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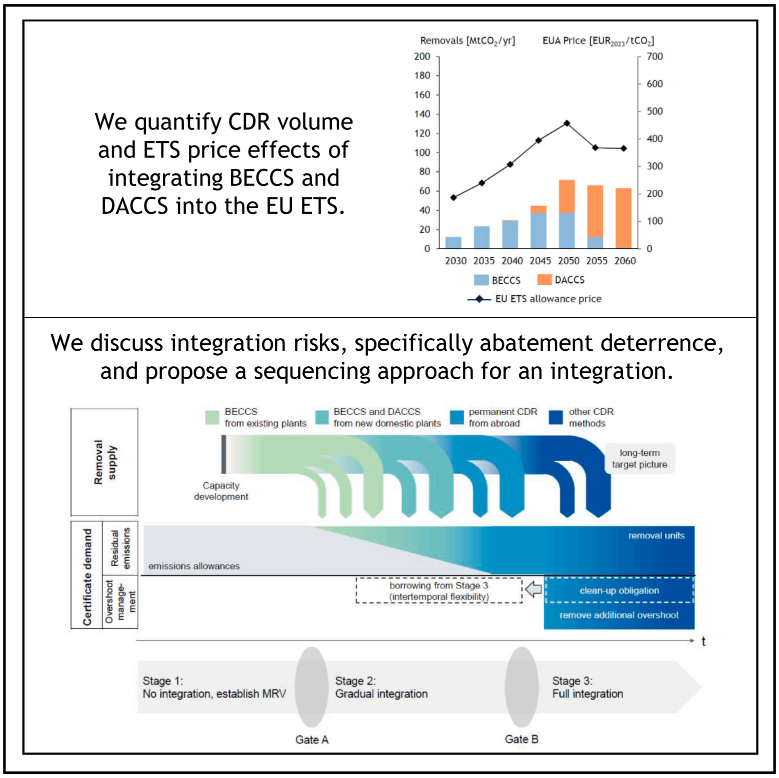
How the EU can utilize its carbon market to scale up carbon dioxide removal

Graphical abstract



Highlights

- Integrates recent DACCS cost projections into the EU ETS model LIMES-EU
- Evaluates CDR volume and ETS price effects of integrating BECCS and DACCS into the EU ETS
- Assesses integration risks and discusses abatement deterrence in an EU ETS context
- EU ETS could incentivize combined BECCS and DACCS volumes of 68–86 Mt CO_2/year by 2050

Authors

Darius Sultani, Sebastian Osorio, Claudia Günther, ..., Tobias S. Schmidt, Bjarne Steffen, Ottmar Edenhofer

Correspondence

sultani@pik-potsdam.de (D.S.),
tobiasschmidt@ethz.ch (T.S.S.)

In brief

Integrating permanent carbon dioxide removal into the EU emissions trading system offers financial certainty for investors and could therefore play a key role in scaling novel removal technologies. Model results suggest integration could incentivize removals of 68–86 Mt CO_2/year by 2050, provided that a sequencing approach safeguards environmental integrity.

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How the EU can utilize its carbon market to scale up carbon dioxide removal

Darius Sultani,[1,4,6,*] Sebastian Osorio,[1] Claudia Günther,[1] Michael Pahle,[1] Katrin Sievert,[2,3] Tobias S. Schmidt,[2,3,*] Bjarne Steffen,[2,3] and Ottmar Edenhofer[1,5]

[1]Potsdam Institute for Climate Impact Research, Potsdam, Germany
[2]Energy and Technology Policy Group, ETH Zurich, Zurich, Switzerland
[3]Albert Einstein School of Public Policy, ETH Zurich, Zurich, Switzerland
[4]Department for Sustainable Energy Transition, Europa-Universität Flensburg, Flensburg, Germany
[5]Technische Universität Berlin, Berlin, Germany
[6]Lead contact
*Correspondence: sultani@pik-potsdam.de (D.S.), tobiasschmidt@ethz.ch (T.S.S.)
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CONTEXT & SCALE The upcoming European Union (EU) emissions trading system (ETS) revision is set to determine the extent to which novel carbon dioxide removal (CDR) technologies will be integrated into the scheme. However, to date, quantitative analyses of (1) CDR volumes that could be incentivized by an integration as well as (2) the corresponding effects on EU ETS prices are lacking. Deploying the EU ETS model LIMES-EU with recent cost projections for direct air capture technologies, this study investigates how the integration of permanent CDR into the EU ETS could impact both the ramp-up of novel CDR technologies and EU ETS price dynamics in the years to come. By mid-century, an integration of CDR into the EU ETS could incentivize 68–86 Mt CO_2/year of bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS) combined. These volumes are sufficiently large to affect allowance prices, substantially moderating price spikes as the EU ETS cap tightens.

However, an integration also raises challenges. Over-reliance on expected future removals could undermine abatement if cost reductions fail to materialize, and low biomass prices could lead to excessive BECCS deployment with environmental impacts. These risks depend on technology learning, governance, and policy credibility over time. An integration of CDR into the EU ETS should begin with the target picture in mind (policy backward induction) and gradually build on the techno-economic and governance structures in place today (policy sequencing). Since the need for overshoot management will become more prevalent over the next decades, CDR integration should be seen as a starting point for transforming the ETS into a removals trading scheme in the long run. A reframing of the ETS "endgame" is therefore needed, and the system's long-term potential to incentivize negative emissions at a large scale needs to be highlighted.

SUMMARY

Novel carbon dioxide removal (CDR) technologies need to be ramped up rapidly to ensure the Paris goal can still be reached. Under the current geopolitical situation, many now expect the European Union (EU) to maintain and increase momentum in CDR deployment. While fiscal space is limited, the EU's emissions trading system (ETS) offers a unique opportunity to provide CDR investors with long-term financial certainty. At the same time, CDR integration into the EU ETS comes with risks that may prevent the EU from taking this step. Using the numerical EU ETS model LIMES-EU, we show that the EU ETS could incentivize 68–86 Mt/year of bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS) combined by 2050. We discuss abatement deterrence in the context of an ETS and propose a sequencing approach for integration, which could minimize integrity risk while providing long-term prospects for CDR to scale.

INTRODUCTION

The deployment of novel carbon dioxide removal (CDR) technologies needs to be accelerated quickly to keep any plausible pathway in line with the Paris Agreement, both to compensate for residual emissions and to manage overshoot.[1] Given current geopolitical developments, for now, the European Union (EU) remains one of the few players with a sufficiently ambitious climate policy to credibly ramp up CDR in the years to come. However, limited fiscal space suggests that dedicated support programs are unlikely to be implemented at the required scale. Yet integrating CDR into its compliance carbon market, the EU emissions trading system (ETS), might be an alternative.

Whether CDR integration into the EU ETS is indeed a viable and promising option depends on two controversial yet unresolved issues. First, integration bears environmental risks,[2,3] including a failure in scaling removals for techno-economic reasons[4,5] and the crowding-out of emission reduction efforts.[6,7] While the latter risk is sometimes referred to as "mitigation deterrence" in the literature, the IPCC considers CDR itself as a pillar of mitigation.[8] For preciseness, we therefore choose the term "abatement deterrence" instead. With negative experiences from opening up the EU ETS in the past for Kyoto credits,[9–12] policymakers are even more careful in safeguarding integrity. In addition, there is a risk that carbon markets incentivize removals at a scale that violates planetary boundaries,[13] including land competition between energy and food systems.[14] The second issue is whether integration actually provides a long-term prospect for CDR to play a role in the EU ETS, which is a prerequisite to creating long-term financial certainty for investors. This prospect is unclear because the cap in the EU ETS declines at a rate that implies that the last allowances will be issued around 2040, i.e., the entire system will practically "end" by then,[15] while some CDR players only expect to reach industrial scale later on. At the same time, novel CDR will be needed to achieve net-negative emissions in the long run. Integration would only be a long-term solution if the EU ETS were reformed in a way that allowed CDR to increasingly provide volume and liquidity to the market. How this could be done and what this would imply are all but clear, though.

