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On the Governance of Carbon Dioxide Removal – A Public Economics Perspective

Abstract

This paper highlights the importance of carbon dioxide removal (CDR) technologies for climate policy. We first describe their role in iconic transformation pathways and discuss removal costs and storage duration of different technologies. Based on economic principles, we characterize optimal removal flows and reservoirs for non-permanent removals. Furthermore, we discuss different pricing regimes that achieve an optimal allocation under different information and liability conditions. Notably, seemingly cheap removal technologies in the land sector can indeed be very expensive when increasing opportunity costs and and impermanence are appropriately accounted for. The use of non-permanent removal – though to a certain extent economically optimal – creates high liability to firms and regulators that warrants a careful and deliberative risk management. Based on these insights, we discuss how policy makers can embed the CDR option in the EU's policy architecture. There are four key tasks for regulating bodies to ensure an optimal governance: the management of the net carbon emission cap; support for research, development and diffusion of CDR technologies; certification of the quality of removals; management of the liability implied by non-permanent CDR. We propose that three new institutions, a European Carbon Central Bank, a Carbon Removal Certification Authority and a Green Leap Innovation Authority, are established to carry out these tasks.

JEL-Codes: D610, H230, Q540, Q580.

Keywords: carbon dioxide removal, EU-ETS, social cost of carbon, climate policy, impermanence.

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1 Why CDR? Transformation Pathways

The Paris Agreement has established the goal to limit global warming to well below 2 degree Celsius, preferably to 1.5 degree Celsius. Therefore, greenhouse gas (GHG) emissions should peak as soon as possible and several countries have pledged to achieve net-zero emissions by mid-century.

A consensus among the scientific community has emerged that without deployment of carbon dioxide removal (CDR) the Paris Climate Goal cannot be achieved (IPCC, 2018). CDR technologies have a triple role – illustrated in Figure 1. First, in the short-run, they can serve as a further mitigation option to complement emission abatement efforts. Second, to achieve net-zero emissions, they can compensate residual emissions that are hard to abate. Third, they are needed for net-negative emissions in the second half of the century (Warszawski et al., 2021), which can decrease the global mean temperature after a temporary overshoot. According to Warszawski et al., there are scenarios that rely less heavily on CDR, but these require a highly ambitious transformation of the energy system, both in terms of carbon intensity and energy demand. While the authors argue that CDR is not a silver bullet and instead "all-round portfolios are needed (...) beyond what might be deemed feasible today", it still becomes clear that CDR deployment is a conditio sine qua non for the Paris Target.[1] Metaphorically speaking, CDR is needed to establish a planetary waste management system in order reduce the cumulative stock of carbon in the atmosphere.

A quick back of the envelope calculation shows that the financial flows associated with Paris-compatible CDR deployment are substantial, potentially up to three percent of global GDP.[2] Yet, while technological aspects of CDR have received much attention,[3] research on the public economics of CDR is missing. Only few studies analyze the policy design of CDR. Franks et al. (2023) consider the difference between unilateral carbon taxes and CDR subsidies in terms of interregional leakage. Focusing on the intertemporal dimension, Kim et al. (2008) and van Kooten (2009) calculate discount factors for non-permanent carbon offsets that consider the cost of released emissions. More recently, discount factors derived by Groom and Venmans (2022) also include default risk and non-additionality. Yet, in these contributions, the time trajectory of the social

[1] Merfort et al. (2023) compare the CDR potential with residual emissions in Germany and conclude that achieving "only" net-zero emissions by 2045 is already highly ambitious.

[2] If we assume that in the second half of the century annually 5-15 $GtCO_2$ have to be removed and we further assume removal costs of 100-300 $\$/tCO_2$ (Smith et al., 2023) this implies global annual expenditures on CDR of US$ 0.5-4.5 trillion. In 2021, world GDP was US$ 86 trillion. A constant growth rate of 2% would lead to around US$ 150 trillion in the year 2050, putting global CDR expenditures on the order of magnitude of 0.3-3% of world GDP.

[3] For the most recent overview, see Smith et al. (2023). An extensive summary is provided by Minx et al. (2018); Fuss et al. (2018); Nemet et al. (2018)

cost of carbon and carbon prices remain exogenous, which only allows to evaluate small projects. Kalkuhl et al. (2022), by contrast, use a welfare maximization approach to evaluate larg-scale CDR and to determine how non-permanent CDR should be incentivized when optimal carbon pricing drives long-term climate stabilization. Lemoine (2023) examines optimal carbon pricing and CDR, albeit only for the case of permanent storage. His work corresponds to the CCS bonds introduced by Held and Edenhofer (2009).

The contribution of this paper is three-fold. First, we summarize the currently available knowledge on the governance and public economics of carbon dioxide removal. We discuss socially optimal CDR deployment and policy design options. Second, we identify the most important gaps in our understanding of what good CDR policies are in order to build an agenda for future research. An important insight is that the problem of non-permanence of certain CDR options has far reaching consequences. In particular, seemingly cheap land-based non-permanent removals have high costs due to the carbon debt they imply. Third, we discuss the special case of the European Union, where policy makers are actively working on the design of the future CDR policy framework. We propose new institutions: A European Carbon Central Bank to manage the cap and the carbon liability from non-permanent CDR, a Carbon Removal Certification Authority and a Green Leap Innovation Authority for research, development and demonstration (RD&D) activities.

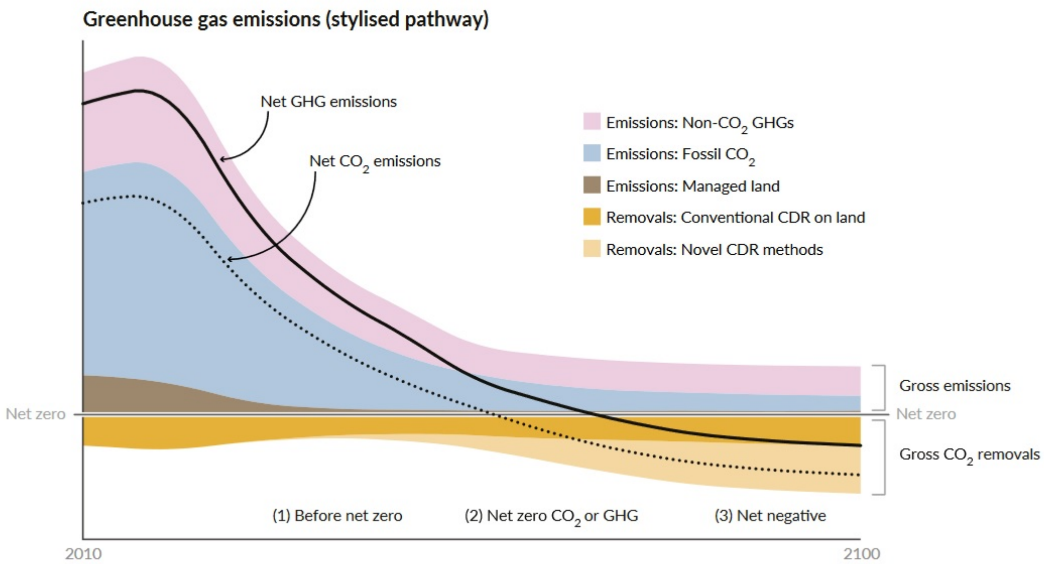

Figure 1: Stylized pathway with reliance on CDR for (1) further lowering net emissions in the near term; (2) counterbalancing hard-to-abate residual emissions in order to reach net-zero emissions in the medium term; and (3) achieving or sustaining net-negative emissions in the long term. Source: Smith et al. (2023).

In Section 2, we shortly introduce the most relevant CDR technologies, which readers who are familiar with the technological aspects can skip. In Section 3, we discuss incentives and policy instruments for CDR deployment, compare them with well-known efficiency rules of climate economics and we introduce different policy designs. In Section 4, we discuss the political economy of CDR policies, that is, international trade and strategic interaction, dynamic efficiency, commitment and technology-specific goals, fiscal balance and the voluntary market. In Section 5, we discuss the special case of the European Union's effort to integrate CDR into its climate policy architecture. Section 6 concludes.

2 Technologies

Several technologies with very different characteristics are under development. First, we briefly describe the most important ones. Then, we summarize costs, potentials and permanence in Section 2.2.

2.1 Types

Almost all currently operating carbon removal projects are so-called *nature-based solutions* such as afforestation and reforestation and the restoration of coastal wetland, peatlands and mangroves. In the long run, these lands are carbon sinks (Shukla et al., 2019).

A second set of technologies combines the plantation of *bio-energy with carbon capture and storage (BECCS)*. Organic materials are either directly combusted to produce energy or are used to produce biogas, biodiesel and bioethanol. The emissions are sequestered and stored in aquifers, coal beds and depleted oil and gas fields. Carbon captured from the atmosphere in the growth process of organic materials ends up under ground.

Biomass can also be used for products that store carbon, such as houses, furniture or even paper. Other products exist that store carbon, for example microalgae products or concrete building materials. Hepburn et al. (2019) refer to these CDR options as carbon capture and utilization (CCU). However, there are other CCU options such as CO_2-based fuels, that do not achieve carbon removal from the atmosphere.

Two types of CDR exploit geochemical principles, one in the oceans, the other on land (Fuss et al., 2018). *Ocean alkalinization* is the addition of alkalinity to sea areas. This increases the capacity of oceans to buffer carbon. Similar geochemical principles apply to terrestrial *enhanced weathering*. The latter describes practices by which the decomposition of rocks, which occurs naturally, is sped up by physical and chemical processes. Rocks and other materials such as mine waste, concrete and alkaline waste are ground up to maximize the available surface size, on which chemical reactions take place that sequester carbon from the atmosphere.

Carbon can be sequestered on farmland by two types of technologies. First, farmers can add *biochar* to their fields. Biochar is produced by pyrolysis, that is, the thermal degradation of biomass in an oxygen-limited environment. Added to soil it can both store carbon for long periods of time and it improves ecosystem properties such as soil fertility. Second, agricultural patterns can be modified in order to change the balance of carbon inputs and losses. Through this approach, also referred to as *soil carbon sequestration*, the equilibrium level of soil organic carbon content can increase. Measures include, for example, ploughing less and planting more ground covers. While easy to implement, this sink can be expected to be saturated over the course of the century.

Finally, carbon can be removed from the atmosphere directly with air filter systems. *Direct air carbon capture and storage (DACCS)* uses energy intensive machines to sequester and store carbon underground. Several materials and processes are currently under research. At the time of writing, only very fews DACCS plants are being operated and are removing only 0.01MtCO_2 per year (IEA, 2022).

2.2 Costs, potentials and permanence

The technologies differ with respect to economic costs, resource intensity (land, energy, minerals), further environmental impacts, especially on biodiversity, as well as costs and technologies for monitoring and verification. Typically, individual options have strongly increasing marginal costs due to some form of scarcity, as for example land scarcity in case of afforestation, which strongly limits their quantitative potential. Besides economic removal costs, CDR technologies differ in how long carbon remains stored in the reservoir. Carbon stored in forests and soils can quickly be released if other management practices become profitable. This can be accelerated by increasing land prices. Of course, storage time will also depend on the impacts of climate change. Increasing droughts and fires reduce expected storage time, while the CO_2 fertilization effect may increase it. Carbon stored in products is released when product lifetime has ended. For example, while the carbon contained in a single family home made of wood has an expected half life storage time of about 100 years, the half-life of carbon stored in paper is only two years.

Fuss et al. (2018) review the literature on potentials and costs of CDR technologies and provide a holistic assessment. Storage times are reported by Smith (2006); Hiraishi et al. (2014); Woolf et al. (2021); Lehmann et al. (2021); Hepburn et al. (2019); Smith et al. (2023). For the reader's convenience, we summarize the numbers in Table 1. As Kalkuhl et al. (2022) show, how long a given CDR technology can store carbon matters fundamentally for the economics of CDR, the specific technology's role for climate policy and the optimal regulatory framework. We discuss this in the next sections.

