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Market-Based deployment of Engineered Carbon Dioxide Removal Technologies in Europe

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Abstract

A multi-country equilibrium model has been developed to assess how engineered carbon removals (BECCS and DACCS) can be integrated into the EU Emissions Trading System (ETS). The goal is to understand what this implies for volumes, prices, technology mix, and the geographic distribution. The model couples country-specific removal cost functions with an aggregate marignal abatement cost under the legislated ETS cap (2025–2050). The study finds that the inclusion of engineered removals into the EU ETS helps in decreasing the 2050 market allowance price from 456.4 EUR/tCO_2 with no CDR to 386.2 EUR/tCO_2 with an unconditional fungibility inclusion, effectively reducing the burden to net-zero on current EU ETS emitters. Using a conditional fungibility or a reverse auction mechanism to limit potential risks associated to a free and unlimited inclusion of removals, compliance cost can still be lowered. National comparative advantages strongly shape where removals occur: Sweden, France and Germany together supply about 82% of cumulative removals under unconditional inclusion. BECCS attracts early investors until biomass becomes scarcer and costs rise. Whereas DACCS is scaling later as learning reduces unit costs and low carbon electricity becomes available. Uncertainty related to energy consumption, DACCS technology, and electricity decarbonization becomes evident. However, the scenarios with a threshold objective drastically reduce this uncertainty.

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1 Introduction

The recent IPCC report presented that carbon dioxide removal (CDR) will have a critical role to play in meeting the 1.5°C objective. This objective can hardly be attained without a large-scale deployment of CDR methods, such as Afforestation/Reforestation (AR), Bioenergy with Carbon Capture and Storage (BECCS), and Direct Air Carbon Capture and Storage (DACCS) (IPCC, 2022). CDR has three key objectives: In the short term, it must contribute to immediate emission reduction efforts. In the midterm, CDR should offset emissions from hard-to-abate sectors to achieve net-zero targets. In the long term, CDR is crucial for removing excess CO_2 from the atmosphere (IPCC, 2023).

Integrated Assessment Model (IAM) scenarios project that several hundred gigatons of CO_2 will need to be removed over the course of the century (Huppmann et al., 2018; Rogelj et al., 2018). The magnitude of these deployment needs raises major economic and policy challenges. CDR competes for scarce resources (such as sustainable biomass and low-carbon energy), raises questions of social justice and biodiversity, and requires reliable governance to ensure permanence and verifiability (**fuss2018**; Heck et al., 2018; Smith et al., 2016). How these technologies are incentivized and integrated into existing climate policy frameworks will therefore shape the feasibility and the cost of reaching net zero.

Within Europe, the central policy instrument for reducing greenhouse gas emissions is the EU Emissions Trading System (EU ETS), which has successfully driven decarbonization across power and industry sectors (Eslahi et al., 2024). At present, however, the ETS does not recognize CDR. The recently adopted Carbon Removal Certification Framework (CRCF) establishes standards for monitoring, reporting, and verification of removals, but it remain unresolved the key political question of whether certified removals should become fungible with EU allowances (EUAs) (Normec Verifavia, 2025).

This has sparked a growing policy debate. One option is to support removals outside the ETS through dedicated schemes such as reverse auctions with contracts-for-difference (CfD), as demonstrated by Sweden's BECCS auction [1] (Beccs Stockholm, 2025). A second option is full ETS

[1] It allocates long-term contracts to Stockholm Exergi to deliver around 800 $ktCO_2/yr$

inclusion, which would integrate removals into European climate policy but risks price deflation, abatement deterrence, and liability challenges (Rickels et al., 2021b). A third pathway is conditional ETS integration through a removal reserve or a removal cap, admitting removals only after certain triggers are met to balance learning and market stability (Rickels et al., 2022).

Against this backdrop, several member states are actively exploring policy instruments for engineered CDR. Member states are diverging: Sweden funds BECCS auctions, Germany consults on a Negative Emissions Strategy, France supports CCS/CDR projects, while the Netherlands remains cautious on ETS inclusion (Schenuit et al., 2021; Meyer-Ohlendorf and Spasova, 2022). These national efforts create a heterogeneous policy landscape within a harmonized ETS, making it crucial to understand how different designs, namely reverse auctions, removal cap, or unconditional ETS inclusion might shape deployment of BECCS and DACCS across Europe.

This study is deliberately concentrate on engineered CDR, restricting the analysis to BECCS and DACCS rather than the wider portfolio of land-use options. Both technologies provide durable removals with geological storage and meet ETS requirements for permanence, liability, and robust MRV, while offering quantifiable and verifiable outputs suitable for price-based instruments and market integration (Rickels et al., 2021b; Kalkuhl et al., 2022; Edenhofer et al., 2023b). By contrast, nature-based approaches remain valuable for mitigation and co-benefits but carry higher risks of impermanence and reversal on policy-relevant horizons (Kalkuhl et al., 2022). For this reason, the analysis restricts its attention to BECCS and DACCS.

This focus enables us to (i) represent country and technology specific CDR supply through removal cost schedules and investment functions, while (ii) capturing economy-wide mitigation responses with an EU-level abatement cost relationship for the ETS as a whole. The model also incorporate liability rules consistent with ETS-grade units, and address transport-and-storage bottlenecks explicitly, including cross-border geological storage. For BECCS, biomass availability and ecosystem interactions are key constraints shaping feasible supply (Donnison et al., 2020). For DACCS, energy demand is a central driver of near-term costs and scale-up potential (Sacchi et al., 2023).

A growing body of work has analyzed the integration of removals into emissions trading systems, presenting issues of price stability, scarcity, and market integrity (Burke and Schenuit, 2021; Edenhofer et al., 2023b). Other studies have assessed the economics of engineered removals, stressing uncertainties around biomass, energy demand, and infrastructure for transport and storage (Donnison et al., 2020; Hale et al., 2022; Sacchi et al., 2023; Fajardy et al., 2018). A study has examined different integration mechanisms, showing the limitations for each (Verbist et al., 2025). Finally, research on policy instruments has explored options such as reverse auctions with contracts-for-difference, with comparative analyses showing that the choice of integration pathway (direct inclusion, cap, or auctions) has major implications for both efficiency and environmental integrity (Theuer et al., 2021; Edenhofer et al., 2023b).

Yet important gaps remain. The most similar analyses either rely on stylized global scenarios (Sultani et al., 2024; Levihn, 2025a; Verbist et al., 2025), leaving unexplored how heterogeneous national CDR supply interacts with a common carbon market. Moreover, while instruments such as reverse auctions and caps have been discussed conceptually, their comparative implications within a multi-country ETS setting remain poorly understood. Addressing these gaps is crucial, because national heterogeneity in CDR potential interacts directly with integration pathways, price stability, and the credibility of compliance markets.

The paper directly responds to these gaps. First, a multi-country modeling of engineered removals within the EU ETS is provided using country-specific removal cost functions for BECCS and DACCS while embedding them in an EU-wide abatement cost representation. This dual structure allows us to capture national heterogeneity in supply while remaining consistent with aggregate ETS price formation. Then, three integration pathways that have been discussed in the policy debate are systematically compared and situated within ongoing European policy initiatives: unconditional ETS inclusion, a removal cap, and reverse auction mechanisms.

This study addresses three interrelated research questions. First, it examines how national heterogeneity in BECCS and DACCS supply affects the integration of engineered CDR into the EU ETS. Second, it evaluates how alternative integration pathways differ in their impacts on deployment, cost efficiency, and market stability. Third, it investigates how these pathways interact with the diverse institutional contexts across European countries.

Results show that integrating engineered removals into the EU ETS contributes to lowering the

2050 allowance price from 456.4 EUR/tCO_2 in a scenario without CDR to 386.2 EUR/tCO_2 when removals are granted unconditional fungibility, thereby easing the net-zero transition burden for current EU ETS emitters. Even under more restrictive designs such as conditional fungibility or reverse auctions, which mitigate risks linked to unlimited inclusion the overall compliance costs can still be reduced. National endowments play a decisive role in shaping the distribution of removals: Sweden, France, and Germany together account for roughly 82% of cumulative removals under unconditional inclusion. BECCS is favored in the early stages until rising biomass scarcity increases costs, while DACCS expands later as technological learning lowers expenses and low-carbon electricity becomes more abundant. The choice of integration pathway thus influences not only aggregate volumes and prices but also the geographic and technological configuration of delivery, with direct implications for infrastructure planning and distributional outcomes.

The paper is organized as follows. The following section compares three integration pathways: unconditional ETS inclusion, a removal cap, and reverse auctions. The next one presents the structure of the model. Then, section 4 discusses the results. Section 5 discusses the implications for the design of European carbon markets, and finally, section 6 concludes.

2 Literature Review

In addition, the large-scale deployment of CDR is impeded by market failures. CO_2 removal produces a positive externality: those who incur the costs of removing carbon do not capture the full social benefits of reduced climate impacts (Edenhofer et al., 2023a). This problem is compounded by the public-good nature of the atmosphere, which weakens private investment incentives even when technologies mature, so dedicated policies and market mechanisms are needed to create reliable demand and revenues for removers (Honegger and Reiner, 2021). As a result, public intervention is required, for example, by incorporating carbon removal credits into carbon pricing schemes (Rickels et al., 2021a). In practice, jurisdictions are exploring several routes: (i) integrating removals directly into Emissions Trading Systems (ETS); (ii) allowing offsets under carbon taxes, though most tax systems use this sparingly because of concerns about additionality, permanence, and MRV, and political sensitivity around "pay to pollute" (Oh et al., 2025); and (iii) leveraging international mechanisms such as Article 6.2/6.4 of the Paris Agreement and CORSIA, which can channel high-quality removals into quasi-compliance and compliance demand (Institute, 2025). Because present carbon prices are typically below the cost of durable removals, complementary fiscal and financial instruments are also important for price stabilization via Carbon Contracts for Difference (CCfD), targeted tax credits, and Carbon Take-Back Obligations to guarantee long-run demand (Winkler et al., 2025). Finally, voluntary markets remain too small and cost-constrained to drive scale on their own (V Battocletti et al., 2023).

Integrating CDR into the EU ETS represents a critical frontier in aligning climate mitigation efforts with economic incentives. While voluntary markets and targeted subsidies have driven initial deployment, the long-term scalability of BECCS and DACCS depends heavily on credible inclusion within compliance markets such as the EU ETS (Levihn, 2025b; Force, 2024). However, this integration poses complex economic, regulatory, and governance challenges that have yet to be fully resolved in the literature. Current allowance prices in the EU ETS are significantly lower than CDR costs, especially for DACCS, complicating immediate integration without additional policy support or dedicated mechanisms to stimulate demand (Levihn, 2025b; Marcu et al., 2025). Theoretical and modeling studies using frameworks such as LIMES-EU show that incorporating CDR into the EU ETS can increase market liquidity and cost-effectiveness, potentially reducing allowance prices by enabling a diverse portfolio of abatement and removal options (Levihn, 2025b; Rickels et al., 2018). However, literature highlights risks such as abatement deterrence, where firms might substitute removals for emissions reductions, and sustainability concerns surrounding biomass supply for BECCS (Force, 2024). To mitigate these, the literature recommends a phased, sequenced approach with safeguards including minimum quantity requirements, sustainability criteria, and robust MRV frameworks (Levihn, 2025b; Force, 2024). Policy proposals advocate initially integrating lower-cost, reliable removals like BECCS, with gradual inclusion of more nascent, higher-cost technologies such as DACCS as markets mature and costs decline (Marcu et al., 2025).

A key unresolved gap in the literature is understanding how integrating CDR into the EU ETS will affect member states heterogeneously. The EU ETS comprises countries with diverse economic structures, energy mixes, carbon intensities, and regulatory environments, which suggests that the inclusion of CDR credits could create uneven economic and environmental impacts across the bloc (Levihn, 2025b; Climate Change and Transition, 2025). Current discourse and modeling primarily consider EU ETS at an aggregate level, failing to capture these cross-country differentials crucial for equitable policy design and political feasibility. Equilibrium models are well suited to explicitly model these heterogeneous effects by simulating interactions across sectors, regions, and agents under varying policy conditions (Bosetti et al., 2024; Golub et al., 2023). Incorporating CDR options into such models can illuminate how allowance prices and technology adoption might shift differently across countries depending on their reliance on carbon-intensive industries, availability of deployment infrastructure, and fiscal capacity to finance removals (Levihn, 2025b; Force, 2024). For instance, resource-rich countries with ready access to storage sites may benefit disproportionately from BECCS and DACCS deployment, while others may bear higher costs or face competitive disadvantages. Generating spatially and sectorally disaggregated equilibrium analyses of CDR integration will provide policymakers with actionable insights into potential winners and losers, helping to tailor allocation mechanisms, compensation schemes, and complementary policies to maintain cohesion and effectiveness. Addressing this research gap is crucial for aligning EU climate ambition with regional equity and ensuring socially acceptable and economically sound pathways for permanent carbon removal deployment.

3 Integration pathways for CDR in the EU ETS

Integrating CDR into the EU ETS has become a pivotal issue for European climate policy. While the system has historically targeted emissions at source, achieving net zero requires that durable removals be admitted into the compliance framework (Schenuit et al., 2021). Competing designs have been advanced in the literature and policy debate, with different implications for efficiency, price stability, and institutional credibility (**fuss2018**). This section reviews three prominent pathways: unconditional ETS inclusion, conditional inclusion through surrender caps, and procurement via reverse auctions. In all cases, attention is restricted to engineered removals from BECCS and DACCS that satisfy ETS-grade requirements for permanence, liability, and monitoring, while accounting explicitly for biomass, energy, and storage constraints. The comparative features of the three pathways are summarized in Table 1.

