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2024

June 2024

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CESifo

Impressum:

CESifo Working Papers
ISSN 2364-1428 (electronic version)
Publisher and distributor: Munich Society for the Promotion of Economic Research - CESifo GmbH
The international platform of Ludwigs-Maximilians University's Center for Economic Studies and the ifo Institute
Poschingerstr. 5, 81679 Munich, Germany
Telephone +49 (0)89 2180-2740, Telefax +49 (0)89 2180-17845, email office@cesifo.de
Editor: Clemens Fuest
https://www.cesifo.org/en/wp
An electronic version of the paper may be downloaded
· from the SSRN website: www.SSRN.com
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CESifo *Working Paper No. 11173*

Sequencing Carbon Dioxide Removal into the EU ETS

Abstract

Novel Carbon Dioxide Removal (CDR) technologies have seen a first wave of deployment, driven by investments through voluntary carbon markets and by specific support policies. To sustain the momentum, a credible long-term policy path is urgently needed to lead removal technologies through the valley of death, and to ramp-up sufficient capacities to limit global warming to well below 2°C. The integration of removals into carbon compliance markets has been widely discussed as a potential option. Even though current allowance prices in markets like the European emissions trading system (EU ETS) are still considerably lower than removal cost, integration and the prospects of rising allowance prices could increase long-term certainty for investors. What is more, integration would also help to find to the efficient mix of emissions abatement and removal. To date, however, it remains unclear how exactly such an integration can take place. We address this gap in three parts. We (1) characterise a first-best vision for removals in the form of an economically desirable, long-term regulatory framework to work towards to. We (2) then analyse the implications of a first-best - i.e. direct and unconstrained - integration of permanent removals into the EU's carbon compliance market using the numerical model LIMES-EU. In our base scenario, we find more than 60 Mt of CDR entering the market annually by 2050, cutting allowance prices considerably. This underpins the general cost-effectiveness of integration. However, high uncertainty on CDR cost and fragmented regulation give rise to the risks of abatement deterrence and excessive biomass use, which need to be accounted for through a second-best sequencing approach. We consequently (3) derive a three-stage path for removal integration into the EU ETS, based on risk reduction contingencies that serve as preconditions for entering subsequent stages.

JEL-Codes: H230, Q520, Q550, Q580.

Keywords: carbon dioxide removal, emissions trading, policy sequencing, technology learning.

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This version: June 2024

1 Introduction

With societies' failure to address climate change by emissions abatement in time, CDR technologies will play a central role in keeping global temperature increases well below 2 °C. The IPCC has sketched three distinct phases for CDR - or removals in short - on societies' mitigation pathways (Babiker et al, 2023). In the near term (Phase 1), on the "road to net-zero", they complement emission reductions, albeit at a limited scale only. In the midterm (Phase 2), during the phase of "net-zero", removals compensate for residual emissions from hard-to-abate sectors. For this phase, defining which emissions will be categorised as "hard-to-abate" will be crucial (Buck et al, 2023; Merfort et al, 2024). While a definition in economic terms ("too expensive to abate") makes sense from a theoretical efficiency standpoint, in practice societies could deviate from the efficiency logic by excluding certain applications to prevent the perpetuation of fossil infrastructure. In the long run (Phase 3), which we refer to as the phase of "overshoot management", removals will become the central tool for generating net-negative emissions to reduce overshoot, i.e. to bring back greenhouse gas (GHG) emissions that have been released even after the carbon budget has been depleted. While there is consensus on the high-level role of removals, the conceptual details of this vision still need further substantiation. Previous work has shaped a good understanding of the challenges decision-makers will face on the way (Anderson et al, 2023). However, what the path from today's policies to this vision should look like is still unclear.

So far, the economic literature on removal policies is scarce but three main strands are emerging. The first strand looks at efficiency aspects of CDR policy instruments, for example with a theoretical view on non-permanent removals and inter-regional leakage. In essence, these studies are concerned with the optimal balance of carbon pricing between abatement and removals (Groom and Venmans, 2023). In a setting without a global carbon price, a first-best removal subsidy would amount to marginal climate damages (and therefore the optimal carbon tax), but a second-best subsidy for permanent CDR is set above the carbon tax because removing a ton of CO_2 from the atmosphere results in less leakage than an equivalent emission reduction (Franks et al, 2023). For temporary removals, a first-best upstream subsidy would already have to be set below the emissions tax; second-best uniform pricing of emissions and removal, however, comes with considerable welfare losses, which is why any subsidy for temporary CDR would need to be adjusted downwards to account for the social cost of release (Kalkuhl et al, 2022). This theoretical work is complemented by proposals to harness removal obligations (Bednar et al, 2021, 2024) or clean-up certificates (Lessmann et al, 2024) as a means to fulfil overshoot management in line with the polluter-pays principle.

On the more applied side of the economic CDR literature, techno-economic assessments have aimed to project future cost of novel CDR approaches, particularly bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS). Methods commonly used for cost projections include expert elicitations (Shayegh et al, 2021; Abegg et al, 2024), model-based extrapolations based on assumed experience curves (Fasihi et al, 2019; Zhang et al, 2020; McQueen et al, 2021; Young et al, 2023), as well as empirically-grounded experience curves which narrow the cost uncertainty ranges considerably (Sievert et al, 2024). On top of the purely techno-economic literature, the manifold socio-economic challenges of removals have been widely discussed (Fuss et al, 2018; Strefler et al, 2018; Anderson et al, 2023). Several studies have harnessed numerical models to assess the efficiency of CDR deployment in general, including trade-offs between transitional challenges from ambitious carbon abatement policies and the need to deploy CDR at large (Strefler et al, 2021; Galán-Martín et al, 2021; Desport et al, 2024). More specifically, one can identify at least three areas of controversy evolving around CDR deployment. First, doubts have been cast about the techno-economic feasibility of scaling up technology-based carbon removals. This concerns both assumptions about cost and financing, as well as the sheer speed of deployment to have respective technologies available at scale when they are needed (Galán-Martín et al, 2021; Nemet et al, 2023). Second, a range of sustainability challenges arises around removals in terms of energy and land use, especially related to competition for agricultural land for food systems (Turner et al, 2018). In this context, permanence and risks of carbon storage have also sparked a lively debate, affecting both nature-based and technology-based solutions. Third, carbon removals pose a substantial challenge to the integrity of climate policies. Most importantly, they involve risks of abatement deterrence, that is, of crowding out emission reduction efforts by perpetuating fossil infrastructures (McLaren, 2020; Grant et al, 2021a; Carton et al, 2023).[1] In addition, offset certificates have shown to be unreliable across projects in both compliance markets, such as the Clean Development Mechanism (CDM)[2], as well as voluntary carbon markets (Van Der Gaast et al, 2018; Yanai et al, 2020; Filewod and McCarney, 2023), hence posing governance challenges to future compliance market institutions in itself.

A third literature strand is concerned with the governance of CDR policies. This literature covers liability questions for temporary removals (Mac Dowell et al, 2022; Burke and Schenuit, 2023), as well as docking points for CDR in the EU's climate policy architecture (Rickels et al, 2021, 2022; Edenhofer et al, 2024a). Most notably, the Carbon Removal Certification Framework, the Net Zero Industry Act, and the EU ETS have been identified as starting points (Fridahl et al, 2023). A particularly relevant question is time consistency of CDR policies, i.e. whether policymakers can credibly commit to long-term CDR policies in light of the risk of future regulatory interventions, or if a new dedicated institution like a Carbon Central Bank (Edenhofer et al, 2024a) would be needed to that end. From monetary policy and recent research applying its insights to policy for net zero targets (Dolphin et al, 2023), it is known that credibility requires balancing commitment and flexibility. This should best be done by formulating rules that are robust against intervention.

While all these studies develop important perspectives on the way forward, the different strands of CDR research - economic theory, socio-techno-economic assessments, and governance - have remained largely disconnected. Scholars have mostly given static assessments of CDR technologies or policies, hence neglecting important questions of technological change, institutional learning, and policy sequencing (Meckling et al, 2017; Pahle et al, 2018; Sewerin et al, 2023). In terms of credible governance, open questions remain on how rules need to be formulated to efficiently shape expectations, and which institutional requirements a Carbon Central Bank would fulfil to be a successful "rule maker".

We address this gap by combining the thinking around policy sequencing with a backward induction approach (Dolphin et al, 2023). More specifically, we first map out a first-best vision for removals, i.e. characterise an economically desirable regulatory framework to be achieved in the long run. This first-best vision can be understood as the policy path's final destination, and preceding sequencing stages build up towards this first-best vision. Developing the policy framework through a sequencing logic is key as (i) incentive design and governance issues can only be tackled sequentially and need to be prioritised, (ii) technology learning will occur with an uptake in CDR deployment, and (iii) both markets and policy need to accommodate these developments, i.e. regulatory requirements will change over time. In that sense, this work is an attempt to contribute coherence to the ongoing debate, both by connecting the technology with the policy perspective, and by assessing how short-term decisions can facilitate markets and policies that are ready to accommodate new developments in the long run. We demonstrate this coherence by addressing three key questions for an integration of removals into the EU ETS in Box 1.

[1] In the literature, this risk is often referred to as "mitigation deterrence". Since removals are considered mitigation by the IPCC, however, terms like "abatement deterrence" or "hold-up of emissions reductions" would be more accurate.

[2] We discuss experiences from the CDM more in detail in Section 2.2.

What is the goal of integrating removals into the EU ETS or alternative policy schemes, and which instrument(s) would be most appropriate to achieve this?
The ultimate goal of a removal integration is to reach the climate goals at the lowest possible social cost. Even though current allowance prices are still considerably lower than the cost of removals, integration and the prospects of rising allowance prices could increase long-term certainty for investors. In the short-run, this can enhance the build-up of CDR capacity while safeguarding environmental integrity (Section 3.3). Integration would also help to find to the efficient mix of emissions abatement and carbon removal. In the long-run, this ensures a policy architecture that is ready for overshoot management at scale (Section 2). In Europe, the EU ETS offers the most straightforward starting ground to realise a sequencing path for removals that starts with what is in place, and that can credibly guide the system towards a long-term vision for CDR (Section 2.4). However, additional measures will be required to control risks (e.g. biomass use), facilitate technology learning (e.g. stacked revenues through subsidies), and allow inter-temporal flexibility to enable overshoot management already during intermediate sequencing stages (Sections 3.3, 4.2).

