bakshi et al., 2023; Shaw & Mukherjee, 2022). However, its regulation is not well-established and no demonstration plants for carbon storage are in operation (Global CCS Institute, and CO2RE, 2022). Observers have identified a 'lack of policy ecosystem' for CCUS (Malyan & Chaturvedi, 2021b). More recently, and in the context of the net-zero pledge (Mukherjee & Chatterjee, 2022), the issue of CCUS has gained traction and is expected to receive more support (Vishal et al., 2021). For example, the recent National Electricity Plan refers to CCS as an option to retrofit coal plants (Ministry of Power, 2022). However, recent initiatives are not CDR-specific and have a strong focus on CCU and/or CCS to abate fossil fuel emissions (Shaw & Mukherjee, 2022).

5.3.2 CDR innovation

With regard to *LULUCF-based CDR*, voluntary markets are already well established in India and the level of innovation is high. Both international incentives through REDD + and domestic programmes (GIM) have established incentive structures for enhanced afforestation. However, there are criticisms and concerns about the integrity of credits generated for and traded at voluntary markets, as well as perverse incentives (Fleischman et al., 2021).

The level of *CCS-based CDR* innovation is relatively low. Nevertheless, several CCU and CCS initiatives are under way that could potentially become relevant for future CDR initiatives. Indian industries and public sector undertakings are aiming to develop CCS facilities (Malyan & Chaturvedi, 2021b). To date, however, domestic demonstration of the technology in India is very limited (Gupta & Paul, 2019 Vishal et al., 2021;). Recently, the government joined the Accelerating CCUS Technologies initiative under Mission Innovation (MI) (Government of India, 2022b) and research efforts are increasing. For instance, the Institute of Reservoir Studies is conducting CO_2 capture and EOR field studies in Gujarat, and the National Geological Research Institute Hyderabad is testing the feasibility of storing CO_2 in basalt formations (Gupta & Paul, 2019). Additionally, two 'National Centres of Excellence in Carbon Capture & Utilization' have been founded (Ministry of Science and Technology, 2022). However, these projects are usually not with direct reference to CDR. The announcement that CDR could potentially be considered in an ETS could raise the profile of CDR (Carbon Herald, 2023).

5.4 Synthesis of case studies

The case studies illustrate that CDR policy and governance are not starting from scratch in the countries analysed and that there are significant differences (see Table 1 for results of coding, and for more details Supplementary Material 2).

5.4.1. LULUCF-based CDR

For LULUCF-based CDR, we observe an increasing attention to LULUCF-based mitigation potential in the aftermath of the Paris Agreement in all three countries. The coded *level of regulation* is the highest in India, where an explicit, quantified carbon removal target ('additional carbon sink of 2.5–3 billion tonnes of CO_2 equivalent') is part of the pledges in the NDC. However, Brazil and China also score high in the coding. All three countries have well-established governance structures for afforestation, reforestation, and restoration. However, these relatively high scores should not disguise the fact that, as in other countries, the regulation and certification of LULUCF sinks faces major methodological and political challenges. Regarding the *level of innovation*, we see

Table 1. Level of CDR regulation and innovation for LULUCF- and CCS-based CDR in Brazil, China and India, coded based on analytical framework (Figure 3) and case studies (Sections 5.1, 5.2, 5.3), '+' stands for implemented, '0' for announced/emerging, '-' for absent (see Supplementary Material 3 for details about the coding and references).

	Brazil		China		India	
Level of CDR regulation	**LULUCF-based**	**CCS-based**	**LULUCF-based**	**CCS-based**	**LULUCF-based**	**CCS-based**
Implicit accounting	+	+	+	+	+	+
R&D-related incentives	+	0	+	+	+	0
Enabling regulation	+	-	+	0	+	-
Deployment incentives	+	-	+	0	+	-
Regulated CDR mandates	+	-	+	-	+	-
Explicit removal target	-	-	0	-	+	-
Fully-fledged carbon pricing	-	-	-	-	-	-
	Brazil		**China**		**India**	
Level of innovation	**LULUCF-based**	**CCS-based**	**LULUCF-based**	**CCS-based**	**LULUCF-based**	**CCS-based**
R&D	+	0	+	+	+	+
Demonstration projects	+	0	+	+	+	-
Scale-up projects	+	-	+	-	+	-
Voluntary/niche-markets	+	-	+	-	+	-
Demand-pull	0	-	0	-	0	-

that afforestation and reforestation demonstration and large-scale projects have been carried for a long time in all three countries. The differences in the level of innovation observed here are due to the differences in efforts to trade removal certificates.

