The Economics of Carbon Dioxide Removal: A Governance Perspective

Ottmar Edenhofer* Max Franks† Friedemann Gruner‡
Matthias Kalkuhl§ Kai Lessmann¶

November 20, 2024

Abstract

Carbon dioxide removal (CDR) is becoming an emerging topic in climate policy. We review the nascent economic literature on the governance of CDR and discuss policy design and institutions. We first assess the role of CDR in climate policy portfolios that include abatement and adaptation. Cost saving technological progress could make CDR a game changer in climate policy: CDR creates new sectoral, intertemporal and international flexibilities, which reduce overall costs and allow returning to a temperature target after temporary overshooting. Moreover, carbon removal can reduce the problem of international cooperation due to substantially lower supply-side leakage via fossil fuel markets. A key challenge lies in its governance and incentive structure that is complicated by non-permanence of carbon storage and default risks of the firms committed to future CDR. For CDR governance, we survey approaches that incentivize removals by price instruments or include CDR in (modified) emissions trading schemes.

When citing this paper, please use the following: Edenhofer O, Franks M, Gruner F, Kalkuhl M, Lessmann K. 2024. The Economics of Carbon Dioxide Removal: A Governance Perspective. Annu. Rev. Resour. 17: Submitted. DOI: https://doi.org/10.1146/annurev-resource-010224-094505

---

*Potsdam Institute for Climate Impact Research, Germany; Mercator Research Institute on Global Commons and Climate Change, Berlin, Germany; Technische Universität Berlin, Germany. Email: edenhofer@pik-potsdam.de

†Potsdam Institute for Climate Impact Research, Germany; Technische Universität Berlin, Germany. Email: franks@pik-potsdam.de

‡Mercator Research Institute on Global Commons and Climate Change, Berlin.; Faculty of Economics and Social Sciences, University of Potsdam, Germany Email: gruner@mcc-berlin.net

§Mercator Research Institute on Global Commons and Climate Change, Berlin, Germany; Faculty of Economics and Social Sciences, University of Potsdam, Germany. Email: kalkuhl@mcc-berlin.net

¶Potsdam Institute for Climate Impact Research, Germany; Mercator Research Institute on Global Commons and Climate Change, Berlin, Germany. Email: lessmann@pik-potsdam.de

1 Introduction

The policy portfolio for addressing climate change rests on three pillars: emissions abatement, adaptation and carbon dioxide removal (CDR). The first two pillars are well-established. Emissions abatement modifies economic activities to emit less CO_2 at the source, while adaptation refers to activities that moderate climate change impacts. The third pillar, however, has only recently begun a steep ascent on the climate policy agenda, besides traditional afforestation activities (Schenuit & Geden, 2023). By actively removing CO_2 from the atmosphere and storing it in geological, terrestrial, or ocean reservoirs, or in products, CDR enables reducing net emissions in the near term, counterbalancing residual emissions in the medium term, and addressing historical emissions by "cleaning up" past emissions in the longer term (IPCC, 2022). Governments around the world are increasingly implementing regulations and incentives for CDR (Schenuit et al., 2024), as evidenced by current discussions about CDR targets in Germany, tax incentives in the US and emerging public procurement schemes in Sweden.

In principle, the impact of CDR on climate change is similar to emissions abatement, as both approaches reduce atmospheric CO_2 concentrations. However, CDR has unique characteristics that separate it from both emissions abatement and adaptation, offering additional flexibilities for climate change mitigation strategies. One key characteristic of CDR is its ability to decouple the time and location of CO_2 removal from the original emission point, unlike emissions abatement, which is tied to emission activity. This decoupling creates flexibility, for example, to carry out CDR at a later stage or in a different economic sector. The latter feature facilitates the separation of fossil resource use from the goal of reducing damages from global warming. This decoupling has implications for resource prices and rents. Both flexibilities can reduce the costs of mitigating climate change and enlarge the space of feasible paths toward climate neutrality in accordance with the Paris Agreement. With CDR, humanity might even have the option of temporarily exceeding the targeted temperature limits – known as "temperature overshoot" - and removing carbon later to bring temperatures back down by the end of the century. Although highly controversial, many climate change mitigation scenarios rely on CDR to meet ambitious climate targets, often to a substantial degree (Schleussner et al., 2024).

However, the new flexibilities come with their own challenges and risks. The scalability of CDR methods is often constrained by high costs, limited potential, or external effects (Fuss et al., 2018). Furthermore, high uncertainty about future costs and potentials carries the risk that a delay in abatement today will be insufficiently or inefficiently compensated for by CDR in the future (Burke & Gambhir, 2022). The heterogeneity of CDR methods, with varying degrees of permanence and ecological impact, also complicates policy design. Moreover, CDR policies would often have to come on top of already existing climate policies. For CDR to become a solid third pillar in the climate policy portfolio, there is thus a clear need for a carefully designed governance framework.

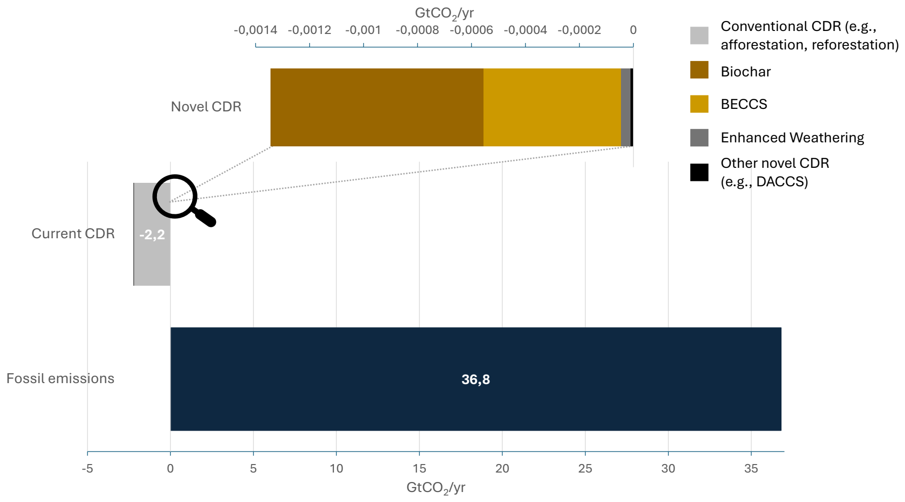

Figure 1: Fossil emissions and total amount of carbon dioxide removal in 2023, split into conventional and novel methods ($GtCO_2$/yr). Almost all of current CDR resulted from conventional methods such as afforestation or reforestation. Adapted from Smith et al. (2024) and based on data from Pongratz et al. (2024) and Friedlingstein et al. (2023).

In this article, we review the literature on the economics of CDR from a governance perspective. The term governance here refers to the design of institutions and policy instruments (Williamson, 1996, Lobel, 2012). Our analysis complements previous literature reviews, which either focused only on technological and empirical aspects of CDR, or examined institutional governance with limited discussion of the economics of policy instruments and their implementation.[1] As a notable exception, Heutel et al. (2016) review economic policy design, interregional and intergenerational equity issues, strategic interactions, and risk and uncertainty surrounding CDR and solar radiation management (SRM). In this review, we focus on CDR and discuss the more recent literature on CDR governance, which has grown considerably since 2016.

We begin by surveying the characteristics of the most common CDR methods, as these are essential for determining whether, when, and to what extent CDR should be utilized. For example, "conventional" land-based methods, such as forest and soil management, are relatively low-cost and currently contribute most of the 2 $GtCO_2$ sequestered annually. By contrast, "novel" technologies, such as capturing and storing CO_2 directly from the atmosphere, remain largely in the development stage, are costly, and account for less than 0.1% of current global CDR (see Figure 1; Smith et al., 2024).

[1] For the former, see Minx et al. (2018), Fuss et al. (2018), Nemet et al. (2018), Hepburn et al. (2019), Smith et al. (2024), Rodriguez Mendez et al. (2024b), for the latter Honegger et al. (2022), Low et al. (2024).

In addition to technological readiness and costs, several factors limit large-scale CDR deployment. The scarcity of land and storage sites constrains both land-based methods and sequestration technologies, while limited storage duration reduces the long-term climate benefits of some CDR methods. Competing uses for land and energy also create externalities, such as increased food prices, which must be considered prior to large-scale deployment.

Conventional land-based CDR methods include *afforestation and reforestation* as well as the *restoration of coastal wetlands, peatlands and mangroves*. These methods rely on capturing CO_2 through photosynthesis and storing it in organic matter. Although relatively inexpensive, their effectiveness can be difficult to monitor, and scalability is limited by site availability. If carbon is stored in harvested wood products, storage duration varies from years, e.g. paper, to centuries, e.g. buildings (Hepburn et al., 2019, Churkina et al., 2020). In addition to capturing CO_2 in crops, farmers can engage in *soil carbon sequestration* by introducing *biochar* (produced by thermal degradation of biomass in an oxygen-limited environment) or by adopting agricultural practices that raise soil organic carbon content, such as shallow plowing and increasing ground cover.

More "novel" CDR methods exploit geochemical principles on land and at sea. Adding alkalinity to marine environments enhances carbon uptake by oceans (*ocean alkalinization*). Through *enhanced weathering*, the natural weathering process is accelerated by grinding rocks and other materials, such as mine waste, concrete and alkaline waste, increasing their surface area for CO_2 sequestration through chemical reactions. Finally, a key focus is on methods that sequester carbon in geological storage, such as aquifers, coal beds, or depleted oil and gas fields, due to the permanence of these storage sites. One example is bio-energy with carbon capture and storage (*BECCS*), which involves cultivating energy crops, combusting the organic material and capturing and sequestering the resulting CO_2 underground. Similarly, carbon can be removed directly from the atmosphere via direct air carbon capture and storage (*DACCS*), which employs energy intensive air filtration systems to capture CO_2.

We structure the remainder of this article as follows. In Section 2, we discuss the efficient use of CDR and its role in the portfolio of addressing climate change in a simple static model. By introducing the time dimension and technological progress, we then discuss the role of an optimal temperature overshoot. In Section 3, we turn to limited duration of storage as a key characteristic of CDR. Non-permanence has strong implications for the intertemporal dimension of policy instrument design, which we review in Section 4 along with the international dimension. Building on the emerging theoretical literature for policy instruments, we then discuss the literature on how to integrate CDR into emission trading systems in Section 5. In Section 6, we outline important open research questions and conclude.

2 The Climate Policy Portfolio: Abatement, Adaptation and Removal

2.1 A Static Model of the Climate Policy Portfolio

To illustrate the key domains of climate policy, consider a stylized static model of abatement M, adaptation A and carbon removal R similar to Heutel et al. (2016). We provide a brief description here and discuss the most important implications. The interested reader can find the full description of the model in the Supplemental Material A.