How does consideration of potential net-negative targets beyond 2050 and managing overshoot change the overall picture, and which additional policy tools does it imply?
Overshoot management implies (i) governments ”switch sides” from supplying emissions allowances towards driving demand for removal units post-2050 (see Section 2.4); (ii) navigating the trade-off between needing overshoot permits when emissions allowances are scarce (i.e. now), but expecting that removal cost will be lower in the future (inter-temporal borrowing, see Section 4.2); and (iii) in the long run, supply-side efficiency for removals in the system will be a central cost factor in achieving the climate targets (Section 2).

What are the functions that a potential new European Carbon Central Bank (ECCB) could fulfil, and what is its advantage compared to existing institutions?
The sequencing path for removals into the EU ETS relies on credible long-term commitment, but also on flexibility to react to technology and policy learning. In analogy to monetary policy, rule-based policy-making has been suggested to navigate this trade-off. While clearly a whole array of functions needs to be performed to govern the integration and the system itself more broadly, the crucial question is whether a ECCB could do this better than existing institutions. Overall, the variety of technical responsibilities alone warrants consideration of a new institution like a ECCB. However, its institutional effectiveness crucially depends on the quality of its rules and the way it deals with information. In this context, it is particularly relevant (1) how broad the mandate of the ECCB would be and (2) how it would actually execute the delegated functions. Against this background, the necessary next step for developing existing proposals would be a specification of ”candidate rules” for each envisaged function (Section 4.4).

Box 1: Key questions for an integration of removals into the EU ETS

The remainder of this article is structured as follows: In Section 2, we map out the first-best vision for removals. We then focus on the EU and deploy the numerical model LIMES-EU to analyse the implications of a first-best (i.e. direct and unconstrained) integration of permanent removals into the EU ETS in Section 3. Building on the risks identified by translating our numerical results into a second-best setting, in Section 4, we derive a sequencing path for integrating removals into the European carbon emissions compliance market. We conclude with a synthesis and suggestions for future research.

2 A first-best vision for removal policy

A credible policy strategy for removals needs to reconcile the short-term with the long-term, i.e. it ensures that initial steps lead up to a long-term vision of how to include removals in the existing climate policy framework. Mapping out a sequencing path for removal policy therefore calls for backward induction with the current policy architecture as starting point for forward-planning; and the long-term regulatory framework for removals, which we coin as the first-best vision, as end point to induce backwards from (Dolphin et al, 2023).

The first-best vision formulates conditions for an economically desirable regulatory framework that could ensure that the use of removals is efficient and thus lowers overall costs of climate policy. It also considers that, after a phase of offsetting residual emissions to attain net zero, removals will be needed for overshoot management, i.e. the reduction of the atmospheric GHG concentration after the Paris goals' carbon budget has been depleted (Bednar et al, 2023). In this section, we formulate and discuss requirements the first-best regulatory framework would have to meet by net-zero the latest. We identify three central conditions, summarised by Figure 1, that such a first-best framework would need to fulfil.

Regulatory framework requirements* ***achieved by net-zero the latest**	**Function**	**Current state in the EU**
Pigouvian efficiency		
Marginal abatement costs equal marginal <u>permanent</u> removal costs (MAC = MRC)	Ensure cost-effective balance between abatement and removals. Could be attained by integrating removals into ETS.	* Pricing (=financing) removals only through voluntary carbon markets so far, but no policy instruments in place yet. * Carbon removal unit as defined per EU's Carbon Removal Certification Framework (CRCF) serves as foundation for fungibility.
Comprehensive Pigouvian pricing	Account for externalities (carbon and other, e.g. biodiversity) in agriculture and other relevant sectors to avoid leakage and distortions, e.g. through inefficient use of biomass for BECCS. Border adjustment required to prevent international leakage.	* Biomass included in ETS, exempted from compliance if certified under RED. * No pricing of externalities (incl. carbon emissions) in agriculture so far.
Enhanced supply-side efficiency		
Integration of international removals	Allow international CDR credits for compliance, ensuring a cost-effective balance between domestic and international removal. Border adjustment required to account for externalities caused in exporting country.	Excluded as per CRCF.
Integration of temporary removals	Establish robust governance – including clarity about monitoring and liability issues – for temporary CDR, ensuring a cost-effective balance between permanent and temporary removal.	* CRCF establishes monitoring and liability framework for permanent CDR. * Use of temporary CDR for target compliance still untested and controversial.
Readiness for overshoot management		
Government ready to act as buyer of removals	Mandate public institutions to procure CDR as needed to reduce overshoot. Could be in ETS or other system.	Still open, but discussions on institutional set-up ongoing.
Overshoot management strategy in place	Establish targets to map out credible pathway towards overshoot reduction over time.	

Fig. 1: Requirements for the regulatory framework to enable a first-best vision of removals. Right column provides a summary of the current state of EU policies.

2.1 Pigouvian efficiency

First, the regulatory framework for a first-best vision of removals should build on Pigouvian efficiency, that is a system ensuring that prices reflect all social costs appropriately (i.e. all externalities are internalized). There are two aspects to be taken into account.

Marginal abatement cost equal marginal permanent removal cost

In order to balance abatement and removals cost-effectively, used (market based) policies need to ensure that marginal abatement costs equal meet marginal cost of permanent removals. Notably, this could be attained by a full integration of removals into carbon compliance markets (full fungibility of emissions allowances and CDR units). This way, supply and demand will determine whether the marginal ton of greenhouse gas will be abated or removed.

Comprehensive Pigouvian pricing

As a second prerequisite, proper and uniform Pigouvian pricing, in particular carbon pricing, should be attained in all relevant input sectors for CDR. To date, carbon pricing in the EU covers the sectors regulated under the ETS I (electricity generation, energy-intensive industry, aviation, shipping) and prospectively the new ETS II (transport, heating, small industry emitters). However, agriculture and forestry, which will serve as removal sources through both BECCS and (later) biogenic sinks, are still missing. If the condition of comprehensive Pigouvian pricing is not met, biospheric removals can serve as channels for arbitrage into the land use sector. An integration of carbon and removal markets would incentivise an inefficiently excessive use of biomass to generate removals, raising concerns of biodiversity loss and rivalries with other forms of land use (e.g. for food systems). Hence, while a comprehensive internalisation of externalities certainly has to apply to greenhouse gas emissions, the concept could also be extended to price other negative externalities like biodiversity loss. Moreover, border measures need to be considered to prevent leakage not only in other sectors, but also other regions with insufficient externality pricing. Only then, price formation after an integration of carbon and removal markets will lead to a balanced outcome between abatement and removals on the one hand, as well as between atmospheric and biospheric removals on the other.

2.2 Enhanced supply-side efficiency

As a second requirement, the regulatory framework for a first-best vision of removals needs to account for enhanced supply-side efficiency, ensuring that credible removal certificates can be supplied cost-effectively. Ideally, this means that - in the long run - removal markets are open to both international and temporary removals.

Integration of international removals

In the long run, a future is conceivable where CDR deployment in one part of the world generates removal certificates, which are then acquired and accounted for in another. Naturally, some regions will be better-suited to deploy removals, for example by having more abundant renewable energy resources to operate DAC installations sustainably, or by having low-cost carbon sinks. In order to enable cost-effective supply of removal certificates, a domestic policy perspective on CDR is insufficient, and the long-term regulatory framework needs to accommodate an integration of international removal units. Policies could furthermore aim for globally harmonised certification frameworks and joint industrial policies to foster innovation and ramp-up deployment.

Opening up compliance markets in industrialised countries to international removals comes with challenges, which have to be addressed beforehand. In discussing international markets for compliance certificates, many will feel reminded about the failures of the Kyoto Protocol's Clean Development Mechanism (CDM) and the acceptance of its certificates in the EU ETS to deliver substantial carbon dioxide reductions. Among other issues, the instrument did not manage to overcome two key challenges: Its economic incentives were diluted by certificates from cheap emissions reductions of GHG other than CO_2, and the governance on additionality and counterfactual baseline emissions was not robust enough to prevent circumvention (Wara, 2007; Gillenwater and Seres, 2011). As a result, certificates were generated and sold internationally, but - in reality - failed to deliver additional emissions reductions at the anticipated scale (He and Morse, 2013; Cames et al, 2016). Not suprisingly, this has fueled concerns about creating global trading regimes for removal certificates. The risk of history repeating itself, however, is less pronounced with removal markets, and policymakers can harness learnings from the CDM to anticipate a robust international governance framework for removals. This is particularly true for DACCS, for which additionality will not be an issue as the counterfactual to building an installation is zero removal. Due to its promising characteristics in terms of monitoring, reporting and verification (MRV), with DACCS, accredited verifiers can furthermore ensure that the amount of certificates issued matches the removals actually occurred at an installation abroad. Still, endeavours towards integrating international removals should avoid the challenges the CDM has faced, and any instrument to that end should be designed accordingly.

More generally, the generation of international value chains for removals needs to take global equity concerns seriously right from the start. From early proposals onwards already, frameworks should be built on the principle of distributional justice, and especially prevent situations in which market participants of the Global North profit from negative externalities caused in the Global South, e.g. from excessive biomass use to generate removal certificates for the international market. Consequently, multilateral agreements to that end need to account for the risk of such distortions, be drafted with removal-supplying nations' interests in mind, and negotiated transparently.

Integration of temporary removals

On top of international removals, the long-term regulatory framework should consider both permanent and temporary CDR methods. By the time societies reach net-zero the very latest, a decision has to be taken on whether temporary CDR will be allowed into the compliance architecture to support the achievement of overshoot management targets. Clearly, integrating non-permanent removals into the EU's climate policy framework poses significant challenges due to liability and integrity risks. First, there is a risk that removal units will be credited a higher mitigation impact than their temporary nature should allow, hence posing challenges for the integrity of climate policy governance. Moreover, since temporary removals will likely be available at much lower cost, the expectation of abundant removal units becoming available in the future would increase the risk of abatement deterrence. On the other hand, the techno-economic potential of temporary removals might surpass that of permanent CDR (European Scientific Advisory Board on Climate Change, 2023). In addition, temporary removals can enhance welfare by shifting carbon sinks from the atmosphere back to the planet, maintaining global carbon cycles by continually recapturing emissions released from non-permanent sinks in a Sisyphus-like effort (Kalkuhl et al, 2022). To reap these benefits, open questions on monitoring and liability regarding temporary removals have to be addressed.

2.3 Readiness for overshoot management

As a third requirement, by the time economies have reached net-zero the very latest, the policy architecture needs to be ready to deliver net-negative emissions for overshoot management. From then onwards, policy instruments need to incentivise endeavours to retrieve GHGs that have been emitted beyond depletion of a Paris-compliant atmospheric carbon budget. Since, to date, policies have been designed with mitigation pathways aimed at net-zero in mind, it is important to consider where the regulatory framework would have to develop towards to in order to incentivise CDR even beyond that point, and at a scale that results in net-negative emissions afterwards. We identify two sub-requirements to get the policy architecture ready for overshoot management.