5.4.2. CCS-based CDR

The levels of regulation and innovation of CCS-based CDR are much lower. With respect to the *level of regulation*, we find that none of the countries (Brazil, China, India) has fully implemented carbon pricing that includes CCS-based CDR, an explicit and legally binding removal target, or CDR-related regulatory mandates. In none of the cases is a CDR-specific enabling regulation in place. Notably, China is the only country that shows some evidence of specific deployment incentives through its 'carbon peak pilots' (Chinese Government, 2021, p. 38). However, increasing funding for R&D, or preparations to establish them, can be identified in all three countries. As for the *level of innovation*, we did not identify any demand-side, voluntary, or niche markets, nor any large-scale deployment of these CDR methods. Nevertheless, the emerging interest of the Brazilian bioethanol sector in BECCS is noteworthy, as is the large number of patents in China indicating a potential frontrunning position in the future. As in many other countries, the current CO_2 injection capacity is a limiting factor for CCS-based CDR. Consequently, the next steps to scale up CCS-based CDR methods would need to include a detailed and systematic mapping of the storage potential as well capacity for permitting and monitoring future projects (Akhurst et al., 2021 Krevor et al., 2023).

5.4.3. CDR's role in climate policy

In all three countries, LULUCF-based CDR is a key element of strategies to accelerate near-term emission reductions. CCS-based CDR does not play a comparable role in plans to achieve near-term targets. The lack of enabling regulations and demonstration projects for CCS-based CDR as well as the long upscaling timescales are a significant barrier in the short – to medium term. Given the significant scale of CDR required, specific CDR policies with incentives for projects that remove CO_2 from the atmosphere rather than abate fossil fuel emissions would also be required to achieve net-zero targets. The long-term role of CDR in achieving net negative emissions is not addressed in the countries, and targets for net negative emissions do not play a role. However, the Indian government makes reference to it, calling on developed countries to create carbon space for developing countries through net negative emissions (Mohan et al., 2021).

5.4.4. 'Repurposing policies' as a new idealized type of CDR policy

The case studies conducted here help to further develop the conceptual distinction of idealized types of CDR policy proposed by Schenuit et al. (2021). The study of 9 OECD cases identified three types – *incremental* *modification*, *early integration and fungibility*, and *proactive entrepreneurship*. The case studies conducted here show that a fourth type could be added: *repurposing policies* (see also Supplementary Material 3 for an overview of commonalities and differences of the four types).

We found that CDR-relevant policies aiming to increase LULUCF-based removals are already in place and that the diffusion of net-zero targets has brought greater attention to the approach of achieving mitigation targets through removals. Existing policies have been proactively repurposed to focus more on their contribution to achieve net-zero – efforts that have been criticized as reducing complex ecosystems to their capacity to sequester carbon (Li et al., 2022; Roy & Fleischman, 2022). However, research on LULUCF-based removals shows that, with well-designed policies and incentives, this mitigation option offers opportunities to simultaneously address enhanced carbon sequestration and sustainability challenges (Roe et al., 2021; Schulte et al., 2022).

This facet of using existing governance structures and repurposing them to the new strategic relevance of CDR as part of mitigation strategies was not yet covered by the previous three types (for details see Supplementary Material 3). It is worth including it in a conceptual distinction of idealized types for CDR policy to cover a policy approach characterized by: including CDR to help achieve near-term climate targets, treating emissions reductions and carbon removals as fully fungible, and pursuing a full integration into the broader climate policy mix (see Supplementary Material 3 for comparison on commonalities and differences). The repurposing practices observed in this study are limited to LULUCF-based removals. Nonetheless, it is expected that the strategy of 'repurposing' will also play a role in future policy-making for CCS-based CDR. Future research should examine what policy instruments are and could being repurposed for CCS-based CDR in these and other countries and what risks this approach entails. Already existing examples include the integration of removals into compliance markets (Rickels et al., 2021, 2022), reverse auction schemes (Lundberg & Fridahl, 2022) and tax credits (Hickey et al., 2023). Further research, including in-depth case studies and large-n studies, is needed to explore and test this conceptual distinction between idealized types of CDR policy.