3.1 Unconditional ETS inclusion

Unconditional inclusion treats verified removals as fully fungible with allowances. Under the net-cap architecture (illustrated in Figure 1), the compliance rule becomes

$$e_t \leq CAP_t + R_t^{\text{ETS}}$$

where e_t denotes the number of allowances surrendered by emitters in year t, CAP_t is the annual emissions cap set by the regulator, and R_t^{ETS} is the quantity of certified removal credits released into the ETS in that year. This formulation implies that gross emissions can exceed the cap by the volume of admitted removals, while net emissions remain constrained at or below CAP_t. In other words, the ETS cap in this setting applies explicitly to net rather than gross emissions.

This design establishes a single allowance price that minimizes compliance expenditures, and provides a clear investment signal. A uniform carbon price also enhances market liquidity and allows heterogeneous national potentials to be exploited where they are cheapest, while keeping compliance harmonized across member states.

These efficiency gains are offset by several risks. If removals are available below the prevailing abatement cost, allowance prices may decline, weakening incentives to abate (Sultani et al., 2024). Expectations of future price deflation can further delay investment (Rickels et al., 2021b). Integrity depends on robust liability: permanence discounts cannot substitute for long-term monitoring, insurance or buffer arrangements, and enforceable remedies in case of reversal (Edenhofer et al., 2025). Interaction with the Market Stability Reserve (MSR) is also non-trivial, as expanded effective supply may require recalibration of thresholds (Sultani et al., 2024). Distributional effects are significant, since countries with cheap biomass, energy, or storage may capture rents, while others remain net buyers. Allowance prices alone are unlikely to finance first-of-a-kind BECCS and DACCS projects (Gagern et al., 2022). Transitional instruments such as contracts for difference or grants will therefore be required to bridge early capital cost barriers (Marcu and Varricchio, 2025).

3.2 Conditional ETS inclusion

Conditional integration can be represented by a surrender cap, under which removals are admissible only up to a fixed share of the annual cap:

$$e_t \leq CAP_t + R_t^{\text{ETS}}, \qquad 0 \leq R_t^{\text{ETS}} \leq \overline{R}_t, \qquad \overline{R}_t = \alpha\, CAP_t.$$

Here $\overline{R}_t$ denotes the ceiling on admissible removals in year t, and $\alpha \in [0,1]$ is a policy-determined parameter that defines the maximum share of the cap that can be met with removals.

A surrender cap has been discussed in the context of the EU CRCF, where the fungibility of certified removals is expected to be subject to quantitative limits in the initial years (Meyer-Ohlendorf et al., 2025). This design permits removals to substitute for abatement when cost-effective, while preventing large inflows that could otherwise depress allowance prices and undermine abatement incentives. If the ceiling binds, compliance costs are higher than under unconditional inclusion; if the ceiling is set very high, outcomes converge towards full fungibility.

The distributive effects of surrender caps also differ from unconditional inclusion. Countries with low-cost biomass or storage potential capture rents up to the ceiling, while other member states face higher compliance costs once the limit binds. Politically, surrender caps are often viewed as a compromise, as they allow the ETS to accommodate removals while maintaining visible control over their scale (Meyer-Ohlendorf et al., 2025). Administratively, they are straightforward to enforce at the point of compliance and provide regulators with a transparent mechanism to balance efficiency with market stability (Metayer and Cardenas Monar, 2025). For these reasons, surrender caps can be interpreted as transitional instruments that enable the phased integration of removals into the ETS. A graphical representation of conditional inclusion would closely resemble the net-cap structure in Figure 1, but with an added ceiling on admissible removals at $\overline{R}_t$.

3.3 Reverse auctions under volume cap for CDR procurement

A third pathway is regulator-led procurement through reverse auctions. The authority commits to procure a specified volume of removals, for example a share of the annual cap, and accepts bids from projects. Thus, the third pathway is modeled as an auction-based procurement with one-way top-up CfDs. The lowest-cost bids are contracted, and the verified removals are released into the ETS as compliance units:

$$r_t = \min\{\beta CAP_t,\ S_r(p_t^{\mathrm{CDR}})\}, \qquad e_t \le CAP_t + r_t,$$

where r_t denotes the number of removals procured in year t, $S_r(\cdot)$ is the aggregate BECCS–DACCS supply function, p_t^{CDR} is the auction clearing price, and $\beta \in [0,1]$ represents a procurement target set by policymakers. In practice, β can be interpreted as a stylized proxy for policy volumes, comparable in magnitude to Sweden's BECCS auction, which has awarded multi-year contracts for about 800 $\mathrm{ktCO_2}$/yr.

If the clearing price is below the allowance price, projects are remunerated at the market price.

If it is higher, the regulator pays a premium through a CfD, with top-ups when allowance prices fall short and clawbacks when they exceed the strike. Premiums are financed through a levy on surrendered allowances,

$$\tau_t \, e_t = z_t \, R_t, \qquad z_t = (p_t^{\mathrm{CDR}} - \lambda_t)_+, \quad \tau_t \geq 0.,$$

where τ_t is the levy rate in year t and λ_t the allowance price. This ensures that the all-in compliance cost remains equal to the marginal abatement cost. The institutional logic of this pathway is illustrated schematically in Figure 2.

Auctions reduce financing barriers for first-of-a-kind projects, provide transparent price discovery for removals, and allow policymakers to steer deployment volumes in line with infrastructure bottlenecks (Marcu and Varricchio, 2025). Distributionally, competitive bidding curtails rent capture compared to unconditional fungibility, while the levy spreads costs across all market participants. Politically, auctions are often considered more acceptable because they preserve explicit budgetary oversight and provide visible accountability for expenditures (Woods et al., 2025). Their main drawback lies in fiscal and administrative requirements: long-term funding commitments are necessary, and coordination with allowance markets is essential (Metayer and Cardenas Monar, 2025). As with other designs, auction-based procurement expands effective supply and therefore interacts with the MSR, which would require adjustment to accommodate regulator-procured removals (Böning et al., 2023).

The three integration pathways outlined above provide distinct institutional logics that can be represented in a common analytical framework. Unconditional inclusion corresponds to full fungibility of removals and allowances under a net-cap constraint (Figure 1); conditional inclusion introduces an exogenous ceiling on admissible removals; and reverse auctions model regulator-led procurement with contract-based revenue support (Figure 2). Each pathway can therefore be formalized as a modification of the compliance constraint and market-clearing condition, with parameters such as α and β representing stylized prudential limits or procurement targets. This structure enables a systematic comparison of efficiency, price stability, and distributional outcomes in a multi-country ETS setting, as summarized in Table 1, which is the focus of the modeling framework developed in the next section.

Table 1: Comparative features of CDR integration pathways in the EU ETS

Dimension	Unconditional ETS inclusion	Conditional ETS inclusion (surrender cap)	Reverse auctions (procurement)
Compliance rule	Net cap: $e_t \le CAP_t + R_t^{ETS}$	Ceiling on removals: $0 \le R_t^{ETS} \le \overline{R}_t$, $\overline{R}_t = \alpha CAP_t$	Procured removals released: $r_t = \min\{\beta CAP_t, S_r(p_t^{CDR})\}$; $e_t = CAP_t + r_t$
Price effect	Uniform allowance price; risk of depression if removals are cheaper than abatement	Price more stable as long as ceiling binds; higher costs if tight	Auction clears p_t^{CDR}; allowance price preserved via CfD top-up when $p_t^{CDR} > \lambda_t$
Efficiency	Maximizes efficiency via fungibility	Efficiency loss when ceiling binds; converges to unconditional as $\alpha \to 1$	Efficient allocation within procured volume; constrained by β
Distributional impacts	Rents accrue where biomass/energy/storage are cheap	Rents capped by $\overline{R}_t$; higher marginal costs once limit binds	Rent capture reduced by competition; levy spreads costs
Investment signal	Strong but vulnerable to price deflation expectations	Mixed; depends on α	Strong for contracted projects; needs credible multi-year policy
Administrative burden	Low (standard MRV, liability, MSR adjustments)	Low–moderate (ceiling enforcement)	High (auction design, contracting, funding, MSR coordination)
Political acceptability	Low–medium (fear of weakened abatement)	Medium (transitional compromise)	Medium–high (budgetary oversight, accountability)

Notes: $\alpha \in [0,1]$ is the surrender cap share; $\beta \in [0,1]$ the procurement target; λ_t the allowance price; $S_r(\cdot)$ aggregate BECCS–DACCS supply; MSR = Market Stability Reserve.

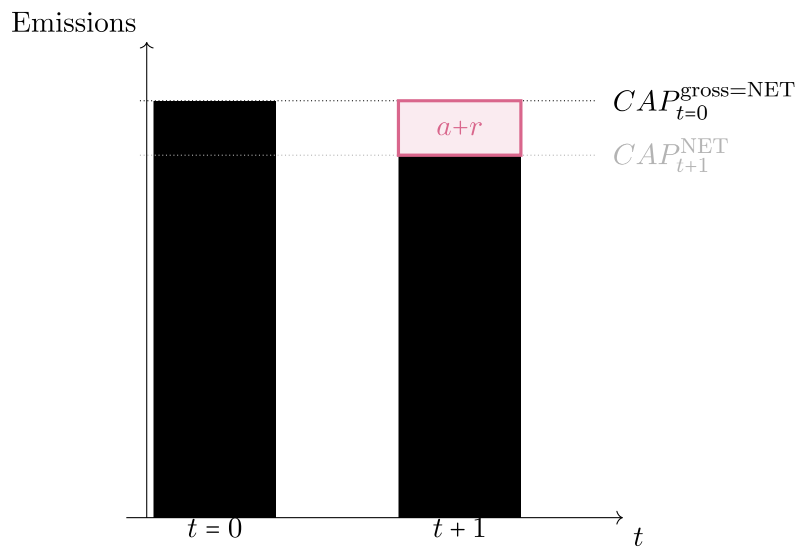

Figure 1: Net-cap representation. Bars show emissions subject to the net cap in each period. At t+1*, the purple strip illustrates the combined contribution of abatement (a) and removals (r) to the reduction relative to* t=0*.*

4 Model

4.1 Overview

The model provides an equilibrium framework to analyze how engineered removals interact with the EU ETS under alternative integration pathways. It is solved for the period 2025-2050, generating a trajectory of allowance prices and deployment that reflects the tightening cap and the scarcity it imposes. Three elements define the system: the declining ETS cap CAP_t, an abatement cost for conventional mitigation within ETS sectors, and removal cost functions for BECCS and DACCS. Together these components determine, in each year, the equilibrium price λ_t, abatement volumes, and removal deployment.

The removal side is resolved at the level of individual countries with access to North Sea storage. The model includes France, Germany, Denmark, Sweden, Norway, and the Benelux region (Belgium, the Netherlands, Luxembourg). These countries hold the dominant share of Europe's biogenic CO_2 sources and planned storage projects, making them central to BECCS and DACCS deployment. They are the EU's policy leaders on engineered CDR, with quantified targets and dedicated national strategies (Meyer-Ohlendorf and Spasova, 2022; Manhart, 2023). They already

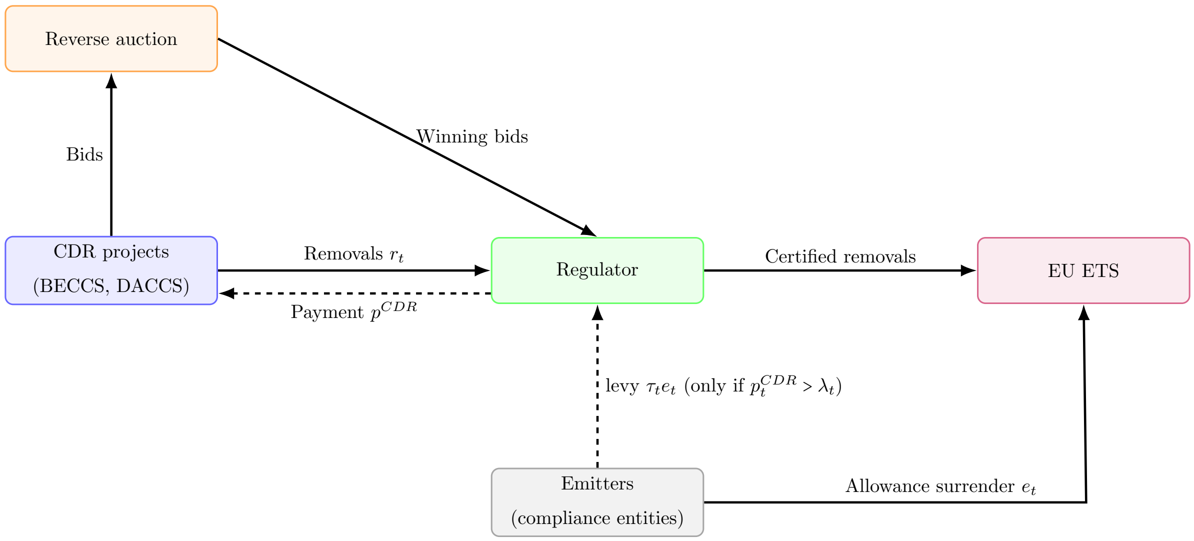

Figure 2: Reverse auction pathway. ***Solid arrows****: carbon/unit flows. Projects deliver removals r_t to the regulator, which injects certified units into the EU ETS; emitters comply by surrendering allowances e_t.* ***Dashed arrows****: money flows. Emitters pay a levy $\tau_t e_t$ to the regulator, which settles a CfD so projects are paid the auction strike p^{CDR} (top-up if $p^{CDR} > \lambda_t$, clawback if $\lambda_t > p^{CDR}$).*

operate funding and market instruments for BECCS/DACCS and are advancing MRV, registry pilots, and EU-ETS integration, supported by large industrial hubs and CO_2 transport–storage networks (Carbon Gap, 2025). Restricting to these countries yields higher-quality, comparable inputs and lower uncertainty than a heterogeneous pan-EU scope. Removal investment functions in each country capture investment dynamics, learning, biomass and energy needs, and storage constraints. Aggregating across them yields an EU-wide supply function, while national differences determine which countries supply removals at a given price. This shapes the distribution of rents.

