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# Bargaining powers in cooperative Carbon Dioxide Removal deployment

Emma JAGU SCHIPPERS<sup>a,b,c,\*</sup> ✉, Solène CHIQUIER<sup>d,e,f,g,\*</sup>, Olivier MASSOL<sup>a,b,c,h</sup>, David LOWING<sup>a</sup>, Niall MAC DOWELL<sup>d,e</sup>

**Abstract** – International cooperation has the potential to significantly reduce the costs of implementing Carbon Dioxide Removal (CDR) in line with the Paris Agreement. However, the success of interregional cooperation depends on whether a satisfying agreement can be reached. Regional bargaining powers may heavily influence the outcome of such an agreement. This paper uses cooperative game theory to assess bargaining powers in the cooperative deployment of CDR between the United States (US), the European Union (EU), Brazil, and China. We compute least-costly CDR pathways under multiple cooperative configurations using the Modelling and Optimisation of Negative Emissions Technologies (MONET) framework, assuming regional CDR targets that are proportional to greenhouse gas emissions. Then, we apply cooperative game theory to derive relative bargaining powers from the cost evaluations in MONET. We find that cooperation can lead to substantial CDR cost reductions, ranging from 11% to 43%. Furthermore, we identify two distinct types of regions that possess considerable bargaining power: 1) regions with minimal historical responsibility towards climate change but abundant resources for CDR implementation (exemplified by Brazil in this study); and 2) regions with limited domestic resources amidst large CDR targets (represented by either the USA or China, here). These findings illustrate the potential leverage certain regions in the Global South could wield in the collaborative deployment of CDR under Article 6 of the Paris Agreement.

## Key policy insights:

- International cooperation has the potential to significantly reduce the costs of implementing Carbon Dioxide Removal (CDR).
- The longer climate change mitigation is delayed, the fewer opportunities for CDR cooperation remain.
- Regions with high CDR targets and constrained domestic resources may hold significant bargaining power in CDR cooperation.
- In parallel, regions with high resource endowments (e.g., bioenergy crops/biomass) and lower responsibility towards climate change may also benefit from significant bargaining power.

**Keywords** – Carbon Dioxide Removal; Negative emissions; International cooperation; Cooperative game theory; Bargaining power; Paris Agreement

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# 1. Introduction

The Paris Agreement's goal of limiting global warming to 1.5°C or 2°C above pre-industrial levels will require a rapid and profound decarbonization of our economies. The IPCC Sixth Assessment Report (AR6) (IPCC, 2022) highlights that all 1.5°C pathways require reaching net-zero GHG emission before 2100. This can only be achieved through a combination of emissions reductions and carbon dioxide removal (CDR), in order to counterbalance any residual emissions, and reach net-negative emissions thereafter). In 2050, pathways that limit global warming to 1.5°C<sup>1</sup> with no or limited overshoot require, in median, 5.6 GtCO<sub>2</sub>/y of conventional CDR (e.g., Afforestation) and 4.5 GtCO<sub>2</sub> of novel CDR (e.g., Bioenergy with Carbon Capture and Storage (BECCS), biochar), on top of a gross emissions reduction of 39 GtCO<sub>2</sub>/y (Gidden et al., 2024; IPCC, 2022). However, in 2023, only around 2.2 GtCO<sub>2</sub> was removed from the atmosphere, with a mere 1.3 MtCO<sub>2</sub>/y attributed to novel CDR methods (primarily from BECCS and biochar) according to the State of CDR report (Smith et al., 2024).

Scaling CDR up to the levels projected in 1.5°C pathways poses significant challenges, including concerns related to scaling-up and innovation (Nemet et al., 2024, 2018), socio-economic barriers (see, e.g., Bellamy et al., 2019; Sovacool, 2023), and environmental impacts and limitations (see, e.g., Fajardy et al., 2018; Qiu et al., 2022; Smith and Torn, 2013; Yamagata, 2018). Assuming that these challenges can be overcome, achieving the projected CDR levels in 1.5°C-consistent scenarios necessitates substantial investments, even in more conservative scenarios (Edelenbosch et al., 2024; Strefler et al., 2021b). In fact, some estimates suggest that CDR investments could reach as high as 3.9% of global GDP annually by 2100 (Bednar et al., 2019),

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<sup>1</sup> With a 50% likelihood, classified as C1 scenarios in the AR6

highlighting the need for significant financial commitments at a global level. This raises important questions about how the financial burden of CDR deployment will be shared among nations.

With its notion of “common but differentiated responsibilities and respective capabilities”, the Paris Agreement acknowledges that developing and developed countries are not expected to contribute equally to the 1.5–2°C goals (UNFCCC, 2015). As a result, multiple principles have been discussed to ensure that the financial burden of climate change mitigation is equitably divided between nations (Ringius et al., 2002; Zhou and Wang, 2016), including responsibility for climate change and/or capability. More recently, studies have also focused on the fair burden-sharing of CDR deployment specifically (Fyson et al., 2020; Pozo et al., 2020; Raupach et al., 2014; Torvanger, 2023; van den Berg et al., 2020).

However, without international cooperation, burden-sharing principles do not align with a cost-efficient delivery of the Paris Agreement, as they impose how much CDR should be deployed in each country. For instance, Pozo et al. (2020) showed that only a few EU nations could meet their CDR quotas under most burden-sharing principles due to biophysical limits — low availability of natural resources, such as sustainable croplands for bioenergy or CO<sub>2</sub> storage. Conversely, Chiquier et al. (2022a) found that low and medium-income nations with lower responsibility for climate change and higher availability of sustainable bioenergy croplands or potential for afforestation/reforestation, such as Brazil, might have the natural resources to deploy more CDR than required by any burden-sharing principle. By taking most advantage of the unevenly distributed natural resources (*e.g.*, bioenergy, CO<sub>2</sub> storage, or renewables) across the planet, international cooperation can be instrumental in meeting the Paris Agreement cost-efficiently while maintaining fairness, supporting national sovereignty, and reducing international inequalities (Bauer et al., 2020; Chiquier et al., 2022a; Fajardy and Mac Dowell, 2020; Strefler et al., 2021a). To achieve effective international cooperation, an agreement among the various parties must be reached. However, due to different availabilities of natural resources and

historical responsibilities towards climate change, regions may have varying bargaining powers to reach such an agreement for the deployment of CDR at the Paris Agreement's scale.

In this paper, we use cooperative game theory to measure bargaining powers in inter-regional CDR cooperation. To that end, we model the cost reductions from cooperation in the deployment of CDR as a cooperative game, using the Modelling and Optimization of Negative Emissions Technologies (MONET) framework (Chiquier, 2022; Chiquier et al., 2022a). Here, MONET focuses on the deployment between 2020 and 2100 of 5 CDR options — afforestation/reforestation (AR), biochar, bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), and enhanced weathering (EW) — among four regions — the United States (US), the European Union (EU), Brazil, and China. Assuming all regions cooperate, we can measure their respective bargaining power using the Shapley value, a well-known solution concept from cooperative game theory (Hubert and Ikonnikova, 2011; Morbee, 2014; Shapley, 1953). This solution assigns each region a bargaining power based on its expected contribution to overall cost reductions. Consequently, the Shapley value allows us to derive bargaining powers endogenously from the cost evaluations in MONET (see Hubert and Ikonnikova (2011) for a similar analysis in the context of gas networks).