Technology	Potentials	Costs	Storage duration
Afforestation/reforestation	0.5 - 10	0 - 50	Decades to centuries
BECCS	0.5 - 11	100 - 200	Millenia
Ocean alkalinization	1 - 100	14 - 500	Centuries
Enhanced weathering	2 - 4	50 - 200	Centuries
Biochar	0.3-6.6	30 - 120	Centuries
Modified patterns of agriculture	2 - 5	0 - 100	Years to decades
DACCS	5 - 40	100 - 300	Millennia

Table 1: Global potentials, in gigatonnes of CO_2 per year (estimate for 2050), and costs, in dollars of today's purchasing power per ton of CO_2, of relevant CDR technologies. Storage time for different CO_2 removal technologies is given by the half-life. Based on Smith (2006); Hiraishi et al. (2014); Hepburn et al. (2019); Woolf et al. (2021); Lehmann et al. (2021); Smith et al. (2023)

3 Incentives and Policy Instruments

Carbon emissions cause a negative externality. In theory, the correction of the market failure can be achieved with a carbon price, implemented as a tax or an emission trading scheme. Analogously, the removal of carbon from the atmosphere entails a positive externality and calls for a subsidy.[4] If carbon storage is permanent, then abating the emission of one ton and removing one ton have the same effect on the carbon concentration in the atmosphere, thus global mean temperature and ultimately the damages caused by climate impacts. Therefore, both options have the same social value, namely the social cost of carbon, which aggregates over time and space the economic costs due to the addition of one ton of CO_2 to the atmosphere.

3.1 Socially Optimal Deployment of CDR

We abstract from the aggregation over regions and focus on the time dimension. Assuming a simple stock-pollution problem where carbon emissions E accumulate in the atmospheric carbon stock, X by $dX/dt = \dot{X} = E$, the social cost of carbon emissions is

[4] Upscaling carbon removal can create significant negative and positive (environmental) externalities beyond climate change (Fuss et al., 2021). For a brief discussion of the most important issues in the context of incentives and policy instruments, see Kalkuhl et al. (2022).

given by

$$\text{SCC-E}(t) = \int_0^{\infty} d'\left(X(t)\right) e^{rt} \mathrm{d}t \tag{1}$$

where d' measures marginal climate damages as a function of $X(t)$, the carbon concentration in the atmosphere at time t. Damages are discounted at the rate r.

If someone removes carbon only temporarily, then the social value of this removal is not as high as the SCC-E. Instead, if we assume a release rate of δ, one initially removed ton of carbon causes a perpetual flow of carbon from storage to the atmosphere, where it causes climate damages again, the costs of which can be expressed as a function of the SCC-E. Kalkuhl et al. (2022) show that the *social cost of carbon removal* of non-permanent removal technologies with release rate δ is given by

$$\text{SCC-R}(t) = \left[\delta \int_t^{\infty} \text{SCC-E}(s) e^{-\delta(s-t)} ds\right] e^{rt} \tag{2}$$

In the long run in certain cases, Kalkuhl et al. (2022) show that SCC-E and SCC-R are constant and that, in these steady states, the one can be expressed as a fraction of the other, which depends only on the discount and the release rate.

$$\frac{\text{SCC-R}}{\text{SCC-E}} = \frac{\delta}{\delta + r} \tag{3}$$

Note that in the special case where removal is permanent, $\delta = 0$, the SCC-R become zero. When the discount rate r becomes very small or converges to zero, the social cost of carbon emissions is close to the social cost of carbon removal, diminishing any social value of offsets in the long-run. Nevertheless, removal can be valuable in the short-run to achieve net-negative emissions until the optimal steady state temperature is achieved. Considering non-permanent carbon removals, thus, creates two distinct social cost of carbon prices – one that measures the social damage caused by one ton of carbon, and a second one that describes the damage caused by one ton of carbon that is initially removed and released back in the atmosphere over time. The two different prices reflect the scarcity of the limited disposal space in the atmosphere and in reservoirs for removals.

As shown in Kalkuhl et al. (2022), the optimal amount of carbon removal is determined by the condition

$$\text{MPRC} + \text{SCC-R} = \text{SCC-E} \tag{4}$$

where MPRC denotes the marginal private removal costs, that is, the costs firm face when removing and storing carbon, for example, in geological reservoirs, in soils or in forests. For cost minimization, the SCC-R need to be added to the private marginal removal costs to reflect the social damages of the carbon that will be eventually released. The sum of the private and the social marginal removal costs need to equal the social marginal benefit of removing one ton of carbon, the SCC-E, that measures the avoided marginal damage of the carbon removed.[5] We illustrate this in Figure 2.

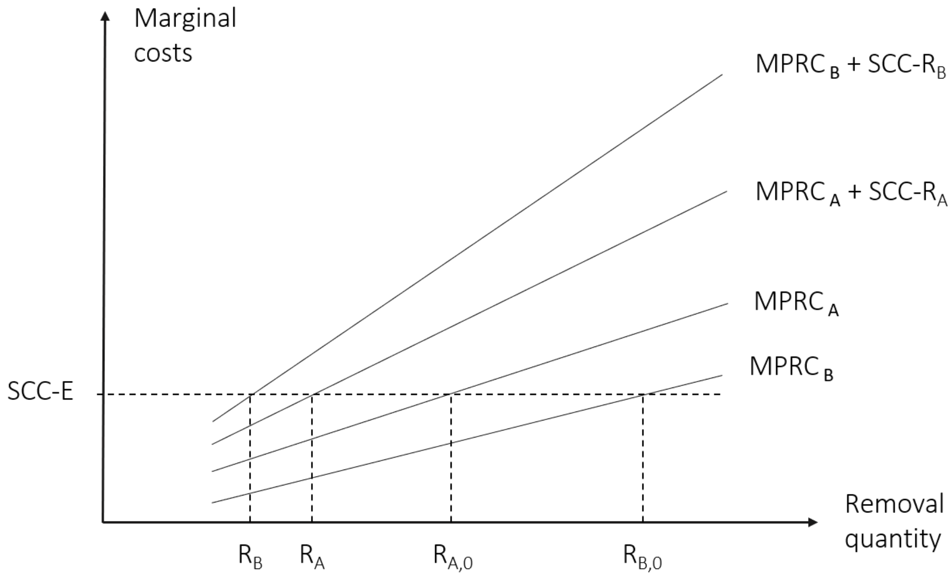

Figure 2: When the regulator implements a Pigouvian carbon price equal to the social cost of carbon emissions (SCC-E), but neglects the social cost of carbon removal (SCC-R) of non-permanent technologies A and B, then the resulting quantities of carbon removal $R_{A,0}$ and $R_{B,0}$ will be too high. Here technology A has higher marginal private costs ($\text{MPRC}_A > \text{MPRC}_B$), but the latter has higher overall costs since the difference in the SCC-R overcompensates the difference in the MPRC. That is, $\text{MPRC}_A + \text{SCC-R}_A < \text{MPRC}_B + \text{SCC-R}_B$. Consequently, the optimal removal quantity with technology A is higher than with technology B, that is, $R_A > R_B$.

Importantly, while CDR with non-permanent storage is less valuable than with permanent storage, it should still, in general, be used in the social optimum (Kalkuhl et al., 2022) as SCC-E > SCC-R for any $\delta < 1$ and $r > 0$. This can be seen in equation (4), in which all three terms can be assumed positive. When the release rate δ approaches one or the discount rate r approaches zero, the optimal marginal private removal costs MPRC approach zero and only very small removal projects should be realized.

Non-permanent storage is not equivalent to mitigation options that reduce emissions once and forever compared to a baseline scenario. As long as cumulative fossil resource

[5] The social value of offsets (SVO) that Groom and Venmans (2022) calculate corresponds to the difference between the SCC-E and the SCC-R, that is, SVO = SCC-E − SCC-R. However, Groom and Venmans (2022) do not derive the SVO from welfare or cost optimization but base their formula on an exogenously given SCC path.

extraction has not exceeded a certain threshold, the optimal temperature target is independent of the availability of non-permanent CDR. Instead, the role of non-permanent CDR is rather to increase the size of available carbon sinks, which reduces overall economic costs of achieving a given temperature target. In this case, non-permanent CDR constitutes a substitute for emission reduction, allowing to increase fossil resource use in the short-run. The social planner faces a trade-off: On the one hand, non-permanent CDR allows to save cost since its availability allows for reducing emission abatement. On the other hand, deployment of non-permanent CDR commits future generations to incurring the costs of permanently refilling the carbon that is released from storage sites. Kalkuhl et al. (2022) compare the task of perpetual refilling non-permanent storage with Sisyphus' task of rolling the big rock up a hill only to let it slip and watch it roll down to the bottom again.

In a remarkable way, the inclusion of CDR with non-permanent storage adds complexity to the canonical understanding of climate change economics as a reservoir depletion problem, captured in the Hotelling model. From the intertemporal optimization, two modified Hotelling rules can be derived.

$$\widehat{\text{SCC-E}} = r - \frac{d'(X)}{\text{SCC-E}} \tag{5}$$

$$\widehat{\text{SCC-R}} = r + \delta \left(1 - \frac{\text{SCC-E}}{\text{SCC-R}}\right) \tag{6}$$

The hats denote growth rates. Together, equations (5) and (6) determine the optimal use of the atmosphere and the carbon reservoirs. Both equations describe an arbitrage condition determined by the discount rate, the damages caused by carbon in the atmosphere and the carbon released from storage sites. Increasing the discount rate leads to higher deployment of CDR and more rapid use of fossil fuels. Higher damages caused by fossil fuel emissions makes abatement of emissions more desirable, and lower release rates makes carbon removal more attractive.

3.2 Carbon Pricing – Design Options

When governments consider the possibility of both emissions abatement and temporary carbon removal, they face a set of design choices with respect to carbon pricing. Policy makers can implement carbon prices at different points in the carbon cycle. First, due to economic activity in the energy system and land use, carbon is either emitted into the atmosphere or abated (lower left box in Figure 3). Then, CDR firms remove carbon from the atmosphere and store it for a certain time. Over time, storage sites release some of the carbon again into the atmosphere.

Four different policy design options are worth considering (see Figure 3). The most simple concept is *downstream pricing*. Under downstream pricing, polluters pay the same carbon price, the SCC-E, for all emissions, regardless of whether they constitute an initial GHG emission resulting from some form of economic activity such as the combustion of fossil fuels or the release of previously stored carbon from temporary storage. For removing a ton of carbon, governments pay a subsidy that is equal to the carbon price on emissions.

Second, under *upstream pricing*, only initial GHG emissions, that is, from burning fossil fuels, are taxed at the SCC-E. Emissions from sinks that store previously removed carbon are exempted from carbon pricing. Instead of pricing those emissions released from non-permanent storage, the government discounts the subsidy for carbon removal in accordance with the expected release rate of the respective CDR technology used. The subsidy for carbon removal has to equal the SCC-E net of the SCC-R and accounts for the non-permanence. Kalkuhl et al. (2022) show that over time, the subsidy for carbon removal converges to $\lambda \times$ SCC-E with $\lambda := \frac{r}{r+\delta}$. The shorter the storage time, that is, the higher δ, and the lower the discount rate r, the lower the subsidy should be. As a special case, a permanent storage technology ($\delta = 0$) should receive the full carbon price. Likewise, if discount rates are very small, $r \approx 0$, removal becomes worthless in the long-run and the subsidy becomes zero. An illustration of the size of the subsidies is given in Table 2: If carbon is stored with a half-life of one decade, the removal subsidy should range from 7–50% of the SCC-E. The range is very sensitive to the discount rate: for very low discount rates, for example 1%, the value of temporary storage is also very low because the emissions released later require costly removal activities again. For high discount rates, for example, 7%, the subsidy to temporary storage is quite high because the subsequent removal costs of released emissions are also discounted much more. Hence, the more future costs are discounted, the more valuable temporary removal becomes since it 'buys' time.

Third, instead of subsidizing the flow of carbon removal, the government could pay an annual *storage stock subsidy* proportional to the size of the carbon reservoir at the rate $d'(X)$, which measures the marginal damages of the existing atmospheric carbon stock. Contrary to upstream and downstream carbon pricing, the stock subsidy does not require to calculate a social cost of carbon path, which depends on an assumed carbon emission trajectory from now until infinity.

The three designs discussed so far imply different informational and measurement requirements for the government, different public and private financial flows and different consequences for private firms' behavior. Kalkuhl et al. (2022) describe these difference in detail, here we briefly discuss the most important insights.

