ANNUAL REVIEWS

Annual Review of Resource Economics

The Economics of Carbon Dioxide Removal

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Annu. Rev. Resour. Econ. 2025. 17:301–21

First published as a Review in Advance on
July 7, 2025

The *Annual Review of Resource Economics* is online at
resource.annualreviews.org

https://doi.org/10.1146/annurev-resource-010224-094505

JEL codes: H23, Q54, Q58

Keywords

carbon dioxide removal, climate policy, carbon pricing, carbon storage, emissions trading

Abstract

Carbon dioxide removal (CDR) is 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 a return to a temperature target after temporary overshooting. Moreover, CDR 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, which are complicated by the nonpermanence 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.

1. INTRODUCTION

CO_2: carbon dioxide

CDR: carbon dioxide removal

SRM: solar radiation management

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 carbon dioxide (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. To date, CDR has focused mainly on afforestation activities (Schenuit & Geden 2023), but interest in other forms of CDR is growing rapidly. 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 (Shukla et al. 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 United States, and emerging public procurement schemes in Sweden.

In principle, the impact of CDR on climate change is similar to that of 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. A key characteristic of CDR is its ability to decouple the time and location of CDR 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 CDR is highly controversial, many climate change mitigation scenarios rely on it to meet ambitious climate targets, often to a substantial degree (Schleussner et al. 2024).

However, these 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 not be compensated for adequately or efficiently 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 supplement existing climate policies. For CDR to become a solid third pillar of the climate policy portfolio, a carefully designed governance framework is clearly needed.

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

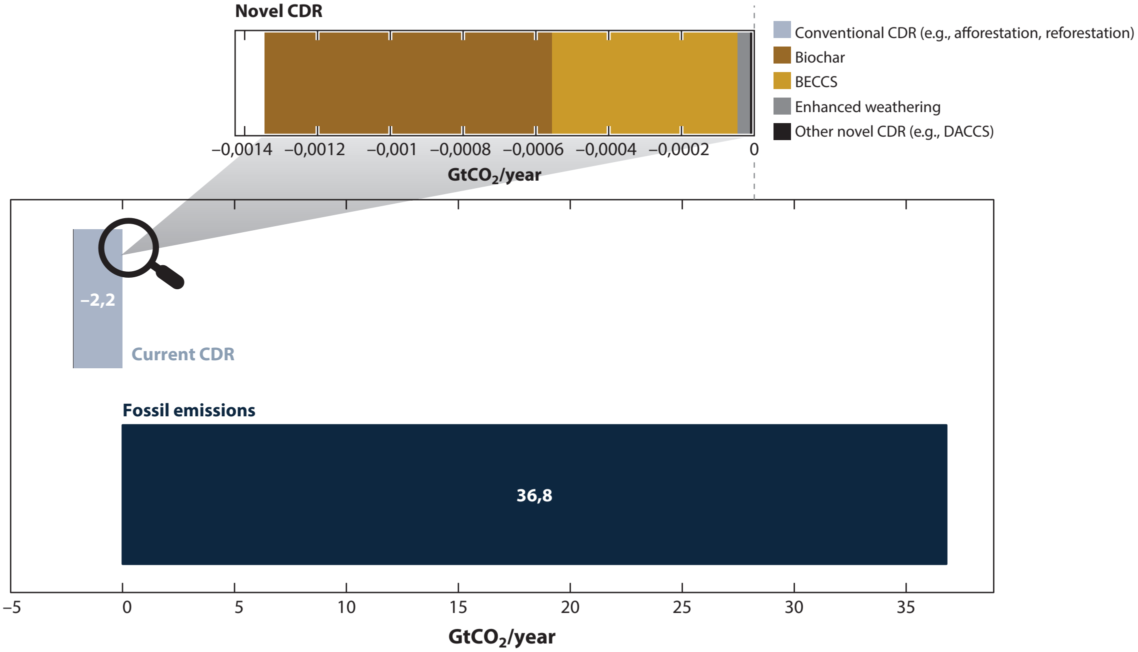

Figure 1

Fossil emissions and total amount of carbon dioxide removal (CDR) in 2023, split into conventional and novel methods ($GtCO_2$/year). Almost all current CDR resulted from conventional methods such as afforestation or reforestation. The figure reflects fossil fuel emissions in 2023 and is based on data from Friedlingstein et al. (2023) and Pongratz et al. (2024). Abbreviations: BECCS, bioenergy with carbon capture and storage; DACCS, direct air carbon capture and storage. Figure adapted from Smith et al. (2024) (CC BY 4.0).