With this work, we propose and analyze an approach that can resolve the controversies around these two issues. Compared with previous research on the topic, which is mainly conceptual, we contribute quantitative analysis and implementation considerations tailored to the EU context—both in terms of energy system integration and policy.[16–18] For the EU ETS context in particular, the size of effects on both the carbon price and levels of CDR deployment is unclear, and by extension, it is hard to assess which path is best suited to minimize risks. First, we establish a long-term prospect for CDR in the EU ETS, highlighting the instrument's ability to provide credible investment incentives. Second, we employ the numerical EU ETS (and energy system) model LIMES-EU to assess how an integration would impact CDR deployment and the functioning of the carbon market. We find that a direct integration of permanent CDR into the EU ETS could incentivize both bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS) deployment while cutting carbon prices in times of allowance scarcity post 2040. However, unconstrained integration comes at a risk for the environmental integrity of the EU's climate policy architecture, most notably from abatement deterrence and excessive biomass use. Lastly, we discuss ways to minimize these risks by developing a sequencing stage-gate approach, which aims to resolve the controversy by shaping the debate away from *whether* to integrate and toward *how* to integrate.

RESULTS

From emissions trading to removals trading in the very long run

For CDR integration to be a feasible option, the first main question that needs answering is whether there can be a long-term prospect for CDR in the ETS.[19] This is important because long-term financial certainty and corresponding incentives would set the EU ETS apart from voluntary carbon markets and national support measures, where frequent changes imply high uncertainty about future income streams. In fact, some observers have raised doubts about whether trading removals in the EU ETS could function economically and have proposed separate removals trading (or compliance) systems (RTS) instead.[20–22] Two particular concerns related to economic functioning are (1) that in the mid-term market prices might be too low to incentivize CDR deployment sufficiently early, and (2) that in the long term a shrinking ETS is not capable of incentivizing sufficient CDR to achieve a net-zero target post-2050 to which the EU has already committed itself in its Climate Law. If either of those concerns materializes, integration of CDR would likely not lead to the required scale up effect.

Yet these concerns neglect core economic features of trading CDR in the EU ETS, a system that allows the banking of certificates over time: CDR would essentially enter the market to efficiently balance hard-to-abate emissions. This implies that the market equilibrium price would be at the level where marginal abatement cost equals marginal removal cost. In anticipation of rising abatement costs, firms already have an incentive to invest in CDR technologies now if they expect future costs to be lower than costs for decarbonizing hard-to-abate emissions. In the very long term, the carbon market could be transformed from an ETS into an RTS for managing overshoot by switching the role of buyers and sellers in the market: governments would start to buy allowances from private suppliers, who receive a removal allowance for each unit (ton) of CDR supplied. This could also be combined with a borrowing of future removals.[23] The corresponding phases are depicted in the "tilted hourglass" in Figure 1, in which the EU ETS is given an "afterlife" as an RTS instead of closing the market after its endgame in the 2040s.

Importantly, it must not necessarily be governments who buy removal allowances in phase 3. Alternatively, removal obligations or liabilities could be put, for example, on regulated emitting companies,[23–25] fossil fuel producers, or fossil fuel importers. However, once the EU has reached net-zero, such an obligation would be hard to impose since only a few companies might be left as residual emitters, and the production or import of fossil fuels is very limited. While the question of who has to buy or pay for removal allowances is of distributional relevance, it

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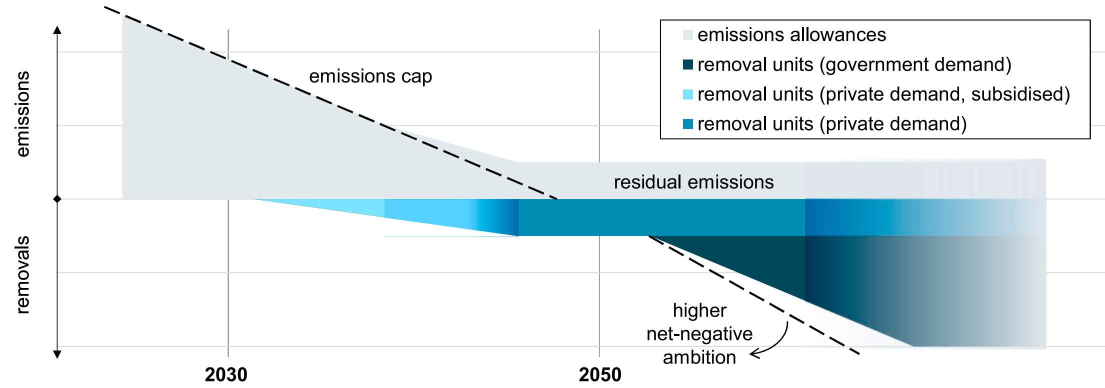

	Phase 1: Road to net-zero	Phase 2: Net-zero	Phase 3: Overshoot management
Net emissions	>0	0	<0
Certificate supply	• government • removal firms (permanent)	• removal firms	• removal firms
Certificate demand	• emitters (all)	• emitters (residual)	• government • emitters (residual)

Figure 1. Illustration of transition from ETS to RTS

In the very long run, the ETS can be transformed into an RTS to predictably scale up demand for removals via governmental CDR targets. This approach, which takes the shape of a tilted hourglass, provides investors with long-term certainty. While the government is responsible for the supply side of emission allowances during phase 1, it determines demand for removal units during phase 3.

should be separated from the general market mechanism and functioning (selling and buying of removal allowances).

Having endorsed the tilted hourglass as a target picture, the next question is to what extent an integration into the EU ETS would actually scale up CDR (volume and technologies). We address this question in the following section, focusing on phase 2 (net-zero target) as the current legislation in place. In that regard, it is important to note that the volume may increase considerably contingent on a future merger of the existing EU ETS and the new ETS for buildings, transport, and smaller industries (ETS II) to be commenced in 2027.

Carbon market integration can incentivize substantial deployment of permanent CDR

On the surface, current carbon price levels (in the range of 50–100 EUR/ton CO_2 during 2022–2024) appear to be too low to incentivize the deployment of costly technologies like BECCS and DACCS. However, two important dynamic effects need to be considered. First, removal costs will decrease with increased deployment in the future, due to technological learning and economies of scale. This can be expected for DACCS in particular, notwithstanding that uncertainty remains on how cost curves are going to develop.[26] In fact, recent news from a leading developer suggests that learning and cost reduction might be slower than expected,[27] implying a more important role for BECCS, at least in the near future. Second, upon integration, CDR firms will invest according to the anticipated carbon price increase over time. In that sense, it is primarily the expectations on future CDR costs and carbon prices—rather than current costs and prices—that determine the ETS's ability to scale up CDR.