At each time step t, emitters face a uniform allowance price λ_t that equilibrates abatement and removal supply with the declining cap CAP_t. The compliance condition requires that net emissions remain within the annual budget. Institutional design determines how removals enter this equilibrium: under unconditional inclusion they are fully fungible with allowances, under conditional inclusion they are subject to a surrender ceiling, and under reverse auctions they are procured directly by the regulator at a strike price that may differ from the allowance price. This equilibrium structure makes it possible to compare integration pathways in a transparent way. It shows how the position of abatement and removal cost curves relative to the declining cap shapes allowance prices, technology deployment, and the distribution of costs and rents across countries.

4.2 Emissions cap trajectory

The EU ETS cap CAP_t is defined as the annual limit on verified emissions under the scheme. The legislated trajectory follows the 2023 revision of the ETS Directive, consistent with the EU Climate Law and the Fit-for-55 package. It raises the Linear Reduction Factor (LRF) to 4.3% per year from 2024–2027 and to 4.4% from 2028 onwards, delivering a 62% reduction in net emissions by 2030 relative to 2005 (European Commission, 2023; Clean Energy Wire, 2023). In addition, two rebasing events tighten the path by 90 million allowances in 2024 and a further 27 million in 2026 (European Commission, 2023), such that the cap for 2024 equals 1.386 billion allowances (European Commission, 2024). By 2030, the legislated trajectory implies a cap of roughly 847 $MtCO_2$. Extending the LRF beyond 2030 drives the cap toward zero by the late 2030s, consistent with the Commission's proposal of a 90% reduction by 2040 (Reuters, 2025) and the legally binding objective of climate neutrality in 2050 (European Union, 2021).

In regulatory terms, the LRF corresponds to an absolute reduction in allowances each year, rather than a constant percentage decline. This produces a piecewise linear path in $MtCO_2$ with downward "steps" at each rebasing event. Figure 3 illustrates this stylized trajectory, with the legislated series to 2030 and linear absolute reductions between the 2030, 2040, and 2050 milestones.

To capture this logic, the model implements the cap as linear in absolute terms between policy milestones. Let CAP_{2030}, CAP_{2040}, and $CAP_{2050} = 0$ denote the legislated or proposed levels. The cap is then

$$CAP_t = \begin{cases} \text{Legislated trajectory}, & 2025 \le t \le 2030, \\ CAP_{2030} - \delta_1 (t - 2030), & 2030 < t \le 2040, \\ CAP_{2040} - \delta_2 (t - 2040), & 2040 < t \le 2050, \end{cases}$$

with annual absolute reductions

$$\delta_1 = \frac{CAP_{2030} - CAP_{2040}}{10}, \qquad \delta_2 = \frac{CAP_{2040} - CAP_{2050}}{10}.$$

This representation ensures that the cap path is consistent with both the short-term Fit-for-55 target and the long-term neutrality goal, while reflecting the regulatory principle of absolute

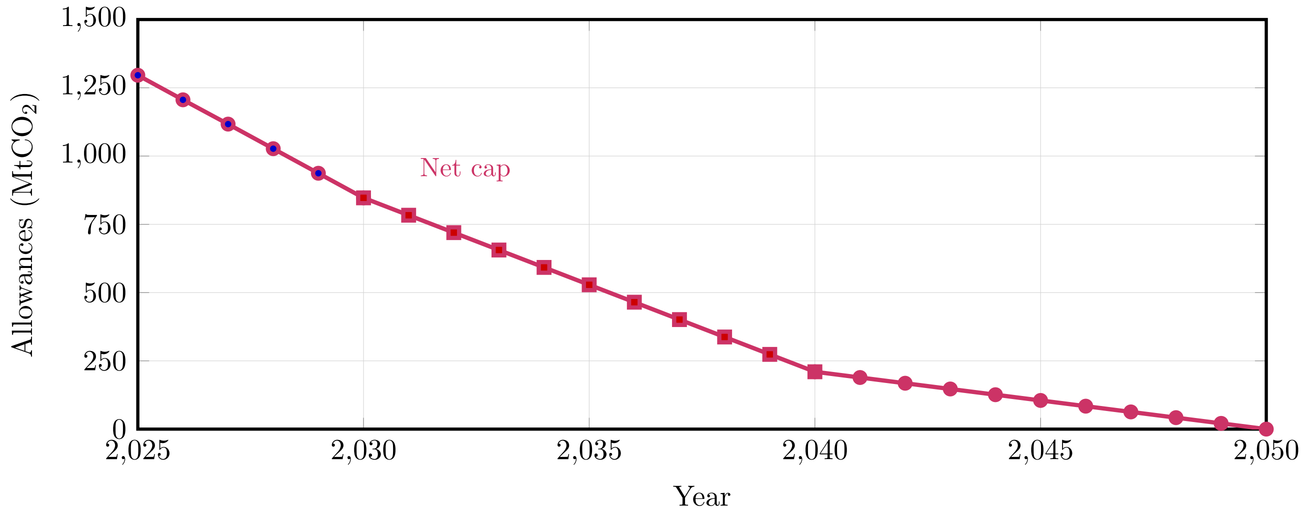

Figure 3: Net cap trajectory. Legislated path to 2030, then linear absolute reductions from 2030 to 2040 (to 210 Mt) and from 2040 to 2050 (to net zero).

annual cuts. It also provides a transparent benchmark: the legislator fixes the net cap in line with the climate neutrality objective, while the market outcome depends on the volume of removals admitted. Gross emissions may therefore exceed the net cap by the amount of certified removals, with the integration pathway determining how R_t^{ETS} is set.

$$\text{Gross emissions}_t = CAP_t + R_t^{\text{ETS}},$$

Unconditional inclusion allows removals to expand the gross cap endogenously at the EUA price, conditional inclusion limits this expansion to αCAP_t, and auctions introduce regulator control through a procurement target r_t.

4.3 Regulator

The regulator is responsible for enforcing the ETS cap and for determining the volume of certified removals admitted into the compliance framework. In every year t the regulator issues allowances equal to CAP_t, decides the admissible removal volume R_t^{ETS}, and verifies that covered emitters surrender e_t units for compliance. All flows are expressed in $MtCO_2$/yr and one EUA equals one tonne of CO_2 equivalent.

The compliance constraint is

$$e_t \le CAP_t + R_t^{\text{ETS}}. \tag{1}$$

This inequality caps net emissions at CAP_t. At the equilibrium the constraint binds and hence

$e_t = CAP_t + R_t^{\text{ETS}}$. The integration pathway determines how R_t^{ETS} is set:

Unconditional inclusion: removals enter the market according to market supply evaluated at the allowance price,

$$R_t^{\text{ETS}} = S_r(\lambda_t). \tag{2}$$

Conditional inclusion (surrender ceiling): admissible removals are capped at a fixed share of the cap,

$$R_t^{\text{ETS}} = \min\{\, S_r(\lambda_t),\ \overline{R}_t \,\}, \qquad \overline{R}_t = \alpha\, CAP_t, \quad \alpha \in [0,1]. \tag{3}$$

Reverse auctions (procurement): the regulator procures removals by competitive bidding and injects procured units into the ETS,

$$r_t = \min\{\, \beta\, CAP_t,\ S_r(p_t^{\text{CDR}})\}, \qquad R_t^{\text{ETS}} = r_t, \tag{4}$$

where p_t^{CDR} is the auction clearing price and $\beta \in [0,1]$ the procurement target. Under the auction pathway, the regulator may finance any premium between the auction strike and the allowance price through a levy on surrendered units; the precise accounting is set out below.

levy and CfD accounting

Define the positive part operator

$$(x)_+ := \max\{x, 0\}.$$

When the auction clearing price exceeds the allowance price, the regulator pays a CfD to contracted projects. The CfD budget balance equates the total levy collected from surrendering entities to the CfD top-up required for procured removals:

$$\tau_t\, e_t \;=\; \left(p_t^{\text{CDR}} - \lambda_t\right)_+ r_t, \tag{5}$$

where τ_t denotes the per-unit levy applied to surrendered allowances and r_t denotes the procured removals injected into the ETS (so $R_t^{\text{ETS}} = r_t$ under the auction pathway). From (5) the per-unit levy (for $e_t > 0$) is

$$\tau_t \;=\; \frac{\left(p_t^{\text{CDR}} - \lambda_t\right)_+ r_t}{e_t}. \tag{6}$$

Emitters thus face an effective per-unit compliance price

$$c_t^{\text{eff}} \;=\; \lambda_t + \tau_t, \tag{7}$$

Remarks:

1. If $p_t^{\text{CDR}} \le \lambda_t$ then $(p_t^{\text{CDR}} - \lambda_t)_+ = 0$. In that case $\tau_t = 0$ and $c_t^{\text{eff}} = \lambda_t$; no levy is required because the market price covers the strike.

2. In general $c_t^{\text{eff}} \neq p_t^{\text{CDR}}$. For $p_t^{\text{CDR}} > \lambda_t$, equality $c_t^{\text{eff}} = p_t^{\text{CDR}}$ would require

$$\frac{\left(p_t^{\text{CDR}} - \lambda_t\right)_+ r_t}{e_t} = p_t^{\text{CDR}} - \lambda_t,$$

which simplifies to $r_t = e_t$. Thus, unless procured removals equal the total surrendered volume, the levy spreads the CfD top-up across all surrendered units rather than directly setting the emitters' marginal cost equal to the auction strike.

3. When implementing the emitters' optimisation, substitute τ_t from (6) into (7) so that abatement choices respond to the combined effect of the EUA price and the (volume-weighted) CfD financing requirement.

4.4 Emitters

All covered installations are modeled as a single representative agent minimizing resource costs. Let E_t^{BAU} denote counterfactual emissions (MtCO_2/yr) in year t. Abatement is $a_t \in [0, E_t^{\text{BAU}}]$ with a non-decreasing marginal abatement cost $\text{MAC}_t(\cdot)$ and convex abatement cost as follows:

$$C_t^{\text{abat}}(a_t) = \int_0^{a_t} \text{MAC}_t(\xi)\, d\xi. \tag{8}$$

Emitters may surrender certified removal credits if the pathway allows. Let $r_t^{\text{use}} \ge 0$ be removal units surrendered by emitters in year t (under the reverse-auction pathway $r_t^{\text{use}} = 0$). The net-cap requires that post-abatement emissions do not exceed the sum of the regulator's cap and admitted removals:

$$E_t^{\text{BAU}} - a_t \le CAP_t + r_t^{\text{use}}. \tag{9}$$

Let p_t^R denote the pathway-specific price of a removal unit surrendered by emitters. Under unconditional inclusion $p_t^R = \lambda_t$ (the EUA price). Under conditional inclusion with a binding ceiling one has $p_t^R \in [0, \lambda_t]$. Under reverse auctions emitters cannot buy removals, so $r_t^{\text{use}} = 0$ and the regulator injects procured removals externally.