We model an economy that is affected by climate damages $D(E^n, A)$, which are a function of net emissions, E^n, and the level of adaptation, A. Net emissions are defined as the exogenous business-as-usual emissions, $\bar{E}$, minus abatement and carbon removal, $E^n := \bar{E} - M - R$. Climate damages are convex in net emissions, $D_E > 0$ and $D_{EE} > 0$, while adaptation reduces climate damages for any given level of net emissions, $D_A < 0$, $D_{AA} > 0$ and $D_{EA} < 0$.[2] The costs associated with abatement, removal and adaptation are denoted as $C^M(M)$, $C^R(R)$ and $C^A(A)$, respectively. Assuming convex cost, the optimal climate policy is determined by

$$D_E(E^n, A) = C^M_M(M) = C^R_R(R) \tag{1}$$

$$-D_A(E^n, A) = C^A_A(A) \tag{2}$$

with subscripts denoting partial derivatives. The first optimality condition governs the optimal mitigation level (including abatement and removal) such that marginal mitigation costs equal marginal damages of carbon emissions. Equation (1) highlights two fundamental ethical principles. The first equality is the well-known *polluter-pays principle*, which requires that emissions should be priced at marginal damages, i.e. the social cost of carbon. The second equality in (1) requires carbon sinks to be rewarded at the level of the social costs. This might be called the *restorer-reward rule*. Condition (2) determines the optimal level of adaptation that is achieved when the marginal adaptation costs equal the marginal benefits of adaptation. Both optimality conditions are inter-dependent, since changes in adaptation affect marginal climate damages and changes in mitigation affect the marginal benefits of adaptation.

2.2 Technological progress and the role of CDR

Using our simple model, we can further explore the role of CDR within the triad of the climate policy portfolio. From equation (1), we observe that CDR functions as

[2] Solar radiation management (SRM) could be represented as a form of adaptation that is an imperfect substitute for abatement and removal: $D(E^n, A) := \mu D^T(E^n - A) + (1-\mu) D^N(E^n)$. Here, SRM ($A$, in emission equivalents) lowers temperature-related damages D^T, but does not affect non-temperature damages D^N. The parameter μ measures how effectively SRM reduces overall climate damages. This formulation subsumes the social costs and risks of SRM in its cost function. For a more detailed model, see Belaia et al. (2021).

an additional mitigation option and should be used such that the marginal costs of all mitigation options (abatement and removal) are equalized. While mitigation and adaptation are substitutes, a cost reduction shock in removals may also crowd-in abatement, depending on specific assumptions about functional forms.[3]

Our model also generates a profound insight about how the climate policy portfolio might evolve over time: with increasing technological progress and increasingly scarce low-cost abatement options, carbon removal will become ever more important. To see this, compare two scenarios with a *ceteris paribus* multiplicative cost reduction shock θ_M, θ_R of equal magnitude in the removal and the abatement sector, i.e., $C^M_{M\theta_M} = C^R_{R\theta_R}$. Then, the cost reduction increases the optimal quantity of carbon removal relative to abatement under the condition that

$$C^M_{MM} > C^R_{RR} \tag{3}$$

That is, if marginal abatement costs exhibit greater curvature than marginal removal cost, then technological progress in CDR will result in a larger increase in the quantity of carbon removal compared to the quantity increase in abatement following a similar level of technological progress in abatement.

It seems plausible that condition (3) will hold in the future: As $M \to \bar{E}$, avoiding to emit the last ton of carbon becomes prohibitively expensive. This Inada condition (Inada, 1963) for abatement is intuitively appealing and supported by many modeling works (see, for example, IPCC, 2022, Ch. 3.6.1, Merfort et al. 2024). In contrast, no such Inada condition applies to the removal sector (Merfort et al., 2024) as there is no plausible natural, technological or physical threshold for any finite amount of removal. Consequently, the more ambitious climate policy becomes – for example, due to rising marginal damages – the more important will be the role of carbon removal in the climate policy portfolio.

The simple static model can also be used to discuss a *ceteris paribus* cost reduction shock of equal magnitude in the removal and adaptation sector as well as the special case of solar radiation management. We relegate these to Supplemental Material A.2 where we show that a similar but more nuanced condition for the convexity of marginal removal costs and marginal costs of adaptation (or solar radiation management) holds.[4] If marginal social costs of solar radiation management are steep (due to increasing environmental or geopolitical risks), the optimal policy portfolio shifts from solar radiation management to carbon removal.

2.3 A Dynamic Model of Climate Policy: Optimal Overshooting

To demonstrate the dynamic implications of carbon removal when marginal abatement costs become infinite for $M \to \bar{E}$, we include time dependency and introduce technological cost parameters $\theta_M(t) = \theta_R(t) = \theta(t)$ such that (1) reads

$$C^M_M(t) = C^R_R(t) = \theta(t) D_E(t) = \theta(t) SCC(t) \tag{4}$$

[3]Crowding-in of abatement may happen if the cross-derivative of marginal damages with respect to adaptation is sufficiently large. See equations (A.13) and (A.14) in Supplemental Material A.1.

[4]See equations (A.28) – (A.30).

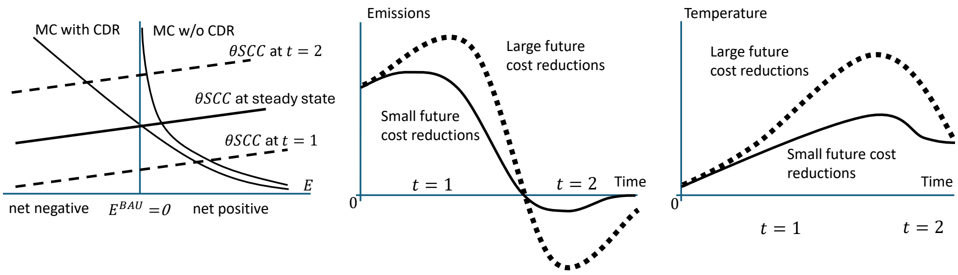

Figure 2: Illustration of the dynamic model. The left panel shows marginal costs (MC) of reducing atmospheric carbon without and with CDR and θSCC at different points in time. The middle and right panel show emissions and temperature for small and large future removal cost reductions.

The dynamics can be sketched as follows: Initially, costs are high, accordingly $\theta(t)$ is low, and marginal damages are low so that we have low levels of abatement and removals. Therefore, net emissions are positive (”$t = 1$” in Figure 2). Due to positive net emissions, the carbon concentration grows and with convex damages, the $SCC(t)$ grow. Additionally, technological progress reduces marginal cost of abatement and removal. As $\theta(t)SCC(t)$ increases, abatement and removal increase as well. Due to the Inada condition in abatement, however, R increases more than M when M approaches baseline emissions. When $\theta(t)SCC(t)$ has become sufficiently large, $M(t) + R(t) > \bar{E}$ and net emissions become negative (”$t = 2$” in Figure 2). This, in turn, eventually reduces $SCC(t)$ as marginal damages become smaller due to declining temperature levels. The economy can reach a steady state with net-zero emissions (i.e. $M(t) + R(t) = \bar{E}$) when growth rates of technological progress and the social cost of carbon are equal.

Hence, the stylized dynamic model indicates already that optimal climate policy might follow different phases – from net-positive to net-negative to net-zero emissions (Figure 2, middle panel; see Hoel, 2024, for a more comprehensive model). The existence of carbon removal creates an important intertemporal flexibility that allows for a temporary ’overshooting’ of the optimal long-term temperature. This pattern is also found in more complex numerical integrated assessment models that include CDR and allow for temperature overshoot (e.g., IPCC, 2018, Bauer et al., 2023).

When a certain cumulative net carbon budget is given, Lessmann et al. (2024) show that the extent of overshooting increases in the rate of marginal removal cost reductions and the discount rate. It seems plausible that this should also hold in a cost-benefit framework but we are not aware of an analytical analysis. Currently, the costs of many emerging carbon removal methods are higher than the costs of emissions abatement. Without significant cost reductions in novel CDR technologies, these solutions will struggle to find a market, making abatement the more attractive option. Hence, the level of overshoot will be relatively low. If, by contrast, rapid technological learning occurs in the removal sector, abatement efforts become less appealing. Firms increasingly opt for removal, and cumulative emissions as well as the extent of overshoot rise, as illustrated in the right panel of Figure 2.

3 Non-permanent removals

The previous section demonstrated that permanent carbon removal has comparable effects to avoiding emissions. However, as discussed in Section 1, the vast majority of CDR methods deployed today provide only temporary storage. The non-permanence of storage has implications for both the use and the regulation of these CDR methods. In this section, we discuss the optimal use of non-permanent CDR and turn to optimal policy instruments in the subsequent section.

The implications of non-permanence of carbon storage have been explored early on in the context of forest management. For example, Tahvonen (1995) finds that optimal forest management requires two policies: subsidizing carbon accumulation in forests at the same rate as a carbon tax, and taxing emissions from timber use. Kim et al. (2008) expanded the analysis to soil and land-based carbon storage, finding that non-permanent storage should be priced well below the carbon tax. Subsequent research on carbon sequestration in forests has considered further issues such as additionality, permanence and leakage, see Sedjo & Sohngen (2012) for an overview.

Despite these complications, non-permanent CDR methods can withhold CO_2 from the atmosphere for considerable duration and at substantial scales. For example, wood used in manufacturing or construction can store carbon for decades or even centuries, respectively (Smith et al., 2006, Hepburn et al., 2019, see also Table 1). Given the vast demand for new buildings in modern cities, there might be a potential to store up to one gigaton of CO_2 per year in construction materials (Mendez et al., 2024, see also Churkina et al., 2020). Accordingly, model based studies find that non-permanent CDR should be used to maximize social welfare, although the benefits decrease substantially as the permanence of storage diminishes (Rickels et al., 2018, Franks et al., 2024). Furthermore, Franks et al. demonstrate that, if the availability of permanent CDR is delayed, non-permanent options serve as a bridge technology. Hence, non-permanent CDR can help to smooth the transition to a Paris-compatible world.

To illustrate the key findings of the literature, we extend our simple model to account for non-permanence (following Franks et al., 2024). We track the stock of stored carbon Z and assume that a fraction $\delta \in (0,1)$ of the removed CO_2 does not remain in storage. This fraction is then called release rate. The emissions released from temporary storage contribute to the accumulation of carbon in the atmosphere, in addition to emissions from other economic activities. Minimization of the net present value of future costs of abatement, removal and adaptation reveals that non-permanence of storage drives a wedge between the marginal costs of abatement and removal of (1), as we show in Supplemental Material B.

$$C_M^M = \mathrm{SCC} = C_R^R + \mathrm{SCR}(\delta) \tag{5}$$

Non-permanent removal has the same benefit as abatement, namely the social cost of carbon, SCC, that is, the cumulative future damage of a marginal unit of CO_2 in the atmosphere. However, in contrast to abatement its social benefit needs to balance with the sum of private costs (C_R^R) and the social cost of removal (SCR), which is the cumulative future marginal damage of CO_2 returning to the atmosphere from temporary storage:

$$\mathrm{SCC}(t) = \int_t^\infty e^{-r(\tau-t)} D_E(\tau) \mathrm{d}\tau \tag{6}$$

$$\mathrm{SCR}(\delta, t) = \int_t^\infty e^{-r(\tau-t)} \delta e^{\delta(\tau-t)} \mathrm{SCC}(\tau) \mathrm{d}\tau \tag{7}$$

The two social costs evolve over time according to

$$\widehat{\mathrm{SCC}} = r - \frac{D_E}{\mathrm{SCC}} \qquad\qquad \widehat{\mathrm{SCR}} = r + \delta \left(1 - \frac{\mathrm{SCC}}{\mathrm{SCR}}\right) \tag{8}$$

where the hats denote growth rates. Incorporating non-permanent storage, thus, introduces additional complexity to the traditional view of the climate problem, which is typically modeled as a resource extraction problem (Hotelling, 1931).