In order to (1) assess the extent to which a CDR integration into the EU ETS could incentivize removals and to subsequently (2) quantify how pertinent risks of such an integration would be, we use the numerical EU ETS model LIMES-EU. We utilize DACCS cost estimates by Sievert et al.,[26] who have developed cost projections as a function of deployment by analyzing multi-component experience curves of pioneering DAC plants. We then account for transport and storage costs and apply projected technology shares to global deployment scenarios[28] to derive two additional DACCS cost scenarios over time. For BECCS, biomass prices are taken from the integrated assessment model (IAM) REMIND,[29] which reflects price formation driven by demand from various sectors. We report the levelized cost of removals for BECCS and DACCS investment in LIMES-EU in Figure S2.

Modeling results suggest that EU ETS integration could lead to substantial deployment of BECCS and DACCS, though actual removal volumes depend on the cost-effectiveness of CDR vis-à-vis abatement (Figure 2). In the default scenario, overall permanent CDR deployment under the EU ETS stabilizes at around 60 Mt CO_2 per year from 2050 onward. This is the amount required to compensate for residual emissions from industry, which are more costly to abate than to remove. Depending on the relative cost between abatement and removals, we find that the EU ETS can incentivize between 21% and 75% of the required BECCS and DACCS volumes for 2050 as estimated by the European Scientific Advisory Board on Climate Change.[30] Subsequently, an integration can pave the way for achieving full scalability later on as the EU ETS is transformed into an RTS with negative emissions targets.

In addition, integrating permanent CDR into the EU ETS effectively moderates long-term carbon prices in the model. Compared

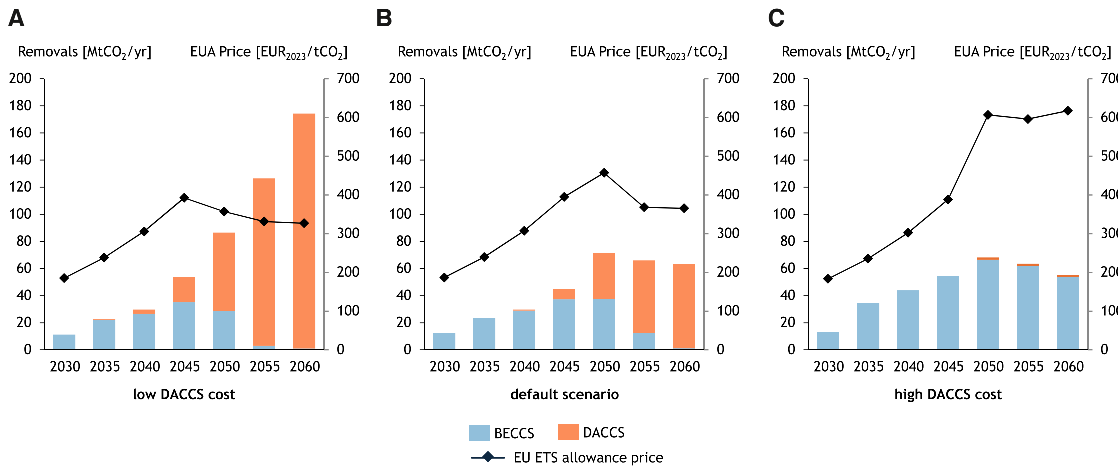

Figure 2. CDR deployment for phase 2 (net-zero) in the EU ETS and respective allowance prices for 2030 to 2060
The center panel shows our default scenario, and the left (right) represents more (less) global DACCS deployment and, therefore, lower (higher) DACCS cost. In scenarios with low to moderate DACCS cost (A and B), the CDR integration incentivizes the ramp-up of BECCS deployment first, which is then crowded out by DACCS from the late 2040s onward. When DACCS costs are high (C), residual emissions remain stable but are almost fully compensated by BECCS. The EUA price is sensitive to higher DACCS costs (C) but robust when DACCS costs are lower than in the default scenario. Gross residual emissions increase substantially when DACCS costs are low.

with a counterfactual without CDR in the market, a direct BECCS and DACCS integration roughly halves EU ETS prices post-2050 (Figure 3). Due to allowance banking, moderate carbon price effects are also observed in the near- to mid-term already. These effects are mainly driven by expected DACCS costs since, in the long run, biomass is too costly to compete with industry abatement in our default scenario. In that sense, DACCS serves as a pressure valve to the system. This is highlighted by Figures 2A and 2C, where deployment volumes in the EU ETS change according to changes in relative cost between BECCS, DACCS, and industrial abatement measures.

Cost/price and environmental risks must be accounted for when designing the integration

An important concern related to CDR integration into the EU ETS is that firms expect low (future) CDR costs and hence invest less in abatement measures today. If expectations turn out to be overly optimistic, too little abatement investment has occurred in hindsight during the early integration phase. As a consequence, there will be less CDR in the market than expected, and a risk of high carbon prices may materialize. The longer it takes for firms to align their expectations with the true cost of removals, the more serious an EU ETS supply shortage may become. This risk is illustrated by Figure 4A, where an update of DACCS cost expectations in 2040 not only leads to a spike in carbon prices but also to a sharp increase in biomass demand to compensate for residual emissions.

A second prominent concern is the risk of excessive biomass use to generate removals.[31] Given the high value of biogenic carbon relative to the cost of biomass,[32] this can lead to sustainability challenges. This risk is increased by a lack of Pigouvian pricing of environmental externalities (notably carbon) in the land use and forestry sectors. In consequence, this leads to an over-reliance on BECCS as it becomes more profitable to generate an EU ETS allowance from biomass. The risk of excessive biomass use is illustrated by Figure 4B. If biomass costs turn out to be 30% lower than in our default scenario as estimated from REMIND, DACCS is pushed out of the EU ETS and fully replaced by BECCS in our model. In addition, the ramp-up of CDR is shifted forward in time, with an addition of almost 40 Mt of annual removals in the 2040s compared with the default scenario. The long-run equilibrium volume of CDR in the EU ETS remains stable in this case.

Both of these risks could become exacerbated when they are instrumentalized by actors with vested interests. To a certain degree, this could already be observed during the EU 2040 climate target negotiations: while the majority of stakeholders in the public consultation spoke out in favor of a separate CDR target to safeguard the policy architecture, the European Commission ended up recommending a single net 2040 target instead—arguably to simplify regulation, but also more in line with positions expressed by incumbent fossil and hard-to-abate industries.[33] Such strategic interventions could give rise to abatement deterrence risk, which we discuss in the following.

Abatement deterrence in the EU ETS context

Abatement deterrence has been widely recognized as a risk of CDR[7,8] and broadly entails three mechanisms: (1) substitution and failure, which refers to a situation in which expected CDR volumes directly substitute emissions reductions but are then not delivered later on; (2) unintended rebound effects; and (3) mitigation foregone, meaning expectations on CDR lead to a reduction in abatement efforts that goes beyond a direct substitution as entailed in the first mechanism.[6] Since within-ETS abatement deterrence by definition requires a direct substitution of an emissions allowance with a removal certificate, substitution and failure is the only applicable mechanism. Abatement deterrence effects outside the ETS, on the other hand, could generally

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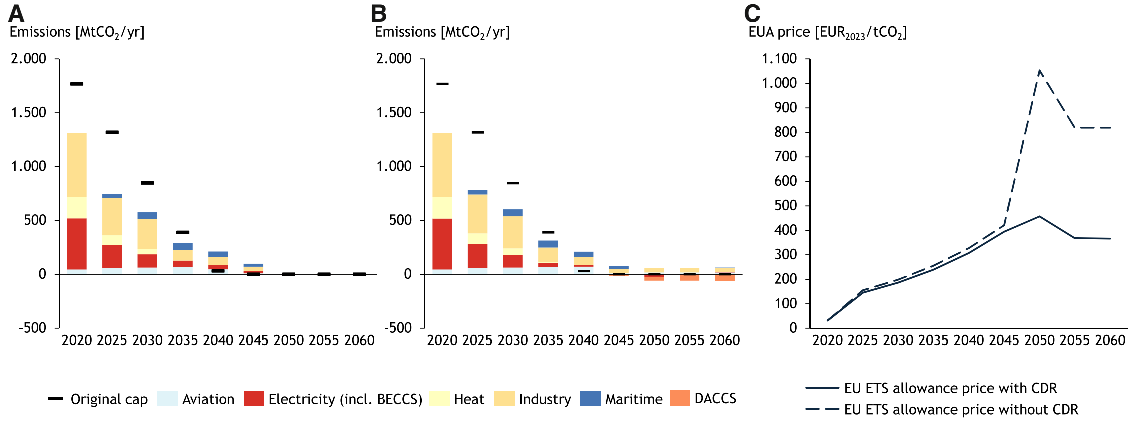

Figure 3. ETS emissions by sector and resulting carbon prices with (i.e., the default scenario) and without CDR integration from 2020 to 2060

(A) EU ETS sector emissions without CDR integration.