The representative emitter's two-control problem is

$$\min_{a_t \in [0, E_t^{\mathrm{BAU}}],\ r_t^{\mathrm{use}} \geq 0} \quad C_t^{\mathrm{abat}}(a_t) \ + \ p_t^R r_t^{\mathrm{use}} \tag{10}$$

$$\text{s.t.} \quad E_t^{\mathrm{BAU}} - a_t \ \leq \ CAP_t + r_t^{\mathrm{use}}, \tag{9}$$

$$r_t^{\mathrm{use}} \leq \overline{R}_t \qquad \text{(conditional inclusion only)},$$

$$r_t^{\mathrm{use}} = 0 \qquad \text{(reverse-auction pathway)}.$$

Behaviorally, abatement responds to the marginal compliance price faced at the margin:

$$\mathrm{MAC}_t(a_t) \ = \ c_t^{\mathrm{eff}}, \qquad c_t^{\mathrm{eff}} = \begin{cases} \lambda_t, & \text{unconditional inclusion,} \\ \lambda_t, & \text{conditional inclusion (marginal unit is an EUA),} \\ \lambda_t + \tau_t, & \text{reverse auctions (emitters pay a levy per surrendered EUA).} \end{cases}$$

$\mathrm{MAC}_t(\cdot)$ is specified as a DICE-style power function of the abatement fraction (Nordhaus and Sztorc, 2013). Define the abatement fraction

$$f_t \ := \ \frac{a_t}{E_t^{\mathrm{BAU}}} \in [0, 1].$$

Let $\theta_2 > 1$ be a convexity parameter and $p_B(t)$ the backstop price (the marginal cost at full abatement in year t). The marginal abatement cost and the associated abatement cost are

$$\mathrm{MAC}_t(a_t) \ = \ p_B(t)\, f_t^{\theta_2 - 1}, \qquad C_t^{\mathrm{abat}}(a_t) \ = \ \int_0^{a_t} \mathrm{MAC}_t(\xi)\, d\xi \ = \ \frac{p_B(t)}{\theta_2}\, E_t^{\mathrm{BAU}}\, f_t^{\theta_2}. \tag{11}$$

Convexity holds for $\theta_2 > 1$. At the optimum, the abatement choice solves $p_B(t)\, f_t^{\theta_2 - 1} = c_t^{\mathrm{eff}}$, hence

$$a_t^{\star} \ = \ E_t^{\mathrm{BAU}} \left(\frac{c_t^{\mathrm{eff}}}{p_B(t)} \right)^{\frac{1}{\theta_2 - 1}} \quad \text{truncated to } [0, E_t^{\mathrm{BAU}}]. \tag{12}$$

Parameters and units are as follows. $\theta_2 = 2.6$ is used, so the MAC exponent is $\theta_2 - 1 = 1.6$ (Nordhaus, 2016). The backstop path $p_B(t)$ is expressed in 2020 euros using a proportional conversion from 2019 USD:

$$p_B^{\mathrm{EUR2020}}(t) \ = \ \kappa\, p_B^{\mathrm{USD2019}}(t), \qquad \kappa \ = \ \frac{\mathrm{CPI}_{2020}/\mathrm{CPI}_{2019}}{(\mathrm{USD/EUR})_{2020}} \ = \ 0.886118,$$

with $\mathrm{CPI}_{2019} = 255.7$, $\mathrm{CPI}_{2020} = 258.8$, and the 2020 average USD/EUR = 1.1422. The backstop path follows

$$p_B^{\mathrm{USD2019}}(t) = p_{2050} \cdot 1.01^{\,t - 2050}, 2025 \leq t \leq 2050, \qquad p_{2050} = 515\ \mathrm{USD/tCO_2}.$$

Table 2: Marginal abatement cost $p(f,t) = p_B^{\mathrm{EUR2020}}(t)\, f^{1.6}$ *with* $\theta_2 = 2.6$ *(€/tCO_2, 2020 euros).*

Abatement f	**2025**	**2030**	**2040**	**2050**
0.05	4.8	4.6	4.2	3.8
0.10	14.7	14.0	12.7	11.5
0.15	28.1	26.8	24.2	21.9
0.20	44.6	42.4	38.4	34.7
0.25	63.7	60.6	54.9	49.7
0.30	85.3	81.1	73.4	66.5
0.35	109.1	103.8	94.0	85.1
0.40	135.1	128.5	116.4	105.3
0.45	163.1	155.2	140.5	127.2
0.50	193.1	183.7	166.3	150.5
0.55	224.9	213.9	193.7	175.3
0.60	258.4	245.9	222.6	201.5
0.65	293.8	279.5	253.0	229.1
0.70	330.7	314.7	284.9	257.9
0.75	369.3	351.4	318.1	288.0
0.80	409.5	389.6	352.7	319.3
0.85	451.2	429.3	388.7	351.9
0.90	494.4	470.5	425.9	385.6
0.95	539.1	513.0	464.4	420.4
1.00	585.2	556.8	504.1	456.4

Applying κ yields the waypoints. For transparency marginal abatement costs are reported $p(f,t) = p_B^{\text{EUR2020}}(t)\, f^{1.6}$ for selected years $t \in \{2025, 2030, 2040, 2050\}$ and abatement fractions $f \in \{0.05, 0.10, \ldots, 1.00\}$ in table 2.

This specification includes the compliance choices in (10). The emitter meets the constraint (9) by combining internal abatement determined by (12) with the use of removals r_t^{use} when admissible, taking prices λ_t and p_t^R and any levy τ_t as given. Figure 4 summarizes the equilibrium structure of the model. The regulator sets the annual cap and pathway-specific rules, while emitters minimize compliance costs and removal suppliers maximize operating profits subject to their cost functions and constraints. The EUA price λ_t equilibrates abatement and removal supply with the declining cap, with institutional design determining how removals enter this balance.

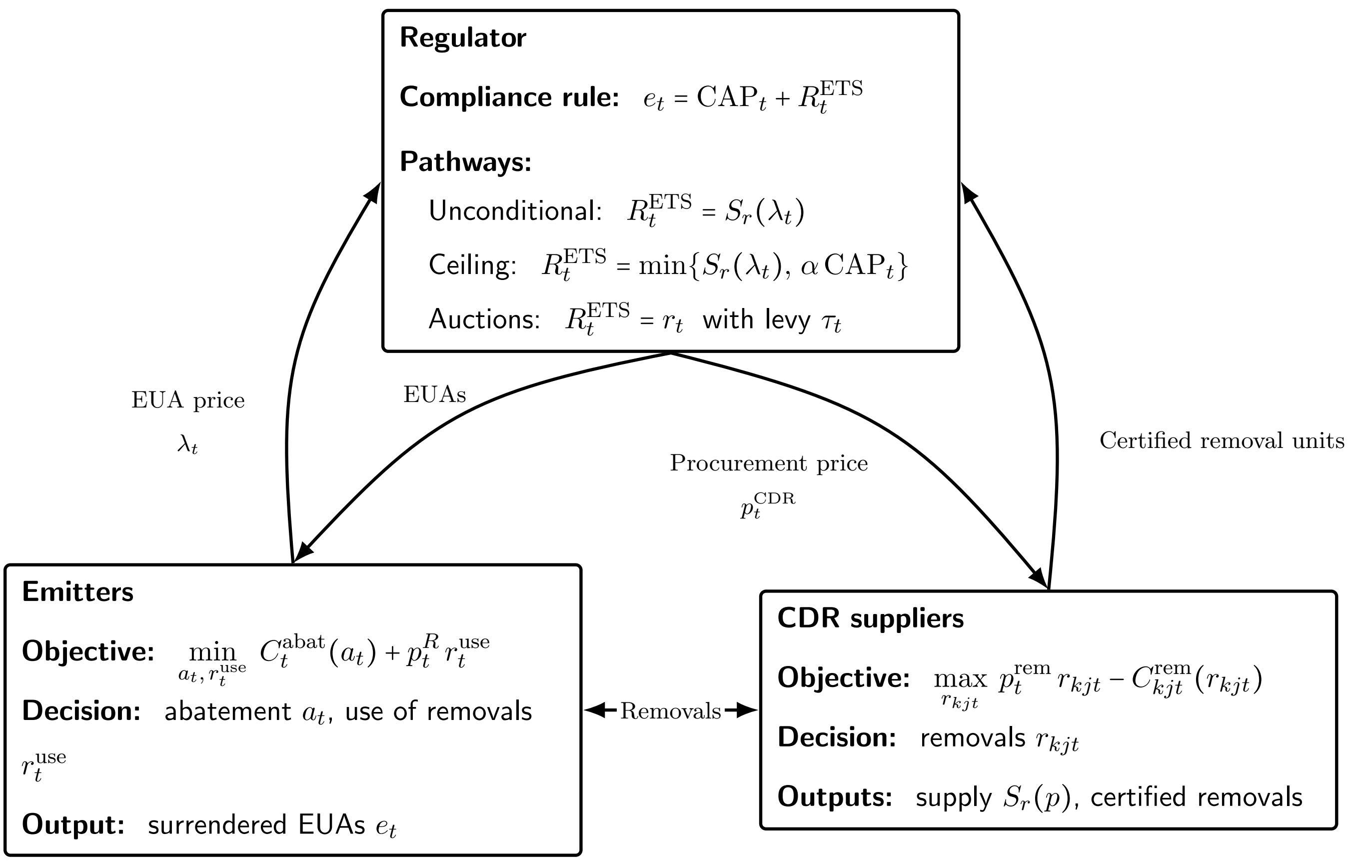

Figure 4: Schematic of the equilibrium: regulator, emitters and CDR suppliers (paths for unconditional inclusion, ceiling and auction-based procurement).

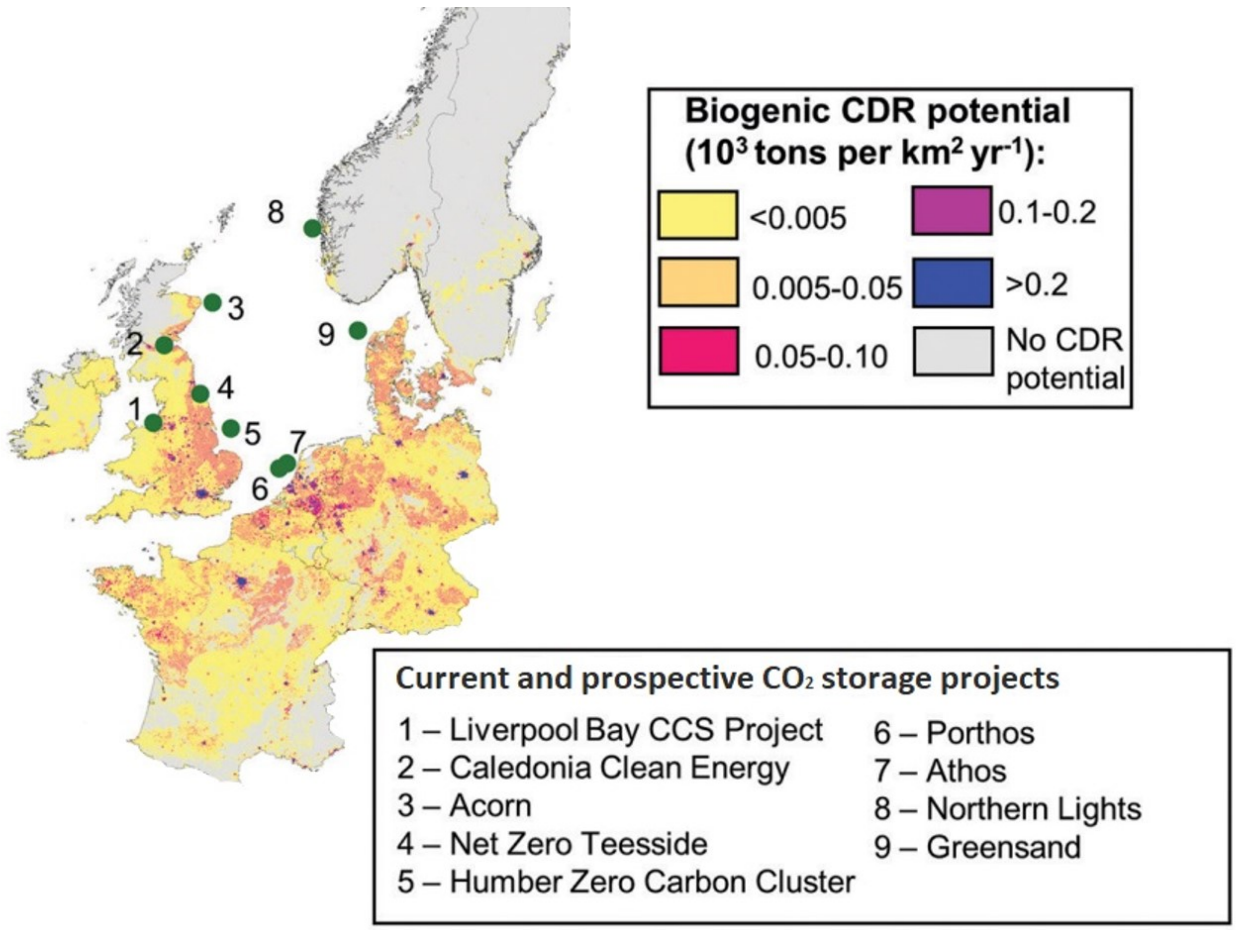

Figure 5: Biogenic CDR (BECCS) potential across selected capture countries and associated offshore geological storage points ($n \in \mathcal{N}$). The map indicates prospective supply regions (by $k \in \mathcal{K} = \{\mathrm{FR}, \mathrm{DE}, \mathrm{DK}, \mathrm{SE}, \mathrm{NO}, \mathrm{BEN}\}$) and storage nodes used in the model calibration. UK appears on the figure but is not included in the study (not included in EU ETS).

4.5 CDR suppliers

Removals are supplied by project developers deploying BECCS and DACCS in a set of capture regions with access to offshore geological storage. All flow variables are annual and expressed in tonnes of CO_2 per year (tCO_2/yr) unless stated otherwise. Figure 5 provides an overview of the biogenic CDR (BECCS) technical potential in the selected countries and the location of storage points (nodes $n \in \mathcal{N}$) that receive injected CO_2.

Countries are indexed by $k \in \mathcal{K} = \{\mathrm{FR}, \mathrm{DE}, \mathrm{DK}, \mathrm{SE}, \mathrm{NO}, \mathrm{BEN}\}$, storage nodes by $n \in \mathcal{N}$, technologies by $j \in \mathcal{J} = \{\mathrm{BECCS}, \mathrm{DACCS}\}$, and years by t. As illustrated in Figure 5, storage nodes and capture regions define the spatial structure of supply. Let $r_{kjt} \geq 0$ denote delivered ETS-grade removals (tCO_2/yr) from country k, technology j, and year t; these are tonnes injected and certified for permanent geological storage, net of capture efficiency and life-cycle emissions.