The wedge created by the SCR in (5), which increases in the release rate δ, pushes marginal removal costs below the marginal damage. With temporary storage, removal R is reduced compared to the case of permanent storage in (1). This result carries over to the optimal pricing of non-permanent removal relative to emissions abatement. While a tax on emissions should equal the SCC, a subsidy on non-permanent removal should fall below the SCC, the difference being the SCR. Franks et al. (2024) show that in the steady state of this dynamic setting, the carbon that is released from non-permanent storage is perpetually returned to storage by a renewed removal effort. They find, however, no effect of the availability of non-permanent storage on the optimal CO_2 concentration in the atmosphere, which is determined by the balance of marginal abatement costs and benefits and marginal removal costs of removal technologies that store carbon permanently.

Several studies confirm the dependency of optimal removal quantities on storage duration as well as the differentiation of carbon pricing of abatement and removal, as for example Brander & Broekhoff (2023), Meier et al. (2022) and Groom & Venmans (2023). Often, the literature elaborates on particular details, as for example, Kim et al. (2008) and van Kooten (2009), who focus on land based removal. Rickels & Lontzek (2012) and Rickels et al. (2018) study the specific case of ocean sequestration, where the stock of stored carbon in the ocean is linked to the atmosphere by uptake and outgasing of CO_2. For a storage site thus linked to atmospheric carbon, Rickels & Lontzek (2012) find that the optimal atmospheric CO_2 concentration is higher when ocean sequestration is available. With ocean sequestration, the steady state atmospheric carbon concentration is reached later due to the inertia in the carbon cycle. An open question is how incorporating additional damages from ocean acidification would impact the cost-benefit analysis within such a model. This specific question points more broadly at the need for additional detailed modeling of individual CDR technologies that do not store carbon permanently.

Meier et al. (2022) integrate an arbitrary number of (non-permanent) carbon reservoirs into a tractable integrated assessment model. They derive the social cost of carbon for CO_2 in every one of their reservoirs. The optimal use of non-permanent storage is then driven by the benefit of moving CO_2 to a reservoir with lower social costs, compared to the opportunity costs of extracting and combusting fossil resources.

Building on the concept of social cost of carbon, Groom & Venmans (2023) define the social value of an offset (SVO) generated by CDR. Non-permanent storage is then reflected in a correction factor that reduces the SVO. Similar correction factors are derived for including risk of failure and risk of non-additionality of CDR. The latter is a concern for all CDR options where the counterfactual is not known with certainty. Whereas the counterfactual for some CDR technologies such as DACCS is rather straightforward, it is often difficult for land-based, non-permanent CDR, to know, for example, whether extra trees would not have been planted anyway for other reasons than carbon capture, and adverse incentives to falsely claim additionality exacerbate this uncertainty (Nolan et al., 2024). The issue of non-additionality also arises for abatement projects with uncertainty about the counterfactual and has been discussed extensively in this context (e.g. Michaelowa et al., 2019). Certification is one way to reduce the risk of non-additionality. In Groom & Venmans (2023), the risk of non-additionality is modeled as the risk of assuming a wrong counterfactual.

The literature provides ample discussion of the need to consider the non-permanence of storage in optimal policy design for CDR. In the following section, we discuss relevant policies.

4 Optimal design of policy instruments for CDR

In the preceding section, we established a framework to calculate the optimal use of non-permanent CDR. We now move on to a discussion of policy instruments. We devote most of our attention to the literature regarding instruments for non-permanent removal. The temporary nature of some CDR technologies makes the design of regulation more complicated and several papers discuss these issues. However, we also cover a selection of papers for permanent CDR and then discuss the international dimension of CDR policies.

Table 1: Optimal ratio of a subsidy for carbon removal to a tax on emissions with non-permanent storage in the steady state with a constant release rate δ. Calculated following Franks et al. (2024) as $r/(r+\delta)$ for a discount rate of r.

Expected lifetime (years)	Exemplary removal and storage pathway	Discount rate r 0.01	0.02	0.05
4	wood products: paper[a]	0.04	0.07	0.17
43	wood products: furniture[a]	0.3	0.46	0.68
144	wood products: single family home[a]	0.59	0.74	0.88
200	enhanced weathering[b]	0.67	0.8	0.91
2000	DACCS, BECCS[c]	0.95	0.98	0.99

[a] Smith et al. (2006, Table D3)
[b] storage duration of "centuries" (Hepburn et al., 2019)
[c] storage duration of "millennia" (Hepburn et al., 2019)

4.1 Dynamic incentives

As a "rule of thumb", Groom & Venmans (2023) give the range 33 to 50 percent for the SVO of a ton stored for 50 years compared to the value of a ton of carbon permanently removed. The estimate of Kim et al. (2008) of a 50 percent discount as "common" coincides with the upper bound, which is plausible considering that they focus exclusively on the issue of non-permanence. Franks et al. (2024), too, find a comparable optimal correction factor for a half-time of 50 years around 50 percent. They show that the correction factor depends sensitively on the discount rate, ranging, for example, from 42 to 83 percent for a discount rate between 1 to 7 percent, see Table 1.

An implicit assumption of the correction factors above is that the non-permanence is taken into account when the flow of CO_2 to the storage is subsidized. This approach has the appealing property that the removal is priced once and for all at its social value. Going forward, no further action is required. The downside of pricing CO_2 "upstream", when the CO_2 enters storage, is a lack of an incentive for diligent maintenance of the storage site (Franks et al., 2024), as the operator has already received all the benefit. Franks et al. (2024) point out that payment of the subsidy could be "staggered", that is, spread out over time, while monitoring the diligence of the operator. However, monitoring costs could be high, adding to an already challenging informational need of estimating the storage duration for a correct pricing of the subsidy.

Two alternatives are discussed in Franks et al. (2024). The first is to implement comprehensive carbon pricing such that CO_2 is taxed "downstream" at the end of the storage time. This way, the full subsidy equal to the SCC can be paid even for CDR with temporary storage. Downstream pricing would indeed create an incentive for optimal diligence in storage maintenance. Informationally, downstream pricing could rely on monitoring the flow to and from storage, or alternatively the change of CO_2 in the storage. Whether this is less costly than upstream pricing may depend on the specific CDR technology under consideration.

The downstream pricing scheme, however, also faces an incentive problem. Firms that are liable for operation of storage and subject to the tax on associated emissions may be out of business at the end of the storage duration. The knowledge that their liability is thus limited distorts the incentive set by the subsidy. The firm is "judgment-proof" in the sense that if it anticipates default it can operate as though its storage were permanent. Regulators need additional instruments to address the judgment-proof problem, for example by demanding firms to post a collateral that they can claim in case of bankruptcy. Some scholars have suggested to design financial instruments that would make the collateral tradable to avoid limiting firms' liquidity. In the context of carbon emissions, Held & Edenhofer (2009) have suggested state-issued, tradable bonds for this purpose, Lemoine (2020) suggests "carbon shares" for a similar purpose (discussed below).

The second alternative is to price carbon stocks instead of carbon flows. Similar to the staggered payment of the upstream removal subsidy, subsidizing the stock of stored carbon instead of the flow spreads out the payments over time. That way, the regulator can preserve the incentive for optimal removal and diligent maintenance (Franks et al., 2024).

Instead of subsidizing stocks of removed carbon, Lemoine (2020, 2024) suggests a rental charge on the stock of carbon stored in the atmosphere, albeit focusing only on permanent removal. Rental charges would create an incentive to remove CO_2 from the atmosphere as early as possible. As future rental charge payments (in contrast to a stock subsidy) may be forgone, Lemoine also discusses how to address the emerging incentive problem: The rental charge is brought forward as a bond, and by providing "carbon shares" in exchange for the bond, firms stay liquid.

A few other notable publications consider policy instruments to incentivize CDR under the assumption that it is permanent. Among these, Bednar et al. (2021) also suggest to harness financial markets. They introduce carbon removal obligations, linking emissions to carbon debt, which appears on emitters' balance sheets similarly to financial debt. The risk of default on this debt is managed by applying a higher interest rate, thus involving the financial sector rather than carbon markets. Their simulations suggest that interest on carbon debt can reduce reliance on carbon dioxide removal. Carbon takeback obligations, as described by Jenkins et al. (2021, 2023), require fossil fuel companies to remove a percentage of their emissions, aiming to reach 100% over time, without using the concept of carbon debt since removal occurs before extraction or import.

To conclude, pricing removal when storage time is endogenous becomes considerably more challenging for economic policies. This requires further research and solutions.

4.2 International cooperation and carbon leakage

The analysis of nationally implemented CDR policies abstracts from the international cooperation problem related to climate change mitigation. In contrast, research on international environmental agreements (surveyed, e.g., in Chan et al., 2018, Raiser et al., 2020, Kornek & Edenhofer, 2020, Tavoni & Winkler, 2021) acknowledges that the effectiveness of international climate policy is undermined by free-riding (as avoiding climate damages is global public good) and carbon leakage (as a unilateral reduction of fossil fuel demand lowers fuel prices and spurs demand elsewhere). The literature incorporated geoengineering options early on (e.g. Barrett, 2008). But even though CDR is often subsumed as a geoengineering option, the discussion almost exclusively focuses on solar radiation management (see, e.g., Barrett, 2014, McEvoy et al., 2024, or the reviews in Heutel et al., 2016 and Flegal et al., 2019). Lessons from SRM, however, cannot be transferred to the case of CDR: key differences of SRM are the relatively low private cost and imperfect substitutability to abatement, whereas (permanent) CDR is expensive and a perfect substitute. For participation in cooperative climate policy, which is analyzed by balancing the costs and benefits of contributing to a global public good, this difference is crucial.

Barrett & Moreno-Cruz (2015) (albeit without formal analysis) note that CDR does not require large-scale international cooperation but simply coordination: It can be done by a small coalition of the willing and is less vulnerable to free-riding and emission leakage. However, a conceptual analysis of the implications of carbon removal for international cooperation on climate policy is still missing in the literature. In the following, we sketch a stylized model of free-riding and carbon leakage to illustrate one important feature of removal in this domain. As a starting point, consider the asymmetric role of CDR and abatement for carbon leakage. Franks et al. (2022) analyze optimal mitigation and removal in a multi-country model with a global fossil fuel market. They find that because abatement reduces fossil fuel prices, it induces supply-side leakage, reducing the unilateral benefits of domestic climate policy. As CDR is assumed to not reduce fossil fuel supply, the authors find that this raises the optimal subsidy rate on domestic removal relative to the carbon tax on domestic emissions.[5]

This asymmetry in leakage of CDR and abatement on international policies can be integrated in a standard game theoretic climate policy model with N symmetric countries that maximize their individual payoff, affecting global net emissions $\bar{\Omega}$:

$$\pi_i = b\bar{\Omega} - \frac{c}{2}M_i^2 - \frac{r}{2}R_i^2 \tag{9}$$

$$\bar{\Omega} = \sum_{j=1}^{N} \left((1-LR)M_j + R_j\right) \tag{10}$$

[5]This holds all else equal – in equilibrium, the net effect is complicated by rent appropriation and trade balance effects.