We begin by surveying the characteristics of the most common CDR methods, as they 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 (Smith et al. 2024) (**Figure 1**).

In addition to technological readiness and costs, several other 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 pecuniary externalities, such as higher food prices. This does not warrant public intervention on efficiency grounds. However, the distributional consequences must still 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 they are 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., for paper) to centuries (e.g., for 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

BECCS: bioenergy with carbon capture and storage

DACCS: direct air carbon capture and storage

practices that raise soil organic carbon content, such as shallow plowing and increasing ground cover. Overall, conventional land-based CDR has potential for substantial annual volumes of removal (double-digit $GtCO_2$ per year), but its long-term potential is limited by saturation effects and its dependency on land availability (Fuss et al. 2018).

More novel CDR methods exploit geochemical principles on land and at sea. Adding alkalinity to marine environments enhances carbon uptake by oceans (i.e., 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, an important set of methods involves sequestering 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 bioenergy with carbon capture and storage (BECCS), which involves cultivating energy crops, combusting the organic material, and capturing and sequestering the resulting CO_2 underground at a cost of US\$100–200 per ton CO_2 in 2050 (Fuss et al. 2018). Similarly, carbon can be removed directly from the atmosphere via direct air carbon capture and storage (DACCS), which employs air filtration systems to capture CO_2, a process that is costly due to its high energy intensity (US\$600–1,000 per ton CO_2 today, which may decline to \$100–300; Fuss et al. 2018). The CO_2 can subsequently be sequestered in geological storage or stored in mineralized form. While their use is currently limited by their high costs, BECCS and DACCS are limited to a lesser degree by other factors. For example, BECCS is limited not by saturation but by the available land area, which affects its yearly removal potential but not the cumulative potential. DACCS is limited only by its costs, which are determined primarily by energy prices. To what extent technological learning can reduce these costs is highly uncertain.

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. We then introduce the time dimension and technological progress to discuss the role of an optimal temperature overshoot. In Section 3, we turn to the limited duration of storage as a key characteristic of CDR. Nonpermanence 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 emissions trading schemes (ETSs) 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

Supplemental Material >

To illustrate the key domains of climate policy, consider a stylized static model of abatement M, adaptation A, and carbon removal R, similar to that of 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 that underlies the arguments in this section in **Supplemental Material A**.

We consider 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 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,[1] while adaptation reduces climate damages with decreasing marginal

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[1] Using subscript notation for partial derivatives (i.e., $D_E := \partial D/\partial E$), we specifically assume that $D_E > 0$ and $D_{EE} > 0$.

effectiveness, and reduces marginal damages.[2] The cost functions associated with abatement, removal, and adaptation are denoted C^M, C^R, and C^A, respectively. Assuming convex cost, the optimal climate policy is determined by an equalization of marginal costs and benefits:

SCC: social cost of carbon

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

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

with subscript notation for 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 emissions to be priced at marginal damages, that is, the social cost of carbon (SCC). The second equality in Equation 1 requires carbon sinks to be rewarded at the level of the social costs, which 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 interdependent, 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 Carbon Dioxide Removal

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 an additional mitigation option and should be used such that the marginal costs of all mitigation options (abatement and removal) are equalized. But while mitigation and adaptation are substitutes, a cost reduction shock in removals may also crowd in abatement if marginal damages are sufficiently sensitive to adaptation.[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 understand how, compare two scenarios with multiplicative cost reduction shocks θ_M and θ_R of equal magnitude in the removal and the abatement sector (i.e., $C^M_{M\theta_M} = C^R_{R\theta_R}$), and all else equal. Then, the cost reduction increases the optimal quantity of carbon removal relative to abatement if the marginal costs of mitigation increase more steeply than the marginal costs of removal ($C^M_{MM} > C^R_{RR}$). That is, if marginal abatement costs exhibit greater curvature than marginal removal costs, then technological progress in CDR will result in a greater increase in the quantity of carbon removal compared with the increase in abatement following a similar level of technological progress in abatement.

It seems plausible that marginal mitigation costs will indeed rise faster than marginal removal costs in the future: Once mitigation M approaches business-as-usual emissions $\bar{E}$, the last ton of carbon needs to be avoided, which is likely to be prohibitively expensive. This Inada condition (Inada 1963) for abatement is intuitively appealing and supported by many modeling studies (e.g., Shukla et al. 2022, chapter 3.6.1; Merfort et al. 2025). In contrast, no such Inada condition applies

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[2] That is, we assume that $D_A < 0$, $D_{AA} > 0$, and $D_{EA} < 0$. SRM can 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) reduces temperature-related damage D^T but does not affect nontemperature damage 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).