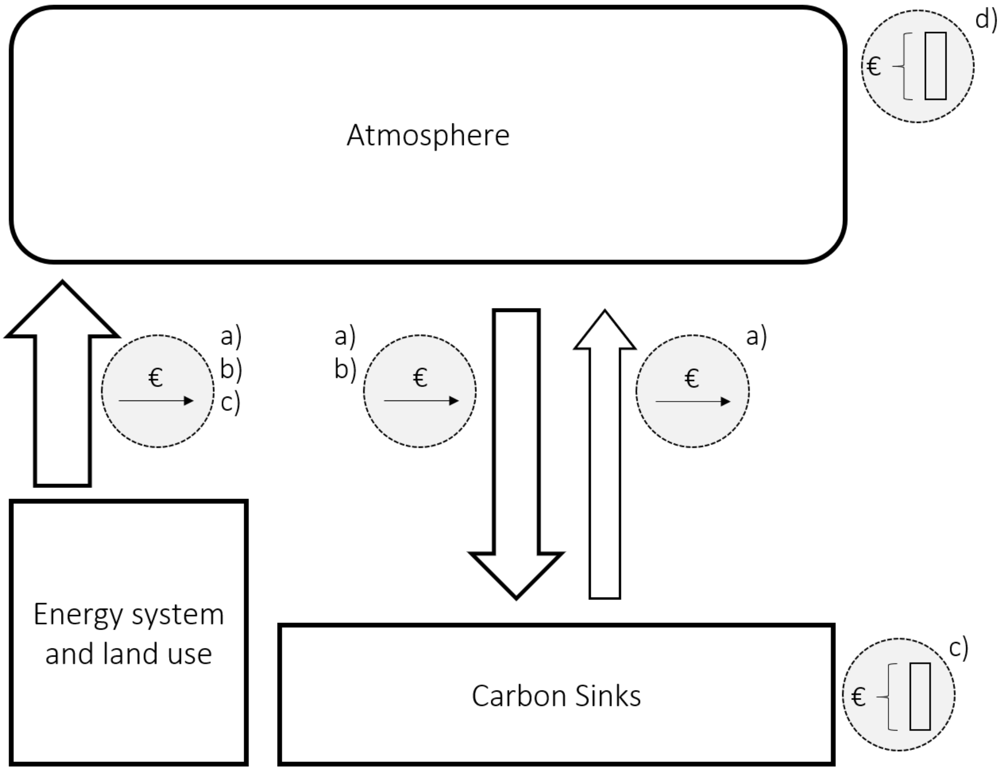

Figure 3: Carbon pricing instruments can be implemented at different stages in the carbon cycle and either target stocks (€{□}), or flows (€ →). Downstream pricing (a) consists of a carbon tax on emissions from economic activity and on emissions released from storage stocks. Upstream pricing (b) includes only the carbon tax on emissions from economic activity and a subsidy adjusted for the social cost of carbon removal (SCC-R). The carbon tax can also be combined with a storage stock subsidy (c). If the stock of carbon in the atmosphere is taxed (d), no other instruments are required.

		Discount rate r				
Half time (years)	δ_i	0.01	0.02	0.03	0.05	0.07
1	0.69	0.01	0.03	0.04	0.07	0.09
5	0.14	0.07	0.13	0.18	0.27	0.34
10	0.07	0.13	0.22	0.30	0.42	0.50
50	0.014	0.42	0.59	0.68	0.78	0.83
100	0.007	0.59	0.74	0.81	0.88	0.91
500	0.0014	0.88	0.94	0.96	0.97	0.98
1000	0.0007	0.94	0.97	0.98	0.99	0.99

Table 2: CDR subsidy in an upstream carbon pricing system as fraction of the carbon price on carbon emissions, λ. Numbers are calculated for a steady state economy, see Kalkuhl et al. (2022).

When a government wants to implement downstream pricing or a storage stock subsidy, it has to be able to monitor either the removal flow or the stock of carbon stored. Transaction costs relative to the amount of carbon stored, in particular for dispersed land-based carbon sinks, could be quite high for this design. However, if the amount of carbon released from storage depends on diligence that is costly to CDR firms, both downstream pricing and the stock subsidy ensure that firms still have an incentive for optimal management. Upstream pricing requires less detailed information. Here, governments only have to know the expected release rate associated with the specific CDR technology to calculate the discount factor for the CDR subsidy. However, optimal pricing requires substantial differentiation between removal activities, for example, afforestation by one forest species might get a different subsidy due to different rotation lengths. Upstream pricing has the disadvantage that it may not incentivize due diligence; complementary regulatory policies such as diligence standards might therefore be necessary to ensure that release rates are not strategically lowered. An upstream subsidy for carbon removal due to afforestation, for example, could be complemented by a commitment to implement a specific rotation length.

The three pricing principles differ also in terms of liability and solvency risks. Since payments are made upfront, upstream pricing is judgement proof. That is, if firms go out of business, then no further costs to the public arise since the social cost of carbon removal has already been payed by the CDR firm due to the lower subsidy. Similarly, the stock subsidy also sets incentives favorably. Since firms receive the subsidy always for the carbon stored at that time, firms cannot profit from neglecting due diligence or going bankrupt strategically. Under a downstream pricing scheme, however, full removal payment is upfront while high costs of releasing emissions occurs at later periods. Firms might take sub-optimally high risks in their strategic decisions potentially leading to bankruptcy, betting on a bail-out with public money.

A fourth design principle is discussed by Lemoine (2023) who suggests a policy of carbon shares. In essence, this can be understood as a tax on the stock of carbon in the atmosphere. Polluting firms pay a rental charge for using the atmosphere as storage space for carbon until they clean it up again. To ensure that this policy is judgement proof, Lemoine suggests that the carbon shares are tradeable and should include up-front payments through bonds. However, the study does not consider where or how carbon is stored after removal, nor issues of non-permanence.

To be able to implement the rental charge, governments need to keep track of how much carbon in the atmosphere each firm is responsible for. This includes carbon that firms have stored impermanently and that is released again. Therefore, carbon shares are very similar to the above discussed downstream pricing in terms of informational requirements and political economy considerations.

4 Political Economy: Second-Best Options

As argued in the section above, a uniform carbon price for abating or removing carbon – potentially corrected for expected release from non-permanent carbon stocks – guarantees an efficient allocation of activities. However, there are normative as well as political-economy reasons for deviating from this first-best policy and to price removals differently, or, equivalently, have a separate removal target. As it will become clear in this section, these reasons are due to second-best settings arising from other market or policy failure.

4.1 International Trade and Strategic behavior

Besides the heterogeneity in storage permanence, a missing global uniform carbon price may constitute another reason for the CDR subsidy to differ from the price on the emission of GHGs. Franks et al. (2023) describe how different forms of interregional carbon leakage should influence unilaterally optimal carbon taxes and the CDR subsidy. Interregional carbon leakage occurs when climate mitigation measures implemented in one region lead to an increase in emissions elsewhere. Franks et al. find that CDR subsidies may tend to induce less leakage – in particular on the supply side of fossil fuels – than carbon taxes. A corresponding difference between the level of the CDR subsidy and the carbon tax is therefore optimal.

Following the terminology introduced by Jakob et al. (2014), carbon taxes may cause both free-rider leakage (Hoel, 1991) and supply-side leakage (Bohm, 1993; Gerlagh and Kuik, 2014) when they are implemented unilaterally by one region and the global climate policy regime is fragmented. *Supply-side leakage* occurs due to the drop in the international price for fossil fuels when one country unilaterally reduces emissions by reducing demand for fossils. Due to the price drop, other countries will then increase their demand for fossil fuels. *Free-rider leakage* is due to the unilateral reduction of emissions by one region that leads to a reduction in climate damages. Lower climate damages also affect other regions so that in their unilateral cost-benefit analysis, the optimal level of emissions increases.

Carbon removal has no direct impact on international markets for fossil fuels. Hence, CDR subsidies only cause free-rider leakage. Considering this difference implies that ceteris paribus CDR subsidies should be higher than carbon taxes.

However, governments have further strategic considerations when deciding on unilateral carbon pricing policies (Franks et al., 2017, 2023; Franks and Lessmann, 2019). If, for example, a country is a net-exporter of fossil fuels, then it may have a further incentive to reduce the carbon tax relative to the CDR subsidy in order to maintain a high price for fossil resources and, thus, higher income from selling resources on the international market. If, by contrast, the country is a net-importer of fossil fuels, it may have additional strategic incentives to appropriate the resource rent of fossil fuels. Then, the unilateral carbon tax would be higher and could even exceed the CDR subsidy again.

The above reasoning is based on a generic CDR technology. Certain CDR technologies, however, may have features that make their use more susceptible to additional leakage effects. DACCS, for example, is relatively energy intensive, while BECCS is quite land-intensive. Large-scale deployment of either technology may have strong impacts on international energy and land markets. To sum up, in unilateral climate policy regimes, strategic interactions between carbon exporting and carbon importing nations may lead to different carbon prices for emissions and removals.

4.2 Dynamic efficiency, commitment and technology-specific policies

A fundamental concern against a uniform carbon price in all sectors is that the inclusion of low-cost mitigation or removal options into a comprehensive emissions trading scheme reduces carbon prices and, thus, investments into long-term mitigation options. Despite high up-front costs, such investments into innovation and up-scaling of novel mitigation and removal technologies, low-carbon infrastructure or building renovations might be necessary for dynamic cost-efficiency (Rozenberg et al., 2020). In the case of carbon removal, the potential to store carbon in natural sinks via afforestation and increasing soil carbon at low costs is very limited. After the removal potential has been exhausted, removal technologies with (currently) higher costs but larger scale like BECCS and DACCS become necessary (Smith et al., 2023). As scaling up these technologies in short periods of time is very costly or even infeasible due to planning, construction and deployment periods, deployment should already start early to ensure sufficient removal capacity in the future.

With a credible commitment to a socially optimal carbon price path or emission cap, optimal discount rates by investors and rational expectations, dynamically efficient investment into more expensive long-term mitigation and removal options would occur. There are, however, several reasons why at least some of these three assumption might be violated in practice: First, commitment to future climate policy is rather loose. While the EU and national governments have emission targets, these targets lack effective compliance mechanisms. On the EU-level, the cap in the existing EU-ETS is currently determined until 2039. Because of uncertainties about the future reduction factors and missing futures markets on allowances beyond 2039, there is no liquid future market allowing for long-term expectation formation. Likewise, national governments are reluctant to commit to target-consistent policies. The German national carbon price, for example, has been fixed in nominal terms only until the year 2026 – with substantial uncertainty how the price corridor of the national emissions trading scheme will further develop. Second, there is evidence that investment decisions suffer from short-termism due to managerial incentive structures in firms (Dallas, 2011). Also, consumers who decide about investments into transport technologies and residential energy systems suffer from myopia (Gillingham et al., 2021). Finally, bounded rationality may explain why firms, and in particular consumers, extrapolate current carbon (and energy) prices as basis for investment decisions rather than engaging in (costly) information acquisition of potential future carbon price developments (Barazza and Strachan, 2020).

All of these reasons may explicate why there might be under-investment into expensive but dynamically efficient long-term abatement or removal options even in a uniform carbon pricing scheme. In all of these cases, higher instantaneous carbon prices in sectors with under-investment may help to reduce dynamic inefficiency although they create a static inefficiency. By contrast, lower carbon prices – for example, by allowing for off-sets in low-cost removal technologies like afforestation – may exacerbate dynamic inefficiency.

The concern for dynamic efficiency could be a key political economy explanation for sector targets, sector policies and carbon price differentiation among different technologies. In many countries, subsidy rates for wind power and solar energy differ in order to incentivize 'sufficient' investment in *all* of these technologies. When policy commitment, myopia and bounded rationality cannot be addressed, additional technology- or sector specific carbon prices constitute a second-best policy to improve dynamic efficiency. This approach concerns both the mitigation vs. removal sector and specific technologies within these sectors.

Further, Fabra and Montero (2023) show that the question whether policies should be technology-specific or -neutral also depends on the asymmetry in costs, the degree of substitutability, the extent of information asymmetry and the costs of public fund. Especially with fairly asymmetric technologies and high costs of public funds (and, thus, a strong rent extraction motive), policies should rather be technology specific.

Finally, setting sector- or technology-specific goals does not guarantee the enforcement of these goals. The delegation to an independent authority might be an option. The capacity of commitment of the authority increases when the mandate is narrow and specific (Boyer and Laffont, 1999; Dixit, 1998; Moe and Caldwell, 1994). Policy makers might intervene when sector-specific targets lead to large price gaps and, thus, create large uncertainties among investors. Therefore rule-based adjustments are essential. In Section 5.2, we discuss this in the context of the EU and the liability for carbon removals.

4.3 Energy prices vs. fiscal balance

Besides normative arguments for differentiated prices, there may be strong political economy reasons for price differentiation. Suppose that policy makers agree on a net-zero target. An efficient allocation between abatement and removal is given when marginal abatement costs equal the marginal removal costs of a permanently removed ton of carbon (see Figure 4).[6] The efficiency criterion gives an optimal level of 'residual' emissions that require removal. The optimal level may change when abatement or removal costs change.