Government ready to act as buyer for removals

In a post-net-zero world, the government has to be ready to act as buyer of removals for compliance with overshoot management targets. This entails commitments in terms of the fiscal budget, but also a complete institutional framework to govern carbon markets and removal procurement. Such a framework could build on existing institutions, but could also include newly established authorities. Previous work has established initial corner stones for institutional governance, most prominently around establishing a Carbon Central Bank to govern the market for carbon removal certificates (Rickels et al, 2022; Edenhofer et al, 2024a). These proposals stem from both the need to govern a credible compliance market for removal certificates, but also from the requirement to conduct overshoot management in the long-term. We discuss the question of building-up the necessary institutional governance more in depth in Section 4.

Overshoot management strategy in place

Getting the regulatory framework ready for net-negative emissions at scale involves a strategy for overshoot management. Such a strategy consists of the necessary institutions as discussed above, but also of targets to determine the speed at which GHGs are retrieved from the atmosphere over time. Target-setting for overshoot management poses a variety of questions which have to be discussed on both national and international fora. Most importantly, controversies around inter-generational and national responsibility in terms of required removals, as well as around distributional impacts (including the question who pays) need to be resolved. While the notion of creating primary demand for removal certificates with public funds will certainly spark controversy, it is the logical extension of the current cap-and-trade-regime under jurisdictions with a carbon market in place. After all, the need to incentivise removals at a large scale stems from societies' failure to fight climate change by abatement measures in time in the first place. As governments have failed to ratchet-up abatement policies in time, this approach provides them with a last resort to address the problem, namely by taking financial responsibility for overshoot management before future generations are left with the effects of catastrophic climate change. In that sense, debates on inter-generational justice will be reflected in the question about who is going to pay for net-negative removals.

2.4 Removals in the EU ETS: Attaining the first-best vision with a market-based policy approach

The regulatory framework conditions above abstract from policy instruments, and in itself are independent of both the architectural start point and the path of how to achieve them. In the most general way, they are set out for markets to attain an efficient ramp-up of CDR. So far, advanced removal policies have either taken a demand-pull or a market-based approach. The regulatory framework conditions are applicable to either of the two (see Box 2).

In the real world, however, the long-term vision needs to be related to policy processes and the current policy architecture as a starting point. Although the demand-pull approach (as taken by the U.S., for example) has arguably been implemented at a more advanced stage, demand-pull policies for removals co-exist with emissions abatement policies and are not dependent on the integration of two initially distinct architectures. As a result, demand-pull measures do not require a sequential integration of removals into existing mitigation policies. For the market-based policy approach, on the other hand, timing matters, and the design of a dynamic policy path for an integration is essential.

The most straightforward path to attain the regulatory framework conditions consequently builds on an advanced carbon compliance market such as the EU ETS. From a theoretical efficiency standpoint, ideally, the system would span across all sectors with a uniform carbon price even before a removal integration. While this condition obviously does not hold for any existing carbon compliance market, the EU ETS is considered the world's most advanced market of this sort at a continental scale.

To date, governments with advanced removal strategies have addressed the ramp-up either through demand-pull, or through market-based policies. In principle, the first-best vision framework is applicable to both approaches, even though it would be operationalised differently.
The demand-pull approach has been taken by Canada and the United States, where it is implemented through a combination of tax credits (45Q of the U.S. Inflation Reduction Act (Yarmuth, 2022)), public procurement of removals, and direct subsidies (Manhart, 2024). In such a setting, long-run Pigouvian efficiency implies that demand-side incentives are aligned with incentives for emissions abatement, e.g. by adjusting the tax credit to the shadow price of carbon emissions used by the government at each point in time. In terms of supply-side efficiency, demand-pull incentives could in principle be extended to international and temporary removals. However, national tax credits are unlikely to be a suitable instrument to ramp-up international removals. To incentivise removals from abroad, other incentive channels would therefore have to be explored. What is more, the demand-pull approach is well suited to achieve overshoot management readiness. With an established direct procurement policy, the United States currently sets a strong example in this area. It remains to be seen, though, whether this policy will be extended to actively pursue an overshoot management strategy. Additional direct subsidies, such as the U.S. Department of Energy's CAPEX support (U.S. Department of Energy, 2024) or the DAC hub subsidy scheme (Office of Clean Energy Demonstrations, 2023), may be justified during early stages of technology deployment either to address innovation externalities (first-mover disadvantage) or to establish strategic technology leadership. However, as removal technologies become more mature further down the line, subsidy schemes do not play a role in an efficiency-motivated first-best vision.
The market-based policy approach, on the other hand, has been discussed in the EU, but also for other jurisdictions such as the UK, Japan and California (Manhart, 2024). Two options are currently being considered: integration into carbon emissions compliance markets or separate trading systems for removals. Following the Pigouvian efficiency principle, in the long-run, cost benefits can only be fully reaped by integrating emissions and removal compliance markets. Supply-side efficiency is then achieved by opening up the integrated market to international and temporary removal units. The third regulatory requirement, overshoot management readiness, could eventually be fulfilled in- or outside the system. For the former option, i.e. overshoot management through an integration of removals into compliance markets, this means that the government will drive demand for removals certificates in the long run. This implies a shift in the role of governments on such markets: While nowadays governments determine the *supply* of cap-and-trade-based carbon markets, in a net-negative future they switch sides and act as drivers for removal certificate *demand* (see Figure 2).

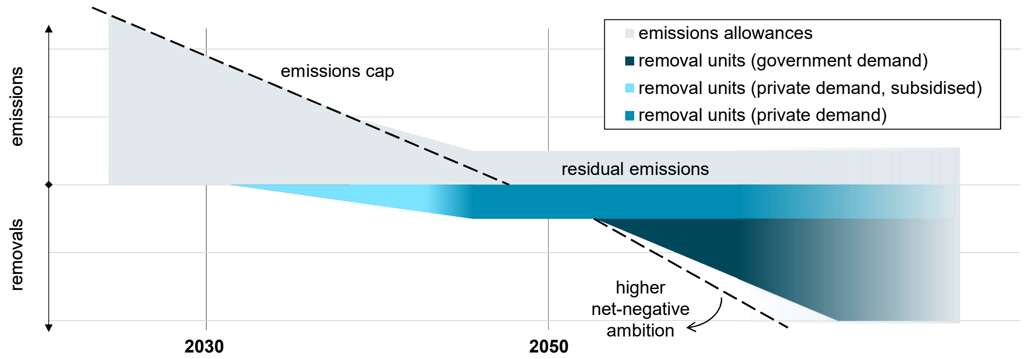
Box 2: The first-best vision for demand-pull vs. market-based policy approaches

The remainder of this work therefore operationalises the first-best vision for a market-based policy approach, with a specific focus on the EU ETS. The respective path from a carbon compliance market towards an all-encompassing emissions and removal market takes the shape of a "tilted hourglass" as depicted in Figure 2.

Today, on the road to net-zero, the compliance market consists of CO_2 allowances only. Primary supply of certificates is directly provided by the government, and demand stems from emitting installations. With a gradual integration of carbon and removal markets, removal certificates slowly enter the system. At the beginning, this would only be allowed at a limited quantity and – at least when it comes to removals from DACCS – would likely only occur with removal units that are subsidised by the government.[3]

Phase 2, net-zero, starts as soon as the emission cap comes down to zero. Banked certificates aside, from that point onwards every ton of CO_2 emitted has to be met with an equivalent removal. When marginal abatement cost break even with marginal removal cost, government subsidies for removals are phased-out and, for the remainder of the second phase, installations with residual emissions clear the allowance market that is supplied by removal firms. For a limited timeframe, the market will operate without government intervention, that is, neither with public carbon allowance supply nor with public removal

[3] We discuss the road to net-zero as the initial steps on the sequencing path more in detail in Section 4.



	Phase 1: Road to net-zero	Phase 2: Net-zero	Phase 3: Overshoot management
Net emissions	>0	0	<0
Certificate supply	• government • removal firms (permanent)	• removal firms (mainly permanent)	• removal firms (permanent and temporary)
Certificate demand	• emitters (all)	• emitters (residual)	• government • emitters (residual)*

*Including perpetual renewal of temporary removals, which could also be mandated to removal firms.

Fig. 2: The implementation of the first-best vision with a market-based policy approach takes the shape of a tilted hourglass. While the government is responsible for the supply-side of emissions allowances during Phase 1, it will turn into a demand-side actor for removal units during Phase 3. Our numerical analysis in Section 3 considers integration up to Phase 2. We do not provide any quantitative assessment of Phase 3 in this work, hence the increasingly blurred vision post-2050.

unit demand.

The system then enters into the third phase, overshoot management, depending on the targets set by the government. From that point onwards, the government creates a credibly increasing additional demand for removal certificates, hence offering a stable revenue stream for removal producers. As a complementary option to incentivise net-negative emissions within the system, clean-up certificates could be introduced, which combine an emissions overshoot allowance with a carbon debt (Lessmann et al, 2024). The remaining demand for removal units will come from residual emitters as before, and potentially from additional compensations for the release of temporarily removed units from previous periods. With the government as demand-side driver, expectations can be set to reflect that demand for removals will rise over time. Removal certificate prices increase accordingly and up to the point where new producers enter the market to provide additional supply. Over time, the increase in demand is then mainly driven by the government's overshoot management strategy as discussed in the next paragraph: the more ambitious overshoot management targets, the steeper such a "negative cap" will have to look like.

In the following, we analyse an integration of permanent removals into the EU ETS I for the power sector and energy-intensive industry. Building on the requirement to match marginal abatement and removal cost, in the next section, we investigate the implications of a first-best, i.e. immediate and unconstrained integration of BECCS and DACCS into the EU's carbon compliance market. In that, we implement the first two phases of Figure 2 - up until net-zero - for the case of the EU in the model to derive numerical insights from a first-best setting. This approach allows us to shed light on the implications from such an unconstrained integration, and to derive requirements for a second-best policy sequencing path later on. The overarching questions that motivate our numerical modelling are: Given a first-best integration of permanent removals into the EU ETS, 1) when (and which volumes of) DACCS and BECCS can be expected to enter the compliance market, and 2) how this would affect the EU's carbon price.