[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**).

Supplemental Material >

to the removal sector (Merfort et al. 2025), 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, as a result of rising marginal damages—the more important will be the role of carbon removal in the climate policy portfolio.

Supplemental Material >

The simple static model can also be used to discuss a ceteris paribus cost reduction shock of equal magnitude in the removal and adaptation sectors, as well as the special case of SRM. We relegate these issues 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 SRM) holds (see Equations A.28– A.30). If the marginal social costs of SRM are steep (due to increasing environmental or geopolitical risks), then the optimal policy portfolio shifts from SRM 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 Equation 1 reads

$$C_M^M(t) = C_R^R(t) = \theta(t) D_E(t) = \theta(t)\mathrm{SCC}(t). \qquad 3.$$

The dynamics can be sketched as follows: Initially, costs are high, $\theta(t)$ is accordingly low, and marginal damages are low such that we have low levels of abatement and removal. Therefore, net emissions are positive ($t = 1$ in **Figure 2**). Due to positive net emissions, the carbon concentration grows, and with convex damages, the $\mathrm{SCC}(t)$ grows. Additionally, technological progress reduces the marginal cost of abatement and removal. As $\theta(t)\mathrm{SCC}(t)$ increases, equilibrium 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 $\theta(t)\mathrm{SCC}(t)$ has become sufficiently large, $M(t) + R(t) > \bar{E}$ and net emissions become negative ($t = 2$ in **Figure 2**). The net-negative emissions, in turn, eventually reduce $\mathrm{SCC}(t)$ as marginal damages decrease as a result of declining temperatures. The economy can reach a steady state with net-zero emissions [i.e., $M(t) + R(t) = \bar{E}$] when the growth rates of technological progress and the SCC are equal.

Therefore, the stylized dynamic model already indicates that optimal climate policy might follow different phases—from net-positive to net-negative to net-zero emissions (for a more

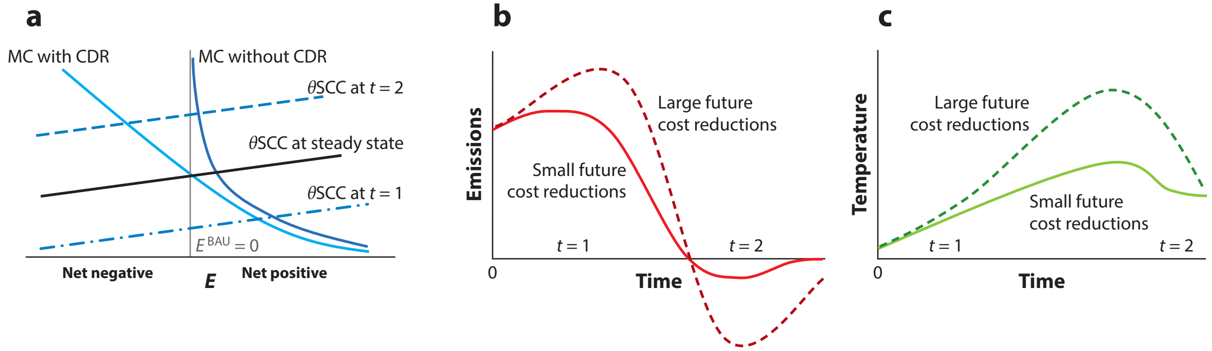

Figure 2

Illustration of the dynamic model. (*a*) Marginal costs (MC) of reducing atmospheric carbon without and with carbon dioxide removal (CDR) and θSCC at different points in time. (*b*) Emissions and (*c*) temperature for small and large future removal cost reductions. Panel *a* adapted from Edenhofer & Kalkuhl (2024) (CC BY 4.0).

comprehensive model that exhibits similar phases, see Hoel 2024) (**Figure 2*b***). 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., Allen et al. 2018, Bauer et al. 2023).

Lessmann et al. (2024) show that, when a certain cumulative net carbon budget is given, the extent of overshooting increases in the rate of (removal) cost-saving technological progress and the discount rate. It seems plausible that the same should be true for a cost–benefit framework, but we are not aware of a formal analysis of this case. 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. Therefore, the level of overshoot will be relatively low. If, by contrast, technological learning in the removal sector is rapid, abatement efforts will become less appealing. Firms will then increasingly opt for removal, and cumulative emissions as well as the extent of overshoot will rise (**Figure 2*c***).