For each pair (k, j) and year t, the unit-cost components are taken from Presty, 2025: annuitized investment (CAPEX), fixed O&M, variable O&M (chemicals, sorbents), electricity cost per tCO_2 removed, and a combined transport-and-storage (T&S) marginal cost that increases with volume as low-cost options are exhausted. CAPEX and O&M learning by doing are exogenous in time t. Define the annualization factor

$$\mathrm{CRF}(r, L_j) = \frac{r(1+r)^{L_j}}{(1+r)^{L_j} - 1}$$

using discount rate r and lifetime L_j. Denote by $\mathrm{CAPEX}_{kjt}(t)$ the overnight CAPEX, by $\mathrm{FOM}_{kjt}(t)$ the fixed O&M (expressed in €/tCO_2), and by $v_{kjt}(t)$ the non-energy variable O&M, so that $\mathrm{CAPEX}_{kjt}(t)\,\mathrm{CRF}(r, L_j)$, $\mathrm{FOM}_{kjt}(t)$, and $v_{kjt}(t)$ are in €/tCO_2. Let $\gamma^{\mathrm{el}}_{kj}$ be electricity intensity (MWh/tCO_2) with corresponding price p^{el}_{kt} (€/MWh). Let $\tau^{\mathrm{TS}}_{kjt}(r)$ denote the combined marginal T&S charge per additional tonne removed, modeled as non-decreasing in r. The marginal removal cost is

$$\mathrm{MRC}_{kjt}(r_{kjt}) = \underbrace{\mathrm{CAPEX}_{kjt}(t)\,\mathrm{CRF}(r, L_j)}_{\text{annuitized CAPEX}} + \underbrace{\mathrm{FOM}_{kjt}(t)}_{\text{fixed O\&M}} + \underbrace{v_{kjt}(t)}_{\text{non-energy VOM}} + \underbrace{\gamma^{\mathrm{el}}_{kj}\,p^{\mathrm{el}}_{kt}}_{\text{electricity cost}} + \underbrace{\tau^{\mathrm{TS}}_{kjt}(r_{kjt})}_{\text{combined T\&S}}. \tag{13}$$

The associated total cost is

$$C^{\mathrm{rem}}_{kjt}(r_{kjt}) = \int_0^{r_{kjt}} \mathrm{MRC}_{kjt}(\xi)\,d\xi.$$

With exogenous time paths for $\mathrm{CAPEX}_{kjt}(t)$, $\mathrm{FOM}_{kjt}(t)$, $v_{kjt}(t)$, electricity prices and the T&S schedule, $\mathrm{MRC}_{kjt}(\cdot)$ is non-decreasing in r_{kjt}.

Supply is limited by technological/potential and electricity constraints. BECCS potential is represented directly (biogenic CDR potential is taken as given; see Figure 5 for its spatial distribution):

$$0 \leq r_{k,\mathrm{BECCS},t} \leq \bar{R}^{\mathrm{BECCS}}_{kt}, \tag{14}$$

and electricity availability imposes

$$\sum_{j \in \mathcal{J}} \gamma^{\mathrm{el}}_{kj}\, r_{kjt} \leq \bar{E}^{\mathrm{el}}_{kt}. \tag{15}$$

Non-decreasing gross capture by site are required, $q_{kj,t} \geq q_{kj,t-1}$ for $t > t_0$. This reflects lumpy investment with long-lived assets and network lock-in: once capture, transport and storage capacity is built, it is rarely mothballed in early years. The condition regularizes the intertemporal path, curbs implausible stop-and-go patterns driven by short-run price noise, and approximates commissioning ramps and contracting frictions.

Suppliers maximize within-year operating profit; the unit revenue p_t^{rem} per tonne removed is determined by the market arrangement. In a competitive setting p_t^{rem} is taken as given; in settings with market power, p_t^{rem} may depend on aggregate supply and the corresponding price-impact term enters suppliers' first-order conditions. The baseline operational problem (parametric in p_t^{rem}) is

$$\max_{\{r_{kjt}\}\geq 0} \quad \sum_{k,j} p_t^{\text{rem}} r_{kjt} - \sum_{k,j} C_{kjt}^{\text{rem}}(r_{kjt}) \tag{16}$$
$$\text{s.t.} \quad (14),\ (15),\ \text{and if conditional inclusion: } \sum_{k,j} r_{kjt} \leq \overline{R}_t.$$

Alongside net delivered removals r_{kjt} (tCO_2/yr), the gross captured CO_2 q_{kjt} (tCO_2/yr) is tracked. The two are linked by a net factor $\nu_{kj,t} \in (0,1]$ that embeds capture-to-storage efficiency and scope-2 emissions from electricity use:

$$r_{kjt} = \nu_{kj,t}\, q_{kjt}, \qquad \nu_{kj,t} = \frac{\eta_{kj,t}}{1 + e_{k,t}^{\text{grid}}\, \gamma_{kj}^{\text{el}}}.$$

Here $\eta_{kj,t}$ is capture-to-storage efficiency, γ_{kj}^{el} is electricity intensity in MWh per tCO_2 removed, and $e_{k,t}^{\text{grid}}$ is the grid emission factor (tCO_2/MWh). Electricity affects (i) mass via the factor $\nu_{kj,t}$ and (ii) cost via $\gamma_{kj}^{\text{el}} p_{kt}^{\text{el}}$; this avoids double counting.

4.6 Equilibrium

The Karush-Kuhn-Tucker (KKT) system below presents a complete complementarity formulation for the equilibrium model of removals, abatement and allowance markets under the three integration pathways.

Index sets. Countries $k \in \mathcal{K} = \{\text{FR}, \text{DE}, \text{DK}, \text{SE}, \text{NO}, \text{BEN}\}$, technologies $j \in \mathcal{J} = \{\text{BECCS}, \text{DACCS}\}$, years $t \in \mathcal{T} = \{2025, \ldots, 2050\}$.

Primal variables.

Supply / project:	q_{kjt} (gross capture), r_{kjt} (net removed),
System:	R_t (total admitted removals), e_t (surrendered allowances),
Demand / emitters:	a_t (abatement),
Prices / policy:	λ_t (EUA shadow price), p_t^{rem} (removal price),
Auctions:	τ_t (levy ≥ 0), p_t^{CDR} (strike), z_t (auxiliary $= (p_t^{\text{CDR}} - \lambda_t)_+$).

Dual / multiplier variables. Mass accounting: ϕ_{kjt} (equality $r_{kjt} - \nu_{kj,t} q_{kjt} = 0$); capacity: $\alpha_{kjt}^{\text{cap}} \geq 0$; monotonicity: $\psi_{kjt} \geq 0$; electricity shadow: $\pi_{kt}^{\text{el}} \geq 0$; compliance shadow: $\lambda_t \geq 0$ (also appears as price); ceiling multipliers: μ_t, $\mu_t^{\text{proc}} \geq 0$; CfD auxiliary: $z_t \geq 0$.

Primal feasibility (all scenarios)

$$\text{(Gross-to-net)} \qquad r_{kjt} - \nu_{kj,t}\, q_{kjt} = 0, \tag{17}$$

$$\text{(Removal clearing)} \qquad R_t - \sum_{k,j} r_{kjt} = 0, \tag{18}$$

$$\text{(Flow identity)} \qquad e_t - \left(E_t^{\text{BAU}} - a_t\right) = 0, \tag{19}$$

$$\text{(Compliance)} \qquad 0 \leq CAP_t + R_t - e_t \ \perp\ \lambda_t \geq 0, \tag{20}$$

$$\text{(Capacity bounds)} \qquad 0 \leq Q_{kj}^{\max} - q_{kjt} \ \perp\ \alpha_{kjt}^{\text{cap}} \geq 0, \tag{21}$$

$$\text{(Monotonicity)} \qquad 0 \leq q_{kjt} - q_{kj,t-1} \ \perp\ \psi_{kjt} \geq 0 \quad (t > t_0), \tag{22}$$

$$\text{(Electricity availability)} \qquad 0 \leq \bar{E}_{kt}^{\text{el}} - \sum_j \gamma_{kj}^{\text{el}}\, r_{kjt} \ \perp\ \pi_{kt}^{\text{el}} \geq 0. \tag{23}$$

Stationarity (all scenarios)

Supplier-side (per k, j, t). Suppliers maximize $p_t^{\text{rem}} r_{kjt} - C_{kjt}^{\text{rem}}(r_{kjt})$ subject to (17)–(23). The marginal stationarity conditions are:

$$\boxed{0 \leq r_{kjt} \ \perp\ \text{MRC}_{kjt}(r_{kjt}) - p_t^{\text{rem}} - \phi_{kjt} + \gamma_{kj}^{\text{el}}\, \pi_{kt}^{\text{el}} \ \geq 0}, \tag{24}$$

$$\boxed{0 \leq q_{kjt} \ \perp\ -\nu_{kj,t}\, \phi_{kjt} - \alpha_{kjt}^{\text{cap}} + \psi_{kjt} - \psi_{k,j,t+1} \ \geq 0}. \tag{25}$$

At the margin a supplier supplies net removals until marginal resource cost equals the net price p_t^{rem}, adjusted for the mass accounting multiplier ϕ_{kjt} and the electricity shadow price (24). Gross capture is chosen taking into account the effect on net removals (through ν), capacity scarcity and monotonicity rents (25).

Emitters / abatement. Emitters' minimization (private problem) yields:

$$\text{(unconditional / conditional):} \qquad 0 \le a_t \perp \text{MAC}_t(a_t) - \lambda_t \ \ge 0,$$

$$\text{(reverse auctions):} \qquad 0 \le a_t \perp \text{MAC}_t(a_t) - (\lambda_t + \tau_t) \ \ge 0.$$

Under auctions emitters face an extra per-unit levy τ_t that raises their effective marginal compliance cost.

Removal price / R_t stationarity. From the clearing identity (18) and the compliance complementarity (20), the stationarity condition for the free variable R_t yields the supplier-side price link. The result depends on scenario:

- **Unconditional inclusion:** no ceiling on R_t. Stationarity implies

  $$\boxed{p_t^{\text{rem}} = \lambda_t},$$

  i.e. removals trade at the EUA shadow price.

- **Conditional inclusion (surrender ceiling):** add

  $$0 \le \overline{R}_t - R_t \perp \mu_t \ge 0, \qquad \overline{R}_t = \alpha\, CAP_t.$$

  Stationarity gives

  $$\boxed{p_t^{\text{rem}} = \lambda_t - \mu_t, \quad \mu_t \ge 0},$$

  so the removal price is below λ_t by the ceiling shadow value μ_t when binding.

- **Reverse auctions (procurement cap):** add

  $$0 \le \beta\, CAP_t - R_t \perp \mu_t^{\text{proc}} \ge 0.$$

  Stationarity gives

  $$\boxed{p_t^{\text{rem}} = \lambda_t - \mu_t^{\text{proc}}, \quad \mu_t^{\text{proc}} \ge 0},$$

  and the procurement rent μ_t^{proc} parallels the conditional case.

Introduce $z_t \geq 0$ with complementarity

$$0 \leq z_t \ \perp \ z_t - (p_t^{\mathrm{CDR}} - \lambda_t) \geq 0,$$

which enforces $z_t = \max\{p_t^{\mathrm{CDR}} - \lambda_t, 0\} = (p_t^{\mathrm{CDR}} - \lambda_t)_+$. Then the CfD budget identity is written as the equality:

$$\tau_t \, e_t = z_t \, R_t, \qquad \tau_t \geq 0.$$

This equality, together with $e_t = E_t^{\mathrm{BAU}} - a_t$, links the fiscal top-up to aggregate surrendered volume.

5 Results

The presentation of results is organized in three parts. The first subsection provides an integrated, EU-wide analysis of deployment, price effects, technology composition and the associated cost and revenue patterns across the three integration pathways, compared to a no-CDR baseline. The second subsection examines country-level outcomes, explaining geographic concentration, technology specialization, rent incidence and the role of infrastructure and energy constraints. Finally, the implications of the results are discussed.

5.1 Global analysis

The results from the model are represented at the global scale on four distinct scenarios. Engineered CDR integration pathways matter for both cumulative removals and peak prices. Table 3 summarizes the main findings.

First, the no-CDR counterfactual on Figure 6 establishes a baseline for an allowance-price trajectory without any CDR intervention on the market. The inclusion of engineered removals under unconditional fungibility on Figure 7 admits the largest cumulative removals (1.67 $GtCO_2$) and delivers the greatest short-term moderation of the allowance peak (386 EUR/tCO_2 versus 456 EUR/tCO_2 in the no-removal case). The conditional fungibility under a 5% surrender ceiling on Figure 8 and the inclusion of removals through a 5% procurement auction on Figure 9 present lower cumulative volumes (roughly 1.00–1.14 $GtCO_2$) and preserve higher peak prices (426 EUR/tCO_2). Relative to the ceiling, unconditional raises cumulative removals by 0.668 Gt (+66.6%), and relative to auctions by 0.529 Gt (+46.3%). In 2050 the annual flow of removals is roughly doubled under unconditional inclusion (134.2 $MtCO_2$) compared to either the conditional or auction designs

(67.7 $MtCO_2$). These volume gains occur alongside a pronounced reduction in the peak EUA price (from 456.4 EUR/tCO_2 with no CDR to 386.2 EUR/tCO_2 under unconditional inclusion), a drop of 70.2 EUR/tCO_2 (approximately 15.4%). Designs that limit the annual use of removals (surrender cap or procurement) attenuate this price-suppression effect: their peak price is 420.4 EUR/tCO_2 (a reduction of 36.0 EUR/tCO_2, or 7.9%, relative to no CDR). Relaxing the conditional fungibility to admit more removals increases total negative emissions, but it reduces the scarcity signal for abatement, consistent with the theoretical discussion in (Rickels et al., 2021b; Edenhofer et al., 2023b; Sultani et al., 2024).