3 First-best integration of permanent removals into the EU ETS: A numerical analysis

To analyse the implications of a first-best - i.e. direct and unconstrained - integration of permanent removals into the EU ETS, we utilise the numerical model LIMES-EU, which includes a detailed representation of both supply and demand in the EU's carbon market. While the supply of allowances is modelled through the scheme's design features, including the Market Stability Reserve (MSR), demand for carbon certificates is represented through all sectors under the EU ETS' scope. More precisely, the power sector is represented in detail, considering each country as a demand node and covering 35 power generation and storage technologies. Other sectors, namely energy-intensive industry, maritime, and district heating, are represented through marginal abatement cost curves.

Regarding policy and market design, we implement the EU ETS 2023 reform, setting the main system parameter up until 2030 and extrapolating most of these elements. Since the stationary cap would reach zero by 2039[4], we assume that allowances can only be traded until the end of this year[5]. This also implies that the MSR remains operational until this year. We calibrate the model to historical data up to the year 2020. The 2030 emissions reduction target is 62% emission reduction w.r.t. 2005. This is operationalised through a linear reduction factor (LRF) of 4.3% in 2024–27 and 4.4% as of 2028, and additional one-off supply reduction (rebasing) of 90 million EUAs in 2024 and 27 million EUAs in 2026. The MSR adjusts the volume of annual auctions downwards (upwards) if the total number of allowances in circulation (TNAC) in the previous year was above (below) a given intake (outtake) threshold. The main rules that determine its core functioning remain unchanged by the 2023 reform. The main parameters are (i) the intake rate (24% prolonged until 2030, and 12% afterwards), (ii) the thresholds (lower threshold of 400 million EUA, upper TNAC threshold of 833 million EUAs, and adaptative threshold of 1096 million EUAs); (iii) outtake volume (100 million EUA); and (iv) cancellation (invalidation) threshold (EUAs in the MSR over 400 million EUAs). The intake volume is equal to the intake rate times TNAC if TNAC exceeds adaptative threshold, else to TNAC minus upper threshold if TNAC is between the upper and adaptative thresholds. We also represent the UK ETS, for which a cap is defined until 2030. As for the EU ETS, we assume net zero emissions are to be reached by 2039. We do not represent sectoral expansions nor links between the EU ETS and UK ETS nor to other markets. For a comprehensive description of the model, we refer the reader to the LIMES-EU documentation (Osorio et al, 2023).

3.1 Integrating permanent removal technologies in LIMES-EU

We assess an unconstrained integration of BECCS and DACCS in the EU ETS in a first-best setting, i.e. by fully merging carbon and permanent removal compliance markets in LIMES-EU. More specifically, we deploy the model under the assumptions that emissions and permanent removal certificates are fully fungible, hence allowing equivalence between marginal abatement and marginal permanent removal cost (see first regulatory framework condition in Section 2). In other words, the permanent CDR technologies deployed in the model generate removal units within the EU ETS directly, and for every t CO_2 removed an EU allowance (EUA) is generated.

[4] The aviation cap will reach zero after 2040, but its volumes are rather small.

[5] Since LIMES-EU runs on five-year steps, the year 2040 in the model represents the period 2038-2042. Due to this constraint, we thus assume that the last EUAs can be traded until this year.

Carbon prices are calculated endogenously in LIMES-EU. Up until now, the carbon price ceiling has been determined by marginal abatement cost of EU ETS installations. With the integration of removals, however, a potential new price ceiling comes into play: As soon as removal certificates become available at a lower price than both emissions allowances and technological abatement options, the removal option will be drawn. If global CDR deployment is scaled up sufficiently to bring removal prices down to meet marginal abatement cost under the ETS, we expect a future curb of carbon prices. The upper bound on carbon prices will then not depend on marginal abatement cost of industrial emitters anymore, instead, it would be determined by the marginal cost of carbon removals. Bringing the new cost data for CDR into LIMES-EU allows us to asses whether we can expect such a curb at all, and if so, whether it will come into effect in time to affect the ETS endgame. At the same time, the analysis allows us to determine the extent of the EU ETS's role in promoting BECCS and DACCS deployment.

Modelling BECCS

From 2030 onwards, the model deploys BECCS installations in the electricity sector. As a consequence, BECCS investment is driven by two revenue streams, electricity dispatch and the EUA price from the removals generated. In this paper, we consider maximum biomass potential based on primary energy consumed between 2010 and 2020 (Eurostat, 2023), and an emission factor of -550 kgCO2/MWh$_{elec}$ for BECCS. Biomass prices are taken from the integrated assessment model REMIND (Strefler et al, 2021), which implies price formation with demand from various sectors.

Modelling novel DACCS technologies

We extend LIMES-EU with novel techno-economic data for the three most mature DAC technologies combined with CO_2 transport and storage, namely liquid solvent, solid sorbent, and CaO ambient weathering DACCS[6]. Unlike BECCS, DACCS is "only" a CDR technology, meaning its investments are solely triggered by EUA prices. The net removal costs of DACCS are based on Sievert et al (2024), who conducted a bottom-up calculation of these costs for pioneering DAC plants, including CO2 transport and storage. Sievert et al (2024) project costs using multi-component experience curves, taking into account the technological characteristics of individual components within these DACCS plants. By applying projected technology shares to global deployment scenarios from Grant et al (2021b), we derive cost pathways over time for each technology[7]. These pathways are subsequently incorporated into LIMES-EU to assess the influence of carbon pricing on DACCS deployment within the EU ETS.

DACCS deployment scenarios

Due to the early-stage nature of permanent removal technologies, future cost estimations are subject to considerable uncertainty. This uncertainty can contaminate policy decisions, leading to additional risks for governing the sequencing path of CDR into the existing architecture. This is particularly the case for DACCS, for which a lot of uncertainty around future global deployment - and with it around cost reductions from technological learning - remains. Indeed, projections for DACCS deployment show considerable variability, with estimates ranging from 0-0.02 $GtCO_2$/yr in 2030 to 0.52-1.74 $GtCO_2$/yr in 2050 (Babiker et al, 2023). Assuming that cost reductions will indeed be driven by global deployment, we explore three different DACCS deployment scenarios in response to this uncertainty.

We reflect the technology uncertainty on DACCS cost by incorporating three different deployment scenarios. For short-term DACCS deployment between 2020 and 2025, we base

[6] We consider the most advanced DAC technologies only, however, there currently exist more than ten distinct systems at various stages of technological readiness (Küng et al, 2023). While we have three technologies - each with at least one commercial plant available - represented in the model, for the purpose of this article, we only look at aggregated DACCS deployment as a whole.

[7] DACCS CAPEX and fixed O&M decrease by 41-58% and variable O&M by 18% between 2030 and 2050.

our projections on company-specific announcements for each technology. Post-2025, these technology shares are extended to 2050 across the three scenarios. For 2050, we leverage data from Integrated Assessment Models (IAMs), specifically a review by Grant et al (2021b). To derive three scenarios with low, medium (base), and high global DACCS deployment, respectively, we use the 5th, 50th, and 95th percentiles of anticipated deployment in 2050 under a 1.5°C scenario. For the intermediate period of 2025 to 2050, we calculate the compound annual growth rate (CAGR) needed to align the 2025 projections, based on company announcements, with the 2050 expectations from the IAMs. This CAGR is then employed to ascertain annual deployment figures, considering each technology's proportional share in 2025. For each deployment scenario, we then calculate DACCS costs using the approach by Sievert et al (2024). According to our calculations, if global DACCS deployment is high, CAPEX and fixed O&M are 24-37% lower, and variable O&M are 10% lower by 2050 than in our reference scenario. If global DACCS deployment is low, CAPEX and fixed O&M are 50-100% higher, and variable O&M are 17% higher by 2050 than in our reference scenario.

3.2 Results

3.2.1 The effects of permanent removal technologies in the EU ETS

Figure 3 compares ETS emissions and allowance prices with an integration of removal certificates into the carbon market against a counterfactual without any CDR in the EU ETS. The comparison motivates conclusions on the effect of CDR integration into the scheme.

Our observations from Figure 3c and Table 1 confirm theoretical expectations: Integrating permanent removals into the EU ETS effectively moderates both medium- and long-term carbon prices in our model. Up until 2045, the carbon price follows the Hotelling trajectory in both panels.[8] Starting from mid-century, in scenario (b) permanent removals are then deployed sufficiently to offset residual emissions within the system. From this point onwards, carbon prices are not determined by marginal abatement cost anymore, but by marginal cost of permanent removal instead. Consequently, "residual" emissions are redefined as those emissions more costly to abate than to remove.[9]

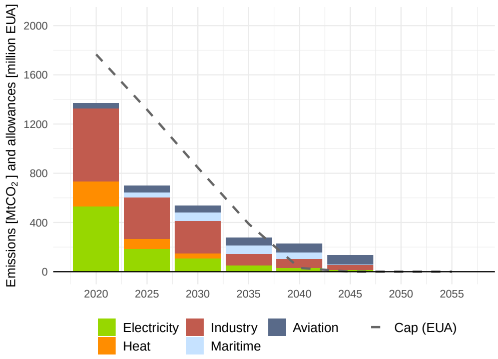
EUA prices in €/t	2030	2040	2050	2060		**cumulative MSR invalidations in mil. EUA**
Without CDR	164	271	650	650		7.9
With CDR	145	240	343	299		7.5

Table 1: Comparison of EU ETS prices in 2030, 2040 and 2050, as well as MSR invalidations with and without removal integration into the compliance market.

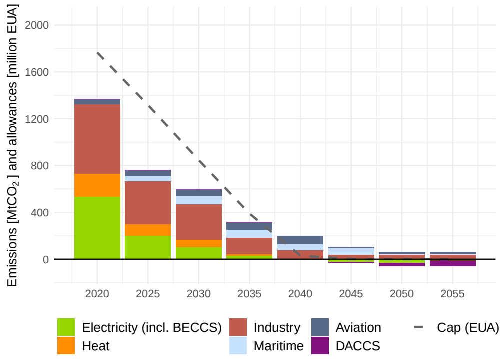
The integration of permanent removals into the EU ETS appears to soothe carbon prices through a direct cost reduction effect, which in turn triggers an anticipatory effect that comes into the picture even before removals become cheaper than abatement. For the direct effect, the introduction of removal certificates both increases market liquidity and allows trading at removal costs, which are presumably lower than abatement costs. Towards the end of the phase-in specifically, the integration of permanent CDR effectively shifts the model's marginal abatement (and removal) cost curve downwards across all sectors. We arrive at this interpretation especially because the difference in MSR invalidations between the scenarios with and without permanent CDR is too small to explain

[8] The Hotelling rule states that - given banking of allowances and absent any market failures - the certificate price level is determined by marginal abatement costs, and prices rise with the interest rate over time (Hotelling, 1931; Rubin, 1996). In the scenario without CDR integration, the deviation from the Hotelling trajectory stems from our banking constraint. With a removal integration into the system, in theory prices still follow a Hotelling curve. However, managing overshoot with full banking pushes the curve's end point far into the future (see Lessmann et al (2024)).