The pay-off π_i of country i in (9) considers an agent i's abatement M_i and removal R_i activities with marginal cost parameters c and r, respectively. However, only abatement causes supply side leakage at a rate of LR.[6] The impact on the aggregate net emissions is captured by equation (10). The model allows to calculate the socially optimal level of mitigation $\bar{\Omega}^*$ and the respective Nash-equilibrium $\bar{\Omega}^N$:

$$\bar{\Omega}^* = N^2\left(\frac{b}{c}+\frac{b}{r}\right) \tag{11}$$

$$\bar{\Omega}^N = N\left(\frac{b}{c}(1-LR)^2+\frac{b}{r}\right) \tag{12}$$

How large the gap between Nash-equilibrium and social optimum is depends on the leakage rate (LR), the cost ratio between abatement and removal and the number of countries. To illustrate the dependence, we define the ratio $\theta = \frac{\bar{\Omega}^N}{\bar{\Omega}^*}$, which ranges from 0 (maximum gap) to 1 (Nash equilibrium and social optimum coincide). Hence, θ measures the degree of cooperation that translates into global ambition levels. In Table 2 we show the value of θ for different cost ratios for adaptation and removals and different leakage rates.[7] As Table 2 shows, if technological progress leads to cost-savings in the CDR sector, that is, $\frac{r}{c}$ falls, the ambition of international cooperation increases considerably. For example, if the marginal cost curve for removals is initially twice as high as the marginal abatement cost curve, $r/c = 2$, and leakage rate is 30%, global emissions of the Nash outcome will be 13 percent of the global cooperative outcome. When substantial cost savings in CDR occur and marginal removal costs are half the marginal abatement costs, $r/c = 0.5$, the Nash outcome falls short of 17 percent of the global optimum. This implies an improvement of ambition levels by roughly one quarter. If the leakage rate is 50%, the Nash outcome is improved already by 50%. Without supply-side leakage of mitigation, the advantage of CDR to improve international cooperation vanishes.

Franks et al. (2022) have emphasized the importance of the terms-of-trade effect for fossil fuel exporters and importers. Instead of assuming N symmetric countries we now allow for I fossil fuel importers and $N-I$ exporters and qualitatively discuss the implications for the international division of labor for abatement and removal. We relegate the formal analysis to Supplemental Material C but emphasize key implications: A reduction in emissions lowers the demand for fossil fuels, which in turn decreases their prices. Consequently, net importers of fossil fuels benefit from climate policy while net exporters lose. Net importers, thus, have a stronger incentive to invest in emissions abatement, whereas net exporters have less motivation to do so. For importers, the terms of trade effect partially offsets the leakage effect. For exporters, the impact is straightforward: They significantly

[6] We disregard potential (negative) leakage rates for removal to avoid additional terms in the equations. They can be added in a straight-forward way.

[7] The leakage rate of a domestic reduction of fossil fuel consumption is calculated by $LR = \frac{-\varepsilon_D}{\varepsilon_S - \varepsilon_D}$ with $\varepsilon_D < 0$ the price elasticity of global demand and $\varepsilon_S < 0$ the price elasticity of global fuel supply. For typical values $\varepsilon_D = -0.2$ and $\varepsilon_S = 0.44$ (Prest, 2022) follows $LR = 0.31$. For $\varepsilon_D = -0.5$, the leakage rate would increase to $LR = 0.53$.

r/c	5	2	1	0.5	0.1
$LR = 0\%$	0.20	0.20	0.20	0.20	0.20
$LR = 30\%$	0.12	0.13	0.15	0.17	0.19
$LR = 50\%$	0.08	0.10	0.13	0.15	0.19

Table 2: Free-riding incentives and relative costs of marginal carbon removal. Numbers show ratio of global net emissions in the Nash equilibrium to net emissions in the social optimum $\theta = \bar{\Omega}^N/\bar{\Omega}^*$ for different leakage rates LR and values of r/c, the relation between the slope of the marginal removal costs and the slope of the marginal abatement costs. Illustration for $N = 5$.

reduce their abatement effort. A key implication is therefore that net-exporters of fossil fuels, *ceteris paribus*, deploy higher removals relative to abatement than net-importers in order to preserve fossil fuel prices.

Since the availability of CDR reduces leakage, it enhances international cooperation. The terms-of-trade effects make CDR in particular beneficial for fossil-fuel-exporting countries; despite of carbon leakage, fossil-fuel-importing countries give abatement a higher priority. In principle, importers and exporters can implement their strategies with price or with quantity instruments. In the next section, we turn our attention to the latter as an increasing share of global emissions is already regulated by emissions trading schemes.

5 Integrating CDR in Emission Trading Systems

New policies for CDR will be designed under political and institutional constraints given by existing instruments. A prominent example of such an instrument is the European Union's Emission Trading System (EU ETS), and the integration of CDR in the EU ETS is rising quickly on the agenda of both researchers and policy makers (Schenuit & Geden, 2023). With the stationary cap reaching zero around 2040, the integration of CDR will be essential to address the "emerging endgame" of achieving net-zero emissions within the ETS (Pahle et al., 2023, Rickels et al., 2021). At the same time, rising allowance prices during the transition to net zero may undermine the political feasibility of the remaining emissions budget (Rickels et al., 2022). Integrating CDR could lower allowance prices and alleviate the problem by achieving a cost-effective balance between abatement and removal. Furthermore, integrating CDR in the EU ETS could help scale up the removal sector by creating a market for removals and providing long-term certainty for investors (Burke & Schenuit, 2024, Sultani et al., 2024). Thus, there are strong reasons to consider the integration of CDR in the EU ETS. We review existing proposals for policy options to achieve a net-zero or net-negative EU ETS below.

5.1 Emissions trading with net-zero targets

The economic logic behind the integration of permanent carbon removals to achieve a net-zero compatible ETS is straightforward: Removal suppliers generate emission allowances by removing an equivalent amount of carbon and selling them in the ETS. The availability of newly generated emission allowances makes the effective cap on gross emissions elastic, thereby lowering the equilibrium price of allowances and decreasing the aggregate cost of a given net-emissions budget (Rickels et al., 2021). While the regulatory cap on net emissions remains unaffected, the effective cap is determined by the intersection of marginal abatement and removal cost. However, if removal remains expensive, no additional allowances will be generated. Given the current development stage of permanent removal technologies, the latter case seems to be relevant in the short-run. Thus, an unconditional integration of CDR might not be effective in scaling up the removal sector in the short-run (Rickels et al., 2021). Further objections to the unconditional integration of permanent removals in the ETS concern unaccounted negative externalities in the removal supply chain and the potentially large-scale substitution of abatement efforts, undermining technological learning in the abatement sector (Rickels et al., 2021, 2022, La Hoz Theuer et al., 2021).

To address these challenges, the regulator could impose qualitative and quantitative restrictions on removal credits in the ETS, or act as an intermediary between the two markets (La Hoz Theuer et al., 2021, Rickels et al., 2021). The intermediary could procure high-cost removals in an initial stage and sell them in the ETS at a lower price, preserving incentives for technological learning in both the removal and abatement sector (Rickels et al., 2021). Furthermore, by building up a strategic reserve of removal credits, the intermediary could support policy objectives like a maximum allowance price by releasing removal credits into the ETS according to some predefined policy rule. The conditional supply of removal credits would make it possible to stabilize the market in the transition to net-zero while keeping net-emission pathways constant (Rickels et al., 2022).

As shown above, separate prices for removal and abatement may violate basic static efficiency conditions. To attain a first-best outcome, recent research has suggested a policy sequencing approach (Burke & Schenuit, 2024, Sultani et al., 2024). Both papers suggest to increase the degree of integration of removals step-by-step conditional on the availability of credible monitoring, reporting and verification (MRV), the containment of sustainability risks and the introduction of liability measures. Whenever a removal technology meets these criteria, integration into the ETS would enable removals according to the prevailing carbon price. For the EU-ETS, integration of BECCS and DACCS could lead to annual CDR deployment of up to 60 Mt by 2050 (Sultani et al., 2024).

Another important question concerns the integration of non-permanent removal credits. Some scholars argue for including these removals alongside international credits to enhance supply-side efficiency (Sultani et al., 2024). Others suggest to focus on permanent removals to reduce costs of monitoring and verification, and to reduce the risk of non-additionality and limited liability (Rickels et al., 2021). Cheap non-permanent removals could also crowd out high-cost permanent removals, thereby reducing technological learning for the latter (Burke & Schenuit, 2024). Conceptually, Edenhofer et al. (2023) discuss how the inclusion of non-permanent CDR gives rise to a liability, interpreted either as a commitment to perpetually refill non-permanent carbon sinks or as a financial liability. The latter case is equivalent to the discount factors discussed in Section 3.

To date, only a few existing ETS have already integrated CDR, primarily focusing on forest-based offsets. For example, New Zealand's ETS includes the whole forestry sector and provides incentives for afforestation and preserving existing forest carbon stocks. In theory, this equal pricing of afforestation and deforestation provides optimal incentives for carbon removal in the ETS (Franks et al., 2022). In practice, low allowance prices and policy uncertainty led to little observable change initially, yet recent price increases and policy reforms seem to have increased afforestation and curbed deforestation (Carver et al., 2022). Another example is California's cap-and-trade program, which allows limited forest-based offset credits for compliance, though concerns about low additionality and the need for stricter standards have been highlighted (Stapp et al., 2023). The Californian regulation defines a storage period of 100 years as permanent, and unintentional reversals are covered by deductions from a buffer pool. In case of intentional reversal, project owners have to surrender an equivalent amount of credits. Other jurisdictions, including the UK and EU, are starting to explore options to incorporate CDR into their ETS.

5.2 Emissions trading with net-negative targets

A conventional ETS, even with full integration of CDR, can only achieve net-*zero* but not net-*negative* emissions. Achieving a phase of net-negative emissions might, however, be necessary as discussed in Section 2.3. In principle, net-negative emissions could be achieved by buying additional removal credits and banking or deleting them. For example, Rickels et al. (2022) suggest that a public authority could build up a reserve of removal credits via public procurement of carbon removal. By deleting these credits instead of releasing them to the market, net-negative emissions are generated. However, such public procurement schemes require additional public funds, which may be challenging to mobilize and protect from diversion (Bednar et al., 2023b, Lyngfelt et al., 2024). Additionally, governments would need to commit to a specific pathway toward net negative (Lessmann et al., 2024), and any prevailing uncertainty about the future time path may cause additional price volatility. Several recent studies have thus investigated how an ETS could be reformed to leverage market mechanisms in financing and achieving net-negative emissions.

Rickels et al. (2021) discuss a negative regulatory cap in a static ETS model. If gross emissions are still positive, a net-negative cap could be achieved by requiring an exchange rate below one between removal credits and allowances. However, as the economy continues to decarbonize, additional public procurement might be required, which faces the challenges outlined above. A number of studies address this concern by holding current emitters liable for future removals, which secures finance for future CDR (Bednar et al., 2021, 2023a,b, Lyngfelt et al., 2024, Lessmann et al., 2024). In essence, these studies suggest applying the polluter-pays-principle by associating emissions that exceed a long-term political carbon budget with "carbon debt". The carbon debt has to be repaid by removing the associated amount of carbon, thus facilitating a later phase of net-negative emissions. The concept could be embedded in an ETS via mechanisms such as Carbon Removal Obligations (Bednar et al., 2021, 2023a,b), Clean-Up Certificates (Lessmann et al., 2024) or Atmospheric CO_2 Removal Deposits (Lyngfelt et al., 2024). While all proposals share the fundamental idea to ensure sufficient financing for CDR by linking carbon debt to emissions allowances, many of them add extensions to address further issues. Bednar et al. (2021), for example, suggests interest payments on carbon debt, at an interest rate determined by financial institutions, which may benefit from their experience in pricing loan risks when pricing the default risk of carbon debt. Bednar et al. (2023a) and Lessmann et al. (2024) suggest collateral requirements to mitigate the default risk, and which the regulator could draw on to carry out carbon removal in case of default.

