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The emerging endgame: The EU ETS on the road towards climate neutrality

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ABSTRACT

The 2023 reform of the EU emissions trading system (ETS) has brought to the forefront the issue of allowance market functioning in the long run. With the emissions cap set to go down to zero by around 2040, the next decade can be said to mark the 'ETS endgame'. That is, when allowance supply approaches zero, the market is bound to undergo fundamental changes. Yet the understanding and modeling of terminal market dynamics with ever-increasing allowance scarcity is limited. We analyze possible changes in market conditions and behaviors, and discuss associated challenges in two steps. First, we use the numerical model LIMES-EU to illuminate the market dynamics instigated by the reform, i.e. key changes in allowance price formation, supply adjustment and abatement by sector. Second, we use our numerical results as a backdrop to identify potential frictions (financial, informational, distributional) that may arise or become exacerbated as the endgame unfolds. Besides shedding light on whether the ETS is fit for climate neutrality, these frictions further delineate avenues for future research to improve the understanding and modeling of emissions trading in the long run.

1. Introduction

In March 2023, the EU enacted a reform of its emissions trading system (ETS) that tightened the emissions cap, with allowance supply bound to dry up in less than two decades. This aligned the ETS with the EU's 2050 climate neutrality goal, notably through a doubling of the cap's linear reduction factor (LRF), entailing a supply path that reaches zero around 2040.[1] Moreover, the main supply adjustment rules of the market stability reserve (MSR) were retained, which may further eat away at supply. With structural supply disappearance now clearly in sight, the reform can be said to have ushered in the 'ETS endgame'.

This outlook brings the puzzle of market behavior with supply nearing zero to the forefront. Such a situation may have potentially profound ramifications for ETS functioning and design that have yet to be explored. Fundamentally, how can an ETS, as an economic instrument, efficiently deliver and manage a net-zero emissions cap, if at all? These issues call for proper investigation as they will be crucial in shaping the next wave of reforms. Indeed, the functioning of an ETS that approaches a final zero-supply state largely remains uncharted territory both scientifically and practically. For instance, there is little practical experience as all ETSs worldwide are still relatively new or have not yet reached their terminal phase. An exception is the US SO_2 emissions trading program, which initially cut emissions cost-effectively but has then been gradually superseded by stricter regulations (Schmalensee and Stavins,

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[1] This does not account for small remaining batches of allowances in the aviation sector, in which case supply reaches 0 in 2044, or possible scope extensions.

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2013). Yet the parallels and implications for decarbonization policies are limited.[2]

We pursue a two-stage approach for analysis. In the first stage, we use the numerical model LIMES-EU to quantitatively address the question of how 'terminal' market dynamics may play out (Section 2). Our results illustrate how the 2023 reform and associated anticipation effects on allowance price and banking behaviors — reinforced by their interaction with the MSR — bring the ETS endgame and greater allowance scarcity forward in time.[3] This analysis connects to the literature that uses both theoretical and numerical models to investigate price formation in the ETS with market stability mechanisms, see notably Osorio et al. (2021) with LIMES-EU, and Perino et al. (2022b) and Borghesi et al. (2023) for reviews.

Our contribution to this literature is to take a first step in closing the gap in existing work where the terminal market phase is not an object of study in itself. In all numerical and theoretical ETS model-based work so far, the system's endpoint is used as a boundary condition to solve for equilibrium paths backwards through intertemporal arbitrage. Accordingly, the two main conceptual frameworks utilized in the ETS literature — i.e., Hotelling and competitive storage (e.g., Rubin, 1996; Schennach, 2000; Lintunen and Kuusela, 2018) and stochastic equilibrium pricing (e.g., Seifert et al., 2008; Grüll and Taschini, 2011; Hitzemann and Uhrig-Homburg, 2018) — do not specifically consider terminal market phases. This is because, in such frameworks, the trajectory and final level of allowance supply — be it zero or not — is essentially irrelevant for their backward-induction solution procedure to apply, with no consideration of what different supply conditions may entail for market functioning and dynamics in the long run. For instance, Heijmans and Engström (2024) study the impact on cumulative emissions of changing the duration of an ETS with different supply adjustment mechanisms, but their competitive equilibrium results hold, by construction, irrespective of the supply trajectory or level.[4] In contrast, our work addresses the system's endpoint as the moment when supply goes down to zero, which is determined by policy design and not merely by methodological considerations such as backward induction. In addition, our analysis explicitly focuses on the modeled market dynamics in the mid to long run.