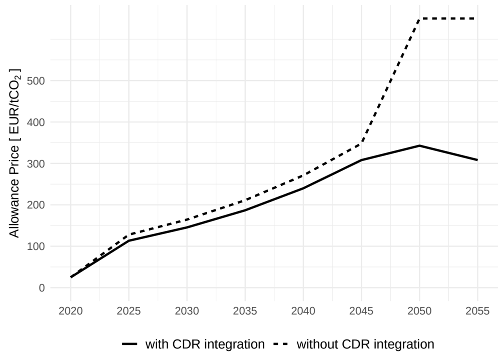
[9] Note that we do consider instantaneous and permanent removals as part of the initial steps of the policy path only. For the effects of non-permanent and delayed removals see Kalkuhl et al (2022).



(a) EU ETS sector emissions without CDR integration.



(b) EU ETS sector emissions with first-best CDR integration.



(c) EU ETS prices with and without a first-best CDR integration.

Fig. 3: ETS emissions by sector and resulting carbon prices from 2020 to 2055. Panel (a) and the dashed line in Panel (c) show a counterfactual without CDR integration, panels (b) and the solid line in Panel (c) show results with a first-best integration of CDR from 2030 onwards. BECCS is visualised as part of the electricity sector, and banking of EU ETS certificates only enabled until 2045.

the significant impact on ETS prices alone. Therefore, with the current market design including respective MSR thresholds, the liquidity increase from an integration of permanent removals is helpful, but the phase-in of cost-efficient DACCS units plays the more prominent role in causing direct cost reductions.

Now turning to the anticipatory effect, the model's perfect foresight leads actors to foresee the future availability of removals in the system. As a consequence, perceived long-term scarcity of allowances is reduced and price expectations are adjusted downwards - even before meaningful amounts of removals enter the market. Due to inter-temporal trading, this effect is projected into the short-term horizon of the model already. With lower carbon prices in the present due to the anticipation of the long-term, firms emit more and bank less allowances. The total number of allowances in circulation is reduced, and the MSR injects more allowances back into the market, further exacerbating the downward adjustment of carbon prices.[10]

[10]The risk that the MSR might exacerbate market developments that are based on future allowance price expectations has been widely discussed in the literature. See Perino and Willner (2016) and Osorio et al (2021) for further details.

Ultimately, the described MSR activity results in a smaller amount of allowances being invalidated, effectively causing abatement deterrence for the emissions covered under the EU ETS. As summarised by Table 1, instead of 7.9 million allowances invalidated by the MSR in the counterfactual without removal integration, the cumulated number of invalidated allowances with removals amounts to 7.5 million only. When removals are not available, more allowances will be held - the number of certificates in circulation increases, and MSR invalidations are higher.

3.2.2 BECCS and DACCS deployment

Zooming in on permanent removal deployment as illustrated in Figure 4, we observe a subsequent ramp-up of BECCS first, which is then crowded out by DACCS from the late 2040s onwards. BECCS first comes into the picture after 2030, initially with removals of 13 Mt CO_2 per year. In line with expectations formulated in the literature, the model deploys permanent removals with carbon market incentives on the road to net-zero already, long before only residual emissions are left to compensate. From 2040 onwards, when DACCS cost have come down slowly, the first DACCS installations are then deployed - however, initially at a very small scale only. In 2050, permanent CDR deployment peaks shortly to meet climate neutrality goals. In the following decade up to 2060, deployment is then slightly adjusted downwards again since more BECCS installations reach their end of life than new DACCS installations are installed. In general, however, overall removals deployment stabilises between slightly above 60 Mt CO_2 per year. It is important to note, however, that we do not model any additional net negative targets, which is why the model only installs CDR to a point where residual emissions under the EU ETS are compensated.

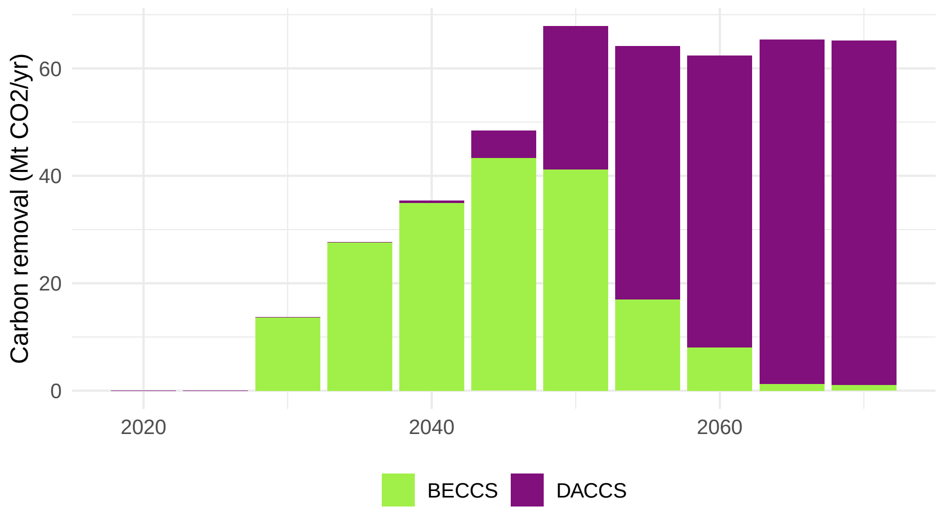


Fig. 4: Annual removals from BECCS and DACCS technologies under the EU ETS. At this point of the analysis, no further net negative targets or subsidy payments for CDR have been considered.

From 2050 onwards, DACCS deployment crowds out the already existing BECCS stock and becomes the dominant removal technology. BECCS installations which reach their end of life between 2050 and 2060 are replaced by DACCS up to a point where BECCS plays an insignificant role after 2060, only accounting for less than 1 Mt of annual CO_2 removals. This change is driven by increasing biomass scarcity and hence surging BECCS cost, as well as cost reductions from economies of scale of global DACCS deployment towards the second half of the century. In the following section, we delve into the latter aspect more in detail.

3.2.3 The role of technology learning from global DACCS deployment

Anticipating uncertainty on DACCS technology cost, we design two additional scenarios for global DACCS deployment, and hence cost reductions from technological learning, in parallel to an ETS integration of removal certificates (see Section 3.1 for further details). Spanning the option space for global DACCS deployment, we exogenously parametrise DACCS installations with higher and lower cost, respectively.[11] Figure 5 visualises the results from our base scenario that was used above, as well as the two additional deployment scenarios.

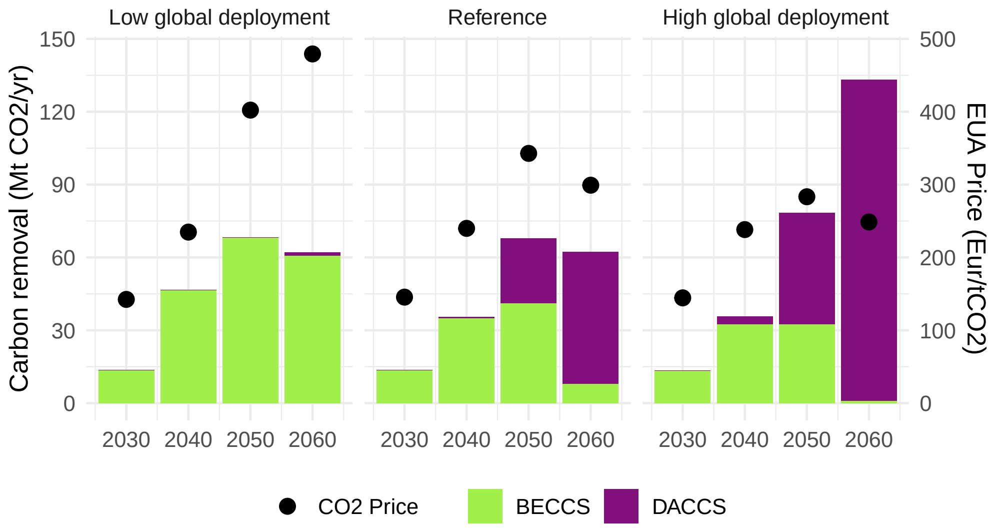


Fig. 5: CDR in the EU ETS and respective allowance prices for 2040, 2050, and 2060. Center panel shows our base scenario, left (right) represents less (more) global DACCS deployment, and therefore higher (lower) DACCS cost.

Impact on removals deployment under the EU ETS

Across all three scenarios, BECCS emerges as the dominant removal method in the EU ETS by 2040. Even under the most optimistic projections for DACCS deployment, the model does not expect any meaningful DACCS removals incentivised from EU carbon prices before 2050. From the middle of the century onwards, however, global deployment (and therefore cost) expectations alter the picture, both in terms of overall CDR deployment and the BECCS/DACCS ratio. With more optimistic projections for global DACCS deployment, total removals are projected to increase to over 75 Mt of CO_2 removed annually in 2050, with over half attributed to DACCS. By 2060, annual total removals more than double compared to the baseline scenario, with DACCS accounting for virtually all CDR activities. Conversely, if global DACCS deployment fails to meet the base scenario's expectations, DACCS deployment within the EU ETS would remain negligible all the way until 2060. In this case, the removals needed to offset residual emissions would primarily be covered by additional BECCS deployment. In addition, a slight increase in abatement efforts is observed, driven by the rising biomass cost in the latter half of the century.

[11] One potential avenue for further work would be to endogenise technology learning in our model.

Effect of DACCS cost scenarios on resulting EUA prices

We find that technology learning from global DACCS deployment influences price formation under the EU ETS from 2050 onwards. In a world with lower DACCS cost and more DACCS deployment integrated in the carbon market, the ETS price in 2050 is lower, landing at 283 instead of the base scenario's 343 Euro per t CO_2. Similarly, if expectations in DACCS cost reductions were not to materialise in 2050, the EUA price would be considerably higher, at 402 Euro per t CO_2. This implies an efficient equilibrium by mid of this century, characterised by marginal costs of abatement equalling marginal costs of removal. Consequently, at that point in time, abatement and removals become substitutable without any considerable effects on the carbon price. In the years before, i.e. up to 2040, however, the effect of DACCS cost on the ETS price remains negligible as DACCS deployment until 2040 is small in all three scenarios.