(B) EU ETS sector emissions with direct integration of BECCS and DACCS.

(C) EU ETS prices with and without CDR integration.

(A) and the dashed line in (C) represent the counterfactual scenario without CDR integration. (B) and the solid line in (C) show results with first-best CDR integration from 2030 onward. BECCS is visualized as part of the electricity sector, and banking of EU ETS certificates is permitted only until 2045.

occur as rebounds or mitigation foregone. We therefore discuss within- and outside-ETS abatement deterrence separately.

Starting with the within-system effects, in principle and under basic premises, the ETS's cap on emissions generally rules out abatement deterrence even in the case of substitution and failure. This is for two reasons: first, our results imply that actual substitution will likely be limited because the vast majority of industrial abatement measures remain more cost-effective than procuring high-quality and permanent CDR. Second, even if CDR substitution occurs ex-ante and then fails, as long as the emissions budget in the form of the cap is retained, the ETS's waterbed effect—in this case, through increased allowance scarcity and hence higher carbon prices—would result in more emissions reductions elsewhere in the system such that the overall emissions target will still be met. The only remaining factor that could then, under basic premises, lead to an increase in cumulative net emissions compared with no integration is the EU ETS's Market Stability Reserve (MSR). We find, however, that virtually all MSR invalidations occur before CDR enters the compliance market. As a result, we only expect a negligible impact of MSR activity on the emissions outcome with CDR integration (see Note S3 and Figure S3 for further discussion).

Nevertheless, beyond those basic premises, abatement deterrence could still occur within the EU ETS despite the fact that emissions are capped. This is because the cap might be softened when allowance prices surpass politically acceptable levels.[34] If firms expect low CDR costs now but those cost reductions will not materialize in the future, the price will rise more strongly (Figure 4A), making a softening intervention more likely. The risk of CDR-cost shocks is even higher when credible information about future CDR costs remains private and is used strategically. As it stands, there is little public knowledge about the long-term costs of CDR, and firms may have an interest in deliberately abating less or communicating biased estimates to attract investors and subsidies. In a cap-and-trade context, substitution and failure, hence, become a problem if two failure components occur jointly, namely a strategic exploitation of information asymmetries (market failure) and a materialization of the regulator's commitment problem (policy failure) in the sense that policymakers change the emissions budget upward. Since such an intervention would have ramifications for the wider policy architecture, it would not only put the ETS's ability to scale up CDR at risk but could also imply indirect abatement deterrence through mitigation foregone outside of the ETS's scope.

Moving on to effects outside the ETS, we identify rebounds in land use sectors as the central abatement deterrence mechanism to account for. The integration of BECCS (or removal through biochar, which we do not model) into the ETS would create incentives to use biomass at scale for ETS compliance. In addition, biomass-based CDR methods are likely going to be strategically instrumentalized as well.[35] Biomass is subject to several conflicting interests, implying that the process of setting standards and certification is prone to regulatory capture. Under high carbon prices specifically, strategic lobbying could lead to a situation in which sustainability criteria are weakened and biomass becomes more widely available at low cost (Figure 4B). In consequence, more biomass would be used than what would be socially efficient, and corresponding sinks, such as peatland and long-standing forests, would be depleted.[6] For the remaining abatement deterrence channels outside of the ETS, both rebounds and mitigation foregone, the degree to which such mechanisms pose a risk depends on whether or not the affected rebounding or foregoing activity will be covered by a cap-and-trade system going forward. As soon as the EU ETS II comes into effect, roughly 75% of EU emissions will be subject to quantity-controlled carbon pricing in the long run.[36] In line with the arguments already made, the EU ETS extension will hence shift many of those instances we would consider as rebounds or mitigation foregone today into the within-ETS category above. The risk of indirect abatement deterrence will then remain highest for those sectors that will remain outside of the EU ETS's scope, mostly

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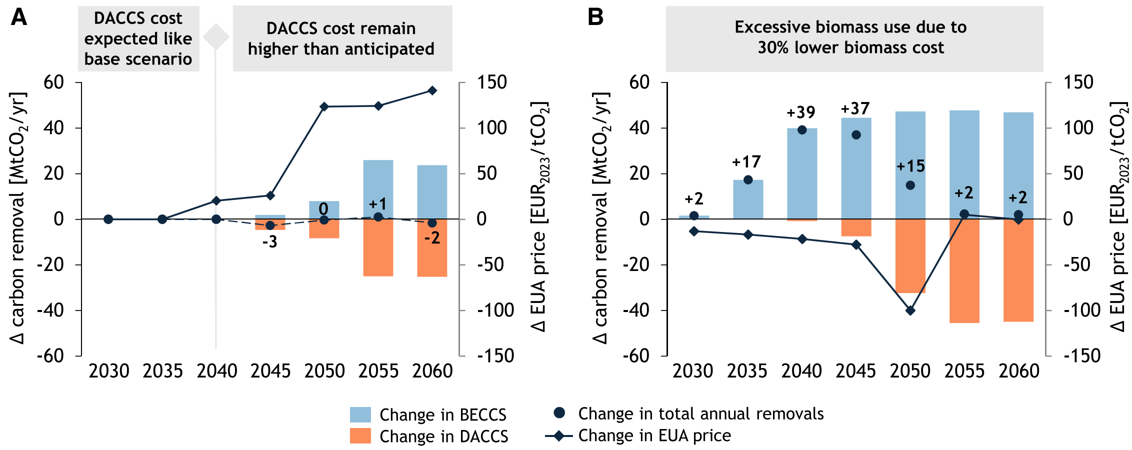

Figure 4. CDR-cost shock and excessive biomass use pose cost/price and environmental risks of an integration

Illustration of a CDR-cost shock and excessive biomass use through changes in removal deployment and carbon prices relative to the default scenario when DACCS learning effects do not materialize as expected or when biomass costs are lower.

(A) Changes in annual removals assuming expected DACCS cost reductions do not materialize. Using a rolling-horizon version of LIMES-EU, we illustrate this effect with a sudden upward adjustment of DACCS cost by 2040.

(B) Changes in annual removals resulting from excessive biomass use (due to a 30% reduction in biomass costs).

agriculture, LULUCF (as discussed), and international aviation and maritime.