Policy makers concerned about the level of energy prices or industries in hard-to-abate sectors might want to reduce abatement efforts by inflating removal flows. This causes some deadweight loss in terms of aggregate welfare. As the deadweight loss is not directly observable or salient, it might not constitute a substantial political cost. A higher than optimal removal flow, however, requires additional fiscal spending, as illustrated in Figure 4. In contrast to the less salient deadweight loss, the increase in public spending might constitute a significant political cost. Note that in the case of an efficient allocation between removal and abatement, fiscal costs are zero as carbon prices for removal and abatement are equal and carbon emissions are net-zero. Hence, by deviating from an efficient allocation, policy makers trade off higher energy prices or industry relocation against higher fiscal spending needs that need to be financed by other tax increases. Likewise, policy makers that value additional revenues strongly might favor a more ambitious abatement goal and less ambitious removal goal than efficient. Because of the strong and popular aversion against carbon taxes or energy price increases (Douenne and Fabre, 2020, 2022) and the very heterogeneous costs of climate policy even within income groups (Hänsel et al., 2022), ultimately strong political forces might arise pushing for an increase in removals at the expense of abatement.

[6] Non-permanent removals have to be discounted as discussed in Section 3.2.

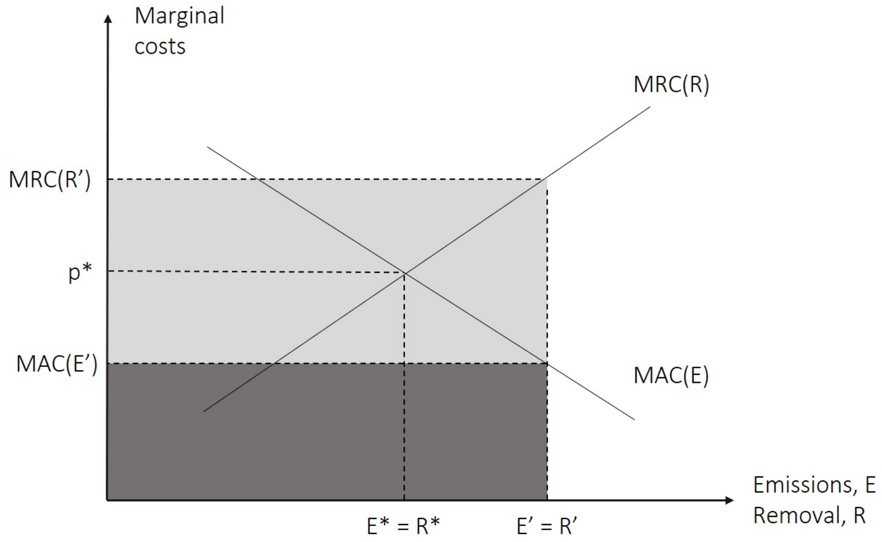

Figure 4: In the optimum, the marginal abatement costs (MAC) and the marginal removal costs (MRC) are equalized. Then, revenues from carbon pricing exactly offset expenditures for carbon removal, $p^*E^* = p^*R^*$. If less abatement is implemented and more CDR is deployed, actual emissions E' are higher than in the optimum. Then, the expenditures required for offsetting these emissions with CDR (light grey area and dark gray area together) are higher than the revenues from taxing these emissions (only the dark grey area).

4.4 Offset markets and voluntary carbon removal markets

Previous parts discussed conditions that may justify different prices for carbon removals than for carbon emissions. These considerations suggest that an integration of carbon removals (or other offsets) in compliance markets is welfare-enhancing if specific regulations ensure an optimal price differential. Nevertheless, voluntary carbon markets have increased substantially over the last decade, partly driven by the huge demand for carbon offsets by firms, municipalities or individuals that aim for climate neutrality. Voluntary offset markets are a tool to harness the heterogeneous willingness to pay for limiting global warming. The establishment of a compliance market or a carbon tax requires societies to agree on one price or emission stringency level, the voluntary market allows consumers or firms to remove additional carbon emissions due to environmental preferences (’warm glow’ preferences) or moral considerations (Andreoni, 1990). Similar to information labeling in organic food markets (McCluskey, 2000; Caswell and Mojduszka, 1996), a precondition for a functioning voluntary market is transparency of the actual off-set amount. Because of information asymmetries, a third-party certification of offsets or ’carbon-neutral’ products is necessary. The need for transparency and information of offsets is also illustrated by recent evaluations on voluntary offsets by consumers (Rodemeier, 2023). Without additional information, consumers do not understand the size and effectiveness of an offset provided.

Voluntary offset or removal markets could serve different purposes: firms that aim to sell carbon-neutral products may use them to compensate emissions that are beyond their direct control (typically emissions related to inputs purchased) and not regulated in a compliance market. This may typically refer to emissions from trade partners outside the EU or from the land sector (including agriculture). Individuals may also wish to compensate emissions even when they are already covered in a compliance carbon market or are subject to carbon pricing.

An emerging voluntary carbon offset market will, in general, exhibit different carbon prices for different offset activities. Offsets may differ again in their permanence or other social or ecological characteristics that consumers value. For example, an afforestation offset might be valued differently by consumers than a DACCS offset. If the compliance market is set exogenously, the offset market (with heterogeneous carbon prices) creates additional carbon removals and improves social welfare as it satisfies heterogeneous demands for climate protection. It remains unclear how large a functioning voluntary offset market will be. Estimates on consumers willingness-to-pay for existing offsets suggest a rather low value of around 16 €/tCO_2 (Rodemeier, 2023). Hence, either offset projects have to be of 'low quality', that is non-permanent or with additional leakage effect, to be competitive at such price levels, or the voluntary offset market has to decrease substantially in scale when more expensive high-quality offsets are procured.[7] This latter case is a likely way forward when the EU adopts its certification framework that should ensure a high quality of carbon offsets. When the integrity of the offset market is guaranteed, it will be cost-efficient to link the offset market to the compliance market and the ETS (see the discussion on a path towards comprehensive carbon pricing in the next section). This will increase demand for offsets, driving up prices further and potentially diminishing the size of voluntary markets considerably. [8]

[7]See, for example, the broad range of offset prices estimated by 2050, depending on the offset quality at Bloomberg New Energy Finance (2022).

[8]It is beyond this paper to assess the optimal level of stringency and regulation of voluntary markets nor its long-term and strategic interplay with compliance markets. Bento et al. (2015) have discussed the question of instrument choice in a static setting without impermanent CDR. Interesting questions for future research remain: While in the short-run the cap on the compliance market may be taken as given, stringency of climate policy is dynamic and will be adjusted over time. Hence, if voluntary markets would induce a significant amount of high-quality carbon removal, a net-zero target can be achieved at a less stringent cap in the future. Strategic moral consumers, however, might anticipate such a 'crowding out' effect on the regulatory side. Then, a voluntary markets may only work with a strong commitment by the regulator to prevent crowding-out such that voluntary offsets always lead to additional emission reductions.

5 CDR in the EU

How should the EU integrate CDR into its climate policy architecture? In the following we explore this question and apply, where possible, what is known about the governance of CDR. We begin by briefly describing the EU's current policy strategy on carbon removal. Then, we collect thoughts on how to address key challenges of CDR integration, which instruments are necessary and propose new institutions like a European Carbon Central Bank and a Green Leap Innovation Authority.

5.1 EU's current strategy

The EU's pathway toward climate neutrality by 2050 consists of ambitious emission reduction combined with a drastic up-scaling of CDR technologies (European Commission, 2018, 2021, 2022). The EU intends to enhance three different types of CDR options: permanent storage technologies, carbon farming and carbon storage in products. An option to be qualified as permanent should store atmospheric or biogenic carbon for several centuries. This definition includes bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS). Carbon farming results in the increase of carbon storage in living biomass, dead organic matter and soils by enhancing carbon capture and reducing the release of carbon to the atmosphere. Atmospheric or biogenic carbon can be stored in long-lasting products or materials for several decades.

An EU-wide quality control, certification and registration system has been proposed to testify the quantity of the removed carbon. These removal activities should be additional compared to activities in the baseline scenario. Duration of storage and impacts on other sustainability issues like biodiversity should also be considered. Based on the agreed standards, a governance structure for the use of CDR certificates can be designed. The proposed certification scheme should serve as a first step to establish a high quality removal market, primarily for voluntary offsets. Once policy makers have improved potential shortcomings and the voluntary market has proved its integrity, the EU governments could use it to scale up removals via public spending. Finally, the removal market can be linked to compliance markets. In principle, soft- and hard-linking are conceivable, where the latter means direct integration of CDR into the EU-ETS. The former refers to adjustments of the EU-ETS cap depending on removal quantities.

The recently agreed revision of the EU's land use, land use change and forestry legislation, for the first time sets a net removal target for biogenic carbon dioxide removals of 310 million tons in 2030 which is shared between EU Member States (European Parliament Committee on the Environment, Public Health and Food Safety, 2022).

5.2 CDR governance within the current institutional framework

We now discuss how the governance of CDR within the current institutional framework of the EU could be designed. Two questions have to be addressed. First, which tasks will the governance structure have? Second, which of these tasks can be carried out based on simple rules and which of the tasks require an institution such as a carbon central bank or a certificate clearing house with a mandate for discretionary policy.

The answer to the question which tasks there are is straightforward: (i) The cap has to be managed (including the allocation with respect to abatement and removals), (ii) RD&D and deployment of new removal technologies has to be financed and (iii) carbon removals have to be certified, in particular in terms of the storage time and additionality. It is less obvious how to decide which institutions should carry out the tasks and whether they should be strictly rule based or require a certain degree of discretion under a well-defined mandate. In the following, we collect some considerations on the three tasks that should inform this decision. Finally, we discuss institutional requirements in Section 5.2.5 and summarize them in Table 5.

5.2.1 Managing the cap

In a world without impermanence of storage or the need to spur innovation, carbon removals coming from technologies with nearly permanent storage, for example, DACCS and BECCS, can easily be integrated into the EU-ETS. In the medium term, the designated second emissions trading scheme for the building and transport sector (ETS-II) should also be integrated into the the EU-ETS such that there exists only one comprehensive carbon pricing scheme for mitigation and (permanent) removal. To a certain extent, CCS is already included into the EU-ETS as a mitigation technology but not as a removal technology (when combined with bioenergy or direct air capture). In particular, the prospect for BECCS in the EU-ETS has become more favorable. Biomass-CO_2 emissions have increased gradually over past years. However, the ‚negative emissions‘ of BECCS are unfortunately not yet recognized in the existing EU-ETS as no additional allowances can be created by BECCS or DACCS. The latest ETS-I compromise acknowledges this (European Parliament Committee on the Environment, Public Health and Food Safety, 2023), and requests the Commission to address the issue. The legal possibility to create allowances with DACCS and BECCS would constitute an important investment incentive to scale up removals. This would even be the case for yet expensive (and not competitive) DACCS technologies because expectations about future cost reductions due to up-scaling and expectations about high future carbon prices already provide incentives to invest.

An alternative to directly integrating technologies with permanent removal would be the creation of a separate carbon market. Such a market could be established, for example, via auctions to achieve a specified removal goal, with an explicitly stated goal to integrate removal technologies into the ETS at a later point of time. This option would, however, contain some regulatory uncertainty about the future removal goals or prices as well as the timing and regulatory details of the integration into the ETS. The regulatory uncertainty may increase risk premiums and therefore costs for up-scaling these technologies.

Regulators might prefer to set a CDR quantity target due to political considerations.[9] A separate removal target likely prevents a cost-efficient removal quantity as marginal removal costs will, in general, not be equal to carbon prices in the ETS. The magnitude of the welfare losses depends on the current and on the future shape of the marginal abatement cost curve and on the marginal removal cost curve (see Figure 4): In the short run, marginal removal costs are relatively high (Smith et al., 2023). Hence, integrating CDR early would stimulate almost no additional removal activities and a small or moderate quantity target for CDR would therefore imply too much removal from a static efficiency perspective. From a dynamic perspective, however, it might be justified to scale-up innovative technologies (see Section 5.2.2 below). In the long run, marginal removal costs might become much flatter due to significant technological progress (Smith et al., 2023) while marginal abatement cost become steep because of the remaining emissions in the hard-to-abate sectors. CDR would therefore play a significantly larger role. A sub-optimally set removal target would then lead to sustained welfare losses when carbon prices in abatement and removal sectors are not equalized.

Therefore, setting an explicit CDR target might be a politically reasonable starting point at the phase-in period for CDR technologies. In the long run, price convergence through gradual integration of the CDR sector into the ETS sector can then realize significant welfare gains. The price convergence policy should be complemented by a minimum price path to avoid stranded assets in the abatement sector. Also, the integration process of (permanent) removals in the ETS should be clarified as soon as possible to reduce regulatory uncertainties.