In the following decade - around 2060, when the pathway to climate neutrality has already been completed - the effects of DACCS deployment and cost on the ETS price become even more pronounced. Here, the downside risk - i.e. DACCS being more expensive as expected in the base scenario - dominates: With cheaper DACCS and more deployment, the EU carbon price lands at 249 Euro per t of $CO2$ in 2060, which is 17% lower than the base scenario of 299 Euro. If DACCS does not meet cost expectations, however, the amount of removals is insufficient to shift carbon cost away from the higher end of the marginal abatement cost curve. As a result, carbon prices climb up to over 479 Euro per t of CO_2 in 2060, which is still considerably lower than not integrating CDR at all, but 60% higher than in the case with medium DACCS deployment and cost.

We furthermore find that abatement deterrence under the EU ETS remains virtually unaffected by different levels and cost of DACCS deployment. In both scenarios with higher and lower DACCS deployment, cumulative MSR invalidations land at a level of 7.4 million EUA, which is close to above's base case with 7.5 million invalidated EUA.

In a net-zero world post 2050, removals can only be expected to stabilise the carbon market when they are driven by cost-efficient technologies. In our model, DACCS provides sufficient removals to lower the carbon price in our base and more optimistic cost scenarios. Relying on BECCS with expensive biomass only, however, e.g. when DACCS cost remain high, would still lead to surging carbon prices by 2060.

3.3 Additional risks motivate a second-best approach to integration

While the above results can provide guidance on the market effects of a full (unconstrained) integration, actual policy implementation needs to consider further risks for environmental integrity that are not captured in the modelling.

Market and policy failures bear risk of political instrumentalisation

A first risk is abatement deterrence. Its root cause is the high long-term cost uncertainty of CDR. This may lead to a hold-up problem: there is an option value for regulated firms to wait with decarbonising investments until there is more information about the costs of abatement measures available (Dixit and Pindyck, 2012). The longer firms wait though, the more allowances they will use in the meantime, implying that the price will rise steeper as the ETS cap approaches zero towards the end of the next decade. This in turn could lead to a softening of the cap when prices surpass the politically acceptable level (Pahle et al, 2022), which would undermine environmental integrity at least indirectly.

The risk of abatement deterrence could be exacerbated when credible information about future CDR costs is mostly private, and used strategically. As it stands, there is little public knowledge about the long-term costs of CDR. In particular for DACCS, technology firms and fossil fuel suppliers are currently putting out the numbers. However, these firms may have an economic interest in communicating biased estimates to shape policy and business in their favour. That is, communicating relatively low long-term costs could help them attract investors and subsidies. To the degree to which downward-biased communicated estimates are dominating and credible, they might exacerbate the investment hold-up of regulated firms.

A second risk is excessive use of biomass (Rasmussen and Vermeulen, 2024). Its root cause is the current lack of Pigouvian pricing of environmental externalities (notably carbon) in the land use and forestry sectors. In particular, the economic value of forests as carbon sinks is not reflected. In consequence, this may lead to excessive (inefficient) use of biomass for BECCS when it is more profitable to use biomass in the ETS. The current safeguard to prevent excessive use of biomass is sustainability certification. However, certification, like all technical standards, generally lack efficiency.

This risk of excessive biomass use could be exacerbated by attempts to politically instrumentalise biomass applications (Taylor et al, 2024). Biomass is subject to a number of conflicting economic and value interests, implying that the process of setting standards and certification is particular prone to regulatory capture by vested interest. To the degree that this influence cannot be contained, the risk of excessive use of biomass will prevail, and governments would remain unable to address the issue with first-best policies. In this case, channels for arbitrage of BECCS certificates into the integrated carbon market would be maintained, allowing firms to capitalise on externalities in land-use and forestry.

Requirements to architecture change over time: Motivating the sequencing approach

The motivation to sequentially integrate CDR into the ETS is that it can help to manage the main risks of integration, namely abatement deterrence and erosion of environmental integrity through excessive biomass use. More specifically, the time structure of both integration risks is that they can be increasingly mitigated over time as technology and policy learning progresses. Only during the early stages of a sequencing path, when risks contaminate the policy architecture in particular, temporary safeguards are needed. Correspondingly, sequencing breaks down to integrating CDR into the ETS in successive phases, in which safeguards are lifted more and more as new risk-reducing technology and policy arrives. Concurrently, the scale of removals at stake for an integration will grow over time. Further down the line, cost-effectiveness of removals deployment will therefore become a more relevant concern.

Given that requirements to the architecture change over time, removals should be integrated into the EU ETS with a sequencing approach. Along the way, policies should be designed with sufficient stability to signal credibility, but with enough flexibility to react to technology and policy learning. Translating our first-best numerical results into a second-best setting, we conclude that the sequencing path needs to fulfil three criteria:

1. In its early stages, the architecture needs to be designed for environmental integrity. Safeguards need to be in place.
2. Later, a gradual build-up to the first-best vision is required (backward induction). This implies a sequential shifts away from risk management and towards efficiency.
3. Along the way, progress to an economically more desirable stage can only be allowed if risks are contained to a sufficient degree (stage-gate approach).

In that sense, the main task is to devise a path that addresses the challenges removals pose for environmental integrity yet, at the same time, gradually implements the first-best vision.

4 Sequencing removals into the EU ETS: Three stages for an integration in a second-best setting

The sequencing path for integrating removals into the EU ETS starts today. It is built from existing policies, and comprised of several sequencing stages to bring CDR into the climate policy architecture. The pursuit of sequencing obviously poses the question how exactly the steps along the way should look like. In the following, we propose an approach that starts with separate systems, but ends in full integration by the time the first-best vision (see Section 2) is accomplished.

Building on three governance stages brought forward by Burke and Schenuit (2023), we propose a stage-gate model for a step-wise path of integrating removals into the EU ETS.[12] Figure 6 summarises the approach, including the gate opening conditions that would need to be met in order to progress to the subsequent stage (Panel 6b).

4.1 Stage 1: No integration, establish MRV

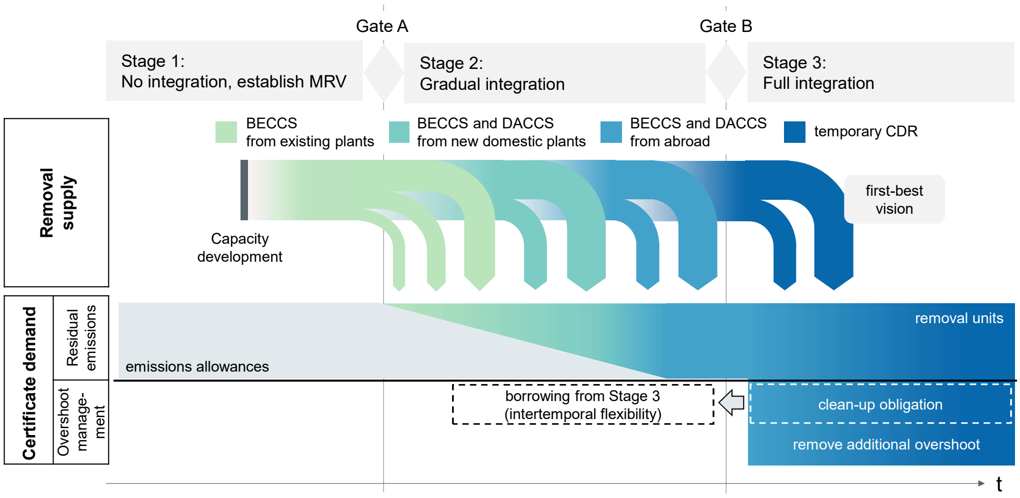
Minimising governance risk with a gradual approach implies that the sequencing path starts with a preparatory phase with no integration. Most importantly, during Stage 1, rules on the certification of removal units are established. For the EU, the Carbon Removal Certification Framework (CRCF) already offers a starting point for this very exercise (Fridahl et al, 2023). Moreover, this stage should be used to define sustainability criteria and accounting guidance for removal units (Burke and Schenuit, 2023). In addition to setting the MRV architecture, the government can implement demand-side policies to incentivise initial removal capacities. This can happen for example through public procurement of removal units directly, or through subsidy schemes for novel permanent removals as discussed in Section 2. If those policies are successful in building sufficient removal capacities already, a separate market for permanent removals could be established before completing the first stage, however with the clear intention to integrate this market into the EU ETS in the long run.

Gate A to Stage 2 unlocks when the MRV architecture is in place, when questions on certification and sustainability of removals have been addressed, and when the Market Stability Reserve has been reformed to account for the integration of removal units into the system. Given that a gradual integration of removals should start way ahead of the ETS endgame in the late 2030s, this first gate should be passed until 2030 as part of the EU's endeavours to implement its 2040 climate targets ("Fit-for-90" package).

4.2 Stage 2: Gradual integration

Upon reaching the second stage, removal units are gradually integrated into the ETS. Gradual here has three dimensions: (1) scope, (2) volumes and (3) time. Gradual integration "in scope" refers to starting with existing plants, then extending to new plants, and finally to international removal units. Gradual integration "in volumes" refers to setting (direct or indirect) limits on the inflow of removal credits into the ETS. This is visualised by initially more narrow flows in Figure 6. Gradual integration "in time" refers to considering employing intertemporal flexibility by allowing borrowing from future removals. More specifically, regulated firms could be allowed to emit if they enter an obligation to compensate this emission through a removal in the future. (Lessmann et al, 2024) have proposed so-called clean-up certificates to that end. They bundle an allowance for emissions with an obligation for their removal in the future. To ensure that the obligation (carbon debt) is met, a collateral must be paid in addition to the price of the clean-up certificate. In this way emitters who purchase clean-up certificates provide up-front finance

[12] A similar approach is sketched in the consultation call on how to integrate Greenhouse Gas Removals (GGR) in the UK Emissions Trading Scheme; see section "Pathway to integration" in the consultation document (last accessed: 30 May 2024).



(a)

	Gate A to gradual integration (Stage 2)	Gate B to full integration (Stage 3)
Opening conditions (unlocked when…)	• Certification & MRV for permanent CDR in place • Sustainability criteria established (biomass) • Market stability reform to account for CDR	• Risks (abatement deterrence, excessive biomass use) addressed • First-best regulatory framework in place (major decisions about architecture to be made)
Related processes	• Potential CDR subtargets • 2026 MSR Review • CRCF elaboration	• Assessment of merging ETS I and ETS II in 2031 • Potential further ETS extensions
Tentative timeline	Until 2030; connected to "Fit-for-90" package (2040 target)	Until 2040; connected to "Fit-for net-zero" package (2050 target)

(b)

Fig. 6: Stage-gate approach with three governance stages of integrating removals into the EU ETS, building on Burke and Schenuit (2023). The approach starts with separated systems, but ends in full integration. Before a subsequent stage is entered, certain conditions - serving as safeguarding gates as described in Panel (b) - have to be fulfilled. From Stage 2 onwards, removal certificates are admitted to the system, albeit in a restricted way at first (indicated by the initially more narrow inflows of removal supply). Integration starts with existing BECCS plants, but opens up gradually until the first-best vision materialises upon integration of international and temporary removals. Borrowing from future removals provides intertemporal flexibility. This could be realised through clean-up certificates, which come with a clean-up obligation for the overshoot emitted (Lessmann et al, 2024).

for CDR, thereby relieving future public finances of this burden. Finally, to avoid the risk of abatement deterrence, for every issued clean-up certificate an emission allowance could be deduced from the cap such that CDR is fully additional (cap neutral).