Furthermore, when carbon debt is linked to additional allowances as in Lessmann et al. (2024), their introduction puts downward pressure on allowances prices by expanding the supply of allowances. The decline in allowance prices can be offset by adjusting the carbon budget towards a higher environmental ambition to address concerns of mitigation deterrence (see also Rickels et al., 2021). Lessmann et al. (2024) point out that the trade-off between environmental ambition level and carbon prices can be relaxed due to the additional intertemporal flexibility from introucing clean-up certificates. They show a balance can be found between the extent of carbon debt in the system and the adjustment of the budget that improves the ETS in all four of the dimensions of short-term carbon prices, cumulative compliance cost, avoided climate damages, and fiscal revenue generated. There might therefore be room for political win-win outcomes between industry, the regulator and environmental associations.

From a governance perspective, there is an important caveat to the additional flexibility. From the perspective of a social planner, adherence to the intertemporal budget constraint is time-consistent if climate damages are taken into account and emissions follow an optimal path. However, under a cost-effectiveness analysis, it becomes rational for the social planner to constantly postpone the repayment of the carbon debt because the flexibility gained does not incur any social costs in the form of additional climate damage. When allowing for overshoot in emissions trading schemes, a broader perspective including the SCC damage metric is necessary to determine the size of the carbon debt and the time horizon for overshoot compensation.

Thus, integrating CDR into an ETS framework poses several institutional challenges, such as ensuring the quality and comparability of removal credits, preventing mitigation deterrence, and guaranteeing the adherence to a credible long-term climate policy target. To address these challenges, scholars have proposed of a (European) Carbon Central Bank (CCB). Acting as an intermediary between markets, the CCB could buy and sell CDR credits, manage the carbon portfolio and serve as a clearing house for different removal methods with varying degrees of permanence (Rickels et al., 2021, 2022). In addition, Edenhofer et al. (2023) and Lessmann et al. (2024) suggest expanding the mandate of the CCB to include the independent intertemporal management of the carbon budget, ensuring that the resulting overshooting follows closely an optimal path from a cost-benefit perspective. The CCB would then also be in charge of collecting and investing the financial collateral associated to carbon debt and act as "lender-of-last-resort", i.e. remove carbon when firms default on their removal obligation.

6 Conclusion

In this article, we have surveyed the nascent field of CDR governance. While the progress has been rapid in recent years, we also perceive substantial gaps in the literature. It remains a fundamental challenge to create incentives for scaling up the use of novel removal technologies, which currently exist mostly as demonstration projects or prototypes. Up-scaling will also accelerate innovation and induce further cost reductions such that novel removal technologies might become eventually competitive within carbon pricing schemes. Fuss et al. (2024) discuss the role of voluntary and compliance carbon markets for the upscaling of novel CDR. The authors suggest advanced market commitments and forward purchasing, besides reliable standards for monitoring, reporting and verification as essential economic tools to establish compliance markets. Other potential instruments include start-up financing through the creation of lead markets, as for example implemented by the German Federal Ministry for Economic Affairs and Climate Action (2024), or by reverse auctions (Lundberg & Fridahl, 2022), as in the case of BECCS in Sweden. However, to date, we are not aware of any empirical or quantitative analyses that assess the extent of innovation and network externalities of novel removal technologies. This, in turn, is necessary to determine welfare-maximizing levels of complementary technology policies besides carbon pricing.

Scaling-up CDR will also have substantial implications on resource use and on the environment, which deserve more attention. While the implications can be positive, e.g. increasing biodiversity in agroforestry systems, in many cases, there will be negative externalities of large-scale CDR, e.g. due to higher energy, mineral or land use (Fuss et al., 2018, Prütz et al., 2024). And while the general nature of these co-externalities has been understood, there is only little work in quantifying these external effects and determining optimal policy mixes or optimal technology portfolios from a broader social welfare perspective: Migo-Sumagang et al. (2023) provide a portfolio optimization for Southeast Asia, Rodriguez Mendez et al. (2024a) explore trade-offs and portfolios under uncertainty.

A key resource impact identified in the literature has been land-use for land-intensive technologies like BECCS. Integrating BECCS into carbon pricing without pricing the emissions of the induced land-use change may substantially undermine the effectiveness in reducing net-emission (Merfort et al., 2023). Besides approaches to exogeneously limit BECCS deployment, we are not aware of studies on second-best policies for land-intensive carbon removals when carbon pricing is globally and sectorally fragmented.

The aggregate efficiency gains from integrating carbon removal in carbon pricing may involve further fiscal or distributional effects. With increasing land-demand, distributional effects through higher food prices can also be expected. Andreoni et al. (2024) highlight two further distributional challenges. First, high public expenditures for carbon removal could "dry up" public funds needed for social transfers. Second, high carbon prices could lead to windfall profits for removal firms that operate at the lower range of the cost curve. As carbon removal decreases carbon prices, it reduces also adverse distributional effects to the extent that carbon pricing is regressive, which depends on country context (Dorband et al., 2019, Ohlendorf et al., 2021, Feindt et al., 2021).

With ongoing technological progress in novel removal technologies and increasing social cost of carbon due to continued global warming, carbon dioxide removal could become the third pillar of climate policy. Carbon removals create large sectoral and intertemporal flexibility, which reduce the costs of climate policy and may also imply that optimal climate policy involves an overshoot of the global mean surface temperature. Moreover, CDR can help enhance international cooperation through reduced carbon leakage. We have developed stylized models to capture and illustrate key mechanisms that have been reviewed in the largely conceptual literature on governance and policy design for carbon removal. Future research could shed more light on empirical and quantitative aspects of specific policies for carbon removal, e.g. addressing innovation externalities, land-use effects, carbon-leakage effects or implications for international climate policy. Integrating (permanent) carbon removals into emissions trading schemes is challenging, in particular, when emissions should become net-negative eventually. We emphasize that addressing liability problems and the emerging time-inconsistency problem of emissions trading with overshooting flexibility – created by clean-up certificates or removal obligations – may also require the creation of new institutions. Related to the tasks of central banks, a 'carbon central bank' could guarantee functioning and integrity of intertemporal carbon markets, reduce default risks on removal obligations and stabilize expectations on carbon removal incentives.

Acknowledgements

We thank Wilfried Rickels for helpful comments and Lennart Stern for support in the development and analysis of the game-theoretic model on international cooperation. We gratefully acknowledge funding by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) for project number 456947458DFG (CLEANUP), and from the European Union's Horizon Europe research and innovation programme under Grant Agreement No. 101081521 (UPTAKE).

References

Andreoni P, Emmerling J, Tavoni M. 2024. Inequality repercussions of financing negative emissions. *Nature Climate Change* 14(1):48–54

Bahn O, Chesney M, Gheyssens J, Knutti R, Pana AC. 2015. Is there room for geoengineering in the optimal climate policy mix? *Environmental Science & Policy* 48:67–76

Barrett S. 2008. The incredible economics of geoengineering. *Environmental and resource economics* 39:45–54

Barrett S. 2014. Solar geoengineering's brave new world: Thoughts on the governance of an unprecedented technology. *Review of Environmental Economics and Policy* 8(2):249–269

Barrett S, Moreno-Cruz J. 2015. The alternatives to unconstrained climate change: Emission reductions versus carbon and solar geoengineering. In *Towards a workable and effective climate regime*, eds. S Barrett, C Carraro, J de Melo, chap. 25. 353–357

Bauer N, Keller DP, Garbe J, Karstens K, Piontek F, et al. 2023. Exploring risks and benefits of overshooting a 1.5° C carbon budget over space and time. *Environmental Research Letters* 18(5):054015

Bednar J, Baklanov A, Macinante J. 2023a. The carbon removal obligation. IIASA Working Paper. https://pure.iiasa.ac.at/id/eprint/18572/1/WP-23-001.pdf

Bednar J, Macinante J, Baklanov A, Hall JW, Wagner F, et al. 2023b. Beyond emissions trading to a negative carbon economy: a proposed carbon removal obligation and its implementation. *Climate Policy* :1–14

Bednar J, Obersteiner M, Baklanov A, Thomson M, Wagner F, et al. 2021. Operationalizing the net-negative carbon economy. *Nature* 596(7872):377–383

Belaia M, Moreno-Cruz JB, Keith DW. 2021. Optimal climate policy in 3d: Mitigation, carbon removal, and solar geoengineering. *Climate Change Economics* 12(03):2150008

Brander M, Broekhoff D. 2023. Methods that equate temporary carbon storage with permanent CO2 emission reductions lead to false claims on temperature alignment. *Carbon Management* 14(1):2284714

Burke J, Gambhir A. 2022. Policy incentives for greenhouse gas removal techniques: the risks of premature inclusion in carbon markets and the need for a multi-pronged policy framework. *Energy and Climate Change* 3:100074

Burke J, Schenuit F. 2024. Conditional fungibility: sequencing permanent removals into emissions trading systems. *Environmental Research Letters* 19:111002

Carver T, Dawson P, O'Brien S, Kotula H, Kerr S, Leining C. 2022. Including forestry in an emissions trading scheme: Lessons from New Zealand. *Frontiers in Forests and Global Change* 5:956196

Chan G, Stavins R, Ji Z. 2018. International climate change policy. *Annual Review of Resource Economics* 10:335–360

Churkina G, Organschi A, Reyer CP, Ruff A, Vinke K, et al. 2020. Buildings as a global carbon sink. *Nature Sustainability* 3(4):269–276

Dietz S, Bowen A, Doda B, Gambhir A, Warren R. 2018. The economics of 1.5 °C climate change. *Annual Review of Environment and Resources* 43(1):455–480

Dorband II, Jakob M, Kalkuhl M, Steckel JC. 2019. Poverty and distributional effects of carbon pricing in low-and middle-income countries–a global comparative analysis. *World Development* 115:246–257

Edenhofer O, Franks M, Kalkuhl M, Runge-Metzger A. 2023. On the governance of carbon dioxide removal–a public economics perspective. *FinanzArchiv: Public Finance Analysis* 80(1):70–110

Federal Ministry for Economic Affairs and Climate Action. 2024. Lead markets for climate-friendly basic materials. https://www.bmwk.de/Redaktion/EN/Publikationen/Klimaschutz/lead-markets-for-climate-friendly-basic-materials.html

Feindt S, Kornek U, Labeaga JM, Sterner T, Ward H. 2021. Understanding regressivity: Challenges and opportunities of european carbon pricing. *Energy Economics* 103:105550

Flegal JA, Hubert AM, Morrow DR, Moreno-Cruz JB. 2019. Solar Geoengineering: Social Science, Legal, Ethical, and Economic Frameworks. *Annual Review of Environment and Resources* 44:399–423

Franks M, Gruner F, Kalkuhl M, Lessmann K, Edenhofer O. 2024. Pigou's advice and sisyphus'warning: Carbon pricing withnon-permanent carbon dioxide removal. SSRN pre-print article. https://ssrn.com/abstract=4828800, DOI: 10.2139/ssrn.4828800

Franks M, Kalkuhl M, Lessmann K. 2022. Optimal pricing for carbon dioxide removal under inter-regional leakage. *Journal of Environmental Economics and Management* :102769

Friedlingstein P, O'sullivan M, Jones MW, Andrew RM, Bakker DC, et al. 2023. Global carbon budget 2023. *Earth System Science Data* 15(12):5301–5369

Fuss S, Johnstone I, Höglund R, Walsh N. 2024. Chapter 4: The voluntary carbon market. In *The State of Carbon Dioxide Removal 2024 – 2nd Edition*, ed. SMea Smith. https://www.stateofcdr.org, doi:10.17605/OSF.IO/MG3CY

Fuss S, Lamb WF, Callaghan MW, Hilaire J, Creutzig F, et al. 2018. Negative emissions—part 2: Costs, potentials and side effects. *Environmental research letters* 13(6):063002