Taken together, the current level of regulation and innovation suggests that the rapid and substantial ramp-up of CDR identified in the IAM pathways (Section 4) is not plausible in the countries analysed here – especially with regard to CCS-based CDR. Although existing and repurposed policy instruments for LULUCF-based removals provide a starting point, this new set of case studies provides new evidence for lack of dedicated CDR policy and governance. When seeking to improve the realism of IAMs, it is important to consider this lack of regulation and innovation policy, in particular the limitations of CCS-based CDR method.

6. Building blocks of narratives for CDR deployment

Building on existing IAM work that already addresses regional aspects of CDR deployment (Gidden et al., 2023a; Strefler et al., 2021), case studies can be a useful complement to investigate CDR potentials by assessing the level of regulation and innovation of different CDR methods in different countries. These findings can be one source for developing exogenous CDR deployment narratives for IAMs. Based on the findings of the case studies conducted here, the following three overarching building blocks stand out. They should be read as hypotheses and further specified in future work.

First, CDR deployment narratives should make the *regional differentiation* of CDR deployment as explicit as possible. The case studies highlighted the limited level of regulation and innovation in regions with large shares of CDR in current modelled pathways. Narratives should be explicit about assumptions about *when* and *where* and *which* CDR method will be available and deployed. Regional distribution has important implications for equity and fairness (Gidden et al., 2023a), which will become a key element of political struggles over different timings for net-zero and net-negative emissions across countries (Mohan et al., 2021). Covering different assumptions about regional distribution would make the burden-sharing of CDR deployment and the required international cooperation transparent.

Second, the case studies show that narratives should include explicit assumptions about the *delayed deployment of CCS-based CDR*. Like many OECD countries, Brazil, China, and India have low levels of regulation and innovation with regard to CCS-based methods. China's rapid growth in patents and first steps towards supporting innovation suggests that it could become a leader in this area. However, a substantial upscaling of BECCS capacity does not seem feasible in the short-term. To reflect the findings of these and other case studies, the narratives should include a variety of assumptions to explore different pathways and identify the implications of delayed upscaling of specific methods in specific regions.

Third, deployment narratives need to be explicit about how CDR can impact the SDGs and discuss the question of the permanence of LULUCF-based CDR methods in a world of ongoing climate change. We found existing governance and incentive structures for LULUCF-based CDR in these three emerging economies which could accelerate the enhancement of the LULUCF removals in the near future. However, the sustainability and governance challenges of climate impacts, and co-benefits are the subject of ongoing research (e.g. Burke & Schenuit, 2023 Svensson et al., 2021; Zickfeld et al., 2023). Mitigation pathways that rely on large-scale LULUCF-based removals (and biomass for BECCS) should therefore be explicit about the gross numbers of removals and sustainability thresholds for them as well as the risks associated with the lack of credible governance architectures.

7. Conclusions

In current mitigation pathways derived from IAMs, the world regions Asia and Latin America contribute large shares of LULUCF – and CCS-based CDR. However, the level of CDR regulation and innovation in Brazil, China, and India is – like in OECD countries studied elsewhere (Schenuit et al., 2021; Smith et al., 2023) – limited. While Brazil, China and India all have a higher level of regulation for LULUCF-based CDR, the level of regulation and innovation for CCS-based CDR is particularly low, making it very unlikely that CCS-based CDR will be upscaled significantly in the near-term. The case studies show, however, that China might be in a position to become a frontrunner. Taken together, the findings on the state of CDR policy and governance in these countries raise questions about the political feasibility of the scenarios analysed in Section 3. With the building blocks for deployment narratives, this study aimed to contribute to the emerging efforts of interdisciplinary research between IAMs and social science work aimed at improving the political robustness and feasibility of mitigation pathways (Geels et al., 2016; Hickmann et al., 2022; Peng et al., 2021a; Pianta & Brutschin, 2022; Trutnevyte et al., 2019; van Sluisveld et al., 2020).

While these comparative case studies can only provide a snapshot, they helped identify another type of CDR policy: *repurposing policies*. Complementing the three idealized types of incremental modification, early integration and fungibility, and proactive CDR policy entrepreneurship (Schenuit et al., 2021), this fourth type can help structure future analysis as well as interdisciplinary work to bridge case study work and quantitative modelling. Furthermore, it raises the question for future work as to which existing policy instruments can be effectively repurposed for CCS-based methods. As a next step, interdisciplinary research should provide large-n comparisons of emerging CDR governance and policies. The results would not only be a valuable resource for further exploring patterns of effective CDR policies, but could also be the next step in an iterative research process to contribute to politically robust mitigation pathways.

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