Importantly, regional bargaining powers are significantly influenced by their respective CDR targets. Considering that few countries have explicit CDR targets today (Smith et al., 2022), our study examines how different target settings impact regional bargaining powers without prescribing what those targets should be in the future. To do so, we define four different CDR target scenarios based on global CDR budgets needed to limit global warming to 1.5°C and the burden-sharing rules. We derive the global CDR budget needed to reach the Paris Agreement's objectives from the AR6 (IPCC, 2022). Our CDR budget scenarios are based on the medians of two AR6 pathways classes: 1.5°C with limited or no overshoot (C1) and 1.5°C with high overshoot (C2) using processed data from Gidden et al. (2024). The allocation of the global CDR budget to

each region's CDR target is then determined through two burden-sharing scenarios that reflect regional responsibility towards climate change. These rules assign CDR targets proportionally, either based on cumulative emissions from 1990 to 2020 or annual emissions in 2020.

The following section presents the MONET framework (Chiquier, 2022; Chiquier et al., 2022a) used to solve the cost-optimal CDR deployment problem and details the cooperative game theoretic notions applied to assess regional bargaining powers. Section 3 applies these methodologies, first by evaluating the value of international cooperation for the US, the EU, Brazil, and China, then by applying the cooperative game theory concepts to shed light on bargaining powers. Section 4 discusses the policy implications. Finally, conclusions are presented in Section 5.

## **2. Methodology**

In this section, we apply cooperative game theory to assess bargaining power in inter-regional CDR cooperation (Section 2.1). To calibrate our cooperative game approach, we compute the cost reductions from cooperation in CDR deployment using the Modelling and Optimization of Negative Emissions Technologies (MONET) framework (Section 2.2).

### ***2.1. Assessing regional bargaining powers in cooperative CDR deployment***

Assuming full cooperation among regions, we use the Shapley value to assign each region a bargaining power index based on its expected contribution to cost reductions. This index effectively evaluates a region's ability to bring value to any coalition it participates in, reflecting its capacity to reduce coalitional costs. A higher bargaining power index indicates a region's greater desirability as a cooperative partner, thereby providing a meaningful measure of its bargaining power in negotiations.

### 2.1.1. The gain-sharing problem

Let  $N = \{1, \dots, n\}$  be the set of regions. A subset of regions  $S \subseteq N$  is called a coalition and represents a counterfactual in which regions in  $S$  achieve an agreement together. Each region has a CDR target  $t_i$ . A coalition  $S \subseteq N$  has an aggregated CDR target  $\sum_{i \in S} t_i$ . The cost for a coalition  $S \subseteq N$  to reach its aggregated target is  $C(S)$ . Where  $C$  is a mapping obtained by using the Modelling and Optimisation Negative Emissions Technologies (MONET) framework (Section 2.3 and Table A.3). By cooperating, regions can generate cost reductions compared to the standalone situations. Formally, cost reduction achievable for a coalition  $S \subseteq N$  is given by the measure  $v(S)$ , which is defined by

$$v(S) = C(S) - \sum_{i \in S} C(\{i\}).$$

The pair  $(N, v)$  forms a cooperative game. A solution  $x(v)$  for this game assigns, to each region  $i \in N$ , a certain quantity  $x_i(v)$  in view of its contribution to the cost reductions captured by  $v$ . The solution should also verify  $\sum_{i \in N} x_i = v(N)$ , meaning that we assume full cooperation among all regions. In this paper,  $x(v)$  is interpreted as an index of bargaining power.

### 2.1.2. The Shapley value as a power index for CDR cooperation

The literature on cooperative game theory offers numerous bargaining power indices to choose from. No single index is superior to the others, as each has its own properties and characteristics. However, within our framework, we argue that two properties are particularly desirable for an index to satisfy: 1) monotonicity, and 2) symmetry.

First, it seems straightforward to ensure that the bargaining power of a region should be increasing with respect to its contribution to cost reductions. This can be interpreted as a monotonicity property. Second, two regions holding the same contributions to the cost reductions should be guaranteed the same bargaining power. Such property is a symmetry requirement. Let us define these two properties formally by considering an arbitrary index  $x$ .

Monotonicity: if  $v(E \cup \{i\}) - v(E) \geq w(E \cup \{i\}) - w(E)$  for any games  $v$  and  $w$ , any  $E \subseteq N$  and any  $i \in N$ , then  $x$  is monotonic if  $x_i(v) \geq x_i(w)$ .

Symmetry: if  $v(E \cup i) - v(E) = v(E \cup j) - v(E)$  for any  $E \subseteq N$  and any  $i, j \in N$ , then  $x$  is symmetric if  $x_i(v) = x_j(v)$ .

According to Young (1985), the only index satisfying these two properties is the Shapley value, which is defined as follows. Assume that the grand coalition of all regions  $N$  forms step by step. At each step, a region joins the coalition and generates cost reductions. By considering all the possible ordering in which the grand coalition may form, the Shapley value assigns, to each region, its expected contribution to the cost reductions generated by  $N$ . Formally, the index is defined, for each  $i \in N$ , as

$$Sh_i(N, v) = \frac{1}{n!} \sum_{\theta \in \Theta} v(S^{\theta(i)}) - v(S^{\theta(i)} \setminus \{i\})$$

where  $\Theta$  is the set of all linear orders over  $N$ , and  $S^{\theta(i)}$  is the coalition formed after region  $i$  has joined according to the entry order  $\theta$ . The Shapley value captures the relative importance between regions regarding their contribution to CDR deployment. Being the only index satisfying the desirable properties of monotonicity and symmetry, we apply the Shapley value to determine the region's bargaining power.

## ***2.2. Application with the Modelling and Optimisation of Negative Emissions Technologies (MONET) framework***

The cooperative game methodology described above requires cost evaluations  $C(S)$  for the CDR deployment in any coalitions of regions  $S$ . These cost evaluations are computed with the MONET framework. The following subsection describes: the least-cost optimisation in MONET (Section 2.2.1.), the regions (Section 2.2.2.), and the CDR methods (Section 2.2.3.) included in the framework.

### *2.2.1. Overview of the MONET framework*

MONET is a detailed multiperiod and multiregional modelling and optimization framework that investigates the co-deployment of CDR technologies and practices in order to meet the Paris Agreement goals (Chiquier, 2022; Chiquier et al., 2022a). Here, the optimisation in MONET is formulated as a deterministic linear programming problem that minimizes the present discounted value of the total cost incurred over the entire planning horizon, subject to a range of constraints across regions (Section 2.2.2.) between 2020 and 2100 with a 10-year time step. These constraints include (i) long-term CDR targets to be met either at the global or the regional levels (Section 3); (ii) bio-geophysical constraints (*i.e.*, land availability, biomass supply, and maximum water stress); (iii) technology-specific constraints (*i.e.*, possible restrictions in the deployment rates, limitations in the operating lifetimes of the installed equipment) and nature-based constraints (*i.e.*, restrictions on the maximum possible afforestation rates, requirements to maintain forest CO<sub>2</sub> sinks in perpetuity); (iv) regional geological CO<sub>2</sub> storage availabilities. Key information about these constraints can be found in Appendix 1.