Regulators might have strong incentives to hamper the convergence to such a welfare-maximzing uniform carbon pricing policy (recall Section 4.3). If they are dominated by lobby groups in the abatement sector that obstruct the achievement of the optimal abatement effort, or by consumers who strongly oppose high carbon and energy prices, regulators deploy CDR technologies extensively. If it is in their primary interest to generate

[9] For example, concerns have been voiced about mitigation deterrence and that not restraining CDR might jeopardize climate targets.

revenues, imposing constraints on the CDR sector is a very likely outcome because of higher abatement activities and subsequently higher ETS prices. These two conflicting motives can lead to highly time-inconsistent policies that will distort the expectations of investors in both sectors, increase investor's risks and eventually magnify the hold-up problem of investments (Kalkuhl et al., 2020). Below, in Section 5.2.5, Institutional reforms will be discussed to prevent such a disturbing political cycle. In particular, delegating the management of the cap to an independent body can be a solution because discretionary interventions by lobby groups or policy makers are reduced to a minimum.

5.2.2 Innovation

As described in Section 4.2, market actors may be myopic, future markets are incomplete due to missing commitment to future caps in the ETS and there are innovation spill-overs that constitute an externality. Thus, additional policies for up-scaling of new technologies can increase dynamic efficiency. This applies to DACCS, but also to certain abatement technologies that are currently expensive but likely needed at scale, too.

The additional technology support could be implemented via quotas or auctioning procedures. Such quantity-based instruments require only a rough understanding of the socially optimal amount of removal technologies. In principle, also price based support via subsidies is possible. However, this would be more difficult to set as the subsidy would have to be corrected for the degree of dynamic inefficiency.

Technology support has already begun under ETS-I via the Innovation Fund, where the first scalable project received financing (Smith et al., 2023). In parallel, and already for quite a while, EU and member states' research funds have been spent on CDR technologies. Development and testing of CCS technologies, for example, has already been funded 15-20 years ago. But all in all, the level is still insufficient because investors face high risks: excepting the venture capital market, there is virtually no demand for carbon removal and neither a regulatory framework nor public acceptance are given (Smith et al., 2023).

5.2.3 Impermanence

Technologies where permanence cannot be verified in precise and robust ways should be treated differently. Our discussion in Section 3 shows that non-permanent CDR does not affect the long-term temperature target. Nevertheless, it is socially optimal to deploy it in order to reduce costs along the transition. The degree depends on removal costs, the release rate and the social discount rate. The EU-ETS is a quantity based instrument and, hence, based on a cost-effectiveness approach where a carbon budget is set politically. The results from Section 3 are derived from a cost-benefit analysis and concern price based instruments. Applying the latter to quantity instruments like the EU-ETS, therefore, requires some modifications to the formal framework. As it turns out, the key implications are very similar to those derived from the cost-benefit case.

Notably, emissions from non-permanent removal need to be compensated by further (non-permanent) removal projects (Sisyphus' task). Alternatively, those emissions can be offset by liquidating an allowance in the regular cap-and-trade scheme, that is, by effectively decreasing the emission cap. In the following, we discuss both possibilities.

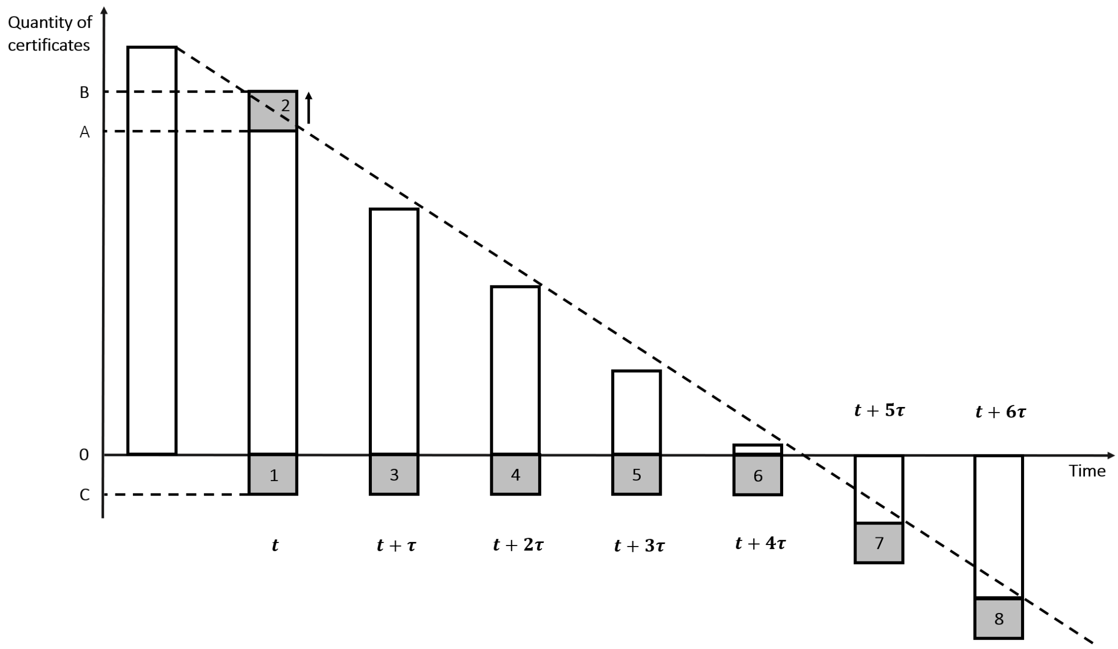

Figure 5: Perpetual removal with quantity targets that fall over time (dashed line). An initial removal of C units (1) with a non-permanent storage activity with storage time τ at time t creates additional certificates (B-A) in the ETS at time t (2). At $t+\tau$, emissions from this reservoir are released and need to be compensated again with the removal technology which stores carbon (3) for another τ years. This goes on in perpetuity (4, 5, 6, ...). With these compensating removals, no certificates for the regular ETS are created.

Figure 5 illustrates the idea of a *perpetual removal* approach, which we discuss first. Such a chain of perpetual removal activities that address emissions from past non-permanent removals basically creates a form of permanent removal. Relating to the Sisyphus metaphor, EU regulators could hold CDR firms liable for a chain of perpetual removal activity as described above. That is, at the end date of a non-permanent removal project, the firm would legally be required to remove all released carbon from the atmosphere again. As shown in Appendix A.1, the liability constitutes a form of debt D that can be expressed as a multiple M of the removal costs $g(R)$, depending on the interest rate r, the guaranteed storage length of a removal project τ and the growth rate of the

		Storage time [years]				
γ_R	r	5	10	20	50	100
0	1%	19.6	9.6	4.5	1.6	0.6
	2%	9.6	4.6	2.1	0.6	0.2
	3%	6.3	2.9	1.2	0.3	0.1
	5%	3.6	1.6	0.6	0.1	0.0
1%	1%					
	2%	19.8	9.7	4.6	1.6	0.6
	3%	9.7	4.6	2.1	0.6	0.2
	5%	4.7	2.1	0.9	0.2	0.0
2%	1%					
	2%					
	3%	20.0	9.8	4.6	1.6	0.6
	5%	6.4	3.0	1.3	0.3	0.1

Table 3: Cost multipliers on private marginal removal costs for non-permanent CDR, depending on discount rate r and the growth rate of the marginal removal cost γ_R. Empty cells imply that multipliers become infinitely high because removal costs grow at a rate larger than the interest rate.

marginal removal costs γ_R:

$$D = Mg(R_t) \qquad \text{with } M := \frac{(1+\gamma_R)^\tau}{(1+r)^\tau - (1+\gamma_R)^\tau} \tag{7}$$

If a firm can store one ton of CO_2 for 10 years at a price of 20 €/tCO_2, it needs to set-aside an additional amount of EUR $M \times 20$ to ensure a perpetual removal after the first project ends. The carbon debt depends crucially on the discount rate since high discount rates imply high financial returns on capital markets. Hence, the factor M becomes smaller because investing EUR $M \times 20$ yields high returns on the capital market, which makes it easier to finance all later removal activities. We show illustrative cases in Table 3 for projects with different storage times, discount rates and growth rates of marginal removal costs. Intuitively, increasing removal costs (high γ_R) makes it more costly to finance perpetual removal. This case is highly relevant for land-based removal projects because land prices have been increasing substantially in the last decades (see Figure 6 for German agricultural land prices). If the opportunity costs of land represent a large share of the removal costs, γ_R will depend largely on the growth rate of the land rental price. An appropriate assessment of expected land price developments is crucial for the proper pricing of the carbon debt induced by non-permanent removals. Additionally, non-permanent removals will likely contribute to land prices because many removal options like afforestation and BECCS are relatively land-intensive.

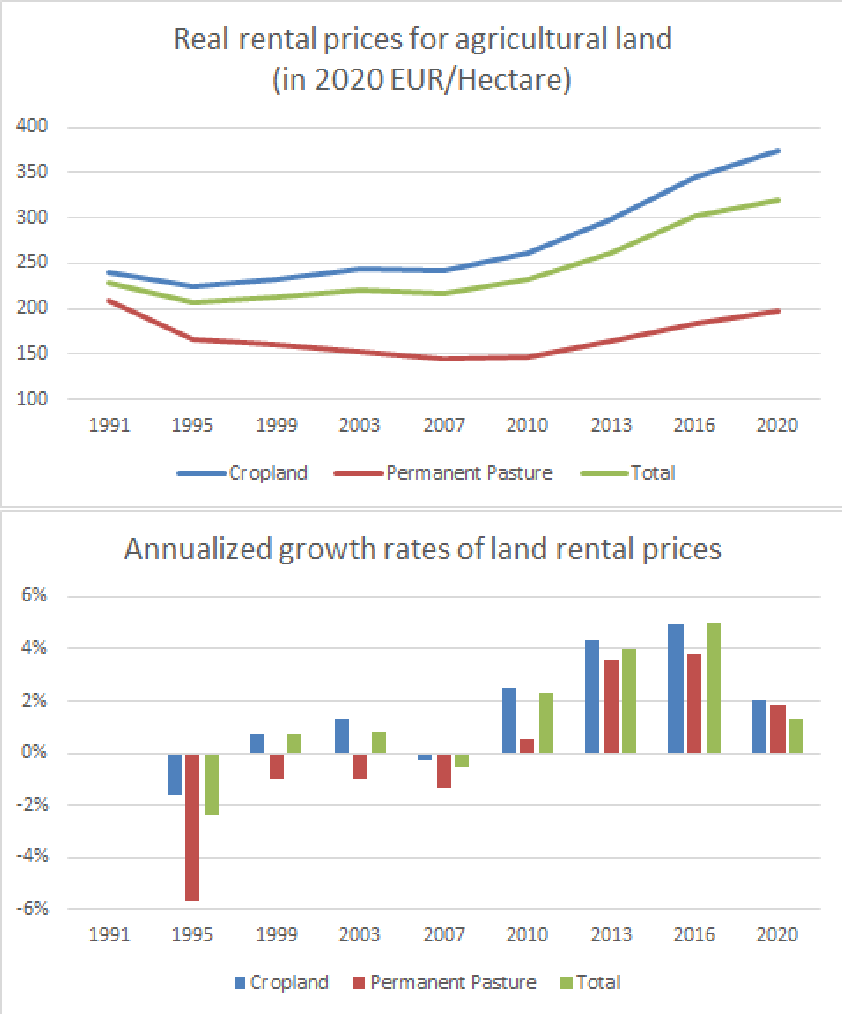

Figure 6: Agricultural land prices (top) and growth rates (bottom). Prices are in real 2020 EUR (using German consumer price index). Sources: Statista.

Table 3 emphasizes that the carbon debt from non-permanent removal activities might be very large or even infinite (empty cells). Considering again the above example of a temporary removal for 10 years: If discount or interest rates are 2% and marginal removal costs do not grow over time, for example due to stable land prices, a land manager has to set-aside a financial amount almost 5 times the initial removal cost. When removal costs grow by 1% per year, this factor increases already to 10 and when removal costs grow by 2% per year, it is impossible to secure funding of a perpetual removal project. This example illustrates that presumably cheap removal costs in the land sector actually imply large future costs when the non-permanence is accounted for.