In the second stage, we use qualitative analysis to illuminate the emerging question of how modeled ETS dynamics may change when economic and political frictions specific to the endgame are considered (Section 3). We structure this analysis around the existing literature on allowance markets that may indirectly speak to the issues and frictions that may become (more) relevant when supply approaches zero by extrapolation of their results to an endgame context. These include informational and trading frictions in relation to the nature of private information (Cantillon and Slechten, 2018), market size (Liski, 2001), and the extent to which allowance banking is possible (Toyama, 2024). Additionally, because such frictions are not specific to allowance markets but concern any thin, small, or scarce-resource markets, we also draw on the literature beyond ETS-related fields. These include alternative allocation mechanisms for scarce resources (Weitzman, 1977), cases where distributional aspects matter for the regulator (Akbarpour et al., 2024), or where a trade-off between short-term operation and long-term investment efficiency exists (Weyl and Zhang, 2022). Such qualitative analysis allows us to identify specific frictions along with potential avenues for future numerical and theoretical work on the ETS endgame.

Reasons for not already considering frictions in the quantitative analysis are twofold. First, they may only arise or be exacerbated in the future, and guidance on which frictions will actually be relevant is currently lacking. Accordingly, we zero in on fundamental changes in the long-run market dynamics produced by a conventional numerical model (i.e., without frictions) as a backdrop to reflect on the impacts that supply going down to zero may have for market functioning and behavior — and thereby investigate which frictions may be relevant. Second, frictions are challenging to include in complex numerical ETS models like LIMES-EU. In fact, just a few papers exist that use considerably more stylized models to represent specific frictions, such as risk aversion (Kollenberg and Taschini, 2016; Tietjen et al., 2021), limited planning horizons (Quemin and Trotignon, 2021), transaction costs (Singh and Weninger, 2017; Baudry et al., 2021), or biased price beliefs (Perino, 2024).

Overall, the essence of our work is to start addressing the pertinent questions of whether the ETS is suitable as a climate policy instrument to attain a net zero target, and how its design and governance framework could be improved to that end. It sheds light on potentially crucial issues for the future of the EU ETS as it approaches zero supply, and invites further research along the lines we put forth.

2. Numerical analysis without frictions

In this section, we first quantitatively analyze the EU ETS dynamics without consideration of frictions using the numerical model LIMES-EU. Specifically, we quantify the implications of the 2023 ETS reform on market developments. Our interest is not so much in the aggregate impacts of the more stringent cap and MSR revisions leading to higher allowance prices and scarcity that have already been studied using this and other ETS models.[5] Rather, we look deeper into different cross-sectoral and cross-technological dynamics, as well as into banking behavior and the related impacts of the MSR, with a focus on the mid to long term. We then consider some implications for market behavior and design.

[2] CO_2 is more ubiquitous in the economy than SO_2, and is a global pollutant. Furthermore, net-zero CO_2 targets entail a need for emission removals—a requirement not applicable to SO_2. Another earlier successful trading program was used for the phasedown of lead in gasoline in the US, but it essentially was a tradable performance standard, not a cap-and-trade program (Kerr and Newell, 2003; Schmalensee and Stavins, 2017).

[3] Note that the 2023 reform does not directly affect the system's endpoint, i.e., the date at which allowances lose compliance and economic values by mandate (or naturally, in the case a zero emission state is reached).

[4] Similarly, by construction, other temporal aspects such as the timing of compliance obligations (Holland and Moore, 2013) or supply adjustments (Hasegawa and Salant, 2014) can only be analyzed through their possible impacts on the feasibility of market equilibrium paths.

[5] See e.g. Osorio et al. (2021) and Sitarz et al. (2024) for such studies using the LIMES-EU model.