### *2.2.2. Four regions: Brazil, China, the EU and the USA*

Here, MONET describes the deployment of CDR across four regions<sup>2</sup>: Brazil, China, the EU, and the USA. Altogether, these regions accounted for 65% of global GDP and 46% of global GHG emissions in 2020 (Climate Watch Data, 2024; World Bank, 2023). Importantly, these regions exhibit a diverse range of natural resources endowments (*e.g.*, sustainable croplands or CO<sub>2</sub> storage), as well as socioeconomic situations (*e.g.*, energy cost or climate policies). Therefore, although MONET does not perform at the global scale, our analysis can nonetheless provide valuable insights into the policy challenges associated with the international deployment of CDR options. MONET can solve any combination of the four regions mentioned above; it determines

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<sup>2</sup> The spatial resolution is at the state/province scale (national scale for the EU), *i.e.*, 169 sub-regions.

the least-cost CDR deployment in the largest geographical coverage possible — Brazil, China, the EU, and the US, which we name the grand coalition — and in any more restricted coverages, ranging from any combination of 3 regions to 1 region. We assume that bio-geophysical resources trade (*e.g.*, trade of biomass dedicated to BECCS and cross-border CO<sub>2</sub> transportation) is only allowed between cooperating regions. Two types of cooperative configurations will be assessed in more details: the “standalone coalitions,” where each region reaches its CDR target in isolation, and the grand coalition, where all four regions cooperate.

### *2.2.3. Five CDR methods: AR, biochar, BECCS, DACCS, and EW*

Five CDR methods are represented in MONET: Afforestation/Reforestation (AR), biochar, Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Carbon Capture and Storage (DACCS), and Enhanced Weathering (EW). We summarize here some of the assumptions. Further key assumptions and data are summarized in Appendix 1, and a full description of the modelling assumptions can be found in Chiquier (2022) (Chapter 3).

### **CO<sub>2</sub> removal permanence**

Note that, while EW, BECCS and DACCS deliver permanent CO<sub>2</sub> removal – CO<sub>2</sub> that, once stored, is highly unlikely to leak and be emitted back into the atmosphere (Alcalde et al., 2018; Scott et al., 2015) – the same is not true for AR and biochar. The integrity of forest carbon stocks is exposed to multiple events that can cause unpredictable and unintended reversal, *e.g.*, wildfires, pests, deforestation (Chiquier et al., 2022b; Mac Dowell et al., 2022). Here, we assume that AR’s CDR potential evolves over time – in fact it reduces after several decades – as the risk of wildfires increases. In the case of biochar, the carbon content is not permanently stored, as a significant portion is released back into the atmosphere over time, with decay rates spanning from several decades to multiple centuries (Woolf et al., 2021). This is represented within MONET through a decay function that depends on the biochar composition and the soil characteristics. Further

details and discussions on the permanence of CDR can be found in Chiquier (2022), Chiquier et al. (2022b), Mac Dowell et al. (2022), and Prado and Mac Dowell (2023).

### **Biophysical constraints**

Large-scale CO<sub>2</sub> removal has raised environmental concerns, e.g., land, water, or ecological footprints. Land-based CDR methods, such as AR, BECCS, and biochar, may compromise food and energy security if deployed at large-scale (Smith and Torn, 2013; Smith et al., 2016, 2013). Poorly managed biomass supply chains could strain water and nutrients, whereas rock mining could jeopardize natural ecosystems, leading to biodiversity loss (Dooley et al., 2021; Smith et al., 2019; Yamagata et al., 2018). Additionally, AR can cause nutrient and water scarcity if deployed unsuitable areas, and indirect land-use changes like deforestation<sup>3</sup> (Gutiérrez Rodríguez et al., 2016; Noretto et al., 2012; Veldman et al., 2015). These constraints are considered in the MONET framework by limiting the land availability for CDR: BECCS and biochar land uses are restricted based on datasets on marginal agricultural land (Cai et al., 2011), agricultural residues from harvested wheat areas (Lu et al., 2020), and forestry residues from forest areas (FAO, 2020). The datasets used for the sustainability constraints are listed in Table A.1.

### **2.3. Scenarios on long-term CDR targets**

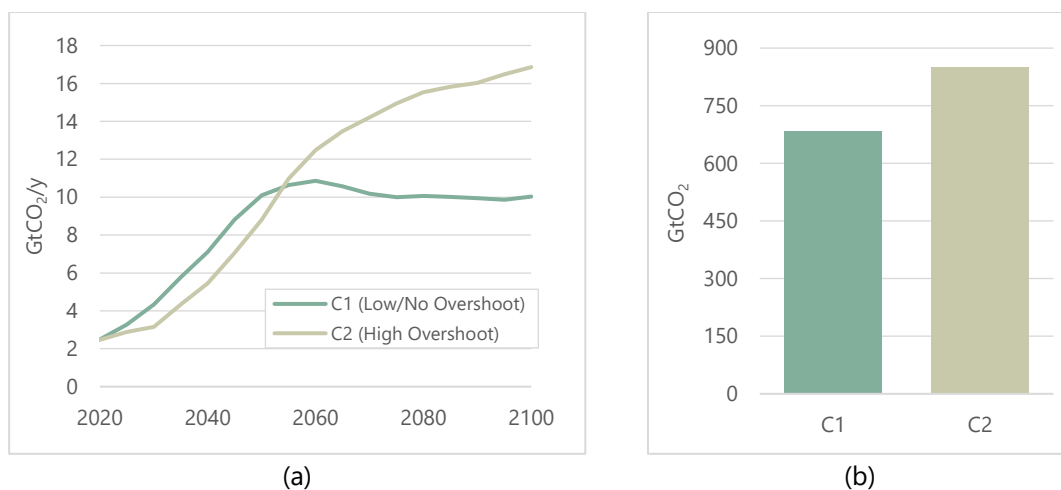
In MONET, the Paris Agreement's 1.5°C objectives translate into regional cumulative CDR targets between 2020 and 2100. This is done in two steps: first, we derive cumulative CDR volumes from pathways that are consistent with 1.5°C (Section 2.3.1). Second, we define regional CDR targets by distributing the required CDR volume based on fair burden-sharing rules (Section 2.3.2).

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<sup>3</sup> *If AR occurs on previously food-dedicated croplands, indirect land use change could lead to deforestation by having to relocate food-dedicated croplands on forest lands.*

### 2.3.1. Two CDR Scenarios for 1.5°C

We use cumulative CDR volumes derived from the IPCC's AR6 database (Gidden et al., 2024; IPCC, 2022). Specifically, we selected the median cumulative CDR volumes from 2020 to 2100 for two distinct pathway categories outlined in the AR6: C1, which represents pathways that limit warming to 1.5°C with no or limited overshoot (>50% probability), and C2, which encompasses pathways that return to 1.5°C after a high overshoot (>50% probability) (as illustrated in Figure 1). For concision, we will refer to these median cumulative CDR scenarios as C1 (No/Low Overshoot) and C2 (High Overshoot) henceforth. Notably, C1 (No/Low Overshoot) projects higher annual CDR amounts until approximately 2055, whereas the cumulative total CDR by 2100 is 25% greater in the C2 (High Overshoot) scenario. By examining these two scenarios, we can investigate how the increased total CDR required influences the bargaining powers for cooperative CDR deployment.