3. NONPERMANENT REMOVAL

The preceding 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 nonpermanence of storage has implications for both the use and the regulation of these CDR methods. In this section, we discuss the optimal use of nonpermanent CDR and turn to optimal policy instruments in the next section.

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

Despite these complications, nonpermanent CDR methods can withhold CO_2 from the atmosphere for considerable periods 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) (**Table 1**). Given the vast demand for new buildings in modern cities,

Table 1 Optimal ratio of a subsidy for nonpermanent carbon removal to a tax on emissions, computed in the steady state with a constant release rate δ[a]

Expected lifetime (years)	Exemplary removal and storage pathway[b]	Removal subsidy/carbon tax ratio at different discount rates r		
		$r = 0.01$	$r = 0.02$	$r = 0.05$
4	Wood products: paper	0.04	0.07	0.17
43	Wood products: furniture	0.3	0.46	0.68
144	Wood products: single-family home	0.59	0.74	0.88
200	Enhanced weathering	0.67	0.8	0.91
2,000	DACCS, BECCS	0.95	0.98	0.99

[a] Calculated following Franks et al. (2024) as $r/(r + \delta)$ for a discount rate r.

[b] Data for wood products are from Smith et al. (2006), and data for enhanced weathering (storage duration of centuries) as well as DACCS and BECCS (storage duration of millennia) are from Hepburn et al. (2019).

Abbreviations: BECCS, bioenergy with carbon capture and storage; DACCS, direct air carbon capture and storage.

SCR: social cost of CO_2 removal

it may be possible to store up to 1 $GtCO_2$/year in construction materials (Rodriguez Mendez et al. 2024; see also Churkina et al. 2020). Accordingly, model-based studies find that nonpermanent 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, nonpermanent options serve as a bridge technology. Thus, nonpermanent CDR can help smooth the transition to a Paris-compatible world.

Supplemental Material >

To illustrate the key findings of the literature, we extend our simple model to account for nonpermanence 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 called the 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 nonpermanence of storage drives a wedge between the balance of marginal costs of abatement and removal, as in Equation 1. As shown in **Supplemental Material B**, this wedge is the social cost of removal (SCR):

$$C_M^M = \mathrm{SCC} = C_R^R + \mathrm{SCR}(\delta). \qquad 4.$$

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

$$\mathrm{SCC}(t) = \int_t^\infty e^{-r(\tau-t)} D_E(\tau)\mathrm{d}\tau, \qquad 5.$$

$$\mathrm{SCR}(\delta, t) = \int_t^\infty e^{-r(\tau-t)} \delta e^{\delta(\tau-t)} \mathrm{SCC}(\tau)\mathrm{d}\tau. \qquad 6.$$

The two social costs evolve over time according to

$$\widehat{\mathrm{SCC}} = r - \frac{D_E}{\mathrm{SCC}}, \qquad \widehat{\mathrm{SCR}} = r + \delta\left(1 - \frac{\mathrm{SCC}}{\mathrm{SCR}}\right), \qquad 7.$$

where the hats denote growth rates. Incorporating nonpermanent 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 Equation 4, which increases in the release rate δ, pushes the marginal removal costs below the marginal damage. With temporary storage, removal R is reduced in comparison to the case of permanent storage in Equation 1. This result carries over to the optimal pricing of nonpermanent removal relative to emissions abatement. While a tax on emissions should equal the SCC, a subsidy on nonpermanent 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 nonpermanent storage is perpetually returned to storage by a renewed removal effort. They find, however, no effect of the availability of nonpermanent storage on the optimal CO_2 concentration in the atmosphere, which is determined by the balance between the marginal abatement costs and benefits and the marginal removal costs of removal technologies that store carbon permanently.

Several studies have confirmed the dependency of optimal removal quantities on storage duration as well as the differentiation of carbon pricing of abatement and removal; examples are studies by Meier et al. (2022), Brander & Broekhoff (2023), and Groom & Venmans (2023). Often, the literature elaborates on particular details, as in studies by 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 outgassing 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 because of inertia in the carbon cycle. An open question is how incorporating additional damages from ocean acidification would influence the cost–benefit analysis within such a model. This question points to 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 (nonpermanent) carbon reservoirs into a tractable integrated assessment model. They derive the SCC for CO_2 in every one of their reservoirs. The optimal use of nonpermanent storage is then driven by the benefit of moving CO_2 to a reservoir with lower social costs, compared with the opportunity costs of extracting and combusting fossil fuel resources.