Table 1
Cap and MSR settings in the Reference and Reform scenarios.

Reference (2018 reform)	Reform (2023 reform)
Cap ∘ 43% emission reduction w.r.t. 2005 ∘ Annual linear reduction factor (LRF) of 2.2% (expressed as a percentage of the 2005 emission level)	**Cap** ∘ 62% emission reduction w.r.t. 2005 ∘ LRF of 4.3% in 2024–27 and 4.4% as of 2028 ∘ One-off reduction (rebasing) of 90 million EUAs in 2024 and 27 million EUAs in 2026
MSR ∘ Intake rate of 24% until 2023 and 12% afterwards, with intake volume equal to intake rate times TNAC ∘ Outtake volume of 200 million EUAs until 2023 and 100 million EUAs afterwards ∘ Upper TNAC threshold of 833 million EUAs above which intakes are triggered ∘ Lower TNAC threshold of 400 million EUAs below which outtakes are triggered ∘ Yearly invalidation of EUAs in the MSR in excess of the previous year's auction volume	**MSR** ∘ Intake rate of 24% until 2030 and 12% afterwards ∘ Intake volume equal to intake rate times TNAC if TNAC exceeds buffer threshold, else to TNAC minus upper threshold if TNAC is between the upper and buffer thresholds ∘ Upper TNAC threshold of 833 million EUAs complemented by an buffer threshold of 1096 million EUAs for intakes ∘ Outtake volume and lower threshold unchanged ∘ Yearly invalidation of EUAs in the MSR in excess of 400 million EUAs

Note: The total number of allowances in circulation (TNAC) is a proxy for the aggregate amount of emission allowances (EUAs) banked by market participants at the end of each year t, i.e. $\text{TNAC}_t = \text{TNAC}_{t-1}$ + supplied EUAs_t − surrendered EUAs_t − MSR intakes_t + MSR outtakes_t. The MSR adjusts the volume of annual auctions downwards (upwards) if the TNAC in the previous year is above (below) a given intake (outtake) threshold. The core rules governing the functioning of the MSR are unchanged by the 2023 reform. For our analysis that does not consider shocks and hedging, the most relevant aspect is the prolongation of the 24% intake rate. The introduction of the buffer intake threshold corrects oscillatory effects identified for the original MSR design (Osorio et al., 2021; Quemin, 2022), while the introduction of the fixed invalidation threshold removes some endogeneity of MSR impacts on auction and invalidation volumes.

Methodology. The EU ETS exhibits more complex market dynamics than a plain-vanilla ETS due to sectoral and technological heterogeneity, an add-on supply adjustment mechanism (MSR), and a historical surplus of allowances. To study these dynamics in sufficient detail, we use the numerical model LIMES-EU, which includes the required features. LIMES-EU is a linear dynamic cost-optimization model covering the entire perimeter of the EU ETS. The model optimizes investment and dispatch decisions in 35 electricity generation and storage technologies, and abatement decisions in the other ETS sectors (e.g., the energy-intensive industry). It allows for intertemporal allowance trading (banking), includes an exact representation of the MSR, and is solved in a deterministic setting. The other ETS sectors are represented in a more stylized way through marginal abatement cost curves.[6] Main modeling, technology and policy assumptions are described in detail in Appendix A.[7]

Regarding policy and market design, we compare the market dynamics in two scenarios, i.e., before and after the 2023 ETS reform (see Table 1 for details). As will be seen, the two main revisions for our analysis are the doubling of the emission cap's LRF and the prolongation of the MSR's intake rate at 24%—both tend to increase allowance scarcity in the future, with the latter indirectly reinforcing the higher cap stringency directly implied by the former. In both the Reference and Reform scenarios, we extrapolate the regulatory status quo beyond the given regulation's horizon, except for the intake rate that is currently stated to go back to 12% post-2030 in the Reform scenario. In particular, we do not represent possible sectoral coverage expansion, linking to other ETSs within or outside the EU, and integration of carbon removals except for some bio-energy carbon capture and storage.