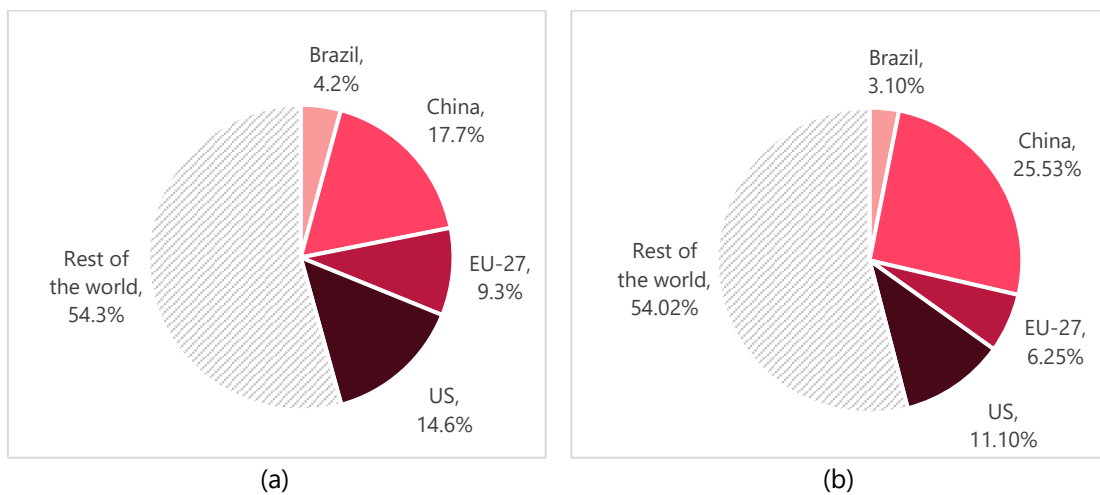


**Figure 1 – (a) Annual volumes, and (b) Cumulative volumes between 2020 and 2100 of CDR in two median pathway categories in the IPCC AR6: C1 – pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, and C2 – pathways that return warming to 1.5°C (>50%) after high overshoot. Based on data processed by Gidden et al. (2024).**

### 2.3.2. Two Burden-Sharing Rules for Allocating Regional CDR Targets

The burden of deploying CDR to the projected levels is subsequently distributed among regions, with each region assigned a CDR target representing a proportion of the total cumulative CDR volume. One key principle for burden-sharing, as emphasized in the Paris Agreement, is the

notion of responsibility towards climate change, often represented in proportion to historic emissions. However, the choice of reference year for assessing historic emissions significantly influences the burden shares, especially for large emerging economies like China. To explore this, we examine two burden-sharing rules: one where CDR targets are proportional to cumulative GHG emissions between 1990 and 2020, and another where targets are proportional to annual GHG emissions in 2020 (see Figure 2). The latter rule serves as a useful comparison to illustrate the implications of the reference year, rather than a realistic burden-sharing scenario. The resulting four CDR targets scenarios are summarized in Table 1.



**Figure 2 – Regional contributions to global GHG emissions (a) cumulatively between 1990 and 2020, and (b) annually in 2020. (Climate Watch Data, 2024).**

**Table 1 – CDR targets scenarios**

Scenario name	C1		C2	
	Cumulative	Annual	Cumulative	Annual
<b>Cumulative Global CDR (2020 – 2100)<sup>1</sup></b>	683 GtCO <sub>2</sub>	683 GtCO <sub>2</sub>	850 GtCO <sub>2</sub>	850 GtCO <sub>2</sub>
<b>Burden-sharing rule</b>	Proportional to Cumulative GHG emissions (1990 – 2020)	Proportional to Annual GHG emissions (2020)	Proportional to Cumulative GHG emissions (1990 – 2020)	Proportional to Cumulative GHG emissions (2020)
<b>CDR targets<sup>2</sup> (GtCO<sub>2</sub>)</b>	<b>Brazil</b>	29	<b>China</b>	121
	<b>EU</b>	63	<b>USA</b>	99
		21		76
		174		124
		43		94
		36		26
		217		53

<sup>1</sup> Amount of CDR deployed globally by 2100 (median) in C1 (Low/No Overshoot) and C2 (High Overshoot) 1.5°C pathways in the AR6.

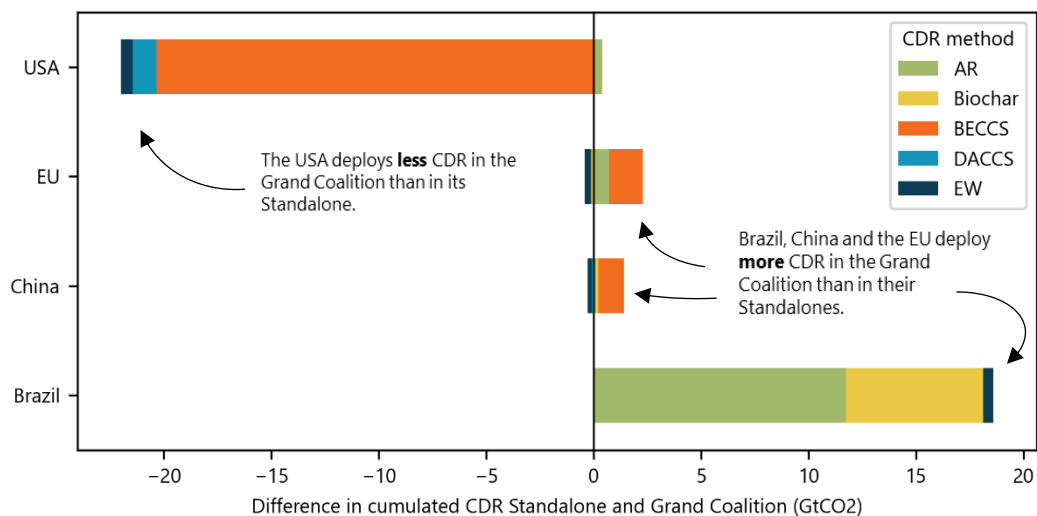
<sup>2</sup> Regional targets for cumulative CDR between 2020 and 2100.

### 3. Results

In this Section, we first identify the cost-optimal CDR deployments under two cooperative configurations: the “standalone coalitions” configuration, where each region reaches its CDR target in isolation, and the “grand coalition” configuration, where all four regions cooperate (Section 3.1 and 3.2). Then, we assess the regional bargaining powers using the Shapley power index (Section 3.3).

#### 3.1. Better resource utilisation through cooperation

In the “standalone coalitions” scenario, each regional CDR target imposes how much CDR must be deployed domestically until 2100. Regional endowments, *e.g.*, limited availability of sustainable lands or CO<sub>2</sub> storage, constrain where, and which CDR options can be deployed, thereby leading to higher costs than in the “grand coalition” configuration (Figure 4). In C1 Cumulative scenario, for example, the resource optimisation through cooperation leads the USA to deploy 21.5 GtCO<sub>2</sub> less CDR in the grand coalition configuration, which is compensated by additional CDR in the three other regions. (Figure 3 and Table A.2).