With high carbon debt, the problem of moral hazard arises since firms might strategically take the payment for the carbon removal and then go bankrupt to avoid the perpetual removal liability. Downstream pricing, under which the firm would receive the equivalent of a full EU-ETS allowance for each ton of CO_2 removed, seems therefore inappropriate,

		Storage time [years]				
γ_R	r	5	10	20	50	100
0	1%	5	9	18	39	63
	2%	9	18	33	63	86
	3%	14	26	45	77	95
	5%	22	39	62	91	99
1%	1%					
	2%	5	9	18	39	63
	3%	9	18	32	62	86
	5%	18	32	54	86	98
2%	1%					
	2%					
	3%	5	9	18	39	62
	5%	13	25	44	77	94

Table 4: Permanence discount factors in percent on removal carbon prices for non-permanent CDR, depending on discount rate r and the growth rate of the marginal removal cost γ_R. Empty cells imply that discount factors are zero or (non-permanent removal is not applicable) because removal costs grow at a rate larger than the interest rate.

particularly for cases of high M. Instead, regulators should consider upstream pricing where non-permanent removals are only allowed if the firm pays an additional fee to cover (part of) the liability of the perpetual removal. In an extreme case, the regulator could finance the perpetual removal completely by charging the removal firm for the carbon debt $Mg(R)$ upfront. This implies a 'permanence discount factor' $1/(1+M)$ to the prevailing carbon price for non-permanent CDR (see Appendix A.2). The corresponding discount factors are shown in Table 4. If the carbon price in the ETS is, for example EUR 100, a 10-year removal project should receive only EUR 9 for every ton removed when $r = 2\%$ and $\gamma_R = 1\%$. This example again illustrates that the value of a non-permanent removal is by far lower than the value of one ton of CO_2 avoided (or permanently removed).

Besides engaging in perpetual removal, firms supplying non-permanent CDR could also settle their carbon debt by surrendering EU-ETS allowances according to the released carbon at the end of their non-permanent removal projects. The liability to perpetually remove carbon would be transformed into a *financial liability* on the regular ETS. When abatement certificates are still available on the market, the non-permanent CDR would effectively just change the timing of emission flows, holding cumulative emissions constant (see Figure 7). When abatement certificates do not exist anymore,[10] the off-set has to occur via a permanent removal certificate, which also ensures that cumulative emissions remain unchanged.[11].

[10]This could also be the case when emissions released from carbon storage at a later point in time are larger than the remaining carbon budget.

[11]This distinction is particularly relevant when two separate caps – one for abatement and one for permanent removals exist. When permanent removals are integrated in the ETS, this distinction becomes

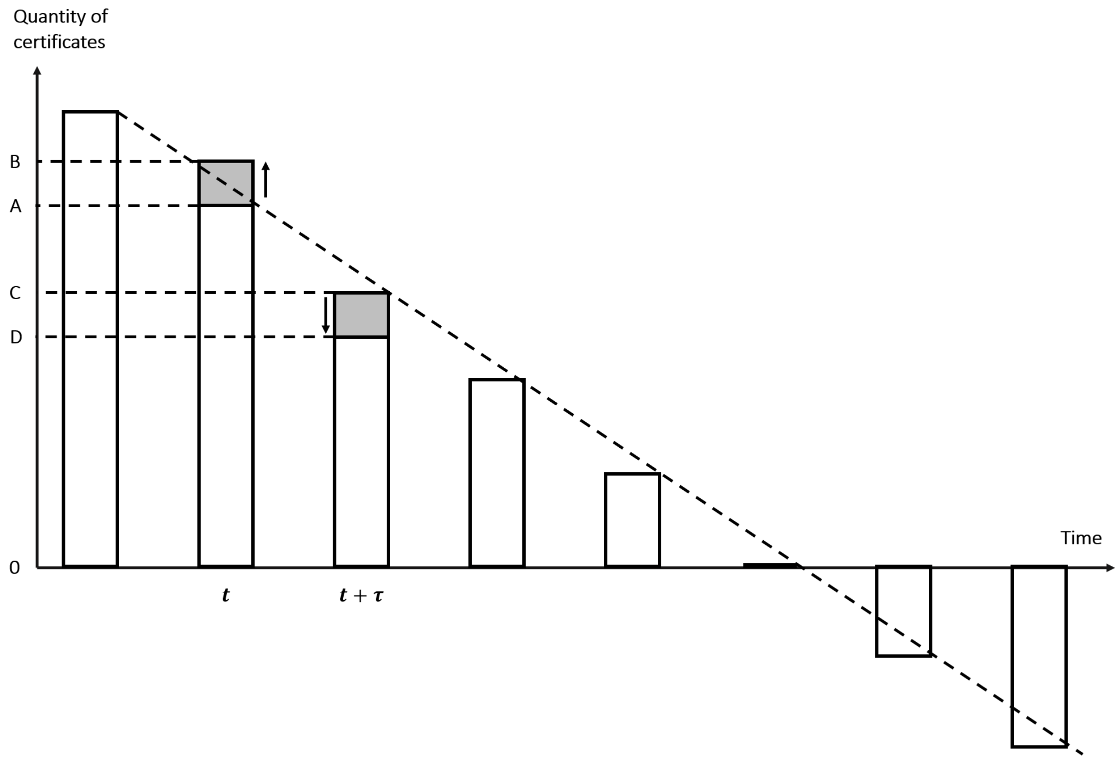

Figure 7: Non-permanent removal at t that is compensated by a regular emission certificate after emissions are released from the reservoir at $t+\tau$.

In Appendix A.3, we show that the financial liability M^F can be quantified in a similar way as the perpetual removal liability. It depends on the growth rate of the carbon price, the interest rate and the duration of the removal project. Hence, the problem of moral hazard due to excessive carbon debt also appears in the case of financial liability.

In principle, firms could choose after the end of each temporary removal project whether to renew the removal project (perpetual removal) or whether to offset the liability in the ETS (financial liability) – depending on which option cause lower (expected) costs.[12] Hence, the size of the carbon debt can be reduced by allowing for flexibility in the form of the liability. Nevertheless, the problem of the carbon debt remains and requires an appropriate instrument imposed by regulators to avoid excessive carbon debts. When the carbon debt cannot be paid by firms, ultimately, society has to pay for the liability. This imposes not only a financial risk; limiting permanent removals may also imply violating the climate targets.

practically irrelevant.

[12]In an intertemporally efficient emissions trading scheme, the growth rate of the allowance price is equal to the social discount rate. In Appendix A.3, we show formally that in this case, non-permanent CDR is never financially viable when ETS price evolves along a Hotelling path (i.e. until carbon prices equal the cost of a backstop or permanent removal technology). The result stands in contrast to the modified Hotelling rule (5) derived from pure cost-benefit analysis in Section 3.1. The reason is that the ETS would need an additional intertemporal adjustment mechanism to optimally account for intertemporal climate damages (Kling and Rubin, 1997; Kalkuhl and Edenhofer, 2014).

In both cases, a sophisticated risk and liability management is necessary. When the regulator calculates the fees or discount factors on carbon prices for non-permanent removal correctly, the debt is well secured. Because of the high leverage effect of M, small errors in assessing storage times, future discount rates or future removal costs can imply dramatic financial implications for society.[13] The high values of M particularly for technologies with short storage times may also justify separate targets for non-permanent CDR. Hence, a societal debate should inform the decision on the non-permanent removal quantity since this involves normative considerations on risk management of carbon debts.

5.2.4 Additionality and general equilibrium effects in the land market

Besides the challenges posed by non-permanent storage, land-intensive carbon removals may lead to land-change induced emission releases at other locations. An afforestation project may, for example, decrease available agricultural land and therefore lead to deforestation in other places. In an extreme case, the afforestation project may, after accounting for general equilibrium effects, lead to zero additional carbon removal. Scholars have studied this problem in the context of indirect land-use change. It has been analyzed mainly in the context of bioenergy production (Fritsche et al., 2010; Lapola et al., 2010; Gawel and Ludwig, 2011) but also afforestation, forest management (Böttcher et al., 2018; West et al., 2023) or soil carbon capture (Jacobs et al., 2020). If carbon removal is subsidized but carbon emissions are not taxed at the same rate, it would also become profitable to cut down a forest just to plant a new one again.[14]

If emissions from land-use change, agriculture and forestry were subject to the optimal carbon price, the induced indirect land-use changes would represent optimal reallocations from a carbon management perspective, which minimizes social costs. Without a comprehensive scheme to price carbon in the land sector or to regulate carbon emissions, however, the effective amount of carbon removed by a removal project – after accounting for all equilibrium effects – remains unclear. While some of the additionality problems in voluntary offset markets might be due to creative accounting measures to inflate baseline emissions or accounted removal emissions (West et al., 2023), the problem of general equilibrium effects is pervasive and persists even under a perfect monitoring, reporting and verification scheme. A pragmatic work-around is to apply an additionality-discount factor that incorporates expected leakage effects from non-regulated activities

[13] Suppose the regulator expected that future discount rates are 2% and calculated M accordingly. When discounting rates unexpectedly drop to 1%, the carbon debt roughly doubles in many cases and might even become infinite when $\gamma_R \geq r$.

[14] Even when regulation prevents this procedure for the same land owner or the same firm, these dynamics may occur among different firms.

through general equilibrium effects (Groom and Venmans, 2022). If a removal project, for example, is estimated to lead to emission increases of 40% elsewhere, carbon certificates (or removal subsidies) should be reduced by this amount accordingly.

Within the EU climate policy architecture, applying such additionality discount factors to land-based removal activities might be a pragmatic starting point. Because these discount factors are difficult to calculate for each project individually with high accuracy, rough estimates for broader categories of removal activities could be used. This, however, implies further welfare losses as projects with lower (or higher) than average additionality characteristics receive too high (or too little) removal subsidies. Therefore, the land-sector should be integrated into a comprehensive carbon pricing scheme like the EU-ETS in the long-run as well. If the land sector is fully covered by carbon pricing, the additionality discount factors could be set to unity. This procedure could also be attractive from a political economy perspective: On the one hand, the land sector has to pay for carbon emissions, on the other hand it gets higher payments for land-based carbon removals which increases support as well.

5.2.5 Institutions required

In the following, we outline which institutions are required for (i) managing the cap, (ii) ensuring public investments in RD&D and diffusion, (iii) certifying removal technologies and (iv) managing the liability of non-permanent removals. We assume that the delegation to an independent body is more likely if the mandate is narrow. Then, also the capacity of commitment increases. A broad mandate allows flexibility, but reduces the willingness of politicians to delegate the tasks to an independent body (Boyer and Laffont, 1999; Dixit, 1998; Moe and Caldwell, 1994) and independence from the European Commission is in danger. We summarize the discussion in Table 5.

Managing the cap A net cap could be set by the co-legislators in primary legislation, and then implemented by an institution we call European Carbon Central Bank (ECCB).[15] As already discussed, removals could be (gradually) integrated in the ETS or there could be a separate cap for removals due to political economy reasons. As long as a separate cap for removals exist, the ECCB has to issue emission allowances to cover residual emissions. The ECCB should organize the procurement of carbon removal certificates via (reverse) auctions. The auctions should be cost-minimizing to secure maximum removal quantities. To facilitate the auctions, the ECCB needs to be informed by

[15] Such an institution has also been proposed by Rickels et al. (2022). However, the sole purpose of their central bank is to act as a safety valve that prevents price spikes in the EU-ETS. The authors do not discuss non-permanence, the problem of additionality, liability issues or other political economy and second best considerations that come along with CDR.

the other newly created institutions that are responsible for certification and for RD&D. First, discount factors for non-permanence and imperfect additionality should be applied, which will be obtained from the certification process. Second, the auctions could be split by CDR option in bundles, for example, depending on the storage duration (involving different degrees of carbon debts), depending on other externalities (for example, to restrict land demand in case of BECCS) and depending on the maturity level and long-term upscaling need of a technology. The latter ensures that options will be developed that are currently still relatively expensive but likely important in the long-run. Targeted subsidies and/or contracts for difference accounting for different externalities of CDR options could be paid to the suppliers of novel CDR.

In order to ensure long-term dynamic efficiency, the ETS-I and ETS-II should be merged over time and emissions from the land sector should also be covered by the comprehensive ETS. A comprehensive carbon pricing scheme in the land-use sector could be established by an ETS-III. The ECCB could provide technical advice to the legislation process. Also, price convergence between the CDR and the abatement sector should be ensured. This, however, requires an adjustment of the caps. To what extent the mandate for adjustments lies with the ECCB or with co-legislators remains an open question.

The ECCB would have to renew non-permanent certificates immediately after their expiry. As discussed in Section 5.2.3, non-permanent removals are a liability for the bank, which has to ensure long-term compliance with the net-zero target. In the second-half of the 21st century, the ECCB will manage the residual emissions and will finance the CDR options in order to become net-negative. Ensuring removal targets where marginal removal costs are higher than marginal abatement costs (see Section 4.3) or ensuring net-negative emissions requires the ECCB to have credible access to further public funds.

RD&D and diffusion Next to the ECCB, other new institutions are required to build technological expertise, to ensure appropriate funding via auctions and subsidies and to reduce risk for investors, who face uncertainty about both regulatory frameworks and public accpetance. We therefore suggest a Green Leap Innovation Authority (GLIA) for the promotion of CDR technologies. Similar institutions already exist in other areas, for example the EU's Innovation Fund, the Important Projects of Common European Interest (IPCEI) and the Green Deal Industrial Plan/Net-Zero Industry Act.