All of the above dimensions require major policy choices. Elaborating all of them would clearly be beyond the scope of the paper. Here, only the mechanism to control the volume will be considered, since it is also (at least indirectly) relevant for the other two dimensions. The general problem is very similar to restricted linkage of two ETS, and thus similar solutions apply. Overall, three options exist (Quemin and De Perthuis, 2019): (1) limiting quantities of CDR credits for integration, (2) taxing credits when integrating them, (3) and applying exchange rates, i.e. partial fungibility.

A first consideration for the choice of an option are price effects. While quantity restrictions are easy to implement on the face of it, price implications of this option are not clear. If the limit is binding, CDR and ETS prices will diverge, but in a way that is hard to predict ex ante and hard to control ex post. In particular, if the limit is tight relative to volume of available CDRs, CDRs will trade at a large discount relative to emissions allowances. This may not encourage use of higher quality CDR, to the extent that CDR price is a proxy for CDR quality. Exchange rates are not without problems, but they can control the price wedge between emissions allowances and CDRs and also allow for different compliance values (and thus possibly for discrimination across CDR types). For some CDR types, for instance, one may want to surrender two CDRs for one emissions allowance.

A second consideration for the choice of an option are distributional effects. On the CDR credit supply side, it is unclear which credits would be eligible for integration when the supply of credits is higher than the limit. The latter would require a competitive allocation mechanism like a tender, but it is unclear what the bidding criteria would be. On the demand side, distributional issues may arise when allowances become increasingly scarce in the endgame (Pahle et al, 2023). Maybe one wants to prioritise use of CDR by certain entities or sectors based on considerations like e.g. strategic relevance of a certain industry.[13] When distributional considerations apply, allocative efficiency through prices needs to be complemented with (re)distributional measures that also ensure distributive efficiency.

The policy process of detailing the integration mechanism (e.g. setting the volume limit), as well as the design of a potential allocation mechanism could be prone to regulatory capture. This poses an additional challenge for designing a gradual integration. For schemes to be palatable to the industries operating under them, the credits need to be cheap and plentiful, which experience suggests means dodgy (The Economist, 2023). Importantly, this risk flags potential governance challenges, to which we will come back at the end of this section when discussing a potential European Carbon Central Bank.

To keep governance risks to a minimum, Stage 2 starts with permanent and domestic removals only. Any initial attempts to integrate CDR into the ETS need to maintain the EU carbon market's integrity. The risks for EU climate policy associated with phasing in "dodgy" certificates into the EU ETS are substantial, and years of trust-building and designing a credible carbon compliance market are at stake. Consequently, in its early stages, the sequencing path can only entail the integration of controlled quantities, which are easy to govern. That brings technology-based options to the forefront of policy interest.

Since some bioenergy is already covered by the EU ETS, starting with BECCS from existing plants makes sense for the immediate first steps. To date, installations purely running on bioenergy are still excluded from the ETS' scope. They, together with other installations which are already covered under the ETS and are partly fueled by biomass, could be accounted for as carbon removals after being retrofitted with a CCS installation - hence providing a starting point for the sequencing path. From an MRV perspective, bioenergy already ticks many of the boxes to guarantee certificate integrity. For example, MRV provisions have been included in the latest revision of the Renewable Energy Directive, and many installations under the EU ETS are already monitoring the amount of bioenergy used. However, even for existing installations, further work is needed to define MRV provisions for carbon transport and permanent storage. As the number of BECCS certificates entering the carbon market will be rather small in the beginning, safeguards are in place to keep distortions to a minimum even without full Pigouvian pricing in the land-use sector. As soon as BECCS becomes increasingly integrated but land-use externalities are still not sufficiently priced (see Pigouvian pricing condition in Section 2), however, bio-energy use for removals needs to be controlled through additional policy measures.

Following the gradual logic, in a second step new yet easy-to-govern installations should be admitted into the system. New domestic BECCS and DACCS installations

[13] This has been framed as a question of "access" to removal certificates (Tamme, 2023).

will be of interest for this sequencing phase. While DACCS technologies offer promising characteristics in terms of removal certificate integrity, their deployment cost and scale will most likely not be developed in time to play a major role during the initial years of an integration. At a later stage, however, DACCS' integration in compliance markets might become a central lever to strengthen the CDR regime in the EU. Depending on the pace of cost reductions and scale-up, DACCS could therefore bridge the first part of the gap between the very first sequencing steps and the first-best vision of removals in the EU.

After learnings from the integration of domestic BECCS and DACCS have strengthened the governance regime further, the second part of the gap towards full integration can be filled by gradually integrating certificates from international removal units into the scheme. As already discussed in Section 2, the integration of removals from abroad seems challenging given the experiences from international compliance markets in the past. However, issues of certification and additionality, which put the CDM to the test, are not as pronounced for BECCS and DACCS and can therefore be addressed. With larger removal capacities at stake further down the line of the sequencing path, efficiency considerations will now gain importance. Once governance solutions are found for international certificates, integrating permanent removals from abroad will bring cost-effective removal supply into the system, minimising compliance cost for both private actors at that point in time, as well as for the government as soon as it decides to phase-in large-scale removal procurement for overshoot management.

From a governance perspective, Stage 2 is also used to shield both the integrated and the non-integrated shares of removals against risk of reversal, that is, to prevent any re-release of captured carbon dioxide back into the atmosphere (Burke and Schenuit, 2023). This holds for both permanent removals, which could be subject to unintended reversal, as well as temporary removal capacities, which could in theory be built-up even if they are not integrated into the scheme yet. Depending on the strategy taken, options like buffer pools or contemporaneous removals come into the picture. On top of that, decisions need to be made on the question of liability for reversal, i.e. which public or private entities will take responsibility, and how the respective consequences from this responsibility will materialise in case of a removal event. If clean-up certificates are already issued at this stage, the removal liability would be directly attached to an emissions allowance. We refer the reader to Burke and Schenuit (2023) and Lessmann et al (2024) for deeper discussions of the matter.

As soon as the risks of abatement deterrence (including reversal risks) and excessive biomass use can be ruled out for both domestic and international removal units, the policy architecture is ready to be developed towards Stage 3. To attain a full integration of emissions and removal compliance markets, the regulatory framework requirements of the long-term vision (Section 2) need to be sufficiently prepared. Since the architecture needs to be ready for overshoot management in time, Gate B should be unlocked by 2040 the latest, and Stage 3 is to be entered right after.

4.3 Stage 3: Full integration

After the previous stages have subsequently built up the level of integration of removal units into the system, Stage 3 will be used to complete a full integration. From this point on, control mechanisms for a gradual integration are no longer needed. As a consequence, domestic DACCS and BECCS installations could also be brought into the system as activities covered under the ETS. Only then, when permanent and easy-to-govern removals both from domestic and international installations have been integrated into to the system, the third and most challenging step can be taken to achieve full supply-side efficiency: temporary removals would be admitted to the scheme. Only if liability risks for temporary removals have been sufficiently contained during Stage 2, a step-wise integration of temporary removal units can now bridge the last gap until the first-best vision as outlined in Section 2 materialises. From now on, the architecture would be ready to scale-up removals even further to implement the EU's overshoot management strategy.

4.4 Sequencing with credibility: The role of signalling, pre-commitment and institutional governance

A final aspect pertains the importance of pre-committing to the three stages early on when adopting new legislation. The economic advantage of doing so is that it could provide long-term financial certainty to investors in CDR. More specifically, scaling up removal technologies does not only rely on immediate financial incentives, but also on the expectations about prospective future incentives. Certainty of inclusion at a later stage could be instrumental for shaping investors' expectations accordingly, and could help to sustain current investment momentum. Such pre-commitment would require implementing integration as a path right from the beginning, i.e. the different stages and respective timelines are formulated in law early on. The potential merger of ETS I and ETS II can serve as good and bad example in that respect. Good in the sense that a review clause - stating that the merger will be assessed in 2031 - has been included in the ETS Directive, which at least gives certainty on the timing of the decision. Bad in the sense that the specific implementation and a year at which the merger will happen (at the latest) have been left open.

However, to provide certainty a policy path must also be credible, which implies a suitable trade-off between early pre-commitment and later flexibility. Private investments only take place if the integration path is credible in the sense that regulation is robust over time and will not be revoked or dismantled in the future. In general, this requires a mix of pre-commitment (to a pathway) and flexibility. The latter is necessary because it cannot be credible to just "stay on the path" when important new information arises in the future or the broader political and economic situations undergo fundamental change over time (Dolphin et al, 2023).

How to exactly balance pre-commitment and future flexibility in the first round of legislation is challenging though. For example, should policy makers define a concrete mechanism or even specific volume for gradual integration (Stage 2) already now, risking efficiency losses due to high uncertainty about what the future (optimal) amount would be (see Section 3)? Or should they keep the mechanism open and only specify in the next revision in later years, e.g. at the onset of Stage 2, at the disadvantage of increasing uncertainty for firms thereby? Experience suggests that, typically, policy makers put more emphasis on flexibility than on pre-commitment, for example in the case of merging ETS and ETS2 (see above). This might be for strategic reasons, i.e. in order to shape expectations of firms and investors, or because they lack the proper commitment devices that can bind future policy makers to their decisions (Brunner et al, 2012). In any case, it implies uncertainty for investors. What is more, flexibility may lead to even higher uncertainty when future policy decisions might be prone to the risk of regulatory capture (Helm, 2010). In the case of CDR, this risk seems to be particular high because of the political and economic stakes.

In face of the difficulties of making credible long-term commitments and the related risk of discretion that may lead to instability, rule-based policy making has been suggested as a solution (Kydland and Prescott, 1977). In monetary policy, where such a commitment problem also exists, it has led to the establishment of rule-based management of price stability through central banks. In analogy, climate central banks have been proposed to manage allowance supply in the ETS, notably because of the structural similarity of money and allowances (both are politically created and thus have no intrinsic value). Such proposals for a climate central bank go back a long way to even before the ETS was established, and were renewed in the context of seemingly discretionary reforms of the ETS; see e.g. Pahle and Edenhofer (2022). Unlike in monetary policy though, they have not gained political traction so far.