Integrating engineered removals also reduces the compliance burden faced by covered emitters. Table 3 shows that emitters effective average compliance cost falls from 175.54 EUR/tCO_2 in the no-CDR baseline to 148.52 EUR/tCO_2 under unconditional inclusion (a reduction of 27.02 EUR/tCO_2, $\approx$ 15.4%), and to 161.71 EUR/tCO_2 under the 5% ceiling or auction designs (a reduction of 13.83 EUR/tCO_2, $\approx$ 7.9%). Mechanically, admitting removals increases effective supply and lowers the EUA shadow price λ_t, which enters the emitters' first-order condition for abatement in equation (12); a lower c_t^{eff} implies a lower abatement fraction $a_t^\star$ for given $p_B(t)$. Under the auction design the CfD accounting matters: emitters face $c_t^{\text{eff}} = \lambda_t + \tau_t$ (equation (7)), so any top-up τ_t partially offsets the direct price benefit. However, in the calibrated runs the net effect remains a reduction in emitter cost relative to no CDR.

Under unconditional inclusion cumulative CDR cost is 361.3 billion EUR and cumulative CDR revenue is 560.8 billion EUR, implying an average margin of 119 EUR/tCO_2. This scenario creates the largest profit, a point of both efficiency and political economy concern by weakening the EUA price signal that drives abatement in covered sectors. The auction pathway compresses per-ton CDR profits by expanding removals volume through higher marginal costs project in early periods. Cumulative CDR revenue increases from 246.35 billion EUR (conditional) to 259.91 billion EUR (auctions), an increase of 13.56 billion EUR, while cumulative CDR cost rises from 172.59 billion EUR to 194.33 billion EUR, an increase of 21.74 bn. Because costs grow more than revenues, average profit per tonne falls from 73.54 EUR/tCO_2 to 57.43 EUR/tCO_2. Figure 9 show that auctions are only needed until 2039, such that conditional and auction scenarios final ETS price coincide.

The technology composition of removals differs across pathway (Table 3). With unconditional fungibility the cumulative BECCS and DACCS split is approximately balanced (about 52% BECCS, 48% DACCS), whereas the surrender cap and the procurement cap bias cumulative supply toward BECCS (75% and 84% BECCS respectively). Three factors explain this pattern in the model. First, BECCS has lower near-term marginal cost in the calibrated regions. While DACCS is more electricity-intensive and scales: its marginal cost declines only as learning progress and as low-carbon electricity becomes more available. Second, when a binding limit restricts annual removals (at 5% of the cap), lower-cost BECCS largely saturates the admissible volume, leaving little room for DACCS. When the limit is relaxed, the system first deploys BECCS up to its rising marginal cost and then scales DACCS once its marginal cost intersects the MAC. Third, BECCS are largely limited through biomass availability, which increases the marginal cost to get this biomass and creates a natural limit to its investments. Figure 10 shows precisely that BECCS ramps earlier and DACCS later.

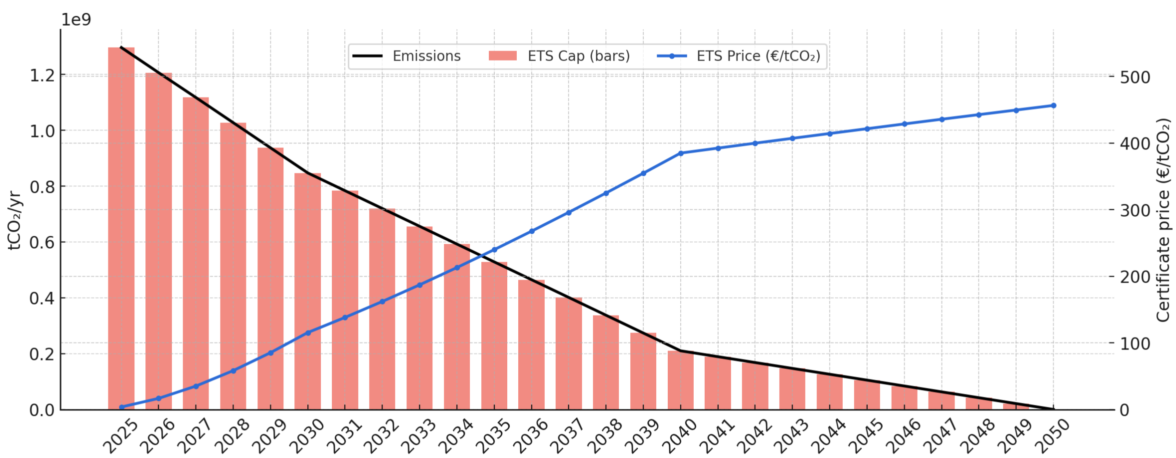

Figure 6: Baseline no CDR ETS Cap Emissions Removals and Price Dynamics 2025–2050

5.2 Country-level analysis

This subsection investigates a country-level analysis based on the unconditional inclusion of engineered removals into the EU ETS. Unlike the two alternative scenarios, which rely on subjective constraints (α, β), this scenario imposes a fixed constraint and thus serves as the central case.

The unconditional pathway produces an asymmetric geography of engineered removals. Three countries account for more than four fifths of cumulative supply over 2025–2050, : Sweden (34.71%), France (25.72%), and Germany (21.58%), with a combined share of 82.02% (Table 4). Benelux

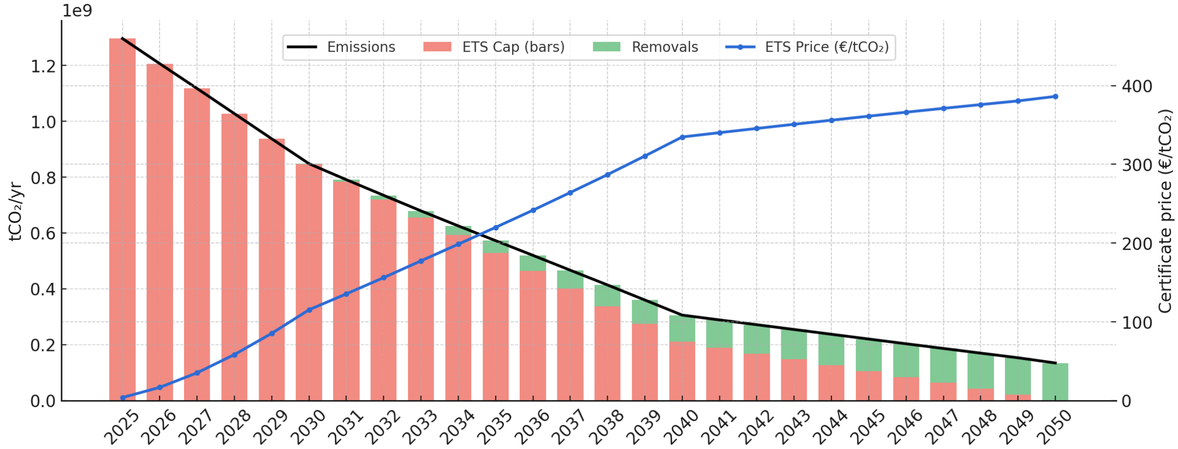

Figure 7: Unconditional inclusion ETS Cap Emissions Removals and Price Dynamics 2025–2050

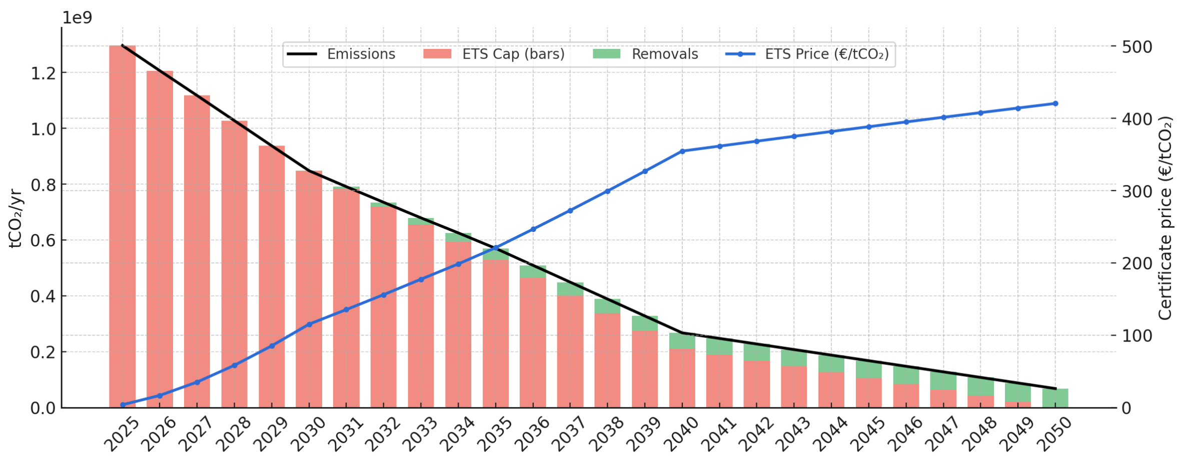

Figure 8: Conditional inclusion ETS Cap Emissions Removals and Price Dynamics 2025–2050

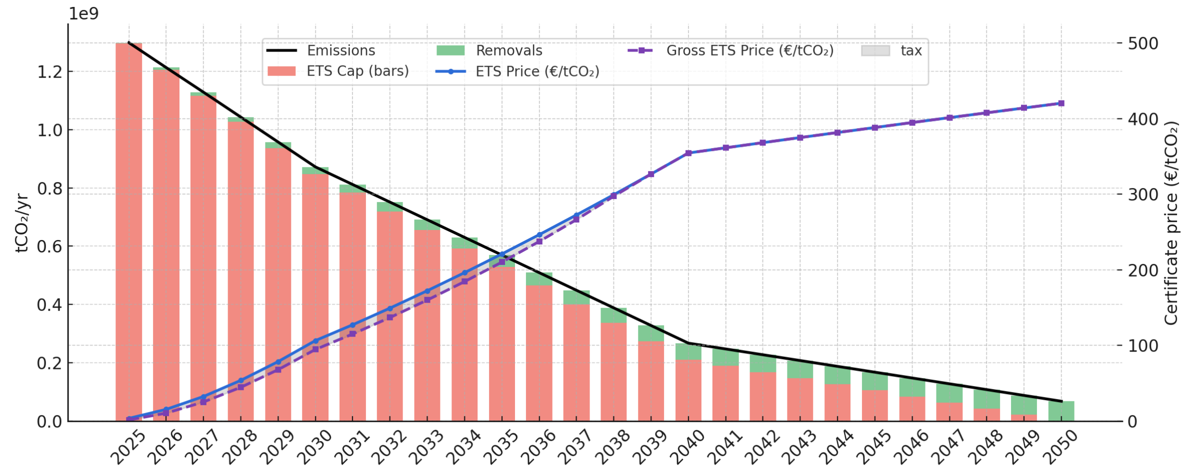

Figure 9: Procurement with contracts for difference ETS Cap Emissions Removals and Price Dynamics 2025–2050

Table 3: Pathway results

Metric	No CDR	Unconditional	Conditional (α = 5%)	Auctions (β = 5%)
Total negative emissions (cum., $GtCO_2$)	0.000	1.671	1.003	1.142
Negative emissions (2050, $MtCO_2$)	0.000	134.184	67.651	67.651
Max ETS price (€/tCO_2)	456.40	386.16	420.44	420.44
Emitter cost (2050, €/tCO_2)	175.54	148.52	161.71	161.71
CDR cost (cumulative, €bn)	0.00	361.29	172.59	194.33
CDR revenue (cumulative, €bn)	0.00	560.79	246.35	259.91
CDR profit (€/tCO_2)	0	119.36	73.54	57.43
Highest annual share R (%)	0	10.1	5.0	5.0
Share BECCS (%)	0.00	51.66	75.42	84.45
Share DACCS (%)	0.00	48.34	24.58	15.55

contributes ≈ 8%, Norway ≈ 9%, and Denmark ≈ 2%.The Herfindahl index of 0.247 is well above the equal-shares benchmark of 1/6 ≃ 0.167, representing a moderate concentration and exposure to country-specific risks in biomass, electricity or transport and storage availability. In practice, three levers matter. First, transport and storage networks expands feasible catchment for both BECCS and DACCS and reduce country concentration (Carbon Gap, 2025). Second, power sector policies that deliver clean electricity at scale to unlock DACCS where biogenic feedstock is scarce (Sacchi et al., 2023). Third, sustainable biomass governance and siting rules determine the ceiling for BECCS and the social license to operate (Donnison et al., 2020).

Technology specialization across countries follows comparative advantage as expressed in the removal cost decomposition in equation (13) and the country specific constraints on biomass, electricity, transport and storage. The decomposition of cumulative removals in Table 4 shows that Sweden supplies the largest BECCS volumes (26.58% of total removals as BECCS), consistent with abundant biogenic point sources and short routes to offshore storage. France contributes disproportionately to DACCS in later decades (18.96% of total as DACCS) alongside meaningful BECCS (6.76%). Germany exhibits a balanced profile (BECCS 11.29%, DACCS 10.29%). Benelux is predominantly BECCS (6.76% of total; DACCS 0.90%). Norway is effectively specializing in DACCS (DACCS 8.75%, negligible BECCS), consistent with abundant storage and low-carbon power, and Denmark contributes at small scale weighted toward DACCS. These specializations matter for infrastructure planning and the design of national support instruments: BECCS expansion emphasizes biomass sustainability and local land-use governance, whereas DACCS expansion emphasizes low-carbon electricity supply, long-term hedging, and grid planning.