Certification A Carbon Removal Certification Authority (CRCA) should be established to carry out independent certification based on scientific assessments of all relevant CDR technologies and in particular their properties with respect to permanence and additionality. This also includes setting up precedures for calculating and verifying discount

Functions	Institutions	Instruments
Managing the Cap	ECCB	Auctioning permits, securing price floor
RD&D and diffusion of technologies	GLIA	Auctioning, subsidizing RD&D
Certification of technologies	CRCA	Scientific assessment
Liability management	ECCB	Fees, mandates, public funds

Table 5: Summary of functions, institutions and instruments for the integration of CDR into the EU's climate policy architecture.

factors due to impermanence and imperfect additionality. Because of ongoing technological and economic progress as well as emerging scientifiy insights, certification rules and discount factors should be updated regularly. Then, harmonized rules and standards can be implemented and carried out by the public and private bodies.

Liability management As discussed in Section 5.2.3, non-permanent CDR implies a liability either for firms or for public bodies. The liability is further subject to substantial risks due to changing costs, prices or interest rates which either translate to financial risks or to climate risks (if permanence cannot be secured). It appears necessary that the ECCB receives an explicit mandate to manage the liability. The mandate should specify with how much public funds the ECCB is backed to secure the procurement and renewal of non-permanent CDR when additional costs due to technology shocks become necessary. Additionally, the allocation of liability risk sharing between firms and society has to be decided – either politically or, if permitted by the mandate, by the ECCB.

6 Conclusion: The new area of climate policy – industrial management of the carbon cycle

Ambitious climate targets consistent with the Paris Agreement cannot be met without CDR. The sustainable management of the global carbon cycle is a core challenge of climate action in the 21st century. The EU has already taken the lead to develop a governance framework for CDR. We have emphasized that carbon pricing remains a crucial ingredient for a successful governance structure. As first-best rule, subsidies for CDR and carbon prices should be equalized. However, the CDR option adds an additional layer of complexity in the design of carbon pricing schemes since non-permanence of storage, imperfect additionality of removals and additional fiscal and political economy considerations come along with it. In this paper, we have described a pathway towards a consistent and a comprehensive carbon pricing scheme within the EU. These ideas may translate to other high-income countries with emission trading schemes in place. However, further research is required to design carbon pricing schemes for developing countries, which might wish to invest in CDR options but have different institutional capacities.

Other open questions remain. For example, differentiating between individual technologies by removal cost would enable appropriation of rents and prevent windfall profits, thus enhancing efficiency. However, practical costs of implementation, high informational requirements and normative questions of distribution complicate matters. Future research could investigate the role of land rent taxation as second-best alternative (Kalkuhl et al., 2018). Another question for EU climate policy concerns those emissions not covered by the EU-ETS, for example, from agriculture and waste, many of which falling under the category of residual emissions. The last open question worth mentioning here is the generation of net negative emissions beyond the balancing of residual emissions under the EU's ETS-I/II/III. This might require a paradigm shift away from quantity-based policies to a stronger focus on the social cost of carbon.

Scaling-up CDR is an urgent issue. Policy makers are tempted to perceive this option as a matter that should be dealt with only when deep and rapid emission reductions are already implemented. However, deployment at scale requires a consistent policy framework and credible incentive schemes as soon as possible. In only little more than two decades from now, the last emission permit will be sold under the EU-ETS. The remaining residual emissions have to be compensated by permits generated by CDR options. Increasing the supply of CDR options, in particular DACCS, and investment in pilot projects has to start now. Leap innovations are needed in the CDR sector. Nevertheless, our considerations also indicate that every form of non-permanent removal implies a liability to the future, which can also become large when costs or permanence characteristics turn out to be different than expected. Therefore, seemingly cheap removal technologies, particularly in the land sector, can indeed be very expensive. This insight warrants not only a careful and sophisticated pricing of non-permanent removals but also a general decision on carbon liability risks that need to be split between removal firms and society.

We propose a European Carbon Central Bank (ECCB), a Green Leap Innovation Authority (GLIA) and a Carbon Removal Certification Authority (CRCA) as new institutional players. We think this proposal is viable within the current EU policy architecture. The ECCB acts an intermediary between the demand and supply side of CDR. It solves some of the long-term commitment problems of carbon pricing, like the liability for non-permanent removals, guaranteeing price convergence and generating price information through reverse auctions. To guarantee independence from the European Commission and the parliament the mandate of the ECCB has to be well-defined. However, the commitment to the long-term target has to be guaranteed by the executive and legislative branches of the EU. Long-term commitment is essential in order to stabilize investor's expectations.

As we approach the second half of the 21st century, the debate about climate policy will increasingly be dominated by CDR in order to make the ambitious Paris targets feasible. CDR should not substitute abatement activities, but rather enable the establishment of a planetary waste management system to reduce the stock of carbon in the atmosphere. Our proposal can only serve as a first step to outline the shape of climate policy to come. Better options for governance structures may exist. However, we believe that our proposal can facilitate and inform this debate. The governance of CDR has to find its way into climate legislation worldwide.

References

Andreoni, J. (1990). Impure altruism and donations to public goods: A theory of warm-glow giving. *The Economic Journal*, 100(401):464–477.

Barazza, E. and Strachan, N. (2020). The impact of heterogeneous market players with bounded-rationality on the electricity sector low-carbon transition. *Energy Policy*, 138:111274.

Bento, A. M., Kanbur, R., and Leard, B. (2015). Designing efficient markets for carbon offsets with distributional constraints. *Journal of Environmental Economics and Management*, 70:51–71.

Bloomberg New Energy Finance (2022). https://about.bnef.com/blog/carbon-offset-prices-could-increase-fifty-fold-by-2050/. Accessed on March 30, 2023.

Bohm, P. (1993). Incomplete international cooperation to reduce co2 emissions: alternative policies. *Journal of Environmental Economics and Management*, 24(3):258–271.

Böttcher, H., Hennenberg, K., and Winger, C. (2018). Waldvision Deutschland – Beschreibung von Methoden, Annahmen und Ergebnissen. Öko-Institut e.V. Berlin.

Boyer, M. and Laffont, J.-J. (1999). Toward a political theory of the emergence of environmental incentive regulation. *The RAND Journal of Economics*, pages 137–157.

Caswell, J. A. and Mojduszka, E. M. (1996). Using informational labeling to influence the market for quality in food products. *American Journal of Agricultural Economics*, 78(5):1248–1253.

Dallas, L. L. (2011). Short-termism, the financial crisis, and corporate governance. *Journal of Corporation Law*, 37(265).

Dixit, A. K. (1998). *The making of economic policy: A transaction-cost politics perspective*. MIT press.

Douenne, T. and Fabre, A. (2020). French attitudes on climate change, carbon taxation and other climate policies. *Ecological Economics*, 169:106496.

Douenne, T. and Fabre, A. (2022). Yellow vests, pessimistic beliefs, and carbon tax aversion. *American Economic Journal: Economic Policy*, 14(1):81–110.

European Commission (2018). A Clean Planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. In depth analysis in support of the Commission Communication COM. https://climate.ec.europa.eu/system/files/2018-11/com_2018_733_analysis_in_support_en.pdf. 773. Brussels. pg. 187 ff.

European Commission (2021). Sustainable Carbon Cycles for a 2050 climate-neutral EU. Technical Assessment. https://climate.ec.europa.eu/system/files/2021-12/swd_2021_451_parts_1_to_3_en_0.pdf. SWD(2021)451 of 15.122021. Brussels.

European Commission (2022). Proposal for a Regulation of the European Parliament and of the Council establishing a Union certification framework for carbon removals. COM. https://climate.ec.europa.eu/system/files/2022-11/Proposal_for_a_Regulation_establishing_a_Union_certification_framework_for_carbon_removals.pdf. 672 final of 30.11.2022. Brussels.

European Parliament Committee on the Environment, Public Health and Food Safety (2022). Provisional Agreement resulting from interinstitutional negotiations: Proposal for a regulation of the European Parliament and the Council amending Regulations (EU) 2018/841 as regards the scope, simplifying the reporting and compliance rules, and setting out targets of Member States for 2030, and (EU) 2018/1999 as regards improvement in monitoring, reporting, tracking of progress and review. https://www.europarl.europa.eu/RegData/commissions/envi/inag/2022/12-21/ENVI_AG(2022)740692_EN.pdf. PE740.692 of 21.12.2022. Brussels. pg. 25.

European Parliament Committee on the Environment, Public Health and Food Safety (2023). Provisional Agreement resulting from Inter-Institutional Negotiations: Proposal for a directive of the EP and the Council amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union. https://www.europarl.europa.eu/RegData/commissions/envi/inag/2023/02-08/ENVI_AG(2023)742381_EN.pdf. PE742.381v01-00 of 8.2.2023. Brussels. pg. 62.

Fabra, N. and Montero, J.-P. (2023). Technology-neutral versus technology-specific procurement. *The Economic Journal*, 133(650):669–705.

Franks, M., Edenhofer, O., and Lessmann, K. (2017). Why finance ministers favor carbon taxes, even if they do not take climate change into account. *Environmental and Resource Economics*, 68:445–472.

Franks, M., Kalkuhl, M., and Lessmann, K. (2023). Optimal pricing for carbon dioxide removal under inter-regional leakage. *Journal of Environmental Economics and Management*, 117:102769.

Franks, M. and Lessmann, K. (2019). Tax competition with asymmetric endowments in fossil resources. *Available at SSRN 3593219*.

Fritsche, U. R., Sims, R. E., and Monti, A. (2010). Direct and indirect land-use competition issues for energy crops and their sustainable production–an overview. *Biofuels, Bioproducts and Biorefining*, 4(6):692–704.

Fuss, S., Gruner, F., Hilaire, J., Kalkuhl, M., Knapp, J., Lamb, W., Merfort, A., Minx, J., and Strefler, J. (2021). CO_2-Entnahmen: Notwendigkeit und Regulierungsoptionen. *Studie im Auftrag der Wissenschaftsplattform Klimaschutz. Berlin*.

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., et al. (2018). Negative emissions—part 2: Costs, potentials and side effects. *Environmental Research Letters*, 13(6):063002.

Gawel, E. and Ludwig, G. (2011). The iluc dilemma: How to deal with indirect land use changes when governing energy crops? *Land Use Policy*, 28(4):846–856.

Gerlagh, R. and Kuik, O. (2014). Spill or leak? Carbon leakage with international technology spillovers: A CGE analysis. *Energy Economics*, 45:381–388.

Gillingham, K. T., Houde, S., and Van Benthem, A. A. (2021). Consumer myopia in vehicle purchases: evidence from a natural experiment. *American Economic Journal: Economic Policy*, 13(3):207–238.

Groom, B. and Venmans, F. (2022). The social value of offsets. *mimeo*.

Hänsel, M. C., Franks, M., Kalkuhl, M., and Edenhofer, O. (2022). Optimal carbon taxation and horizontal equity: A welfare-theoretic approach with application to german household data. *Journal of Environmental Economics and Management*, 116:102730.

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

Hepburn, C., Adlen, E., Beddington, J., Carter, E. A., Fuss, S., Mac Dowell, N., Minx, J. C., Smith, P., and Williams, C. K. (2019). The technological and economic prospects for CO_2 utilization and removal. *Nature*, 575(7781):87–97.

Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Jamsranjav, B., Fukuda, M., and Troxler, T. (2014). *2013 Revised supplementary methods and good practice guidance arising from the Kyoto Protocol*. Intergovernmental Panel on Climate Change Switzerland.

Hoel, M. (1991). Global environmental problems: the effects of unilateral actions taken by one country. *Journal of environmental economics and management*, 20(1):55–70.

IEA (2022). Direct air capture. *https://www.iea.org/reports/direct-air-capture*.

IPCC (2018). Global Warming of 1.5 Degree Celsius: IPCC Special Report on the Impacts of Global Warming of 1.5 Degree Celsius. *Intergovernmental Panel on Climate Change, Geneva, Switzerland, Report.*

Jacobs, A., Heidecke, C., Jumshudzade, Z., Osterburg, B., Paulsen, H. M., and Poeplau, C. (2020). Soil organic carbon certificates–potential and limitations for private and public climate action. *Landbauforschung*, 70:31–35.

Jakob, M., Steckel, J. C., and Edenhofer, O. (2014). Consumption-versus production-based emission policies. *Annu. Rev. Resour. Econ.*, 6(1):297–318.

Kalkuhl, M. and Edenhofer, O. (2014). Managing the climate rent: How can regulators implement intertemporally efficient mitigation policies? *Natural Resource Modeling*, 27(1):25–60.