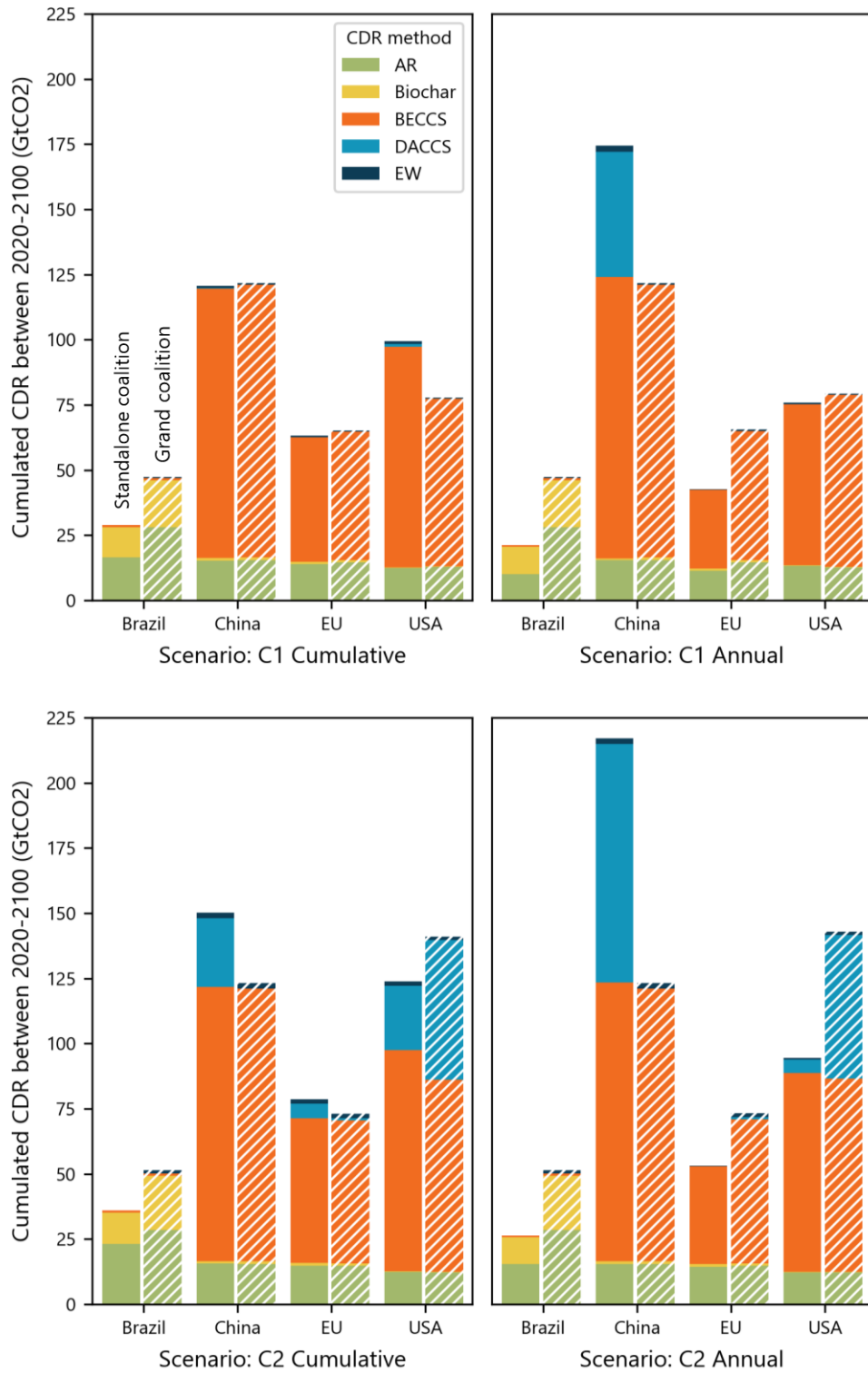


**Figure 3: Difference in cumulated CDR volumes (GtCO<sub>2</sub>) between the Standalone coalitions and Grand coalition in scenario C1 Cumulative.**

### 3.1.1. Biomass and land availability constraints

BECCS, biochar, and AR rely on the availability of sustainable lands dedicated either to bioenergy crops for BECCS/biochar, or to deploying AR. In the standalone configurations, regions with high CDR targets may experience a shortage of croplands, leading to the need for non-biomass-based CDR methods – EW and DACCS – which are typically more expensive<sup>4</sup>. In the C1 Cumulative scenario, cooperation eliminates the reliance on DACCS completely and reduces the amount of EW by 22%. Overall, cooperation enables the optimised utilisation of biomass and land resources, as exemplified by Brazil, which can achieve an additional 18 GtCO<sub>2</sub> of CDR in the grand coalition configuration, largely due to its tropical climate, which facilitates the deployment of AR and biochar production. Similar observations can be made in the three other scenarios represented in Figure 4.

<sup>4</sup> The net marginal cost of CDR for DACCS is more than twice as high as for BECCS and AR in Chiquier et al. (2022). DACCS processes have no other source of revenue than CDR, and carbon capture is costlier when the concentration of CO<sub>2</sub> is low.



**Figure 4: Cumulative CDR deployment in 2100 (Gt CO<sub>2</sub>) in the Standalone coalitions (left), and in the Grand Coalition (right, hatched). The data for this Figure is available in Table A.2.**

### ***3.1.1. CO<sub>2</sub> storage constraints***

Interestingly, the deployment of CDR in standalone configurations is also constrained by a shortage of CO<sub>2</sub> storage. As significant amounts of CDR must be achieved by 2100, it is important to deploy CDR as efficiently as possible – each ton of CO<sub>2</sub> stored matters, and the share of CO<sub>2</sub> emitted, or leaked, that widens the gap between how much CO<sub>2</sub> is removed and how much is effectively stored must be as small as possible. Given that the energy mixes decarbonise over time, DACCS can become more efficient than BECCS in removing CO<sub>2</sub> from the atmosphere and may, therefore, be preferred in standalone configurations despite its higher costs (Chiquier et al., 2022b).

## ***3.2. The scope of cost reductions across CDR target scenarios***

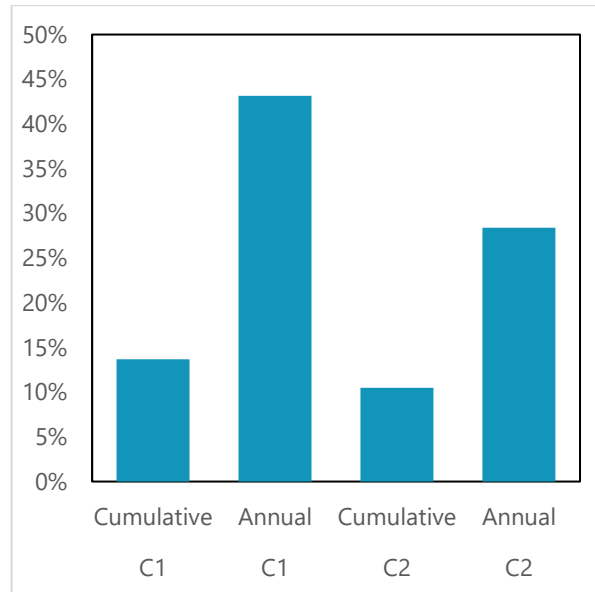
Figure 5 shows that cooperation can reduce costs by 11-43% across all scenarios, depending on the total amount of CDR that must be achieved (C1 or C2) and on the burden-sharing rule applied (annual or cumulative GHG emissions). Notably, the cost reduction from cooperation is higher in C1 scenarios compared to C2 scenarios, and in Annual burden-sharing scenarios compared to Cumulative burden sharing scenarios.

### ***3.2.1. Influence of the total CDR amount: less resources available for cooperation***

As shown in Figure 5, the C2 scenarios deploy the highest total cumulative CDR through 2100 relative to the C1 scenarios (see Section 2.3), and therefore are the most expensive. Yet, international cooperation results into the lowest percentages of cost reduction in the C2 scenarios. A further disadvantage is visible in the C2 Annual scenario, where the absolute cost reduction is also smaller than in the C1 Annual scenario.<sup>5</sup>

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<sup>5</sup> Based on calculations using Table A.3.