The technology drivers also explain the temporal patterns in Figures 11–12. BECCS expands first and then saturates as country-level biomass potentials and hub capacities are exhausted. Whereas DACCS ramps later and becomes the marginal source of growth thereafter (Figure 10). Sweden stagnates near 25 $MtCO_2$/yr of BECCS by the late 2030s due to biomass availability, while France leads the DACCS investments in the 2040s with Germany catching up toward 2050. Norway hosts high DACCS volumes despite limited domestic biomass (Figure 5). Infrastructure and energy constraints shape the country-level deployment patterns. Where electricity prices and grid emission factors are favorable, DACCS enters earlier and at larger scale. Where transport and storage networks are cheaper and biogenic sources abundant, BECCS scales rapidly. Figure 13 shows that

DACCS-centric trajectories materially increase electricity demand in supplier countries.

Costs and rents evolve with the timing of technology deployment and country-specific cost wedges. Figure 14 shows expenditures rising first where BECCS commissions early, then shifting toward DACCS leaders as DACCS investments increase. Figure 15 shows producer surplus accumulating rapidly in Sweden during the 2030s, when low BECCS costs meet a rising EUA price, and then growing in France and Germany during the 2040s as DACCS volumes dominate with lower margin but higher quantity. Under unconditional inclusion this is the expected corollary of uniform pricing with heterogeneous supply: static efficiency at the EU level coincides with rent concentration where marginal costs lie well below the allowance price, especially once infrastructure and siting frictions are resolved (Edenhofer et al., 2023b). From a governance perspective this concentration implies that delays or policy reversals in any one of the top suppliers could materially affect aggregate delivery. Complementary measures that broaden geographic participation and coordinate power-system and storage investments can mitigate concentration risks while preserving market credibility (Eslahi et al., 2024).

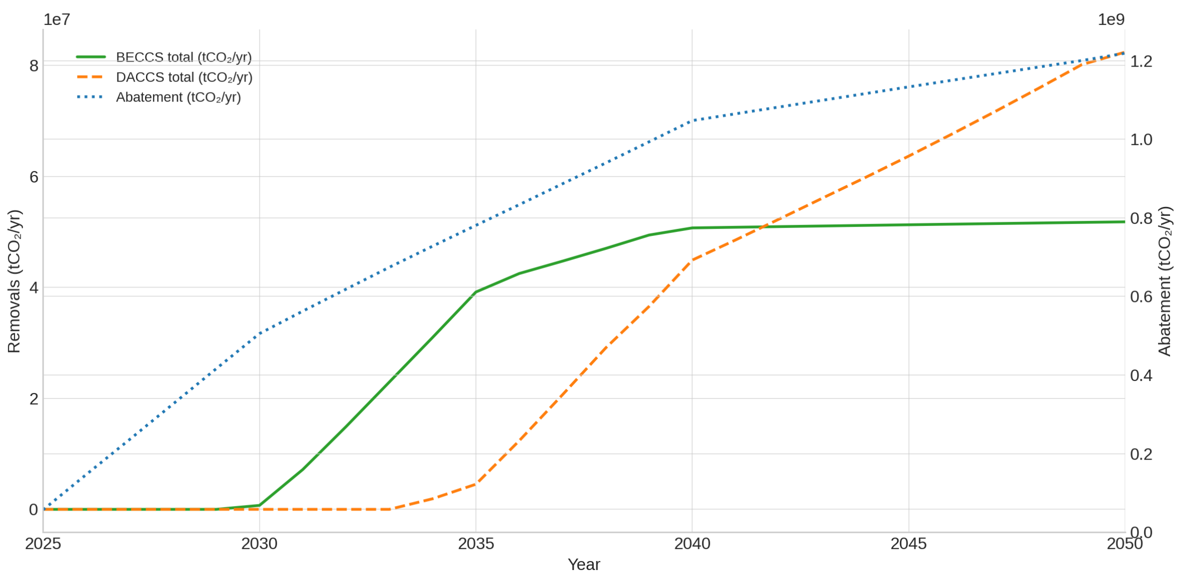

Figure 10: Aggregate technology dynamics (Unconditional scenario). BECCS and DACCS removals and ETS abatement over 2025–2050.

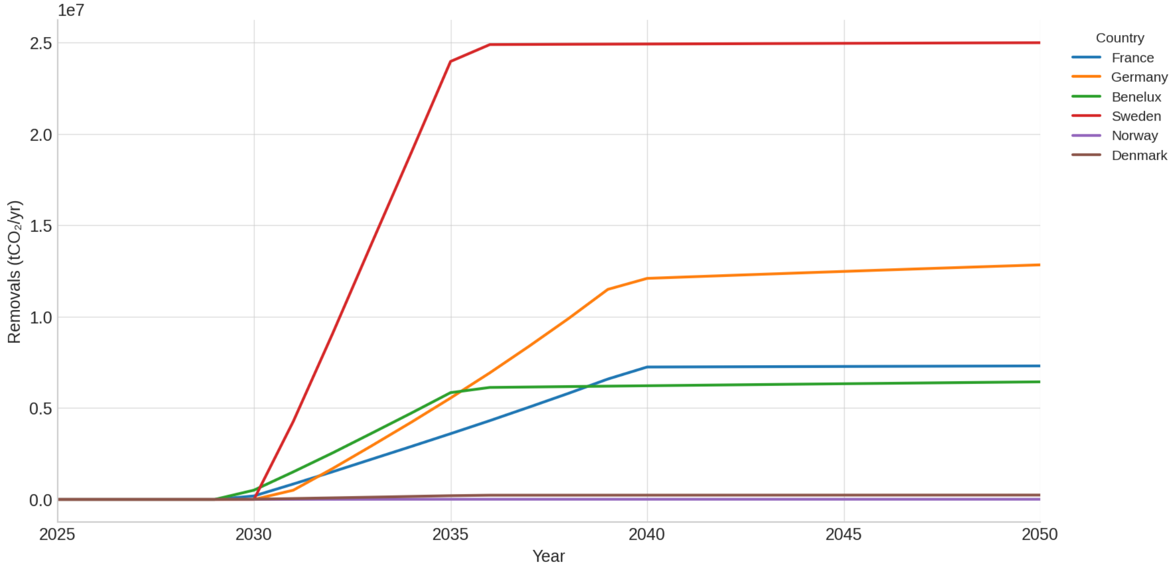

Figure 11: BECCS removals by country (Unconditional scenario, 2025–2050). Country breakdown of annual BECCS over 2025–2050.

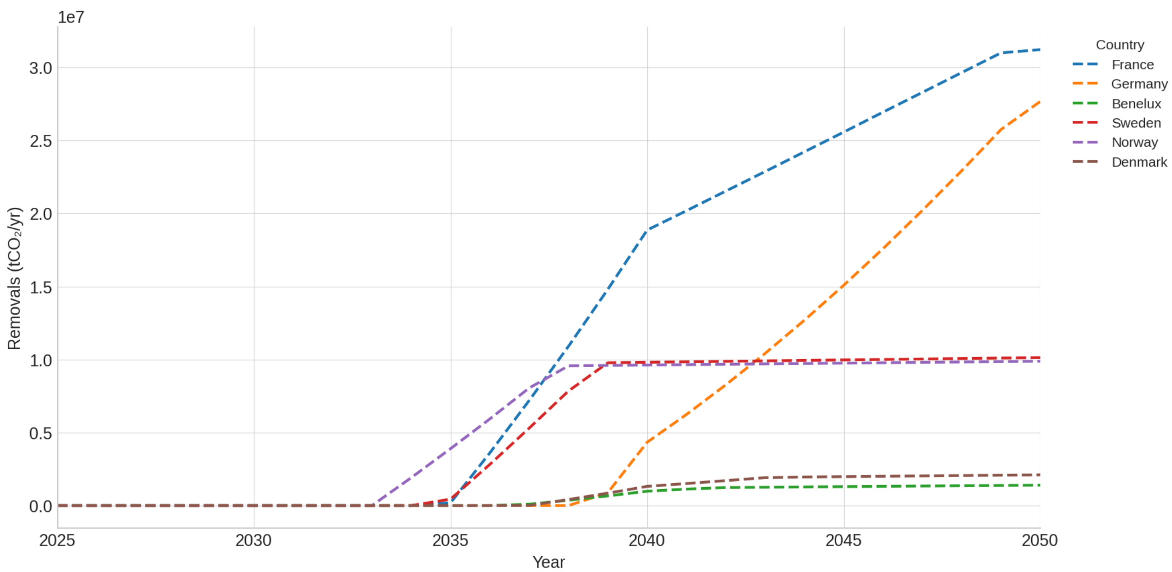

Figure 12: DACCS removals by country (Unconditional scenario, 2025–2050). Country breakdown of annual DACCS over 2025–2050.

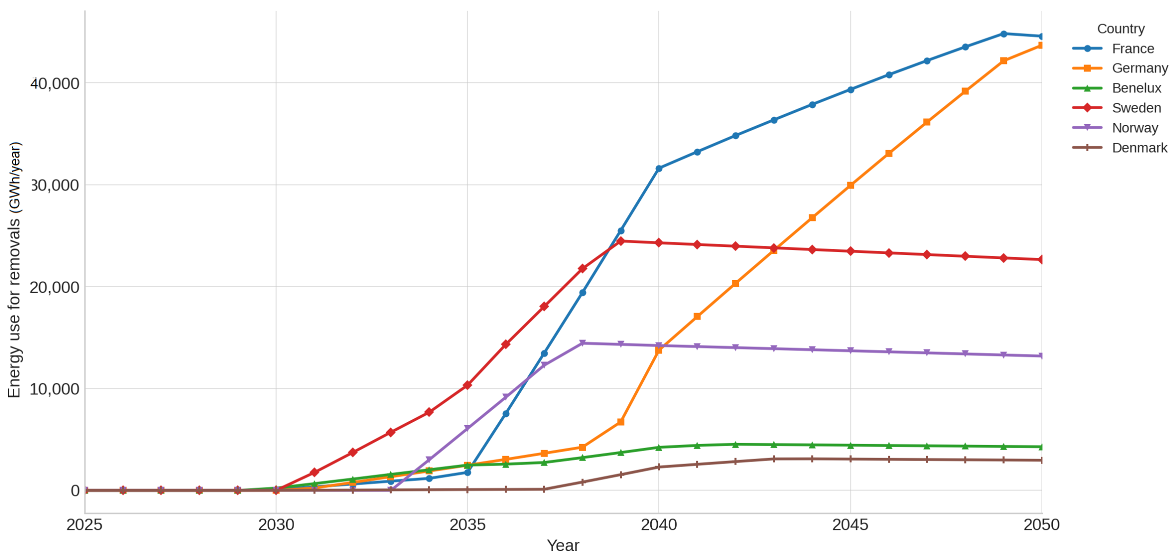

Figure 13: Electricity demand for carbon removal by country (Unconditional scenario, 2025–2050). Annual energy requirements associated with deployed BECCS and DACCS capacity (GWh/yr).

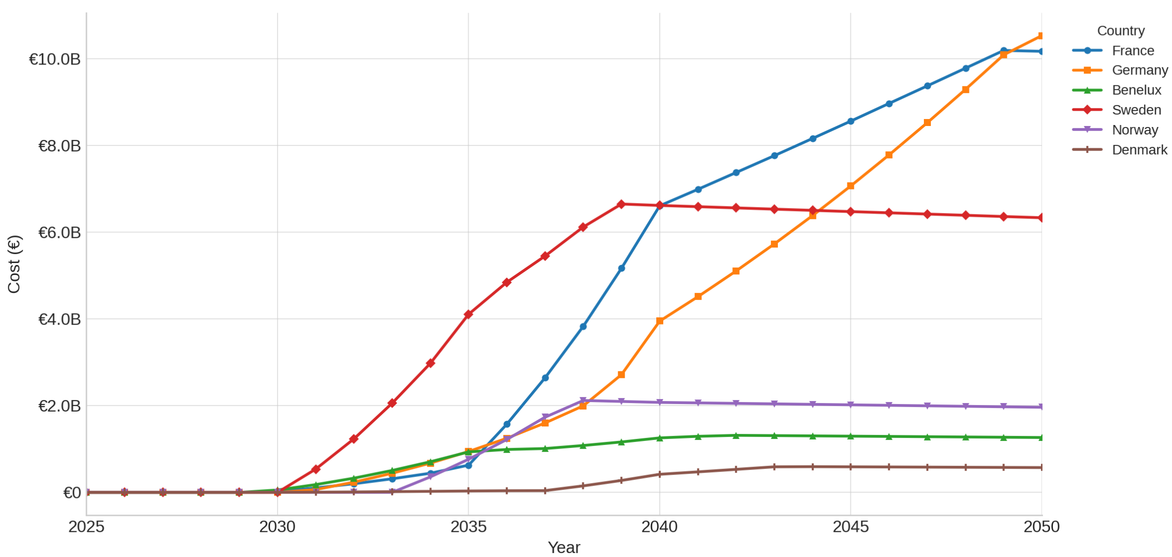

Figure 14: Annual cost incurred by country for CDR operations (Unconditional scenario, 2025–2050).