In light of these risks, critics have argued to "firewall" the EU ETS from CDR integration.[20,37] However, this not only omits the potentials of an integration as outlined above, but also neglects that both identified risks can be increasingly mitigated over time as technology and policy learning progress. In the following, we map out a sequential stage-gate approach to put such CDR integration into action, aiming to inform EU policymakers on upcoming integration decisions. As a matter of fact, the decision whether to integrate CDR into the EU ETS is imminent. Article 5a of the EU ETS Directive requires the European Commission to report on "how negative emissions […] could be covered by emissions trading, if appropriate" by 2026, particularly highlighting "safeguards to ensure that such removals do not offset necessary emissions reduction."[38]

Sequencing enables a long-term prospect for CDR while safeguarding environmental integrity

The approach we propose follows a simple logic: policy sequencing. Here, sequencing comes down to integrating CDR into the EU ETS in successive phases, in which safeguards are put in place first but lifted more and more as new risk-reducing technology and policy arrive.[39,40] Building on three governance stages previously developed,[41] we propose a stage-gate model as outlined in Figure 5 for integrating CDR into the EU ETS.

Managing integration risk implies that the sequencing path starts with a first preparatory phase with no integration. In the EU, the first steps of this stage have already been completed. The Carbon Removal and Carbon Farming (CRCF) Regulation offers a starting point for the certification of removal units.[17] In 2023, more than 200 Mt of biogenic CO_2 emissions were already covered by the EU ETS.[42] Stage 1 is used to improve rules on the certification of CDR units, and sustainability criteria and accounting guidance for CDR are further developed.[41] During this phase, the government can implement demand-side policies to incentivize initial CDR capacities. Gate A to stage 2 unlocks when the monitoring, reporting, and verification (MRV) architecture is in place, when questions on certification and sustainability of removals have been addressed, and when the MSR has been reformed to account for the integration of removal units into the system.

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 domestic plants, and finally to international removal units (i.e., from outside the EU). Gradual integration in volumes means setting limits on the inflow of CDR credits into the ETS. Gradual integration in time refers to considering employing intertemporal flexibility by allowing borrowing from removals that are only delivered later on. Since such an intertemporal mechanism would institutionalize the expectation of future CDR substituting for present emissions (and hence be subject to considerable abatement deterrence risk), additional measures—such as collateral to address risks of bankruptcy or reversal—would be required.[23] In addition, stage 2 is used to strengthen the governance regime against reversal risk, i.e., against incidents where CO_2 is unintentionally re-released into the atmosphere.[41] As soon as excessive biomass use and reversal risks are sufficiently contained, the architecture is ready to be developed toward stage 3.

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 be fully brought into the system as activities under the scope of the ETS. When their full integration has proven successful, the option of admitting other CDR methods should be assessed to achieve full supply-side efficiency. If liability risks for those removals have been sufficiently contained

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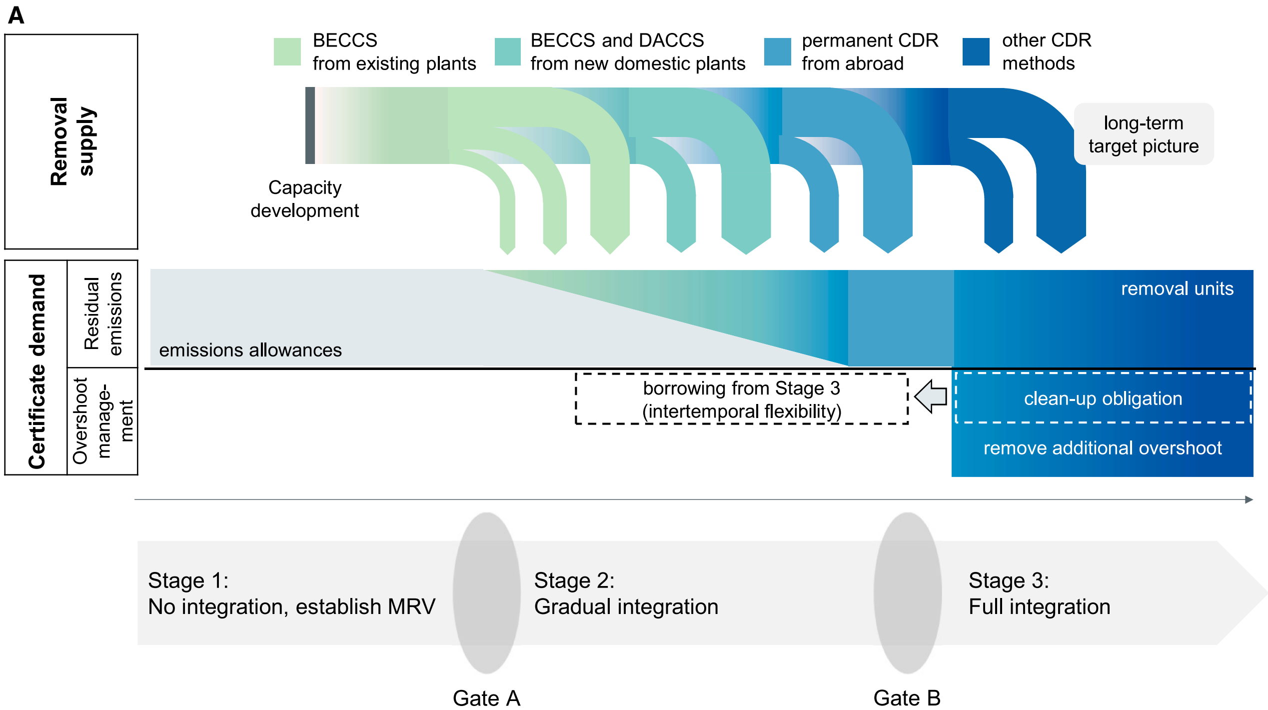

B

	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 • Regulatory framework for long-term target picture in place (major architectural decisions required)
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)

Figure 5. Stage-gate approach with three governance stages of integrating removals into the EU ETS

Building on Burke and Schenuit,[41] 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 (B)—have to be fulfilled. From stage 2 onward, 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 materializes upon integration of international and temporary removals. Borrowing from future removals provides intertemporal flexibility. This could be realized through clean-up certificates, which come with a clean-up obligation for the overshoot emitted.[23]

during stage 2, a stepwise integration of temporary removal units could then bridge the gap until the long-term target picture fully materializes. The architecture is then ready to be developed toward implementing a net-negative emissions strategy.

DISCUSSION

Sequencing can create a long-term financing perspective for CDR in the EU while safeguarding against integration risk. To successfully put it into action, three design choices for a gradual integration are central and require more discussion and research.

First, more clarity is needed as to whether price or volume limits should be used in stage 2. Volume limits seem preferable because they are administratively easier to implement. However, if the supply of cost-competitive, high-integrity CDR turns out higher than the set limit, inefficiencies arise. Further research is therefore required on how to design flexible volume limits that can adapt to CDR ramp-up while addressing efficiency concerns. Carbon market linking—where similar questions arise—can serve as a starting point.[43]

The second design choice concerns market access, i.e., the extent to which limited integration should be specific with respect to CDR methods and technologies. This choice comes with distributional implications since, with a limited integration in particular, rights to sell into the EU ETS would have to be allocated between suppliers/technologies. There is a case for specific quotas as long as the LULUCF sector lacks efficient carbon pricing to contain the risk of excessive biomass use.[44] In

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addition, technology-specific quotas can target the deployment of yet immature (and costly) CDR technologies to promote learning and cost reductions for a variety of technologies. CDR quotas could also be used to address regional distributional issues, for instance, to ensure that not all BECCS originates from Northern Europe, the current leader in this field.[45] Setting quotas at an efficient level is challenging, though, and requires further research.