Building on the concept of SCC, Groom & Venmans (2023) define the social value of an offset (SVO) generated by CDR. Nonpermanent storage is then reflected in a correction factor that reduces the SVO. They derive similar correction factors for including the risk of failure and the risk of nonadditionality 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, nonpermanent CDR to know, for example, whether extra trees would not have been planted anyway for reasons other than carbon capture, and adverse incentives to falsely claim additionality exacerbate this uncertainty (Nolan et al. 2024). The issue of nonadditionality 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 nonadditionality. Groom & Venmans (2023) model the risk of nonadditionality as the risk of assuming a wrong counterfactual.

Several studies estimate how to price nonpermanence of storage when subsidizing CDR. As a rule of thumb, Groom & Venmans (2023) give the range 33–50% for the SVO of a ton stored for 50 years compared with the value of a ton of carbon permanently removed. The estimate by Kim et al. (2008) of a 50% discount as common coincides with the upper bound, which is plausible considering that these authors focus exclusively on the issue of nonpermanence. Franks et al. (2024), too, find a comparable optimal correction factor of around 50% for a half-time of 50 years. They show that the correction factor depends sensitively on the discount rate (**Table 1**). In general, these rules can perform only as well as the underlying assumptions match reality. Groom & Venmans, for example, assume an exogenous carbon price. Franks et al. derive the rules from the steady state of their dynamical system and assume a constant release rate.

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

4. OPTIMAL DESIGN OF POLICY INSTRUMENTS FOR CARBON DIOXIDE REMOVAL

In the preceding section, we established a framework to calculate the optimal use of nonpermanent CDR. We now move on to a discussion of policy instruments. We devote most of our attention to the literature regarding instruments for nonpermanent 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.

4.1. Dynamic Incentives

An implicit assumption of the correction factors above is that the nonpermanence is taken into account when the flow of CO_2 to 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 the lack of an incentive for diligent maintenance of the storage site, 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 for estimating the storage duration for correct pricing of the subsidy.

Franks et al. (2024) discuss two alternatives. The first is to implement comprehensive carbon pricing such that CO_2 is taxed downstream, at the end of the storage time, so that 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 in CO_2 in storage. Whether that 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 that firms post collateral that they can claim in case of bankruptcy. Some scholars have suggested designing financial instruments that would make the collateral tradable to avoid limiting firms' liquidity. In the context of carbon emissions, Held & Edenhofer (2009) have suggested using state-issued, tradable bonds for this purpose. Lemoine (2020) proposes the use of "carbon shares" for a similar purpose.

The second alternative is to price carbon stocks instead of carbon flows. In this case, the regulator monitors and pays a subsidy on the stock of carbon in storage in each period. Similar to the staggered payment of the upstream removal subsidy, subsidizing the stock of carbon 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 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.

Bednar et al. (2021) and Jenkins et al. (2021, 2023) offer additional innovative policy options to incentivize permanent CDR. Bednar et al. suggest harnessing financial markets for the valuation of carbon debt. 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 CDR. Carbon takeback obligations, as described by Jenkins et al., require fossil fuel companies to remove a percentage of their emissions, with the goal of reaching 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 issue 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 in, e.g., Chan et al. 2018, Kornek & Edenhofer 2020, Raiser et al. 2020, Tavoni & Winkler 2021) acknowledges that the effectiveness of international climate policy is undermined by free-riding (as avoiding climate damages is a 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 under geoengineering, the discussion focuses almost exclusively on SRM (e.g., Barrett 2014, McEvoy et al. 2024; reviews in Heutel et al. 2016, Flegal et al. 2019). Lessons from SRM, however, cannot be transferred to the case of CDR: Key differences for SRM are its relatively low private cost and its imperfect substitutability for 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 emissions leakage.[4] However, a conceptual analysis of the implications of carbon removal for international cooperation on climate policy is still missing in the literature. Below, we sketch a stylized model of free-riding and carbon leakage to illustrate an important feature of removal in this domain. As a starting point, consider the asymmetric role of CDR and abatement in carbon leakage. Franks et al. (2022) analyze optimal mitigation and removal in a multicountry 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. Since CDR is assumed not to reduce fossil fuel demand, the authors find that the optimal subsidy rate for domestic removals is higher than the carbon tax on domestic emissions.[5]