**Figure 5: Share of cost reduction from cooperation in the four CDR target scenarios described in Section 2.3. The cost reduction is calculated by computing the difference between the cost in the Grand coalition and the Standalone coalitions:**

$$\text{cost reduction \%} = \frac{\sum_{i \in N} C(\{i\}) - C(N)}{\sum_{i \in N} C(\{i\})}$$

These lower costs reductions in the C2 scenarios can be explained by the regions' diminished capacity to deploy CDR in excess to their individual CDR targets when cooperating. Indeed, as regional CDR targets are roughly 25% greater in the C2 scenarios than in the C1 scenario (Table 1), a larger proportion of regional CDR resources must be utilised domestically. As a result, the remaining potential for international cooperation to reduce costs is limited.

For example, within international cooperation, Brazil is key to reducing the costs of deploying CDR by 2100 through the deployment of AR and biochar, which have lower marginal costs than BECCS, EW, or DACCS. In the **C1** Cumulative scenario, Brazil deploys an additional 18 GtCO<sub>2</sub> of removals by 2100 in the Grand Coalition compared to the Standalone configuration. In contrast, in the **C2** Cumulative scenario, owing to its higher CDR targets between 2020 and 2100, Brazil's cooperative efforts are more limited. As a result, Brazil's additional removals in the Grand Coalition only reach 14 GtCO<sub>2</sub> by 2100. This illustrates that, in the C2 scenario, Brazil has fewer resources available for cooperation. A similar observation can be made with the Annual burden-

sharing rule, where Brazil's cooperative effort goes from 25 in **C1** Annual to 23 GtCO<sub>2</sub> in **C2** Annual by 2100.

### 3.2.2. Influence of the burden-sharing rule

Larger mismatches between the CDR targets and domestic resources of different regions – with some regions lacking the resources to meet their CDR targets at low marginal cost, and others having surplus CDR capacity – create greater opportunities for cooperation (Table 2). Burden-sharing rules can amplify this effect by assigning a larger responsibility to certain countries, as observed with the Annual burden-sharing.

In the Annual burden-sharing scenarios, China's substantial CDR target (25% of the global CDR target) creates a significant gap between its ambitions and its domestic capabilities. Consequently, China's land and biomass resources available to CDR are depleted, necessitating large-scale deployment of DACCS to meet its target (Figure 4). This, in turn, drives up China's marginal CDR costs significantly higher than those of other regions, as shown in Table 2, creating greater opportunities for cooperation, particularly when combined with regions with low marginal CDR costs such as Brazil. Therefore, cost reductions are higher in the Annual burden-sharing scenarios than in the Cumulative burden-sharing scenarios.

**Table 2: Marginal CDR costs in 2100 (in \$/tCO<sub>2</sub>) in the Standalone configurations**

Scenario	Region (in Standalone)	Marginal CDR costs in 2100 (\$/tCO <sub>2</sub> )	
		Cumulative Burden-sharing	Annual Burden-Sharing
C1 (Low/No Overshoot)	Brazil	18	8
	China	39	189
	EU	81	55
	USA	141	110
C2 (High Overshoot)	Brazil	31	9
	China	237	305
	EU	172	81
	USA	246	172

### 3.3. Regions with high bargaining powers in CDR cooperation

This Section evaluates regional bargaining power using the Shapley power index, quantifying each region's cooperative value through its cost-reduction potential (see Section 2.1). The results show that Brazil and the USA hold the highest power indexes under Cumulative Burden-sharing, while Brazil and China dominate under Annual Burden-sharing (Table 3). Notably, these regions correspond to those with the lowest (Brazil) and highest (China and the USA) marginal CDR costs in their standalone configuration (Table 2), revealing two distinct cases of high bargaining power. Importantly, this highlights the fact that, to hold bargaining power, a region doesn't necessarily have to be the one providing the cost reduction. It can also be the one that benefits from it – without these regions, no international cooperation would indeed be necessary.

**Table 3: Regional Shapley power indexes**

Scenario	Region (in the Grand Coalition)	Shapley value as % of total cost reductions	
		Cumulative Burden-sharing	Annual Burden-Sharing
C1 (Low/No Overshoot)	Brazil	44%	21%
	China	13%	57%
	EU	11%	11%
	USA	32%	11%
C2 (High Overshoot)	Brazil	48%	26%
	China	19%	50%
	EU	5%	11%
	USA	28%	13%

#### 3.3.1. Brazil: a country with excess resources for CDR cooperation in all scenarios

Brazil emerges as a key player in CDR cooperation in all scenarios due to its available sustainable lands and favourable climate, enabling it to deploy more AR and biochar production. Its abundant CDR resources (relative to its CDR targets, as imposed by the burden-sharing rules here) present a significant opportunity to address emissions from other regions. Therefore, cooperating with major emitters like China and the USA enables efficient exploitation of these

resources. This cooperation explains Brazil's low standalone CDR cost and substantial bargaining power, as measured by the Shapley index. By leveraging its resources, Brazil can reduce the CDR costs from other regions, making its participation crucial for achieving global CDR targets cost-efficiently.

### *3.3.2. The USA and China: Regions with high marginal costs for CDR*

In contrast, China and the USA face high marginal CDR costs in the Annual and Cumulative burden-sharing scenarios due to limited domestic resources amidst large CDR targets. This creates a strong incentive to cooperate with regions with lower marginal CDR costs to achieve their goal. Interestingly, the Shapley index assigns China and the USA a high bargaining power, as their participation significantly increases the cost reductions that can be achieved through cooperation. These findings underscore that cooperation is not solely driven by countries with excess CDR resources. Rather, regions with ambitious CDR targets also play a pivotal role in fostering cooperation opportunities.

Overall, our findings highlight two types of regions that emerge as key players in CDR cooperation: 1) those with limited climate responsibility and abundant sustainable resources for CDR, and 2) those with ambitious CDR targets, but constrained by domestic resource limitations.

## **4. Discussion: Beyond cost considerations**

Our application of the Shapley power index is focused on cost considerations, but it is essential to acknowledge that the successful deployment of cooperative CDR relies on a multitude of factors beyond cost. In particular, we highlight three critical factors that significantly influence CDR deployment: integrating CDR into climate change mitigation policy, ensuring fairness and feasibility in its implementation, and establishing institutional and legal frameworks.

#### ***4.1. CDR deployment in the context of climate change mitigation***

As the world hurtles towards exceeding its 1.5°C carbon budget, CDR becomes increasingly unavoidable to limit and reverse temperature overshoot (Lamboll et al., 2023). However, it is essential to recognise that CDR is a complementary measure, rather than a substitute, for rapid and deep emissions reductions. Although our analysis has focused on CDR deployment, the CDR volumes deployed are predicated on 1.5°C-consistent pathways, implying significant emissions cuts alongside. We accounted for potential resource competition by employing conservative datasets on resource availability for CDR, as detailed in Table A.1. Importantly, climate policies must ensure that the promise of future CDR does not hinder emissions reduction in the coming decades, a phenomenon known as mitigation deterrence (Brad and Schneider, 2023; Carton et al., 2023). To mitigate this risk, policymakers could consider separating CDR targets from emissions reduction targets, as advocated by McLaren et al. (2019), which remains consistent with our approach. Ultimately, a nuanced understanding of the interplay between CDR and emissions reduction beyond the scope of our analysis is crucial for devising a comprehensive climate strategy that effectively leverages both approaches to maintain a 1.5°C pathway.