Groom B, Venmans F. 2023. The social value of offsets. *Nature* 619(7971):768–773

Held H, Edenhofer O. 2009. CCS-Bonds as a superior instrument to incentivize secure carbon sequestration. *Energy Procedia* 1(1):4559–4566

Helwegen KG, Wieners CE, Frank JE, Dijkstra HA. 2019. Complementing CO2 emission reduction by solar radiation management might strongly enhance future welfare. *Earth System Dynamics* 10:453–472

Hepburn C, Adlen E, Beddington J, Carter EA, Fuss S, et al. 2019. The technological and economic prospects for CO2 utilization and removal. *Nature* 575(7781):87–97

Heutel G, Moreno-Cruz J, Ricke K. 2016. Climate engineering economics. *Annual Review of Resource Economics* 8(1):99–118

Hoel M. 2024. The path to net zero emissions. CESifo Working Paper 10939, CESifo, Munich. http://dx.doi.org/10.2139/ssrn.4723732

Honegger M, Baatz C, Eberenz S, Holland-Cunz A, Michaelowa A, et al. 2022. The abc of governance principles for carbon dioxide removal policy. *Frontiers in Climate* 4:884163

Hotelling H. 1931. The Economics of Exhaustible Resources. *Journal of Political Economy* 39(2):137–175

Inada KI. 1963. On a two-sector model of economic growth: Comments and a generalization. *The Review of Economic Studies* 30(2):119–127

IPCC. 2018. Summary for policymakers. In *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of* *strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, eds. V Masson-Delmotte, P Zhai, HO Pörtner, D Roberts, J Skea, P Shukla, A Pirani, W Moufouma-Okia, C Péan, R Pidcock, S Connors, J Matthews, Y Chen, X Zhou, M Gomis, E Lonnoy, T Maycock, M Tignor, T Waterfield. Cambridge University Press, 3–24

IPCC. 2022. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press

Jenkins S, Kuijper M, Helferty H, Girardin C, Allen M. 2023. Extended producer responsibility for fossil fuels. *Environmental Research Letters* 18(1):011005

Jenkins S, Mitchell-Larson E, Ives MC, Haszeldine S, Allen M. 2021. Upstream decarbonization through a carbon takeback obligation: an affordable backstop climate policy. *Joule* 5(11):2777–2796

Kim MK, McCarl BA, Murray BC. 2008. Permanence discounting for land-based carbon sequestration. *Ecological Economics* 64(4):763–769

Kornek U, Edenhofer O. 2020. The strategic dimension of financing global public goods. *European Economic Review* 127:103423

La Hoz Theuer S, Doda B, Kellner K, Acworth W. 2021. Emission trading systems and net zero: Trading removals. Berlin: ICAP. https://icapcarbonaction.com/system/files/document/icap-netzeropaper_final-draft.pdf

Lemoine D. 2020. Incentivizing negative emissions through carbon shares. NBER Working Paper 27880, National Bureau of Economic Research. https://www.nber.org/papers/w27880

Lemoine D. 2024. Informationally efficient climate policy: Designing markets to measure and price externalities. NBER Working Paper 30535, National Bureau of Economic Research. https://www.nber.org/papers/w30535

Lessmann K, Gruner F, Kalkuhl M, Edenhofer O. 2024. Emissions trading with clean-up certificates: Deterring mitigation or increasing ambition? CESifo Working Paper 11167, CESifo, Munich. https://www.cesifo.org/DocDL/cesifo1_wp11167.pdf

Lobel O. 2012. New governance as regulatory governance. In *The Oxford Handbook of Governance*, ed. D Levi-Faur, chap. 5. Oxford University Press

Low S, Boettcher M, Asayama S, Baum C, Borth A, et al. 2024. An earth system governance research agenda for carbon removal. *Earth System Governance* 19:100204

Lundberg L, Fridahl M. 2022. The missing piece in policy for carbon dioxide removal: reverse auctions as an interim solution. *Discover Energy* 2(1):3

Lyngfelt A, Fridahl M, Haszeldine S. 2024. Financeforfuture: Enforcing a CO2 emitter liability using atmospheric CO2 removal deposits (acords) to finance future negative emissions. *Energy Research & Social Science* 107:103356

McEvoy DM, McGinty M, Cherry TL, Kroll S. 2024. International Climate Agreements under the Threat of Solar Geoengineering. *Journal of the Association of Environmental and Resource Economists* 11(4):853–886

Meier F, Rickels W, Quaas MF, Traeger C. 2022. Carbon dioxide removal in a global analytic climate economy. https://www.ifw-kiel.de/publications/carbon-dioxide-removal-in-a-global-analytical-climate-economy-31796

Mendez QR, Fuss S, Lück S, Creutzig F. 2024. Assessing global urban CO2 removal. *Nature Cities* 1(6):413–423

Merfort A, Strefler J, Abrahão G, Bauer N, Luderer G, et al. 2024. Separating CO2 emission from removal targets comes with limited cost impacts. Available at ResearchSquare. https://doi.org/10.21203/rs.3.rs-4572047/v1

Merfort L, Bauer N, Humpenöder F, Klein D, Strefler J, et al. 2023. Bioenergy-induced land-use-change emissions with sectorally fragmented policies. *Nature Climate Change* 13(7):685–692

Michaelowa A, Hermwille L, Obergassel W, Butzengeiger S. 2019. Additionality revisited: guarding the integrity of market mechanisms under the paris agreement. *Climate Policy* 19(10):1211–1224

Migo-Sumagang MV, Tan RR, Aviso KB. 2023. A multi-period model for optimizing negative emission technology portfolios with economic and carbon value discount rates. *Energy* 275:127445

Minx JC, Lamb WF, Callaghan MW, Fuss S, Hilaire J, et al. 2018. Negative emissions—part 1: Research landscape and synthesis. *Environmental Research Letters* 13(6):063001

Nemet GF, Callaghan MW, Creutzig F, Fuss S, Hartmann J, et al. 2018. Negative emissions—part 3: Innovation and upscaling. *Environmental Research Letters* 13(6):063003

Nolan C, Van Paasschen CA, Field CB. 2024. Additionality, baselines, and the proper accounting for land-based climate change mitigation efforts. *Oxford Open Climate Change* 4(1)

Ohlendorf N, Jakob M, Minx JC, Schröder C, Steckel JC. 2021. Distributional impacts of carbon pricing: A meta-analysis. *Environmental and Resource Economics* 78(1):1–42

Pahle M, Quemin S, Osorio S, Günther C, Pietzcker R. 2023. The emerging endgame: the EU ETS on the road towards climate neutrality. SSRN 437443. http://dx.doi.org/10.2139/ssrn.4373443

Pongratz J, Smith SM, Schwingshackl C, Dayathilake L, Gasser T, et al. 2024. Chapter 7: Current levels of cdr. In *The State of Carbon Dioxide Removal 2024 – 2nd Edition*, ed. SMea Smith. https://static1.squarespace.com/static/633458017a1ae214f3772c76/t/665ed65126947a4bb8884191/1717491294185/Chapter+7-The+State+of+Carbon+Dioxide+Removal+2ED.pdf

Prest BC. 2022. Partners, not rivals: The power of parallel supply-side and demand-side climate policy. *Resources for the Future*. https://www.rff.org/publications/reports/partners-not-rivals-the-power-of-parallelsupply-side-and-demand-side-climate-policy

Prütz R, Fuss S, Lück S, Stephan L, Rogelj J. 2024. A taxonomy to map evidence on the co-benefits, challenges, and limits of carbon dioxide removal. *Communications Earth & Environment* 5(1):197

Raiser K, Kornek U, Flachsland C, Lamb WF. 2020. Is the paris agreement effective? a systematic map of the evidence. *Environmental Research Letters* 15(8):083006

Rickels W, Lontzek TS. 2012. Optimal global carbon management with ocean sequestration. *Oxford Economic Papers* 64(2):323–349

Rickels W, Proelß A, Geden O, Burhenne J, Fridahl M. 2021. Integrating carbon dioxide removal into european emissions trading. *Frontiers in Climate* 3:690023

Rickels W, Reith F, Keller D, Oschlies A, Quaas MF. 2018. Integrated assessment of carbon dioxide removal. *Earth's future* 6(3):565–582

Rickels W, Rothenstein R, Schenuit F, Fridahl M. 2022. Procure, bank, release: Carbon removal certificate reserves to manage carbon prices on the path to net-zero. *Energy Research & Social Science* 94:102858

Rodriguez Mendez Q, Creutzig F, Fuss S. 2024a. Deep uncertainty in carbon dioxide removal portfolios. *mimeo*

Rodriguez Mendez Q, Fuss S, Lück S, Creutzig F. 2024b. Assessing global urban CO2 removal. *Nature Cities* :1–11

Schenuit F, Buck H, Geden O, Hofbauer V, Odeh N, et al. 2024. Chapter 5: Policy and governance. In *The State of Carbon Dioxide Removal 2024 – 2nd Edition*, ed. SMea Smith

Schenuit F, Geden O. 2023. Carbon dioxide removal: Climbing up the EU climate policy agenda. In *Handbook on European Union Climate Change Policy and Politics*. Edward Elgar Publishing, 322–336

Schleussner CF, Ganti G, Lejeune Q, Zhu B, Pfleiderer P, et al. 2024. Overconfidence in climate overshoot. *Nature* 634(8033):366–373

Sedjo R, Sohngen B. 2012. Carbon sequestration in forests and soils. *Annual Review of Resource Economics* 4:127–144

Smith JE, Heath LS, Skog KE, Birdsey RA. 2006. Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the united states. General Technical Report NE-343, United States Department of Agriculture, Forest Service. https://www.fs.usda.gov/ecosystemservices/pdf/estimates-forest-types.pdf

Smith S, Geden O, Gidden M, Lamb W, Nemet G, et al. 2024. The state of carbon dioxide removal. 2nd edition https://static1.squarespace.com/static/633458017a1ae214f3772c76/t/669e6c162eb5af1a357c5ef4/1721658412072/The-State-of-Carbon-Dioxide-Removal-2Edition-3.pdf

Smith W. 2020. The cost of stratospheric aerosol injection through 2100. *Environmental Research Letters* 15(11):114004

Stapp J, Nolte C, Potts M, Baumann M, Haya BK, Butsic V. 2023. Little evidence of management change in california's forest offset program. *Communications Earth & Environment* 4(1):331

Sultani D, Osorio S, Günther C, Pahle M, Sievert K, et al. 2024. Sequencing carbon dioxide removal into the EU ETS. CESifo Working Paper 11173, CESifo, Munich. http://dx.doi.org/10.2139/ssrn.4875550

Tahvonen O. 1995. Net national emissions, CO2 taxation and the role of forestry. *Resource and energy economics* 17(4):307–315

Tavoni A, Winkler R. 2021. Domestic pressure and international climate cooperation. *Annual Review of Resource Economics* 13:225–243

van Kooten GC. 2009. Biological carbon sequestration and carbon trading revisited. *Climatic Change* 95(3-4):449–463

Williamson OE. 1996. The mechanisms of governance. Oxford University Press

Supplemental Material

A Static Climate Policy Portfolio Model

Consider an economy where climate damages, $D(E^n, A)$, are a function of net emissions, E^n, and the level of adaptation, A. Net emissions are defined as the exogenous business-as-usual emissions, $\bar{E}$, minus mitigation efforts, M, and removal efforts, R: $E^n = \bar{E} - M - R$. The costs associated with mitigation, removal, and adaptation are denoted as $C^M(M)$, $C^R(R)$, and $C^A(A)$, respectively.