However, new governance challenges arising from integrating CDR into the ETS and the climate policy framework strengthen the case for a carbon central bank. In response, several proposals for a European Carbon Central Bank (ECCB) specifically for CDR have recently been made. All of them define mandates in the form of (economic) functions such an institution could take on; see Merton (1995) for why a functional perspective is more useful than an institutional one in time of (rapid) change. Depending on the number and potential impact of the functions, their mandate is more or less narrow. Rickels et al (2022, 2024) envisage that an ECCB ensures commitment to long-term climate targets and manages a pool of CDR that can be used to ensure market stability in the ETS. Similarly, Jeszke and Lizak (2024) and Pyrka et al (2024) propose that an ECCB manages the supply and demand for ETS allowances and removal units. Edenhofer et al (2024a) (see Table 2) envisage that an ECCB takes on the management of the cap (i.e. ensuring that the overall budget will be met), and the management of the specific liability risk of CDR. It could also take on procurement and funding, and ensure price convergence and international cooperation (see Figure 7), implying a relatively broad mandate. A further function that has been considered for a ECCB is analysis and information provision, for example about the long-term cost estimates for CDR and the leakage risks of non-permanent CDR.

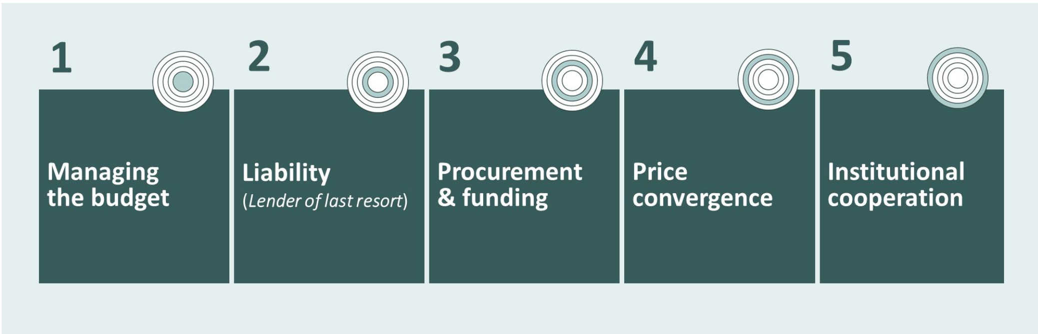


Fig. 7: Proposed mandate for a European Carbon Central Bank (Edenhofer, 2024)

While clearly each of the above functions need to be performed to govern the integration of CDR into the ETS and the system itself more broadly, the crucial question is one of institutional effectiveness, i.e. whether a ECCB could do this better than existing institutions, including the market itself. Two aspects seem particularly relevant: (1) the mandate of the ECCB and (2) how it would actually execute the functions. Regarding (1), it needs to be narrow enough to ensure that politicians would delegate these functions to the ECCB in the first place (cp. Edenhofer et al (2021)). In particular, if functions have substantial distributional implications, delegations seem unlikely. What is more, even with a narrow mandate that primarily focuses on measuring risks and conducting forward looking analysis it is unclear if a ECCB would be able to deliver on its mandate. This is mainly because it is unclear if the ECCB would have better models for analysis than the market (Oman et al, 2024). Related, the welfare effect of increased public disclosures of information is ambiguous when private agents have access to independent sources of information (Morris and Shin, 2002).

Regarding (2) the execution of the functions, it is important to recall that ensuring long-term commitment is a core argument for implementing a ECCB, and that this capacity relies on rule based management. This implies that, in essence, it is the type of management (rule based) rather than the institution itself that may ensure commitment. Accordingly, an ECCB proposal needs to operationalise the rules for each function of its mandate. Only then can it be discussed meaningfully, both in terms of its quality (effectiveness) and stability over time. An important distinction here is between "active" and "passive" rules (Dellas and Tavlas, 2022): Under a passive rule, policymakers are obliged to follow the same course of action in all circumstances. Under an active rule, policymakers can respond to different circumstances in pre-determined ways (i.e. have more discretion). An important example that illustrates the challenges of establishing (passive) rules is the Market Stability Reserve (MSR): While it did perform one function (reducing historical surplus) quite well, substantial concerns exist regarding its capacity to perform its second intended function, i.e. whether it is fit to uphold the ETS' resilience to major shocks by adjusting the supply of allowances to be auctioned (Perino, 2018; Osorio et al, 2021; Perino et al, 2022; Borghesi et al, 2023).

Against this background, the necessary next step for further developing the above proposals would be a specification of "candidate rules" for each function they envisage. This could also help to identify potential pitfalls that are not necessarily apparent on the current general level. For example, the proposal by Rickels et al (2024) envisages a Carbon Remove Reserve (CRC) to replace or complement the MSR. In doing so it falls short of acknowledging the potential substantial distributional challenges that may arise in an ever tighter ETS (Pahle et al, 2023). However, this would be problematic for its mandate (see above). Another example in the proposal by Edenhofer et al (2024a) and the recent extension to clean-up certificates (Lessmann et al, 2024) is the problem that the ECCB would need to decided which (uncertain) rate of technological progress to use to determine the collateral for non-permanent CDR under uncertainty about the leakage rate. How would it make this decision? If it would apply the (cautious) precautionary principle, the collateral would be much higher compared to using a more risky principle.

Overall, the variety of technical responsibilities alone warrants consideration of a new institution like a ECCB (Edenhofer et al, 2024b). However, its institutional effectiveness in the above sense crucially depends on the quality of its rules and the way it deals with information. Some work in this direction already exists. Benmir et al (2023), for instance, propose a cap rule that may significantly reduce price volatility and potential welfare losses. But a lot of open questions remain regarding both its rationale and the used indicators. Accordingly, further research is necessary to come up with more specific proposals for rules to execute the various functions in order to make the case for a ECCB more compelling.

5 Synthesis and outlook

In this work, we substantiate the IPCC's three phases for CDR (Babiker et al, 2023) with respective roles for policies, as well as the implications for an integration of removals into the EU ETS.

In the near-term, we first expect a ramp-up of BECCS capacities, then a gradual and controlled integration of BECCS removal units into the compliance market. These installations will soon be followed by initial DACCS capacities, which are still facing high cost and will only enter the system at a limited scale. Before initial steps of an integration take place, the ramp-up of removals occurs fully separated from the carbon compliance market. At this preparatory first stage without any integration, MRV and certification provisions need to be established first to ensure environmental integrity of the policy architecture. In addition, demand-pull policies will be needed - first for separate capacity building, then as a complement to integration endeavours to secure stacked revenues for a positive business case of removal deployers. During the initial steps of an integration, risks of abatement deterrence need to be contained and rather costly removal units enter the market at a controlled scale only. As a consequence, only limited effects on the carbon price can be expected at this point in time.

In the mid-term, by the time the EU reaches net-zero, we expect DACCS to play a more important role. If our base assumptions on global deployment and technology learning for DACCS materialise, these installations will take over and deliver increasing shares of removals under the EU ETS until BECCS is phased-out almost entirely. Given risks are contained sufficiently, the compliance market can be developed further towards supply-side efficiency and be opened up for international removal units. During this stage, policies should focus on risk management first, leaving the mechanism by which to control the inflow of removal units into the ETS as key policy choice. As time progresses, policy focus shifts to gradually opening up the system until full integration is achieved. This includes the preparation of the remaining regulatory framework conditions for the first-best vision, such as establishing a strategy for overshoot management, which need to be ready by the end of the net-zero phase. In terms of effects on the EU's carbon market, cost-effective DACCS certificates can be expected to mitigate the ETS endgame's squeeze at that time. However, effects will depend on actual cost reductions, and the risk of abatement deterrence from false cost expectations remains imminent.

In the long run, when the scale of removal units increasingly matters for overshoot management, efficiency should be at the heart of the policy strategy. As soon as integrity risks are contained, higher volumes of international and temporary removals become integrated into the system. The policy architecture now fully reflects the first-best vision, implementing Pigouvian efficiency, supply-side efficiency, as well as readiness for overshoot management. On the removals-encompassing compliance market, the government – instead of supplying emissions allowances like it has done in the past – will now turn into a demand-side actor for removal units. The effects on the carbon market then depend on the ambition for net negative targets, as well as the ability to integrate cost-effective yet environmentally sound removal units into the system.

Future work should improve the understanding of market mechanisms in a second-best setting, as well as that of the role of additional policies, including interaction effects with a gradual integration of removals into carbon compliance markets. We have illustrated numerical estimates for a first-best integration and conceptualised which market and policy failures we expect to pose a risk to the sequencing path's environmental integrity. Further work is needed to substantiate the effects of these challenges, and to provide upper bounds for the scale of associated downside risks. Moreover, with our first-best integration estimates, we have taken into account removal deployment incentives from an ETS integration only. Subsequent analyses should delve deeper into the effects of additional instruments, including stacked revenues from additional demand-pull policies, on the ramp-up of removals. This includes a more thorough analysis of the role of signalling, addressing the trade-off between showing credible policy commitment and leaving enough flexibility to accommodate future developments. In this context, further consideration needs to be given to a ECCB's mandate, as well as to the rules by which it should execute mandated functions. Lastly, governance scholars should contribute to managing risks between the different stages of an integration. For example, normative questions on reversal risk need further study, including how liabilities can be distributed between public and private actors. Building on docking points in the existing climate policy architecture, these contributions will pave the way for a sequencing path that enables a secure, yet efficient ramp-up of removal capacities in and outside the EU.

Acknowledgements. The authors would like to thank Tabea Dorndorf, Verena Hofbauer, Kai Lessmann, Anne Merfort, Simon Quemin, Artur Runge-Metzger and Eve Tamme for helpful comments. Sebastian Osorio, Darius Sultani and Michael Pahle gratefully acknowledge funding from the German Federal Ministry of Education and Research under the Kopernikus-Projekt Ariadne (FKZ 03SFK5A). Darius Sultani gratefully acknowledges additional funding from the Foundation of German Business (sdw). Katrin Sievert, Tobias S. Schmidt, and Bjarne Steffen gratefully acknowledge funding from the European Union Horizon 2020 research and innovation programme Marie Sklodowska-Curie (MSC) grant agreement No. 847585, the ETH Zurich ISTP Incubator program, the Swiss State Secretariat for Education, Research and Innovation (SERI) contract No. 22.00541, and the European Union Horizon Europe project PRISMA.

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