#### ***4.2. Fairness and Feasibility***

In this study, we assumed that each country establishes a national CDR target until 2100. We ensured that these national targets adhere to the Paris Agreement fairness notion of “common but differentiated responsibility” towards climate change (UNFCCC, 2015) by setting national CDR targets proportional to national greenhouse gas emissions from 1990 to 2020, or 2020 emissions only. Alternative fairness principles for CDR target setting could be used, but our core finding would persist: two key player types emerge - regions with limited climate responsibility and abundant CDR resources, and regions with ambitious targets constrained by domestic limitations. Additionally, understanding the feasibility of integrating CDR technologies into global mitigation pathways is critical for assessing the practicality and viability of achieving

climate targets (Brutschin et al., 2021; Gidden et al., 2023). Although MONET is based on a partial equilibrium and does not fully represent the global economy, efforts have been made to constrain resource availabilities to ensure consistency with a feasible pathway (Table A.1).

### **4.3. Legal and institutional frameworks**

Finally, our analysis pre-supposes the existence of institutions, certification schemes, and legal frameworks capable of channelling international transfers. However, these are timely challenges considering the rapid growth of voluntary carbon markets and the current lack of consensus on CDR standards under Article 6 of the Paris Agreement (Honegger et al., 2021; Michaelowa et al., 2023; Torvanger, 2019). During COP28 in Dubai, negotiations on Article 6.4 failed, partly because of disagreements on the recommendations for safeguards and rules for CDR (Marcos, 2023). The hope of seeing Article 6.4 become a benchmark for robust and safe CDR cooperation remains. In Europe, the Carbon Removal Certification Framework (CRCF) has marked a significant step towards robust regulation of CDR, but several challenges persist. Notably, the need for clearer distinctions between emissions reduction and CDR, the differentiation between temporary and permanent removals, and the establishment of well-defined system boundaries for accurate carbon removal accounting remain problematic (Schenuit et al., 2023).

## **5. Conclusions**

Article 6 of the Paris Agreement recognizes the possibility of international cooperation to achieve higher climate change mitigation and adaptation ambitions, and its frameworks are still being negotiated within the United Nations Framework Convention for Climate Change (UNFCCC) (Michaelowa et al., 2019). As highlighted by Honegger and Reiner (2018), CDR fits within the scope of the carbon market mechanism outlined by Article 6.4, of which the operationalisation has been agreed upon at COP29 in November 2024 (IISD, 2024; UNFCCC,

2024a).<sup>6</sup> In that context, our findings reaffirmed the importance of global cooperation in reducing costs associated with mitigating climate change. However, the window of opportunity for CDR cooperation narrows when the reliance on CDR to limit global warming to 1.5°C increases. The longer climate change mitigation is delayed, the fewer opportunities for CDR cooperation will remain.

Furthermore, CDR cooperation at the Paris Agreement's scale relies on agreements among parties. Our results showed that discrepancies across natural resources availabilities and climate responsibilities can create unequal bargaining powers among regions. By applying the Shapley power index to CDR deployment in Brazil, China, the EU, and the USA, we revealed that regional bargaining power is predominantly held by regions with either the lowest or highest marginal CDR costs. Notably, these marginal costs are influenced by both domestic resources and the burden-sharing principles used to establish regional CDR targets. In this study, when CDR targets were allocated based on cumulative emissions between 1990 and 2020, the USA and Brazil emerged as the regions with the greatest bargaining power. Similarly, when targets were set proportional to annual emissions in 2020, China and Brazil again held significant bargaining power, as China was assigned a substantial CDR target of 25% of the total amount of CDR.

These insights should be considered in light of certain limitations. Notably, our study relies on assumptions about CDR targets and the existence of enabling institutions and legal frameworks for CDR. Furthermore, our regional scope is limited to the US, EU, Brazil, and China, overlooking potential key players in CDR deployment (such as India (Schenuit et al., 2024), or some African countries (Ampah et al., 2024)). Future studies could strive to expand this scope.

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<sup>6</sup> This operationalisation takes the form of Standards developed by the Supervisory Body of the Article 6.4 mechanism (UNFCCC, 2024b; UNFCCC, 2024c), and approved by the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement (CMA) (UNFCCC, 2024d). Note that, although the Standards have been approved, the CMA encouraged the Supervisory Body to continue working on some key issues for CDR, such as the risk of non-permanence and reversals.

Despite these limitations, our findings shed light on regional CDR bargaining powers, and two types of regions emerge as key players: those with limited climate responsibility and abundant sustainable resources for CDR, and those with ambitious CDR targets constrained by domestic resources limitations.

**Disclosure statement.** The authors report that there are no competing interests to declare.

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# Appendix

## A.1. The MONET framework

The Modelling and Optimisation of Negative Emissions Technologies (MONET) framework provides insight into the location, timing, and scope of CDR pathways that might be deployed to deliver 1.5°C consistent climate targets. The MONET framework is an explicit spatiotemporal model, comprised of two sub-frameworks: 1) the modelling framework provides whole-system analyses of a portfolio of CDR options, including AR, biochar, BECCS, DACCS, and EW 2) the optimisation framework determines the least-cost deployment of that portfolio of CDR options in ten-year time steps between 2020 and 2100 (Chiquier, 2022; Chiquier et al., 2022a; Fajardy, 2020; Fajardy et al., 2018). An exhaustive description of the modelling assumptions for the five CDR methods can be found in Chapter 3 in Chiquier (2022). Full datasets are also available in Appendix A in Chiquier (2022), including, for each CDR option, energy/fuel requirements and emissions factors parameters, working rates parameters, region-specific costs parameters, and other method-specific parameters. We also highlight here that (i) all cost data are in constant 2018 dollars, and (ii) we use a 3% discount rate, which remains constant over the entire planning horizon. The 3% rate is a standard figure recommended by the Office of Management and Budget for assessing federal policies in the US (Office of Management and Budget, 1992).

### A.1.2. Optimisation framework

In the version of MONET used in this study, the objective function is the present discounted value of the cumulative total net cost – i.e., the difference between the capital and operating expenses minus revenues – for any CDR pathway. This objective function is obtained by adding the present discounted value of the deployment cost of the various CDR technologies:

$$CTNC = CTC^{AR} + CTNC^{BECCS} + CTC^{DACCS} \quad \forall t$$

where:

- $CTNC$  is the present discounted value of the total net cost of the CDR pathway,
- $CTC^{AR}$  is the present discounted value of the total cost of AR,
- $CTNC^{BECCS}$  is the present discounted value of the total net cost of BECCS, i.e., total costs of BECCS associated with the biomass supply, the BECCS plant, and the CO<sub>2</sub> transport and storage, minus revenues from electricity generation,
- and  $CTC^{DACCS}$  is the present discounted value of the total cost of DACCS.

The cost optimization is subject to a variety of constraints, including CDR targets that are specified globally or regionally, sustainability limits (land and biomass supply availability, maximum water stress) that are imposed, CDR deployment rates (build and ramping rates and operating lifetimes) that are specified, and geological CO<sub>2</sub> storage limits that are imposed. Table A.1 below provides a short description of the main constraints of the model, based on Chapter 3.8 in Chiquier (2022).