These cost and damage functions are assumed to be convex. Specifically, the partial derivatives of the damage function exhibit the following properties: $D_E > 0$, $D_{EE} > 0$, $D_A < 0$, and $D_{AA} > 0$. In the general case, we assume that $D_{EA} \leq 0$.

The social planner maximizes welfare by minimizing aggregate cost $G(\bar{E}, A, R, M)$.

$$\begin{aligned} \min_{A,R,M} \quad & G = D(E^n, A) + C^A(A) + C^R(R) + C^M(M) \\ \text{s.t.} \quad & E^n = \bar{E} - M - R \end{aligned} \tag{A.1}$$

The first-order conditions for the minimization problem are given by:

$$\begin{aligned} \frac{\partial G}{\partial A} &= D_A + C^A_A = 0 \\ \frac{\partial G}{\partial R} &= D_E \frac{\partial E^n}{\partial R} + C^R_R = 0 \\ \frac{\partial G}{\partial M} &= D_E \frac{\partial E^n}{\partial M} + C^M_M = 0 \end{aligned} \tag{A.2}$$

This implies:

$$\begin{aligned} -D_A &= C^A_A \\ D_E &= C^R_R \\ D_E &= C^M_M \end{aligned} \tag{A.3}$$

where $D_E = \frac{\partial D}{\partial E^n}$, $D_A = \frac{\partial D}{\partial A}$, $C^M_M = \frac{\partial C^M}{\partial M}$, $C^R_R = \frac{\partial C^R}{\partial R}$, and $C^A_A = \frac{\partial C^A}{\partial A}$. Assuming that the cross-derivatives of the cost functions are equal to zero, the Hessian matrix is given by:

$$H = \begin{pmatrix} D_{AA} + C^A_{AA} & -D_{EA} & -D_{EA} \\ -D_{EA} & D_{EE} + C^R_{RR} & D_{EE} \\ -D_{EA} & D_{EE} & D_{EE} + C^M_{MM} \end{pmatrix} \tag{A.4}$$

To ensure a minimum, the Hessian matrix H must be positive definite. This is checked by calculating the signs of the leading principal minors.

$$|H_1| = D_{AA} + C^A_{AA} \tag{A.5}$$
$$|H_2| = (D_{AA} + C^A_{AA})(D_{EE} + C^R_{RR}) - D^2_{EA} \tag{A.6}$$
$$|H_3| = (D_{AA} + C^A_{AA})C^R_{RR}C^M_{MM} + (D_{AA} + C^A_{AA})(C^M_{MM} + C^R_{RR})D_{EE} - (C^R_{RR} + C^M_{MM})D^2_{EA} \tag{A.7}$$

The first leading principal minor is positive by inspection. The second and third leading principal minors are positive under conditions (A.8) and (A.9), respectively:

$$(D_{AA} + C^A_{AA})(D_{EE} + C^R_{RR}) > D^2_{EA} \tag{A.8}$$
$$(D_{AA} + C^A_{AA})C^R_{RR}C^M_{MM} + (D_{AA} + C^A_{AA})(C^M_{MM} + C^R_{RR})D_{EE} > (C^R_{RR} + C^M_{MM})D^2_{EA} \tag{A.9}$$

In the subsequent analysis, we assume that conditions (A.8) and (A.9) are satisfied, ensuring the existence of a minimum.

A.1 Comparative statics

How does the cost-minimizing portfolio of adaptation, removal and mitigation change if there is technological progress? First, consider a technology shock θ_R that reduces marginal removal cost such that $C^R_{R\theta_R} < 0$. Using the implicit function theorem

$$\begin{pmatrix} \frac{\mathrm{d}A}{\mathrm{d}\theta_R} \\ \frac{\mathrm{d}R}{\mathrm{d}\theta_R} \\ \frac{\mathrm{d}M}{\mathrm{d}\theta_R} \end{pmatrix} = - \begin{pmatrix} D_{AA} + C^A_{AA} & -D_{EA} & -D_{EA} \\ -D_{EA} & D_{EE} + C^R_{RR} & D_{EE} \\ -D_{EA} & D_{EE} & D_{EE} + C^M_{MM} \end{pmatrix}^{-1} \begin{pmatrix} 0 \\ C^R_{R\theta_R} \\ 0 \end{pmatrix} \tag{A.10}$$

yields the following comparative statics:

$$\frac{\mathrm{d}A}{\mathrm{d}\theta_R} = -\frac{C^M_{MM}C^R_{R\theta_R}D_{EA}}{|H|} \tag{A.11}$$
$$\frac{\mathrm{d}R}{\mathrm{d}\theta_R} = -\frac{C^R_{R\theta_R}((C^A_{AA} + D_{AA})(C^M_{MM} + D_{EE}) - D^2_{EA})}{|H|} \tag{A.12}$$
$$\frac{\mathrm{d}M}{\mathrm{d}\theta_R} = -\frac{C^R_{R\theta_R}(D^2_{EA} - (C^A_{AA} + D_{AA})D_{EE})}{|H|} \tag{A.13}$$

By inspection of (A.11), adaptation decreases if $D_{EA} < 0$. For removal, the cost-reducing technology shock increases the level of removal.[8] Finally, equation (A.13) is negative only if

$$(C^A_{AA} + D_{AA})D_{EE} > D^2_{EA} \tag{A.14}$$

[8] To see this, note that $(C^A_{AA} + D_{AA})(C^M_{MM} + D_{EE}) > D^2_{EA}$ is implied by (A.9) (proof by contradiction).

In this case, mitigation decreases in response to a decrease in marginal removal cost.[9] In summary, under the given assumptions the comparative statics are given by:

$$\frac{\mathrm{d}A}{\mathrm{d}\theta_R} < 0 \quad \frac{\mathrm{d}R}{\mathrm{d}\theta_R} > 0 \quad \frac{\mathrm{d}M}{\mathrm{d}\theta_R} < 0 \tag{A.15}$$

Next, consider a change in the marginal cost of adaptation, θ_A. Using the implicit function theorem yields

$$\frac{\mathrm{d}A}{\mathrm{d}\theta_A} = -\frac{C^A_{A\theta_A}\left(C^M_{MM}\left(C^R_{RR}+D_{EE}\right)+C^R_{RR}D_{EE}\right)}{|H|} \tag{A.16}$$

$$\frac{\mathrm{d}R}{\mathrm{d}\theta_A} = -\frac{C^A_{A\theta_A}C^M_{MM}D_{EA}}{|H|} \tag{A.17}$$

$$\frac{\mathrm{d}M}{\mathrm{d}\theta_A} = -\frac{C^A_{A\theta_A}C^R_{RR}D_{EA}}{|H|} \tag{A.18}$$

Equation (A.16) is positive by inspection, while equations (A.17) and (A.18) are negative if $D_{EA} < 0$. Thus, the comparative statics have the following signs

$$\frac{\mathrm{d}A}{\mathrm{d}\theta_A} > 0 \quad \frac{\mathrm{d}R}{\mathrm{d}\theta_A} < 0 \quad \frac{\mathrm{d}M}{\mathrm{d}\theta_A} < 0 \tag{A.19}$$

Finally, consider a change in marginal mitigation cost, θ_M. Again invoking the implicit function theorem yields

$$\frac{\mathrm{d}A}{\mathrm{d}\theta_M} = -\frac{C^M_{M\theta_M}C^R_{RR}D_{EA}}{|H|} \tag{A.20}$$

$$\frac{\mathrm{d}R}{\mathrm{d}\theta_M} = -\frac{C^M_{M\theta_M}(D^2_{EA}-(C^A_{AA}+D_{AA})D_{EE})}{|H|} \tag{A.21}$$

$$\frac{\mathrm{d}M}{\mathrm{d}\theta_M} = -\frac{C^M_{M\theta_M}((C^A_{AA}+D_{AA})(C^R_{RR}+D_{EE})-D^2_{EA})}{|H|} \tag{A.22}$$

Equation (A.20) is negative if $D_{EA} < 0$. Equation (A.21) is negative under assumption (A.14), and equation (A.22) is positive due to the condition for the existence of a local minimum in (A.8). The signs are thus given by

$$\frac{\mathrm{d}A}{\mathrm{d}\theta_M} < 0 \quad \frac{\mathrm{d}R}{\mathrm{d}\theta_M} < 0 \quad \frac{\mathrm{d}M}{\mathrm{d}\theta_M} > 0 \tag{A.23}$$

[9] Note that in the special case where the inequality in (A.14) has the opposite direction, (A.13) is positive, and a cost reduction in carbon removal leads to a crowding-in of abatement. Intuitively, increased removal lowers marginal damages D_E, which reduces the marginal benefit of adaptation if D_{EA} is large. As adaptation A decreases, D_E may rise above its pre-shock level, incentivizing more abatement. This effect can only occur if marginal removal costs are steep enough; if they are constant, it holds that $C^R_{RR} = 0$, and (A.8) implies (A.14) and hence no crowding-in.

A.2 The relative favorability of removal

Next, we analyze under which conditions a given rate of technological progress favors an expansion of removals rather than of abatement or adaptation. Put differently, under which circumstances does technological progress in removal lead to a stronger change in the climate policy portfolio than technological progress in one of the other two pillars of climate policy?

A.2.1 Removal and abatement For $C^M_{M\theta_M} = C^R_{R\theta_R}$, the relative change in removal and abatement is given by

$$\frac{\frac{\mathrm{d}R}{\mathrm{d}\theta_R}}{\frac{\mathrm{d}M}{\mathrm{d}\theta_M}} = \frac{D^2_{EA} - \left(C^A_{AA} + D_{AA}\right)\left(C^M_{MM} + D_{EE}\right)}{D^2_{EA} - \left(C^A_{AA} + D_{AA}\right)\left(C^R_{RR} + D_{EE}\right)} \tag{A.24}$$

If this ratio is larger than one, technological progress in removal is leads to a stronger reshuffling of the climate policy portfolio than technological progress in abatement. This is the case under the following condition:

$$C^M_{MM} > C^R_{RR} \tag{A.25}$$

A.2.2 Removal and adaptation For $C^A_{A\theta_A} = C^R_{R\theta_R}$, the relative change in removal and adaptation is given by

$$\frac{\frac{\mathrm{d}R}{\mathrm{d}\theta_R}}{\frac{\mathrm{d}A}{\mathrm{d}\theta_A}} = \frac{\left(C^A_{AA} + D_{AA}\right)\left(C^M_{MM} + D_{EE}\right) - D^2_{EA}}{C^M_{MM}\left(C^R_{RR} + D_{EE}\right) + C^R_{RR}D_{EE}} \tag{A.26}$$

It follows that a *ceteris paribus* cost reduction shock of equal magnitude in the removal and adaptation sector biases the climate policy portfolio more toward the removal sector if and only if:

$$C^A_{AA} + D_{AA} > C^R_{RR} + \frac{D^2_{EA} + C^M_{MM}D_{EE}}{C^M_{MM} + D_{EE}} \tag{A.27}$$

The left-hand side of condition (A.27) represents the combined effect of the convexity of adaptation costs and the diminishing returns for adaptation. The right-hand side includes the convexity of removal costs and a term that accounts for the interplay between removal, abatement, and adaptation. The favorability of removal over adaptation depends on whether the marginal cost of adaptation relative to its effectiveness becomes prohibitively high compared to removal. If removal costs increase less sharply and the interaction term D_{EA} is not too significant, then technological progress in removal will be more favorable.