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

$$\pi_i = b\bar{\Omega} - \frac{c}{2}M_i^2 - \frac{r}{2}R_i^2, \qquad 8.$$

$$\bar{\Omega} = \sum_{j=1}^{N}[(1 - \mathrm{LR})M_j + R_j]. \qquad 9.$$

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[4] This is due to the constant marginal costs of DACCS (Barrett & Moreno-Cruz 2015). A sufficiently large coalition of countries will organize removal when their SCC exceeds the marginal costs of removal. Removal would fall to zero upon a defection from the coalition, if the SCC falls below the constant marginal costs, such that the joint effort in CDR becomes self-enforcing (similar to the effect of minimum participation clauses; see, e.g., Carraro et al. 2009).

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

The payoff π_i of country i in Equation 8 considers 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 mitigation is captured by Equation 9. The model allows us to calculate the socially optimal level of mitigation $\bar{\Omega}^*$ and the respective Nash equilibrium $\bar{\Omega}^N$:

$$\bar{\Omega}^* = N^2\left(\frac{b}{c} + \frac{b}{r}\right), \qquad 10.$$

$$\bar{\Omega}^N = N\left(\frac{b}{c}(1 - \mathrm{LR})^2 + \frac{b}{r}\right). \qquad 11.$$

The lack of ambition of mitigation in the Nash equilibrium (relative to the socially optimum mitigation level) can be taken as an indicator for the challenge of international cooperation (its difficulty). The lower the mitigation effort in Nash equilibrium, the more there is to gain by cooperation—but also the greater is the incentive to free-ride, and the harder it is to overcome the cooperation challenge, for instance, by a climate agreement (Barrett 1994). The level of Nash equilibrium mitigation depends on the LR, the cost ratio between abatement and removal, and the number of countries. To illustrate the dependence, we define the ratio $\theta = \bar{\Omega}^N/\bar{\Omega}^*$, which ranges from zero (maximum gap) to one (Nash equilibrium and social optimum coincide). Thus, a higher θ moves the equilibrium mitigation closer to its optimum and, at the same time, reduces the incentive to free-ride. **Table 2** shows the value of θ for different cost ratios of removal and abatement and for different LRs.[7] As **Table 2** shows, if technological progress leads to cost savings in the CDR sector (i.e., if r/c falls), then the ambition of international mitigation 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 the LR is 30%, then global mitigation in the Nash outcome will be 13% of the global cooperative outcome. If significant cost reductions in CDR lower the marginal removal cost to half that of abatement, $r/c = 0.5$, then mitigation in the Nash outcome increases to 17% of the social optimum—representing an improvement in international mitigation of roughly one-quarter. If the LR is 50%, then the Nash outcome is already improved

Table 2 **Ambition of international mitigation, θ, for different relative marginal costs of CDR**[a]

	Ambition θ for different relative costs				
Relative cost of removal 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

[a] Numbers show the ratio of global net mitigation in the Nash equilibrium to net mitigation in the social optimum $\theta = \bar{\Omega}^N/\bar{\Omega}^*$ for different LRs 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 $N = 5$).
Abbreviations: c, marginal cost of abatement; CDR, carbon dioxide removal; LR, leakage rate; r, marginal cost of CDR.

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

[7] The LR of a domestic reduction of fossil fuel consumption is calculated as $\mathrm{LR} = -\varepsilon_{\mathrm{D}}/(\varepsilon_{\mathrm{S}} - \varepsilon_{\mathrm{D}})$, where $\varepsilon_{\mathrm{D}} < 0$ is the price elasticity of global demand and $\varepsilon_{\mathrm{S}} < 0$ is the price elasticity of global fuel supply. Typical values (e.g., Prest 2022) of $\varepsilon_{\mathrm{D}} = -0.2$ and $\varepsilon_{\mathrm{S}} = 0.44$ imply $\mathrm{LR} = 0.31$. For $\varepsilon_{\mathrm{D}} = -0.5$, the LR would increase to 0.53.

by 50% (from 10% to 15%). Without supply-side leakage of mitigation, the advantage of CDR to improve international mitigation vanishes (see the top row of **Table 2**).