**Table A.1 – Main constraints of the MONET framework**

<b>Constraint</b>	<b>Key elements</b>
<b>CDR deployment rates</b>	<i>Project lifetime:</i>
Deployment rates reflect the maximum speed at which each CDR method can deploy.	- BECCS and DACCS: 30 years
	- EW and biochar: 20 years
	- AR: perpetual
	<i>Maximum deployment rate at the sub-regional scale<sup>1</sup></i>
	- BECCS: 4.5 MtCO <sub>2</sub> /y (Fajardy and Mac Dowell, 2018; Heaton, 2014).
	- DACCS: 4.5 MtCO <sub>2</sub> /y (assumed for comparison with BECCS).
	- Biochar: 2.7 Mtonnes <sub>DM</sub> /yr (assumed for comparison with BECCS)
	- AR: 0.83-1.39%/yr forest area net change rates (IPCC, 2018)
	- EW: 1 mining facility of 450,000 tonnes rocks/y
<b>Land Availability: AR</b>	The land availability for AR is determined using a 740m geographic resolution spatial dataset from (Griscorn et al., 2017) that defines areas with low tree cover (<25%) within

	native forest land types, excluding grasslands, savannas, and croplands, to ensure sustainable land use.
<b>Land Availability: BECCS and biochar</b>	<p>The land availability for biochar and BECCS is limited to marginal agricultural land, agricultural residues, and forestry residues to ensure that biomass production does not compete with food production or lead to excessive land-use change.</p> <p><i>Datasets:</i></p> <ul style="list-style-type: none"> <li>- Marginal agricultural land (Cai et al., 2011)</li> <li>- Agricultural residues from harvested wheat areas (Lu et al., 2020)</li> <li>- Forestry residues from forest areas (FAO, 2020)</li> </ul>
<b>Land Availability: Water Stress</b>	<p>All lands considered for the deployment of AR or the cultivation of biomass for BECCS and biochar are further limited to lands with low water stress, i.e., areas wherein the overall water risk is less than or equal to 3 out of 5, as defined in (Gassert et al., 2015)</p>
<b>Biochar/Rock Dust Application</b>	<p><i>Maximum application rates:</i></p> <ul style="list-style-type: none"> <li>- Biochar: 5 tonnes C/ha/yr (Roberts et al., 2010)</li> <li>- Rock dust: 20 tonnes rock/ha/yr (Beerling et al., 2020)</li> </ul>
<b>Rocks Availability</b>	<p>Rock availability for Enhanced Weathering (EW) was determined using the global lithological map (GLiM) published by Hartmann and Moosdorf (2012), which estimates the availability of basalt and dunite rocks for mineral carbonation.</p> <ul style="list-style-type: none"> <li>- Rock density: 2.9 t/m<sup>3</sup> (Beerling et al., 2020)</li> <li>- Extraction depth: 50m (Renforth, 2012)</li> </ul>
<b>Geological CO<sub>2</sub> storage availability</b>	<p>BECCS and DACCS store CO<sub>2</sub> in geological reservoirs, situated in the vicinity (i.e., 100km) of the BECCS and DAC plant, respectively. Regional availabilities are listed below.</p> <ul style="list-style-type: none"> <li>- Brazil: 0.95 Gt CO<sub>2</sub> (Rockett et al., 2013)</li> <li>- China: 3,106 Gt CO<sub>2</sub> (Dahowski et al., 2009; Li et al., 2009)</li> <li>- EU-27: 102 Gt CO<sub>2</sub> (Poulsen et al., 2014; Vangkilde-Pedersen et al., 2009)</li> <li>- USA: 8,533Gt CO<sub>2</sub> (USDOE, 2015)</li> </ul>

<sup>1</sup>MONET is divided into regions (e.g., Brazil, China, the EU, and the USA). Each region is divided into sub-regions, which are States and Provinces in Brazil, China, and the USA and countries in the EU).

## A.2. MONET results

**Table A.2. Cumulative CDR volumes (2020-2100) in the Standalone and Grand coalition configurations**

Scenario	Region	Standalone CDR (GtCO <sub>2</sub> )					Grand coalition CDR (GtCO <sub>2</sub> )				
		AR	Biochar	BECCS	EW	DACCS	AR	Biochar	BECCS	EW	DACCS
C1 Cumulative	Brazil	16.4	11.5	0.9	0.0	0.0	28.2	17.9	0.9	0.5	0.0
	China	15.2	1.0	103.3	0.9	0.1	15.3	1.2	104.5	0.7	0.0
	EU	13.9	0.8	47.7	0.8	0.0	14.7	0.7	49.3	0.4	0.0
	USA	12.5	0.2	84.6	1.0	1.1	12.9	0.2	64.3	0.5	0.0
C1 Annual	Brazil	10.1	10.5	0.5	0.0	0.0	28.2	17.9	0.9	0.5	0.0
	China	15.4	0.7	107.9	2.3	48.0	15.3	1.1	104.6	0.7	0.0
	EU	11.3	0.8	30.4	0.2	0.0	14.7	0.7	49.6	0.5	0.0
	USA	13.3	0.2	61.7	0.5	0.0	12.7	0.2	65.8	0.5	0.0
C2 Cumulative	Brazil	23.1	12.0	0.9	0.0	0.0	28.5	20.7	0.9	1.4	0.0
	China	15.5	1.0	105.3	2.2	26.2	15.5	1.0	104.7	2.1	0.0
	EU	14.8	0.9	55.6	1.8	5.6	14.8	0.8	55.0	1.5	0.8
	USA	12.5	0.2	84.8	1.7	24.7	12.2	0.3	73.6	1.4	53.6
C2 Annual	Brazil	15.5	10.3	0.5	0.0	0.0	28.5	20.7	0.9	1.4	0.0
	China	15.4	1.0	107.0	2.2	91.5	15.5	1.0	104.7	2.1	0.0
	EU	14.3	1.1	37.6	0.2	0.0	14.8	0.8	55.4	1.5	0.8
	USA	12.3	0.2	76.3	0.6	5.0	12.2	0.3	74.0	1.4	55.1

**Table A.3.: Levelized total CDR costs (billion \$) for all coalitions  $S$ , for all CDR target scenarios. Coalitions 1, 2, 4 and 7 are the Standalone coalitions. Coalition 15 is the Grand Coalition.**

Coalition $S$	Regions included in the coalition				Levelized coalitional costs (billion \$) $C(S)$			
	EU	Brazil	China	USA	C1 Cumulative	C1 Annual	C2 Cumulative	C2 Annual
1	0	0	0	1	4,594	3,103	6,134	3,713
2	0	0	1	0	2,197	9,591	4,350	12,034
3	0	0	1	1	6,553	9,553	10,137	13,725
4	0	1	0	0	171	39	231	69
5	0	1	0	1	3,868	2,277	5,399	2,892
6	0	1	1	0	2,064	4,928	3,787	8,748
7	0	1	1	1	5,863	7,363	9,336	11,618
8	1	0	0	0	1,976	1,026	2,672	1,166
9	1	0	0	1	6,454	3,971	8,703	4,572
10	1	0	1	0	4,044	7,073	7,013	11,175
11	1	0	1	1	8,386	9,060	12,759	13,840
12	1	1	0	0	1,688	818	2,378	974
13	1	1	0	1	5,709	3,252	7,972	3,971
14	1	1	1	0	3,746	5,014	6,429	8,979
15	1	1	1	1	7,717	7,821	11,980	12,162