A.2.3 Special case: Adaptation via solar radiation management In the special case where we interpret A as solar radiation management (*SRM*), we assume that SRM is an imperfect substitute for mitigation in the sense that it can only address temperature-related damages, such that $D(E^n, A) := \mu D^T(E^n - A) + (1 - \mu)D^N(E^n)$. In this case, it holds that $D_{AA} = \mu D^T_{EE} > 0$ and $D_{EA} = -\mu D^T_{EE} < 0$. In this case, condition (A.27) becomes

$$C^A_{AA} > C^R_{RR} + \frac{(1-\mu)D^N_{EE}\left(C^M_{MM} - \mu D^T_{EE}\right)}{C^M_{MM} + (1-\mu)D^N_{EE} + \mu D^T_{EE}} \tag{A.28}$$

The relative advantage of carbon removal over SRM is determined by the slopes of their respective marginal cost curves and an additional term, mediated by the parameter μ. This parameter μ quantifies the extent to which temperature reductions from SRM lead to decreased climate damages. When the majority of climate damages are attributable to temperature increases, μ approaches one, simplifying the condition to:

$$C^A_{AA} > C^R_{RR} \tag{A.29}$$

Hence, uniform technological progress biases climate policy toward carbon removal relative to solar radiation management as long as the marginal removal cost curve is flatter than the marginal cost curve of SRM. Despite significant uncertainties surrounding the costs of SRM and CDR, it seems reasonable to assume that this condition holds true when the cost function for SRM fully incorporates social costs. While the direct marginal cost of SRM (e.g., the cost for sulfat, aircrafts and monitoring) appear to be rather low and flat (see e.g., Smith, 2020, Helwegen et al., 2019, Dietz et al., 2018), the marginal social cost of SRM impacts remain speculative (Bahn et al., 2015, Helwegen et al., 2019, Dietz et al., 2018). However, as SRM impacts such as termination risks, environmental impacts, regional climate shifts, and geopolitical risks could be large and potentially devastating (Dietz et al., 2018), it seems likely that the marginal costs of SRM exhibit greater convexity relative to those of CDR.

If, in contrast, the majority of climate damages is not temperature related, μ approaches zero, and the expression simplifies to

$$C^A_{AA} > C^R_{RR} + \frac{C^M_{MM} D^N_{EE}}{C^M_{MM} + D^N_{EE}} \tag{A.30}$$

Note that if μ approaches zero, only a very low level of SRM will be deployed. However, if marginal damages are high, some additional SRM will be used. This implies temperature smoothing even if marginal costs of SRM are steep.

A.3 The relative favorability of removal: Simultaneous technological progress

In the analysis above, we have focused on *ceteris paribus* cost reduction shocks in the different pillars. Alternatively, we can consider *simultaneous* technological progress in two pillars. This tells us under which conditions the climate policy portfolio is tilted toward removal if both sectors experience a similar cost reduction shock in the same world.

A.3.1 Removal and abatement

For $C^M_{M\theta_M} = C^R_{R\theta_R}$, the relative change in removal and abatement is given by

$$\frac{\frac{dR}{d\Theta_R} + \frac{dR}{d\Theta_M}}{\frac{dM}{d\Theta_M} + \frac{dM}{d\Theta_R}} = \frac{C^M_{MM}}{C^R_{RR}} \tag{A.31}$$

This leads again to the condition

$$C^M_{MM} > C^R_{RR} \tag{A.32}$$

A.3.2 Removal and adaptation

For $C^A_{A\theta_A} = C^R_{R\theta_R}$, the relative change in removal and adaptation is given by

$$\frac{\frac{dR}{d\Theta_R} + \frac{dR}{d\Theta_A}}{\frac{dA}{d\Theta_A} + \frac{dA}{d\Theta_R}} = \frac{\left(C^A_{AA} + D_{AA}\right)\left(C^M_{MM} + D_{EE}\right) + C^M_{MM} D_{EA} - D^2_{EA}}{C^M_{MM}\left(C^R_{RR} + D_{EE} + D_{EA}\right) + C^R_{RR} D_{EE}} \tag{A.33}$$

Assuming that $-D_{EA} \leq D_{EE}$, this leads again to the condition

$$C^A_{AA} + D_{AA} > C^R_{RR} + \frac{D^2_{EA} + C^M_{MM} D_{EE}}{C^M_{MM} + D_{EE}} \tag{A.34}$$

B Dynamic extension

We extend the static model in (A.1) to a dynamic setting that tracks two stocks: The stock of carbon in atmosphere X that accumulates net emissions E^n and carbon in temporary storage Z that accumulates removed CO_2. Thus, the social planner minimizes the net present value of the costs G from (A.1) associated with mitigation, removal, and adaptation in every future period subject to two equations of motion.

$$\max_{A,R,M} \quad -G = \int_0^\infty \exp(-rt)\left[-D(X,A) - C^A(A) - C^R(R) - C^M(M)\right] \mathrm{d}t \tag{B.1}$$

$$\text{s.t.} \quad \frac{dX}{dt} = E^n - M - R + \delta Z \tag{B.2}$$

$$\frac{dZ}{dt} = R - \delta Z \tag{B.3}$$

The non-permanence of storage is captures by a flow δZ of release emissions from storage Z back to the atmosphere X that is proportional to the stock Z.

The present-value Hamiltonian function reads

$$\mathscr{H} := -D(X,A) - C^A(A) - C^R(R) - C^M(M) \tag{B.4}$$

$$+ \lambda\left[E^n - M - R + \delta Z\right] \tag{B.5}$$

$$+ \mu\left[R - \delta Z\right] \tag{B.6}$$

The shadow price λ captures the cost of adding a marginal unit of carbon to the atmosphere (by adding to future climate change impacts), commonly known as the *social cost of carbon (SCC)*. Similarly, the shadow price μ captures the cost of adding a marginal unit of carbon to the storage Z (by adding to atmospheric carbon via the release channel δZ), that is, it represents the *social cost of removal (SCR)*.

Indeed, integrating the first-order conditions of the atmospheric stock X gives the familiar expression for the SCC. The first-order condition along with the associated transversality condition reads

$$\dot{\lambda} = r\lambda - \frac{\partial \mathscr{H}}{\partial X} = r\lambda - [-D_E] \tag{B.7}$$

$$0 = \lim_{t\to\infty} e^{-rt}\lambda(t)X(t) \tag{B.8}$$

By integrating (B.7) using $\exp\{-rt\}$ as the integrating factor and then utilizing (B.8) to determine the constant of integration we confirm the (negative of the) shadow price $\lambda(t)$ is the SCC:

$$-\lambda(t) = \int_t^\infty e^{-r(\tau-t)} D_E \mathrm{d}\tau =: \mathrm{SCC}(t) \tag{B.9}$$

For the storage stock Z and the corresponding transversality condition read

$$\dot{\mu} = r\mu - [\lambda\delta - \mu\delta] = (r+\delta)\mu - \delta\lambda \tag{B.10}$$

$$0 = \lim_{t\to\infty} e^{-rt}\mu(t)Z(t) \tag{B.11}$$

In steps analogous steps to the case of SCC we find that the SCR reflect the SCC of release emissions:

$$\begin{aligned} -\mu(t) &= \int_t^\infty e^{-(r+\delta)(\tau-t)}\delta(-\lambda(\tau))\mathrm{d}\tau && \text{(B.12)} \\ &= \int_t^\infty e^{-r(\tau-t)}\delta e^{\delta(\tau-t)}\mathrm{SCC}(\tau)\mathrm{d}\tau =: \mathrm{SCR}(\delta,t) && \text{(B.13)} \end{aligned}$$

The first-order conditions for R and M show how impermanence drives a wedge between the marginal costs of removal and abatement:

$$0 = \frac{\partial \mathscr{H}}{\partial A} = D_A + C_A^A \tag{B.14}$$

$$0 = \frac{\partial \mathscr{H}}{\partial R} = C_R^R - \lambda + \mu \tag{B.15}$$

$$0 = \frac{\partial \mathscr{H}}{\partial M} = C_M^M - \lambda \tag{B.16}$$

$$C_M^M = SCC = C_R^R + SCR(\delta) \tag{B.17}$$

$$C_R^R = SCC - SCR(\delta) \tag{B.18}$$

C Model of international cooperation and CDR

Assume I fossil fuel importers and $N-I$ exporters. For an importer i, the national payoff is:

$$\pi_i = b\bar{\Omega} - \frac{c}{2}M_i^2 - \frac{r}{2}R_i^2 + \frac{\sigma}{I}\sum_j M_j - \frac{\zeta}{I}\sum_j R_j \tag{C.1}$$

For an exporter x, the national payoff is:

$$\pi_x = b\bar{\Omega} - \frac{c}{2}M_x^2 - \frac{r}{2}R_x^2 - \frac{\sigma}{N-I}\sum_j M_j + \frac{\zeta}{N-I}\sum_j R_j \tag{C.2}$$

Figure C.1 illustrates the equalization of marginal costs and benefits.
Figure C.2 shows how marginal benefits and costs balance for importers and exporter.

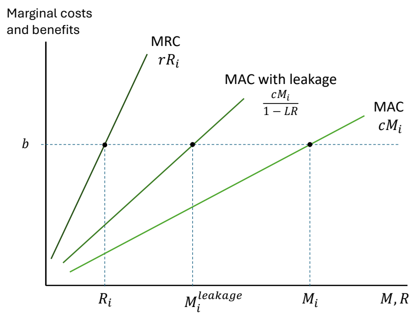

Figure C.1: Marginal benefits and costs of abatement and removal.

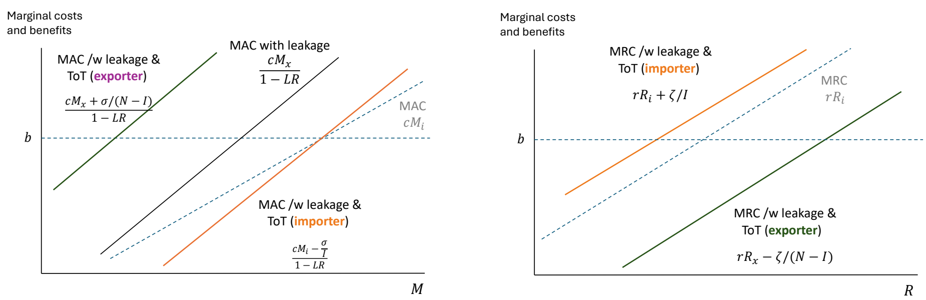

Figure C.2: Optimal abatement (left panel) and removal (right panel) of importers and exporters.

We assume $\sigma > 0$ to model that abatement reduces demand for fossil fuel and thus their world market prices and $\zeta > 0$ so that CDR increases energy demand and thus fossil fuel demand on the world market. Optimal unilateral abatement and removal by an importer i is now given by

$$M_i^N = \frac{b(1-LR)+\frac{\sigma}{I}}{c} \qquad R_i^N = \frac{b-\frac{\zeta}{I}}{r} = \frac{b-\frac{\zeta}{I}}{\gamma c} \tag{C.3}$$

Optimal unilateral abatement and removal by each fossil fuel exporter x is now given by

$$M_x^N = \frac{b(1-LR)-\frac{\sigma}{N-I}}{c} \qquad R_x^N = \frac{b+\frac{\zeta}{N-I}}{r} = \frac{b+\frac{\zeta}{N-I}}{\gamma c} \tag{C.4}$$

It now follows that aggregate global net abatement in the Nash equilibrium is the same as in the simplified case treated at the beginning of Section 4.2 where we neglected terms of trade effects.