Third, international permanent CDR certificates could bear potential for both cost-effectiveness and international cooperation. Agreements on a 5% contribution of international carbon credits toward the EU's 2040 target in both the European Council and the European Parliament have opened the door for this discussion, but it is clear that further work is required to safeguard environmental integrity.[46] In principle, the EU could take a similar approach for international as for domestic permanent CDR. This would offer the opportunity to scale up international CDR markets beyond domestic targets and foster cooperation. However, resulting questions about how EU (ETS) MRV standards can safely be applied to international CDR as well as about how emissions accounting should address internationally traded certificates remain. In this context, we expect institutional considerations, such as around a European Carbon Central Bank,[47–49] to gain further traction in the debate. Both economic and institutional issues therefore warrant more scientific attention and discussion.

METHODS

Scenario implementation in LIMES-EU

LIMES-EU is a linear EU ETS model that optimizes investment and operational decisions for generation, storage, and transmission technologies in the power sector, as well as CDR and emission reduction options in energy-intensive industries, aviation, and maritime. In combination with its detailed representation of emissions allowances supply (in accordance with the EU ETS cap) and banking, the model is able to report carbon prices endogenously, making it one of the leading EU ETS models to date. The model has been widely used in academic policy analysis concerning the EU ETS.[15,34,50] It includes all EU countries (except Cyprus and Malta), five Balkan countries aggregated in one region, Norway, Switzerland, and the United Kingdom. Using a 5-year step intertemporal optimization from 2010 to 2070 in the configuration with a single time horizon, LIMES-EU allows analysis of cost-efficient future scenarios for the ETS I. For investment decisions, the model operates under the assumptions of perfect foresight and applies a discount rate of 5%. In this work, a second configuration with two subsequent time horizons[50] was used to illustrate the update in DACCS cost expectations. Key functions and features of LIMES-EU include a detailed representation of the power sector, while other sectors covered by the EU ETS, such as the energy-intensive industry, aviation, and maritime sectors, are represented by marginal abatement cost curves. LIMES depicts the emissions for all EU ETS sectors and is calibrated to historical EU ETS emissions, including the demand and supply of emission allowances (cap). It also considers the banking of emission certificates between periods.

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. The stationary cap reaches zero by 2039. The aviation cap, although substantially smaller than the stationary one, will reach zero in 2044. Given the time granularity in the model, EU allowance (EUA) trading is allowed until 2045 (which represents the period from 2043 to 2047). 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 a 62% emission reduction w.r.t. 2005. This is operationalized through a linear reduction factor (LRF) of 4.3% in 2024–27 and 4.4% as of 2028, and an 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 downward (upward) 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 (1) the intake rate (24% prolonged until 2030 and 12% afterward), (2) the thresholds (a lower threshold of 400 million EUA, an upper TNAC threshold of 833 million EUA, and a buffer threshold of 1,096 million EUA), (3) outtake volume (100 million EUA), and (4) invalidation threshold (EUA in the MSR over 400 million EUA). The intake volume is equal to the intake rate times TNAC if TNAC exceeds the buffer threshold, else to TNAC minus the upper threshold if TNAC is between the upper and buffer thresholds. We also represent the UK ETS, for which a cap is defined until 2030 and extrapolated afterward. We do not represent sectoral expansions or links between the EU ETS and UK ETS or to other markets. For a comprehensive description of the model, we refer the reader to the LIMES-EU documentation.[51]

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 assumption that emissions and permanent removal certificates are fully fungible, hence allowing equivalence between marginal abatement and marginal permanent removal cost (see Note S1 and Figure S1 for further discussion). In other words, the permanent CDR technologies deployed in the model generate removal units within the EU ETS directly, and for every ton of CO_2 removed, an EUA is generated.

Carbon prices are calculated endogenously in LIMES-EU. Without CDR in the model, the carbon price ceiling is determined by the 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 emission allowances and technological abatement options, the removal option will be drawn. Bringing the new cost data for CDR into LIMES-EU, hence, allows us to assess whether we can expect a carbon price curb due to CDR-cost reductions at all and, if so, whether it will come into effect in time to affect the EU 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.

From the representative year of 2030 (i.e., between 2028 and 2032) onward, the model can endogenously deploy 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. Techno-economic assumptions for BECCS installations are adopted from the EU Commission's Reference Scenario 2020.[52] In this paper, we consider maximum biomass potentials based on the ENSPRESO database[53] and the 2040 climate targets Impact Assessment,[54] which are scaled based on the historic use of biomass in the power sector.[55] An emission factor of −550 $kgCO_2/MWh_{elec}$ for BECCS is assumed, and exogenous biomass price assumptions are taken from the IAM REMIND.[29] These exogenous assumptions are necessary since LIMES-EU only covers EU ETS I sectors, whereas both biomass supply and demand are mainly driven by sectors outside of that scope. REMIND reflects price formation driven by demand from multiple sectors (particularly energy, industry, and transport, such as global aviation/shipping), as well as biomass supply.

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.[57] 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.,[26] who conducted a bottom-up calculation of these costs for pioneering DAC plants, including CO_2 transport and storage[26] 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.,[28] we derive cost pathways over time for each technology. DACCS CAPEX and fixed O&M consequently decrease by 41%–58% and variable O&M by 18% between 2030 and 2050. These pathways are subsequently incorporated into LIMES-EU to assess the influence of carbon pricing on DACCS deployment within the EU ETS.

Due to the early-stage nature of permanent removal technologies, future cost estimations are subject to considerable uncertainty. This uncertainty can lead 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 to 0.02 $GtCO_2$/year in 2030 to 0.52–1.74 $GtCO_2$/year in 2050, according to a review study.[1] Assuming that cost reductions will indeed be driven by global deployment, we reflect the technology uncertainty in DACCS cost by incorporating three different deployment scenarios. For short-term DACCS deployment between 2020 and 2025, we base 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 IAMs, specifically a review by Grant et al.[28] To derive three scenarios with low, medium (base), and high global DACCS deployment, respectively, we use the 5^{th}, 50^{th}, and 95^{th} 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.[26] According to our calculations, if global DACCS deployment is high, CAPEX and fixed O&M are 24%–37% lower, and variable O&M is 10% lower by 2050 than in our default scenario. If global DACCS deployment is low, CAPEX and fixed O&M are 50%–100% higher, and variable O&M is 17% higher by 2050 than in our default scenario.

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Darius Sultani (sultani@pik-potsdam.de).

Materials availability

This study did not generate any new materials.

Data and code availability

- All information and equations of the EU ETS model LIMES-EU are publicly available in the model documentation.[51]
- All results have been deposited at Zenodo under the DOI 10.5281/zenodo.17643836 and are publicly available as of the date of publication.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

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AUTHOR CONTRIBUTIONS

Conceptualization, D.S., M.P., T.S.S., and B.S.; methodology and software, S.O., K.S., D.S., and C.G.; investigation, D.S., S.O., C.G., M.P., K.S., T.S.S., and B.S.; visualization, D.S., S.O., and K.S.; writing – original draft, D.S., S.O., M.P., and K.S.; writing – review and editing, D.S., M.P., K.S., T.S.S., B.S., and O.E.; funding acquisition, M.P., T.S.S., B.S., and O.E.; supervision, M.P., T.S.S., B.S., and O.E.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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REFERENCES