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

Supplemental Material >

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

5. INTEGRATING CARBON DIOXIDE REMOVAL IN EMISSIONS TRADING SCHEMES

New policies for CDR will be designed under political and institutional constraints imposed by existing instruments. A prominent example of such an instrument is the European Union's ETS (EU ETS), and the integration of CDR in the EU ETS is quickly rising on the agenda of both researchers and policy makers (Schenuit & Geden 2023). With the regulatory cap reaching zero around 2040, the integration of CDR will be essential for addressing the "emerging endgame" of achieving net-zero emissions within the ETS (Pahle et al. 2023; see also 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 into 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. In the following subsections, we review existing proposals for policy options to achieve a net-zero or net-negative EU ETS.

5.1. Emissions Trading with Net-Zero Targets

The economic logic behind the integration of permanent CDR to achieve a net-zero compatible ETS is straightforward: Removal suppliers generate emissions allowances by removing equivalent amounts of carbon and selling them in the ETS. The availability of newly generated emissions 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 on gross emissions is determined by the intersection of marginal abatement and removal costs. Thus, the efficient integration of CDR is characterized by the equalization of marginal cost.

To attain this first-best outcome in the long run, two recent papers suggest a policy sequencing approach (Burke & Schenuit 2024, Sultani et al. 2024). Both papers suggest increasing the degree of integration of removals step-by-step, conditional on the availability of credible monitoring, reporting, and verification; the containment of sustainability risks; and the introduction of liability measures. Whenever a removal technology meets these criteria, integration into the ETS would enable removal 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).

In the short run, however, the carbon price in the ETS might be too low to encourage the use of costly permanent removal technologies, thereby failing to deliver sufficient incentives for innovation or to reduce removal cost (Rickels et al. 2021). In this case, the regulator could act as an intermediary between the removal market and the ETS and procure high-cost removals in an initial stage and sell them in the ETS at a lower price (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. Albeit not necessarily efficient from an economic perspective (unless the regulator perfectly manages the timing and quantity of removal credits), this conditional supply of removal credits would make it possible to stabilize the market in the transition to net zero while keeping net emissions pathways constant (Rickels et al. 2022).

Note also that some scholars are concerned about the potentially large-scale substitution of abatement efforts in ETSs resulting from the availability of inexpensive removal credits, which would undermine technological learning in the abatement sector (La Hoz Theuer et al. 2021; Rickels et al. 2021, 2022; Burke & Gambhir 2022). This substitution is generally efficient only in the absence of market failures (e.g., in technological innovation or in the liability of carbon debtors) and policy failures (e.g., in the regulator's commitment to the cap). Otherwise, additional policy instruments might be warranted to address these issues (e.g., support of policies for research and development and technology rollout).

Another important question concerns the integration of nonpermanent removal credits. Some scholars argue that these removals should be included alongside international credits to enhance supply-side efficiency (Sultani et al. 2024). Others suggest focusing on permanent removals to reduce the costs of monitoring and verification and to decrease the risk of nonadditionality and limited liability (Rickels et al. 2021). Cheap nonpermanent 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 nonpermanent CDR gives rise to a liability, interpreted either as a commitment to perpetually refill nonpermanent 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 ETSs have integrated CDR, focusing primarily on forest-based offsets. For example, New Zealand's ETS includes the whole forestry sector and provides incentives for afforestation and the preservation of 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 have 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, although concerns about low additionality and the need for stricter standards have been raised (Stapp et al. 2023). The California 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 United Kingdom and the European Union, are starting to explore options to incorporate CDR into their ETSs.

5.2. Emissions Trading with Net-Negative Targets

A conventional ETS, even with full integration of CDR, can achieve net-zero but not net-negative emissions targets. However, achieving a phase of net-negative emissions might be necessary, as discussed in Section 2.3. In principle, net-negative emissions targets could be achieved by issuing carbon debt instead of emissions allowances.[8] However, carbon debt (i.e., the financial burden of removal) would not find any buyers in a carbon market and, therefore, would need to be assigned in an act of expropriation that may be politically challenging for the regulator. Alternatively, the regulator could bear the financial burden of removal 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. Deleting these credits instead of releasing them to the market would generate net-negative emissions. However, such public procurement schemes would 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 emissions (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. Several studies address this concern by holding current emitters liable for future removals, which secures finance for future CDR (Bednar et al. 2021, 2023a,b; Lessmann et al. 2024; Lyngfelt 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), cleanup certificates (Lessmann et al. 2024), or atmospheric carbon removal deposits (Lyngfelt et al. 2024). While all proposals share the fundamental idea of ensuring 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, suggest interest payments on carbon debt, at an interest rate determined by financial institutions that 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 which the regulator could draw on to carry out CDR 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 allowance prices by expanding the supply of allowances. The decline in allowance prices can be offset by adjusting the carbon budget toward a greater environmental ambition to address concerns of mitigation deterrence (see also Rickels et al. 2021). Lessmann et al. point out that the trade-off between environmental ambition level and carbon prices can be relaxed because of the additional intertemporal flexibility from introducing