Regarding investment and allowance banking decisions, two modeling features and assumptions are of particular importance. First, we assume perfect foresight with a discount rate of 5%. Admittedly, the effects of the MSR and ETS reforms can vary significantly with the degree of foresight (Quemin and Trotignon, 2021; Borghesi et al., 2023). Yet a back-casting analysis using LIMES-EU finds that while limited foresight explains price formation before 2018 well, perfect foresight increasingly performs better later on, suggesting that the 2018 and 2023 reforms (re)introduced some long-term credibility and confidence in the ETS (Sitarz et al., 2024). More generally, perfect foresight constitutes a widely-used normative benchmark. That said, we conduct a sensitivity analysis to different discount rates, recognizing that the relevant rate may change over time (see Appendix B.3). Second, we assume that allowances can be banked and used for compliance until 2055 in the Reference scenario and 2045 in the Reform scenario. These endpoints align with the timeline of, but are not explicitly formulated in, respective policies.[8]

Modeled market dynamics. Here we focus on the main numerical results that can shed light on the difference in the market dynamics in the two scenarios; a more detailed description of the results is provided in Appendix B, and data from all figures is available for download from Zenodo.[9] Beginning with the Reference scenario (Fig. 1), the allowance price increases only moderately to 49 EUR/tCO_2 by 2030 and 134 EUR/tCO_2 by 2050.[10] Emission reductions mainly occur in the electricity sector until 2030, while

[6] The use of marginal abatement cost curves is a standard approach for ETS modeling in general (Perino et al., 2022b; Borghesi et al., 2023) and, in particular, for representing the industry sector in models that have a detailed representation of the electricity sector (see e.g., Bruninx et al., 2020). This approach models abatement as an instantaneous non-permanent activity with costs borne in every period, as compared to investment in abatement technology with upfront costs and permanent effects on allowance demand.

[7] A comprehensive description of LIMES-EU is provided in the documentation available from the model website at this link. See also Osorio et al. (2024).

[8] As indicated in the Introduction, setting a given endpoint is required for numerical solving but does not meaningfully alter the qualitative nature of our quantitative results as discussed in Section 3.

[9] DOI link to Zenodo: 10.5281/zenodo.14233820.

abatement in the industry sector starts materializing only afterwards. Roughly speaking, banking (or its proxy, the TNAC), emissions, supply, and MSR holdings co-evolve from 2025 onwards and decrease relatively smoothly to near zero by around 2055. Banking remains below historical levels due to sufficiently abundant allowance supply (w.r.t. anticipated demand) over the whole horizon. MSR operations lead to total invalidations of 5.0 billion allowances, constricting cumulative allowance supply by the same amount.

In the Reform scenario (Fig. 2), market dynamics differ in notable ways. Emission reductions are considerably accelerated and allowance prices reach considerably higher levels earlier on due to the reform-induced increase in stringency and 'squeeze' on the time horizon. Regarding prices, what stands out is that the price path only grows at the discount rate (Hotelling rule) up until 2045. This is because by 2050 the bank is depleted (TNAC = 0), and the market attains a net-negative equilibrium where the use of carbon dioxide removal (CDR) technologies balances so-called 'residual' emissions from industry that are more costly to abate. Hence the equilibrium is characterized by marginal abatement costs in the industry sector being equal to the marginal costs of CDR technologies. In subsequent years the price declines slightly because of the assumed technology learning that reduces CDR costs.

Regarding emissions, the bulk of reductions occur already in the 2020s, with emissions in 2030 being 57% lower than in 2020, which corresponds to a reduction rate almost three times as fast as in the Reference scenario. The electricity sector is largely decarbonized by 2030 with coal virtually phased out in most countries (electricity production below 10 TWh at the ETS perimeter), implying that in the 2030s abatement will mainly come from the industry sector. This acceleration is in part attributable to a positive feedback effect between banking behavior and MSR operations.[11] Specifically, in anticipation of higher future allowance scarcity due to the higher LRF, banking increases significantly. This leads to larger MSR intakes, which are also augmented by the prolongation of the 24% intake rate until 2030. Accordingly, annual supply is reduced even further, inducing a positive feedback effect. In turn, total invalidations amount to 7.3 billion allowances, roughly a 50% increase relative to the Reference scenario.