1. Babiker, M., Berndes, G., Blok, K., Cowie, A., Geden, O., Ginzburg, V., Leip, A., Smith, P., Sugiyama, M., and Yamba, F. (2023). Cross-sectoral perspectives. In Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, P. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, R. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, and J. Malley, eds. (Cambridge University Press), pp. 295–408. https://doi.org/10.1017/9781009157926.005.
2. Burke, J., and Gambhir, A. (2022). Policy incentives for Greenhouse Gas Removal Techniques: the risks of premature inclusion in carbon markets and the need for a multi-pronged policy framework. Energy Clim. Change *3*, 100074. https://doi.org/10.1016/j.egycc.2022.100074.
3. Anderson, K., Buck, H.J., Fuhr, L., Geden, O., Peters, G.P., and Tamme, E. (2023). Controversies of carbon dioxide removal. Nat. Rev. Earth Environ. *4*, 808–814. https://doi.org/10.1038/s43017-023-00493-y.
4. Galán-Martín, Á., Vázquez, D., Cobo, S., Mac Dowell, N., Caballero, J.A., and Guillén-Gosálbez, G. (2021). Delaying carbon dioxide removal in the European Union puts climate targets at risk. Nat. Commun. *12*, 6490. https://doi.org/10.1038/s41467-021-26680-3.
5. Nemet, G.F., Gidden, M.J., Greene, J., Roberts, C., Lamb, W.F., Minx, J.C., Smith, S.M., Geden, O., and Riahi, K. (2023). Near-term deployment of novel carbon removal to facilitate longer-term deployment. Joule *7*, 2653–2659. https://doi.org/10.1016/j.joule.2023.11.001.
6. McLaren, D. (2020). Quantifying the potential scale of mitigation deterrence from greenhouse gas removal techniques. Clim. Change *162*, 2411–2428. https://doi.org/10.1007/s10584-020-02732-3.
7. Grant, N., Hawkes, A., Mittal, S., and Gambhir, A. (2021). Confronting mitigation deterrence in low-carbon scenarios. Environ. Res. Lett. *16*, 064099. https://doi.org/10.1088/1748-9326/ac0749.
8. Carton, W., Hougaard, I.M., Markusson, N., and Lund, J.F. (2023). Is carbon removal delaying emission reductions? WIREs Clim. Change *14*, e826. https://doi.org/10.1002/wcc.826.
9. Wara, M. (2007). Is the global carbon market working? Nature *445*, 595–596. https://doi.org/10.1038/445595a.
10. Gillenwater, M., and Seres, S. (2011). The Clean Development Mechanism: a review of the first international offset programme. Greenhouse Gas Meas. Manag. *1*, 179–203. https://doi.org/10.1080/20430779.2011.647014.
11. He, G., and Morse, R. (2013). Addressing carbon Offsetters' Paradox: Lessons from Chinese wind CDM. Energy Policy *63*, 1051–1055. https://doi.org/10.1016/j.enpol.2013.09.021.
12. Cames, M., Harthan, R.O., Füssler, J., Lazarus, M., Lee, C.M., Erickson, P., and Spalding-Fecher, R. (2016). How additional is the Clean Development Mechanism? Analysis of the application of current tools and proposed alternatives. Tech. Rep. CLIMA.B.3/SERI2013/0026r Öko-Institut e.V. Berlin. https://www.verifavia.com/uploads/files/clean_dev_mechanism_en.pdf.
13. Cobo, S., Negri, V., Valente, A., Reiner, D.M., Hamelin, L., Dowell, N.M., and Guillén-Gosálbez, G. (2023). Sustainable scale-up of negative emissions technologies and practices: where to focus. Environ. Res. Lett. *18*, 023001. https://doi.org/10.1088/1748-9326/acacb3.
14. Turner, P.A., Field, C.B., Lobell, D.B., Sanchez, D.L., and Mach, K.J. (2018). Unprecedented rates of land-use transformation in modelled climate change mitigation pathways. Nat. Sustain. *1*, 240–245. https://doi.org/10.1038/s41893-018-0063-7.
15. Pahle, M., Quemin, S., Osorio, S., Günther, C., and Pietzcker, R. (2025). The emerging endgame: The EU ETS on the road towards climate neutrality. Resour. Energy Econ. *81*, 101476. https://doi.org/10.1016/j.reseneeco.2024.101476.
16. Rickels, W., Proelß, A., Geden, O., Burhenne, J., and Fridahl, M. (2021). Integrating carbon dioxide removal into European emissions trading. Front. Clim. *3*, 690023. https://doi.org/10.3389/fclim.2021.690023.
17. Fridahl, M., Schenuit, F., Lundberg, L., Möllersten, K., Böttcher, M., Rickels, W., and Hansson, A. (2023). Novel carbon dioxide removals techniques must be integrated into the European Union's climate policies. Commun. Earth Environ. *4*, 459. https://doi.org/10.1038/s43247-023-01121-9.
18. Burke, J., and Schenuit, F. (2024). Conditional fungibility: sequencing permanent removals into emissions trading systems. Environ. Res. Lett. *19*, 111002. https://doi.org/10.1088/1748-9326/ad796b.
19. Dolphin, G., Pahle, M., Burtraw, D., and Kosch, M. (2023). A net-zero target compels a backward induction approach to climate policy. Nat. Clim. Change *13*, 1033–1041. https://doi.org/10.1038/s41558-023-01798-y.
20. Meyer-Ohlendorf, N. (2023). Making carbon removals a real climate solution. How to integrate carbon removals into EU Climate Policies. Tech. Rep. (Ecologic Institute) https://www.ecologic.eu/19290
21. Battersby, F., Guidi, M., Baxter, A., and Selén, V. (2025). From targets to tonnes: exploring compliance options to drive lasting demand for carbon removals in the EU. Tech. Rep. Carbon Gap. https://carbongap.org/wp-content/uploads/2025/10/RCS-policy-paper_layout-2.pdf.
22. Zetterberg, L., and An, E.U. (2025). Removals target and trading system (RTTS) for carbon dioxide – Concept paper for discussion. Tech. Rep. C10061 (Swedish Environmental Research Institute). https://ivl.diva-portal.org/smash/get/diva2:1962407/FULLTEXT01.pdf.
23. Lessmann, K., Gruner, F., Kalkuhl, M., and Edenhofer, O. (2026). Emissions trading with clean-up certificates: How carbon debt can increase climate ambition levels. J. Environ. Econ. Manag. *137*, 103307. https://doi.org/10.1016/j.jeem.2026.103307.
24. Bednar, J., Macinante, J., Baklanov, A., Hall, J.W., Wagner, F., Ghaleigh, N.S., and Obersteiner, M. (2024). Beyond emissions trading to a negative carbon economy: a proposed carbon removal obligation and its implementation. Clim. Policy *24*, 501–514. https://doi.org/10.1080/14693062.2023.2276858.
25. Lyngfelt, A., Fridahl, M., and Haszeldine, S. (2024). FinanceForFuture: Enforcing a CO2 emitter liability using atmospheric CO2 removal deposits (ACORDs) to finance future negative emissions. Energy Res. Soc. Sci. *107*, 103356. https://doi.org/10.1016/j.erss.2023.103356.
26. Sievert, K., Schmidt, T.S., and Steffen, B. (2024). Considering technology characteristics to project future costs of direct air capture. Joule *8*, 979–999. https://doi.org/10.1016/j.joule.2024.02.005.
27. Niranjan, A. (2025). Swiss firm that captures carbon from air to cut workforce by more than 10%. The Guardian. https://www.theguardian.com/environment/2025/may/17/swiss-firm-that-captures-carbon-from-air-to-cut-workforce-by-more-than-10.
28. Grant, N., Hawkes, A., Mittal, S., and Gambhir, A. (2021). The policy implications of an uncertain carbon dioxide removal potential. Joule *5*, 2593–2605. https://doi.org/10.1016/j.joule.2021.09.004.
29. Strefler, J., Kriegler, E., Bauer, N., Luderer, G., Pietzcker, R.C., Giannousakis, A., and Edenhofer, O. (2021). Alternative carbon price trajectories can avoid excessive carbon removal. Nat. Commun. *12*, 2264. https://doi.org/10.1038/s41467-021-22211-2.
30. European Scientific Advisory Board on Climate Change (2025). Scaling up carbon dioxide removals: Recommendations for navigating opportunities and risks in the EU. Tech. Rep. European Environment Agency LU. https://data.europa.eu/doi/10.2800/3253650.
31. Rasmussen, M.B., and Vermeulen, H. (2024). Towards a sustainable deployment of BioCCS in the EU. CONCITO. https://concito.dk/en/udgivelser/towards-a-sustainable-deployment-of-bioccs-in-the-eu.
32. Millinger, M., Hedenus, F., Zeyen, E., Neumann, F., Reichenberg, L., and Berndes, G. (2025). Diversity of biomass usage pathways to achieve