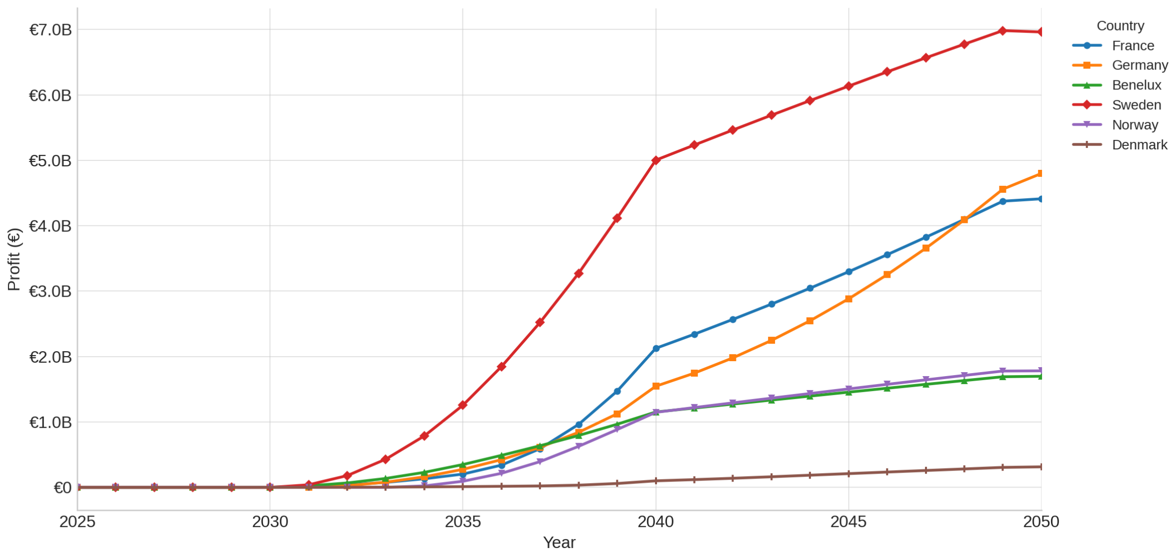

Figure 15: Annual producer profit by country (Unconditional scenario, 2025–2050).

Table 4: Country contributions and geographic concentration (Unconditional scenario; 2025–2050).

Item	Total (% of total)	BECCS (% of total)	DACCS (% of total)
A. Country shares of total EU removals (cumulative)			
France (FR)	25.72	6.76	18.96
Germany (DE)	21.58	11.29	10.29
Benelux (BEN)	7.66	6.76	0.90
Sweden (SE)	34.71	26.58	8.13
Norway (NO)	8.76	0.01	8.75
Denmark (DK)	1.56	0.25	1.31
B. Technology split (cumulative shares)			
Cumulative BECCS share		51.66%	
Cumulative DACCS share		48.34%	
C. Concentration metrics (geographic)			
Top-3 contributors (combined share)		82.02%	
Herfindahl index $H = \sum_k s_k^2$		0.247	

5.3 Discussion

Policy implications are implied directly from the above-mentioned mechanisms. If the policy objective is EU-wide cost minimization, unconditional fungibility is the efficient endpoint. It mobilizes the largest removal volumes but allocates larger scarcity rents to low-cost suppliers and suppresses the allowance signal earlier in the horizon. If the objective is to pace learning, protect abatement incentives during a sensitive investment window, and limit geographic rent concentration, calibrated surrender ceilings or procurement with transparent CfD financing are pragmatic instruments. Ceilings limit substitution ex ante by constraining R_t, while auctions bring forward capacity with competitive price discovery, compress infra-marginal rents, and make transfers explicit and subject to oversight.

General precautions are to be considered from compliance-market integration. Credible MRV, permanence and liability arrangements are a prerequisite for admitting removals without undermining environmental integrity (Rickels et al., 2021b). Procurement schemes require multi-year commitment and clear fiscal accounting if they are to accelerate early deployment without imposing unanticipated costs on market participants. Complementary policies on clean power expansion, coordinated CO_2 storage investments, and measures to broaden geographic participation are needed to reduce concentration risks and improve system resilience as removals scale. Screening for additionality and avoiding double counting remain central to ensure that admitted compliance units are incremental and durable.

The concentration of supply and rents raises coordination questions within a harmonized ETS. Cross-border cost recovery and network tariffs for CO_2 transport and storage affect burden-sharing (Edenhofer et al., 2023b). Uncoordinated national support risks fragmented infrastructure and lock-in. If policymakers value a diversified portfolio, a uniform surrender cap may be insufficient: targeted procurement windows or technology-differentiated auctions can diversify supply without sacrificing price stability (Rickels et al., 2022). The auction architecture spreads financing across ETS participants, softening national distributional tensions while preserving the marginal abatement incentive for emitters via the effective compliance cost c_t^{eff} in (7) (Woods et al., 2025). Because unconditional fungibility delivers the largest removals but also the strongest price suppression, any move toward full inclusion likely requires MSR recalibration (Sultani et al., 2024) and clear liability rules to maintain market integrity (**fuss2018**).

6 Limitations and further research

6.1 Limitations

This study is deliberately stylized to isolate the economic mechanisms of integrating engineered removals into the EU ETS. Several modeling choices and scope restrictions limit the external validity of the quantitative results and point to extensions. First, the analysis focuses on six countries with access to North Sea storage. Results are not a pan-EU inventory and exclude interactions with the UK ETS. Inclusion of additional capture regions and storage basins could redistribute volumes and rents. In addition, the abatement within ETS sectors is modeled with a single representative emitter and a DICE-style marginal abatement cost function (equation (11)). This abstracts from sectoral heterogeneity and technology specific investment specificity. On the removal side, country and technology specific marginal removal costs combine annuitized CAPEX/O&M, electricity, and transport and storage components (equation (13)). Learning-by-doing and cost reductions are exogenous time trends, endogenous learning from cumulative deployment and knowledge spillovers are not represented. This likely understates the dynamic benefits of early deployment and potential lock-in. Electricity prices p^{el}_{kt} and grid emission factors $e^{\mathrm{grid}}_{k,t}$ enter removal costs and netting via $\nu_{kj,t}$, but the power system is not modeled endogenously. Capacity expansion, network constraints, hourly variability, and system adequacy are taken as given. The feedback from large DACCS loads to power-sector investment and prices is therefore omitted. Finally, transport and storage costs $\tau^{\mathrm{TS}}_{kjt}(\cdot)$ capture congestion via increasing marginal costs but abstract from spatial network topology, pipeline routing, hub capacity expansions, and permitting timelines. Contracting structures for storage access, liability allocation across borders, and queueing effects are not represented.

7 Directions for further research

Several targeted extensions could increase policy relevance while keeping model complexity manageable. First, it is possible to endogenize intertemporal market dynamics by embedding allowance banking and an explicit market stability reserve stock flow rule in a multi-period equilibrium with forward looking agents. Second, investigating the introduction of a limited sectoral disaggregation on the demand side to reveal where abatement is most likely to be displaced, how free allocation alters incidence, and which sectors require complementary measures to preserve abatement incentives, for additionality issues. Third, couple the removals model to a simplified capacity-expansion representation of the power system so that electricity prices and grid emission factors respond endogenously to DACCS loads. Fourth, allow for endogenous cost decline through learning-by-doing for BECCS and DACCS so procurement and surrender policies can be evaluated for their effect on long-run costs and technology composition. Finally, expand the geographic scope to a full European scenario when appropriate data would be available.

8 Conclusion

This paper develops a multi-country equilibrium model to assess how engineered carbon removals can be integrated into the EU ETS and what this implies for volumes, prices, technology mix, and the geographic distribution of costs and rents. The analysis compares three pathways that are prominent in the policy debate: unconditional fungibility of removals with EUAs, conditional inclusion via a surrender ceiling, and regulator led procurement through reverse auctions with contracts for difference.

Three findings are central. First, there is a robust trade-off between the scale of negative emissions and the strength of the allowance price signal. Unconditional inclusion mobilizes the largest cumulative removals (1.671 GtCO_2 over 2025–2050) and lowers the peak allowance price most (from 456.4 EUR/tCO_2 without CDR to 386.2 EUR/tCO_2), effectively reducing the financial pressure toward net-zero for EU ETS industries. Pathways that constrain the annual use of removals through a 5% surrender cap or a 5% procurement target deliver smaller volumes (about 1.00–1.14 GtCO_2) and preserve higher peaks (around 420.4 EUR/tCO_2) but are still effectively beneficial for lowering compliance costs. These patterns arise directly from the net-cap compliance identity and the pathway-specific rules that set admitted removals.

Second, institutional design shapes the technology portfolio. Quantitative limits that bind are typically filled by lower-cost BECCS, producing BECCS-heavy mixes under the ceiling and auction designs, whereas unconditional fungibility allows a more balanced BECCS–DACCS split by admitting later DACCS entry when it becomes marginally competitive. The sequencing is consistent with the cost decomposition: BECCS expands earlier until biomass and hub constraints tighten, whereas DACCS scales later as electricity decarbonizes and learning reduces costs. This has system integration implications because DACCS centric trajectories place additional loads on power systems in supplier countries.

Third, integration pathways have distributional consequences. Under unconditional inclusion, higher volumes at allowance linked prices create substantial infra-marginal rents concentrated in a few countries with favorable biomass, electricity, and storage access. Auctions compress per-ton margins by increasing early competition and procuring higher marginal cost projects, shifting part of the surplus away from suppliers and toward the broader market via levy financed contracts for difference. The geography of supply is moderately concentrated: Sweden, France, and Germany account for more than four fifths of cumulative removals in the unconditional scenario. This concentration shows the importance of cross-border infrastructure coordination and clear liability and MRV frameworks.

Policy implications follow from these results. If the policy objective prioritizes EU-wide cost minimization and rapid scale, unconditional inclusion is the efficient endpoint, but it weakens the abatement price signal earlier and concentrates rents. If the objective is to pace learning, preserve abatement incentives during a sensitive investment window, and moderate geographic concentration, calibrated surrender ceilings or transparent procurement with contracts for difference offer pragmatic instruments. Any design that materially expands effective supply should be evaluated jointly with MSR parameters and banking incentives to maintain coherent price and investment signals. Credible MRV, permanence, liability, and additionality rules are the preconditions for admitting removals as compliance units without compromising environmental integrity.

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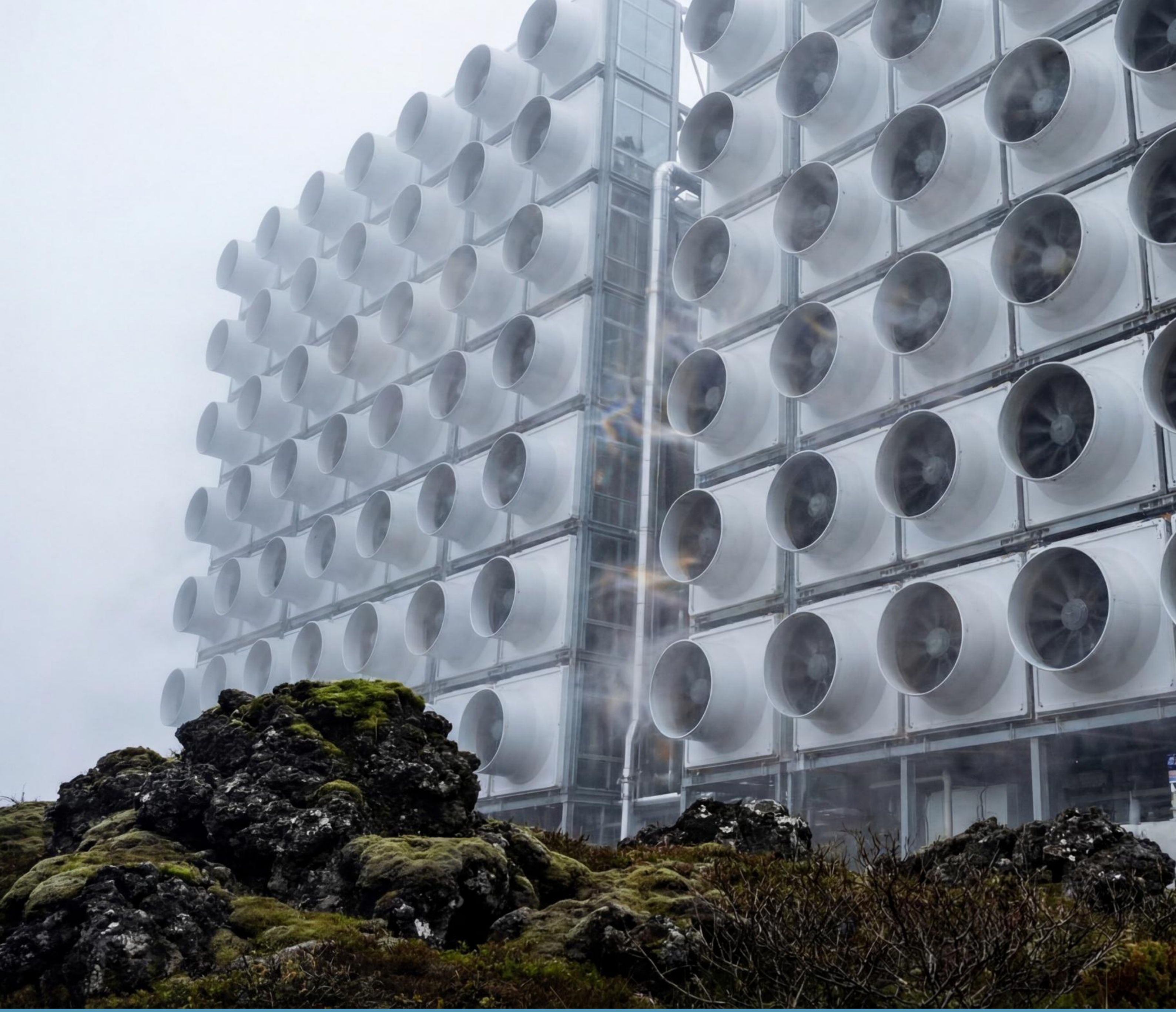

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