Kalkuhl, M., Franks, M., Gruner, F., Lessmann, K., and Edenhofer, O. (2022). Pigou's advice and sisyphus' warning: Carbon pricing with non-permanent carbon-dioxide removal. *CESifo Working Papers*, 10169.

Kalkuhl, M., Milan, B. F., Schwerhoff, G., Jakob, M., Hahnen, M., and Creutzig, F. (2018). Can land taxes foster sustainable development? an assessment of fiscal, distributional and implementation issues. *Land Use Policy*, 78:338–352.

Kalkuhl, M., Steckel, J. C., and Edenhofer, O. (2020). All or nothing: Climate policy when assets can become stranded. *Journal of Environmental Economics and Management*, 100:102214.

Kim, M.-K., McCarl, B. A., and Murray, B. C. (2008). Permanence discounting for land-based carbon sequestration. *Ecological Economics*, 64(4):763–769.

Kling, C. and Rubin, J. (1997). Bankable permits for the control of environmental pollution. *Journal of Public Economics*, 64(1):101–115.

Lapola, D. M., Schaldach, R., Alcamo, J., Bondeau, A., Koch, J., Koelking, C., and Priess, J. A. (2010). Indirect land-use changes can overcome carbon savings from biofuels in brazil. *Proceedings of the national Academy of Sciences*, 107(8):3388–3393.

Lehmann, J., Cowie, A., Masiello, C. A., Kammann, C., Woolf, D., Amonette, J. E., Cayuela, M. L., Camps-Arbestain, M., and Whitman, T. (2021). Biochar in climate change mitigation. *Nature Geoscience*, 14(12):883–892.

Lemoine, D. (2023). Informationally efficient climate policy: Designing markets to measure and price externalities. Technical report, National Bureau of Economic Research.

McCluskey, J. J. (2000). A game theoretic approach to organic foods: An analysis of asymmetric information and policy. *Agricultural and Resource Economics Review*, 29(1):1–9.

Merfort, A., Stevanović, M., and Strefler, J. (2023). Energiewende auf Netto-Null: Passen Angebot und Nachfrage nach CO_2-Entnahme aus der Atmosphäre zusammen? *Kopernikus-Projekt Ariadne, Potsdam.*

Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., et al. (2018). Negative emissions—part 1: Research landscape and synthesis. *Environmental Research Letters*, 13(6):063001.

Moe, T. M. and Caldwell, M. (1994). The institutional foundations of democratic government: A comparison of presidential and parliamentary systems. *Journal of Institutional and Theoretical Economics (JITE)/Zeitschrift für die gesamte Staatswissenschaft*, 150(1):171–195.

Nemet, G. F., Callaghan, M. W., Creutzig, F., Fuss, S., Hartmann, J., Hilaire, J., Lamb, W. F., Minx, J. C., Rogers, S., and Smith, P. (2018). Negative emissions—part 3: Innovation and upscaling. *Environmental Research Letters*, 13(6):063003.

Rickels, W., Rothenstein, R., Schenuit, F., and 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.

Rodemeier, M. (2023). Willingness to pay for carbon mitigation: Field evidence from the market for carbon offsets. *IZA Discussion Paper*.

Rozenberg, J., Vogt-Schilb, A., and Hallegatte, S. (2020). Instrument choice and stranded assets in the transition to clean capital. *Journal of Environmental Economics and Management*, 100:102183.

Shukla, P. R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H. O., Roberts, D., Zhai, P., Slade, R., Connors, S., Van Diemen, R., et al. (2019). IPCC, 2019: Climate change and land: an ipcc special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. *Intergovernmental Panel on Climate Change, Geneva, Switzerland, Report.*

Smith, J. E. (2006). *Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States*. 343. United States Department of Agriculture, Forest Service, Northeastern Research Station.

Smith, S., Geden, O., Nemet, G., Gidden, M., Lamb, W., Powis, C., Bellamy, R., Callaghan, M., Cowie, A., Cox, E., Fuss, S., Gasser, T., Grassi, G., Greene, J., Lück, S., Mohan, A., Müller-Hansen, F., Peters, G., Pratama, Y., Repke, T., Riahi, K., Schenuit, F., Steinhauser, J., Strefler, J., Valenzuela, J. M., and Minx, J. C. (2023). The state of carbon dioxide removal - 1st edition. *DOI: 10.17605/OSF.IO/W3B4Z.*

van Kooten, G. C. (2009). Biological carbon sequestration and carbon trading re-visited. *Climatic Change*, 95(3-4):449–463.

Warszawski, L., Kriegler, E., Lenton, T. M., Gaffney, O., Jacob, D., Klingenfeld, D., Koide, R., Costa, M. M., Messner, D., Nakicenovic, N., Schellnhuber, H. J., Schlosser, P., Takeuchi, K., Leeuw, S. V. D., Whiteman, G., and Rockström, J. (2021). All options, not silver bullets, needed to limit global warming to 1.5 °c: a scenario appraisal. *Environmental Research Letters*, 16(6):064037.

West, T. A. P., Wunder, S., Sills, E. O., Börner, J., Rifai, S. W., Neidermeier, A. N., and Kontoleon, A. (2023). Action needed to make carbon offsets from tropical forest conservation work for climate change mitigation.

Woolf, D., Lehmann, J., Ogle, S., Kishimoto-Mo, A. W., McConkey, B., and Baldock, J. (2021). Greenhouse gas inventory model for biochar additions to soil. *Environmental Science & Technology*, 55(21):14795–14805.

A Technical Appendix: Non-permanent removals within an ETS

Consider a cap-and-trade system for emissions, implying an allowance price path p_t, and a temporary removal technology i, that removes the amount of R_t^i carbon at time t at (weakly) convex cost $g_t^i(R_t^i)$. Suppose, for simplicity, that after τ_i periods, the removed carbon is emitted back into the atmosphere.

A.1 Removal with perpetual removal liability

Consider the case that the non-permanent removal project is only possible when the supplier commits to a perpetual removal of the released carbon such that the carbon – by a chain of subsequent removal project – will be stored permanently. We assume that removal costs may increase over time by a multiplicative factor, such that $g_{t+\tau_i}^i(\cdot) = (1+\gamma_R^i)^{\tau_i} g_t^i(\cdot)$ where γ_R^i is the growth rate of the (marginal) removal cost of technology i and $g_t^i(\cdot)$ is the removal cost in the period of the initial removal activity. The discounted net returns of such a project are then

$$\pi_t^i = p_t R_t^i - g^i(R_t^i) - \left(\frac{1+\gamma_R^i}{1+r}\right)^{\tau} g^i(R_t^i) - \left(\frac{1+\gamma_R^i}{1+r}\right)^{2\tau} g^i(R_t^i) - \left(\frac{1+\gamma_R^i}{1+r}\right)^{3\tau} g^i(R_t^i)... \tag{8}$$

$$= p_t R_t^i - g^i(R_t^i) - \frac{(1+\gamma_R^i)^{\tau}}{(1+r)^{\tau} - (1+\gamma_R^i)^{\tau}} g^i(R_t^i) = p_t R_t^i - g^i(R_t^i) - M^i g^i(R_t^i) \tag{9}$$

In this framework, $M^i := \frac{(1+\gamma_R^i)^{\tau}}{(1+r)^{\tau}-(1+\gamma_R^i)^{\tau}}$ is a multiplier for the short-term removal costs to finance perpetual removal. Hence, $Mg^i(R_t^i)$ constitutes a liability that ensures that the removal project can be financed for an infinite time horizon. Increases in the growth rate of the removal costs γ_R^i have a similar effect on the multiplyer M^i as decreases in the discount rate. Importantly, the multiplier converges to infinity when γ_R^i approaches the interest rate, r.

Profit maximizing removal forms will chose R_t^i such that marginal discounted costs equal the carbon price, i.e.

$$p_t = (1+M^i) g^{i\prime}(R_t^i) \tag{10}$$

A.2 Limited liability of removal firms

Perpetual removal liability implies that firms supplying non-permanent removal effectively incur a debt of $D = M^i g^i(R^i_t) \approx M^i g'(R^i_t) R^i_t$.

When liability of removal firms is limited by some value $\bar{l}$ relative to the removal costs and $D > \bar{l}$, firms may engage in excessive short-term removal and file bankrupt when they have to start financing perpetual removal. This can be avoided when the regulator (carbon bank) charges an additional fee l on the removal price that corresponds to the gap between liability constraint and the removal liability

$$l = D - \bar{l} \tag{11}$$

We assume that removal firms are competitive and take the removal price p^i_R as given. Then, they set their removal quantity such that $p^i_R = g'(R^i)$. Based on the latter, we can derive the payment the regulator should warrant to account for limited liability. When removal firms have strong liability constraints, $\bar{l} = 0$, or are not held accountable for later emission releases (e.g. in case of an upstream pricing system) then the whole debt should be secured by a public institution according to:

$$p^i_{R,t} = \frac{1}{1+M^i} p_t \tag{12}$$

Hence, $\frac{1}{1+M^i}$ can be considered as additional taxes (or fees) on the carbon price of removal firms that are sold to the carbon market (compliance market) where the carbon price p_t prevails.

A.3 Removal with financial liability

Alternatively, let us consider the case in which a firm is priced downstream. That is, at the end of a non-permanent removal project when the carbon is released again, EU-ETS allowances have to be purchased and surrendered by the firm. Consider a marginal removal project at time t that removes R^i_t carbon from the atmosphere which is released back at $t+\tau$. The removal gets priced at the carbon price p_t while the later emission release has to be priced the the prevailing carbon price $p_{t+\tau}$ ('financial liability'). Hence, the discounted net returns of the removal project are:

$$\pi^i_t = p_t R^i_t - g^i(R^i_t) - \frac{p_{t+\tau} R^i_t}{(1+r)^\tau} \tag{13}$$

$$= \left(p_t - \frac{p_{t+\tau}}{(1+r)^\tau}\right) R^i_t - g^i(R^i_t) = p_t \left[1 - \left(\frac{1+\gamma_p}{1+r}\right)^\tau\right] R^i_t - g^i(R^i_t) \tag{14}$$

with γ_p the growth rate of the carbon price (allowance price), which we assume to be constant for simplicity.
The profit maximizing firm's first order condition is thus

$$g^{i\prime}(R_t^i) = p_t \left[1 - \left(\frac{1+\gamma_p}{1+r} \right)^{\tau} \right] \tag{15}$$

which can be re-arranged to

$$p_t = (1 + M^F) g^{i\prime}(R_t^i) \tag{16}$$

with $M^F := \frac{(1+\gamma_p)^\tau}{(1+r)^\tau - (1+\gamma_p)^\tau}$.

We see in (13) that the project needs to earn a positive return at period t, i.e. the carbon price revenue needs to be higher than the removal cost. Additionally, the project involves a financial liability $D = \frac{p_{t+\tau} R_t^i}{(1+r)^\tau}$ due at time $t+\tau$, when the carbon is released and the (later) carbon price needs to be paid. Hence, this regime implies that firms supplying non-permanent removal, effectively incur the debt of D.

From (14), it becomes clear that a positive return can only be realized when $\gamma_p < r$, i.e. the carbon price grows at a rate smaller than the discount rate. In an ETS with intertemporal flexibility, the expected carbon price grows at $\gamma_p = r$. Hence, in such an ETS, temporary removal where the carbon release has to be paid at the carbon price will ex-ante never be profitable. The case $\gamma_p < r$ can occur when intertemporal flexibility is restricted, e.g. when either banking or borrowing of permits is not allowed. In the case of the EU-ETS, borrowing is not possible but banking of permits is. In that case, $\gamma_p < r$ occurs when the decline of the cap is slower than it would be optimal. Hence, when borrowing is limited, non-permanent CDR effectively constitutes a *physical permit borrowing device* which allows shifting emissions from a future cap to the present. By this mechanism, the cap at t can basically be relaxed by the amount R_t^i while the cap at $t+\tau$ gets tightened by the amount R_t^i. However, the physical borrowing comes at the real cost $g^i(\cdot)$. Allowing for intertemporal flexibility (i.e. full permit borrowing) would be welfare increasing (in that case, $\gamma_p = r$ and no non-permanent removal occurs). Additional, the financial liability case can can become profitable ex-post when an (unexpected) negative price shock occurs to the carbon price, implying that $\gamma_p < r$.

Again, moral hazard can be avoided when the regulator (carbon bank) charges an additional fee l on the removal price that corresponds to the gap between liability constraint and the removal liability

$$l = D - \bar{l} \tag{17}$$

As in the case of perpetual removal liability,

$$p^i_{Rt} = \frac{1}{1+M^F} p_t \tag{18}$$

is the additional tax or fee required to cover the liability.