emissions targets in the European energy system. Nat. Energy *10*, 226–242. https://doi.org/10.1038/s41560-024-01693-6.

33. Brad, A., and Schneider, E. (2025). Carbon removal, mitigation deterrence and the politics of target separation. Evidence from the EU 2040 climate target negotiation. Environ. Res. Lett. *20*, 054074. https://doi.org/10.1088/1748-9326/add0c9.
34. Pahle, M., Tietjen, O., Osorio, S., Egli, F., Steffen, B., Schmidt, T.S., and Edenhofer, O. (2022). Safeguarding the energy transition against political backlash to carbon markets. Nat. Energy *7*, 290–296. https://doi.org/10.1038/s41560-022-00984-0.
35. Taylor, D., Chong, K., and Röder, M. (2024). Designing biomass policy: The political economy of renewable energy for net zero. WIREs Energy Environ. *13*, e512. https://doi.org/10.1002/wene.512.
36. European; Scientific; Advisory Board; Climate Change (2024). Towards EU climate neutrality: progress, policy gaps and opportunities. Tech. Rep. (Publications Office of the European Union LU) https://data.europa.eu/doi/10.2800/216446
37. Selén, V., Guidi, M., and Battersby, F. (2024). Position: Integrating carbon removals into the EU ETS. Tech. Rep. Carbon Gap Brussels. https://carbongap.org/position-integrating-carbon-removals-into-the-eu-ets/.
38. European Parliament and Council of the European Union (2023). Directive (EU) 2023/959 of the European Parliament and of the Council. https://eur-lex.europa.eu/eli/dir/2023/959/oj/eng.
39. Meckling, J., Sterner, T., and Wagner, G. (2017). Policy sequencing toward decarbonization. Nat. Energy *2*, 918–922. https://doi.org/10.1038/s41560-017-0025-8.
40. Pahle, M., Burtraw, D., Flachsland, C., Kelsey, N., Biber, E., Meckling, J., Edenhofer, O., and Zysman, J. (2018). Sequencing to ratchet up climate policy stringency. Nat. Clim. Change *8*, 861–867. https://doi.org/10.1038/s41558-018-0287-6.
41. Burke, J., and Schenuit, F. (2023). Governing permanence of carbon dioxide removal: a typology of policy measures. Tech. Rep. (co2re – The Greenhouse Gas Removal Hub)
42. European Commission (2024). Report from the Commission to the European Parliament and the Council on the Functioning of the European Carbon Market in 2023. Staff Working Document 264 (final) Brussels.
43. Quemin, S., and De Perthuis, C. (2019). Transitional restricted linkage between emissions trading schemes. Environ. Resour. Econ. *74*, 1–32. https://doi.org/10.1007/s10640-018-00307-6.
44. Merfort, L., Bauer, N., Humpenöder, F., Klein, D., Strefler, J., Popp, A., Luderer, G., and Kriegler, E. (2023). Bioenergy-induced land-use-change emissions with sectorally fragmented policies. Nat. Clim. Change *13*, 685–692. https://doi.org/10.1038/s41558-023-01697-2.
45. Ahonen, H.-M., Dufour, M., Honegger, M., Michaelowa, A., Möllersten, K., Poralla, M., Samaniego, X., Veen, P., and Weldner, K. (2025). Promoting biogenic carbon capture and storage in the Nordic region through carbon markets: when and how to cooperate under Article 6 of the Paris Agreement? Discussion Paper perspectives climate research Freiburg. https://perspectives.cc/wp-content/uploads/2025/03/Nordic_bio-CCS_Art6_Discussion_Paper-1.pdf.
46. European Parliament (2025). EU 2040 climate target: MEPs want 90% emissions reduction in EU climate law. https://www.europarl.europa.eu/news/en/press-room/20251110IPR31334/eu-2040-climate-target-meps-want-90-emissions-reduction-in-eu-climate-law.
47. Rickels, W., Rothenstein, R., Schenuit, F., and Fridahl, M. (2022). Procure, bank, release: carbon removal certificate reserves to manage carbon prices on the path to net-zero. Energy Res. Soc. Sci. *94*, 102858. https://doi.org/10.1016/j.erss.2022.102858.
48. Rickels, W., Fridahl, M., Rothenstein, R., and Schenuit, F. (2024). Build carbon removal reserve to secure future of EU emissions trading. https://ideas.repec.org/p/zbw/ifwkpb/295745.html.
49. Edenhofer, O., Franks, M., Kalkuhl, M., and Runge-Metzger, A. (2024). On the governance of carbon dioxide removal – a public economics perspective. FinanzArchiv *80*, 70–110. https://doi.org/10.1628/fa-2023-0012.
50. Sitarz, J., Pahle, M., Osorio, S., Luderer, G., and Pietzcker, R. (2024). EU carbon prices signal high policy credibility and farsighted actors. Nat. Energy *9*, 691–702. https://doi.org/10.1038/s41560-024-01505-x.
51. Osorio, S., Pietzcker, R., Sitarz, J., and Sultani, D. (2024). Documentation of LIMES-EU – A long-term electricity system model for Europe. https://www.pik-potsdam.de/en/institute/departments/transformation-pathways/models/limes/documentation-of-limes-202411_vf-1.pdf.
52. European Commission (2020). EU reference scenario. https://energy.ec.europa.eu/data-and-analysis/energy-modelling/eu-reference-scenario-2020_en.
53. Ruiz, P.ENSPRESO; BIOMASS (2019). http://data.europa.eu/89h/74ed5a04-7d74-4807-9eab-b94774309d9f.
54. European Commission (2024). Impact Assessment Report: Securing Our Future – Europe's 2040 Climate Target and Path to Climate Neutrality by 2050 Building a Sustainable, Just and Prosperous Society. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank SWD/2024/63 Final. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52024SC0063.
55. Eurostat (2024). Complete energy balances (nrg_bal_c). https://ec.europa.eu/eurostat/web/products-datasets/-/nrg_bal_c.
56. Küng, L., Aeschlimann, S., Charalambous, C., McIlwaine, F., Young, J., Shannon, N., Strassel, K., Maesano, C.N., Kahsar, R., Pike, D., et al. (2023). A roadmap for achieving scalable, safe, and low-cost direct air carbon capture and storage. Energy Environ. Sci. *16*, 4280–4304. https://doi.org/10.1039/D3EE01008B.
57. We consider the most advanced DAC technologies only; however, there currently exist more than ten distinct systems at various stages of technological readiness.[56] 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.