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[8] We thank an anonymous reviewer for pointing this out.

cleanup certificates. They show that 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 dimensions: short-term carbon prices, cumulative compliance cost, avoided climate damages, and fiscal revenue generated. Therefore, there may be room for political win-win outcomes between industry, regulators, 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 would be rational for the social planner to constantly postpone the repayment of the carbon debt because the flexibility gained does not incur any social cost in the form of additional climate damage. When allowing for overshoot in ETSs, 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 adherence to a credible long-term climate policy target. To address these challenges, scholars have proposed 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 clearinghouse for different removal methods with various 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 closely follows an optimal path from a cost–benefit perspective. The CCB would then also be in charge of collecting and investing the financial collateral associated with carbon debt and would act as the "lender of last resort," that is, remove carbon when firms default on their removal obligations.

6. CONCLUSIONS

In this article, we have surveyed the nascent field of CDR governance. While 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 mainly as demonstration projects or prototypes. Scaling up will also accelerate innovation and induce further cost reductions so that novel removal technologies might eventually become competitive within carbon pricing schemes. Fuss et al. (2024) discuss the role of voluntary and compliance carbon markets for the scaling up of novel CDR. The authors suggest advanced market commitments and forward purchasing, in addition to 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 implemented by, for example, the German Federal Ministry for Economic Affairs and Climate Action (2024), or through reverse auctions (Lundberg & Fridahl 2022), as in the case of BECCS in Sweden. However, we are not aware of any empirical or quantitative analyses that assess the extent of innovation and network externalities of novel removal technologies. Such analyses, in turn, will be necessary to determine the welfare-maximizing levels of complementary technology policies aside from carbon pricing.

Scaling up CDR will also have substantial implications for resource use and for 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 environmental externalities of large-scale CDR (e.g., biodiversity loss and local air pollution due to higher energy, mineral, or land use) (Fuss et al. 2018, Prütz et al. 2024). And although the general nature of these coexternalities is well-understood, few studies have quantified these external effects and determined the optimal policy mixes or optimal technology portfolios from a broader social welfare perspective. For example, Migo-Sumagang et al. (2023) provide a portfolio optimization for Southeast Asia, and Rodriguez Mendez et al. (2025) explore trade-offs and portfolios under uncertainty.

A key resource impact identified in the literature is 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 of reducing net emissions (Merfort et al. 2023). Aside from approaches to exogenously limit BECCS deployment, we are not aware of any studies on second-best policies for land-intensive CDR when carbon pricing is globally and sectorally fragmented.

The aggregate efficiency gains from integrating CDR into carbon pricing may involve additional fiscal or distributional effects. With increasing land demand, distributional effects through higher food prices can also be expected. Andreoni et al. (2024) highlight two additional distributional challenges. First, high public expenditures for CDR 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. By lowering carbon prices, carbon removal can also mitigate adverse distributional effects—provided that carbon pricing is regressive, which varies by country context (Dorband et al. 2019, Feindt et al. 2021, Ohlendorf et al. 2021).

With ongoing progress in novel removal technologies, and with the SCC rising as a result of continued global warming, CDR could become the third pillar of climate policy. CDR creates large sectoral and intertemporal flexibilities that 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 the key mechanisms that have been reviewed in the largely conceptual literature on governance and policy design for CDR. Future research could shed more light on the empirical and quantitative aspects of specific policies for carbon removal, such as addressing innovation externalities, land use effects, carbon leakage effects, or implications for international climate policy. Integrating (permanent) CDR into ETSs is challenging, particularly when emissions should eventually become net negative. We emphasize that addressing liability problems and the emerging time-inconsistency problem of emissions trading with overshooting flexibility—created by cleanup certificates or removal obligations—may also require the creation of new institutions. Related to the tasks of central banks, a CCB could guarantee functioning and integrity of intertemporal carbon markets, reduce default risks on removal obligations, and stabilize expectations on CDR incentives.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might affect the objectivity of this review.

ACKNOWLEDGMENTS

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 from the Deutsche Forschungsgemeinschaft (DFG; German Research Foundation) for project number 456947458 (CLEANUP) and from the European Union's Horizon Europe research and innovation program under grant 101081521 (UPTAKE).

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