Implications for price formation and MSR design. The above results have important implications for both price formation and MSR design, which especially become apparent when analyzing the sensitivities of the results to relevant assumptions (see Appendix B.3). Regarding price formation, the transition from an energy– to industry-centric market by around 2030 implies that the marginal abatement costs in the industry sector and the availability and costs of CDR technologies become the dominant fundamental factor. This is an important deviation from the current state of the ETS (and Reference scenario), in which the fuel switch from coal to natural gas or renewables for electricity production is the dominant fundamental. In fact, in the short term (until 2030) this transition rarely matters for price formation, as different availabilities and costs of CDR technologies have only a marginal effect. However, as time progresses, their price effects become increasingly larger, as the considerably stronger sensitivity of 2050 prices to CDR assumptions makes clear. Correspondingly, there is a large uncertainty about the factors underpinning allowance demand that translates into an increasingly large price uncertainty. In other words, the post-2030 ETS will be marked by very high price uncertainty arising from the reliance on yet mostly undeveloped and relatively immature technologies that can be expected to shape the net-negative equilibrium.

Regarding MSR design, our results raise the question of whether the current MSR design approach to supply adjustment is adequate for an increasingly smaller market. At its core, this adequacy problem concerns the use of banking to determine changes in supply. The issues associated with the positive banking–MSR feedback effect reflect a growing consensus in the literature that the MSR tends to distort intertemporal efficiency and impair interactions with complementary emission-reducing policies. This is because the MSR reacts to an increase in banking as if it unconditionally signaled a decrease in contemporaneous demand when, in fact, it may also be a rational response to a future increase in demand or decrease in supply (Gerlagh et al., 2021; Perino et al., 2022a; Borghesi et al., 2023). Additionally, conditioning supply on banking impairs self-stabilizing market forces (Perino, 2024; Heijmans, 2023; Brinker et al., 2024), whereas the market price is a more robust indicator of scarcity that may be used to adjust supply more efficiently (Burtraw et al., 2022; Perino et al., 2022b).

Our results further suggest that these issues will be magnified in the endgame should the MSR remain unresponsive to the fundamental changes the market is bound to undergo. A crucial parameter in that regard is the discount rate, which can be used as a proxy for the time horizon of market participants and can vary over time as a function of the state of the market and the credibility of the cap. Arguably, credibility is currently high (Sitarz et al., 2024), but it may as well go down again in the future should political commitment wane (which could be captured by a higher discount rate). This motivates the analysis of the sensitivity to different discount rates (see Appendix B.3.1), which shows substantial long-term price uncertainty further magnified by MSR-triggered invalidations already in the year 2030.[12] In light of that, the question arises whether incremental changes in the MSR parameters (i.e., keeping the overarching TNAC-based approach as is) in the context of the upcoming 2026 review might be appropriate to deal with this uncertainty.

To investigate this, we conduct a complementary sensitivity analysis to cap and MSR parameters (see Appendix B.3.2). The adjustments considered tend to have a price-reducing effect, i.e., they lower the price relative to the current setting. While this may dampen the magnitude of the banking–MSR feedback effect, the MSR seems generally unsuited to stabilize the market, notably when discount rates are 'high' and thus short-term prices are 'low'. Relatedly, the general MSR rules are somewhat biased towards

[10] All prices and costs are presented in EUR2023.

[11] The mutually-reinforcing banking–MSR effect is already identified in the literature (Perino et al., 2022b; Borghesi et al., 2023). Here we emphasize its implications on the acceleration of potential endgame issues.

[12] The large uncertainty and sensitivity of MSR invalidations to modeling assumptions and market behavior was identified in prior works (Borghesi et al., 2023). Here we illustrate that the 2023 reform intensifies these effects. Moreover, while our model is deterministic and cannot provide direct insights about hedging pressure, increased price uncertainty could further hike (precautionary) banking and in turn MSR invalidations.

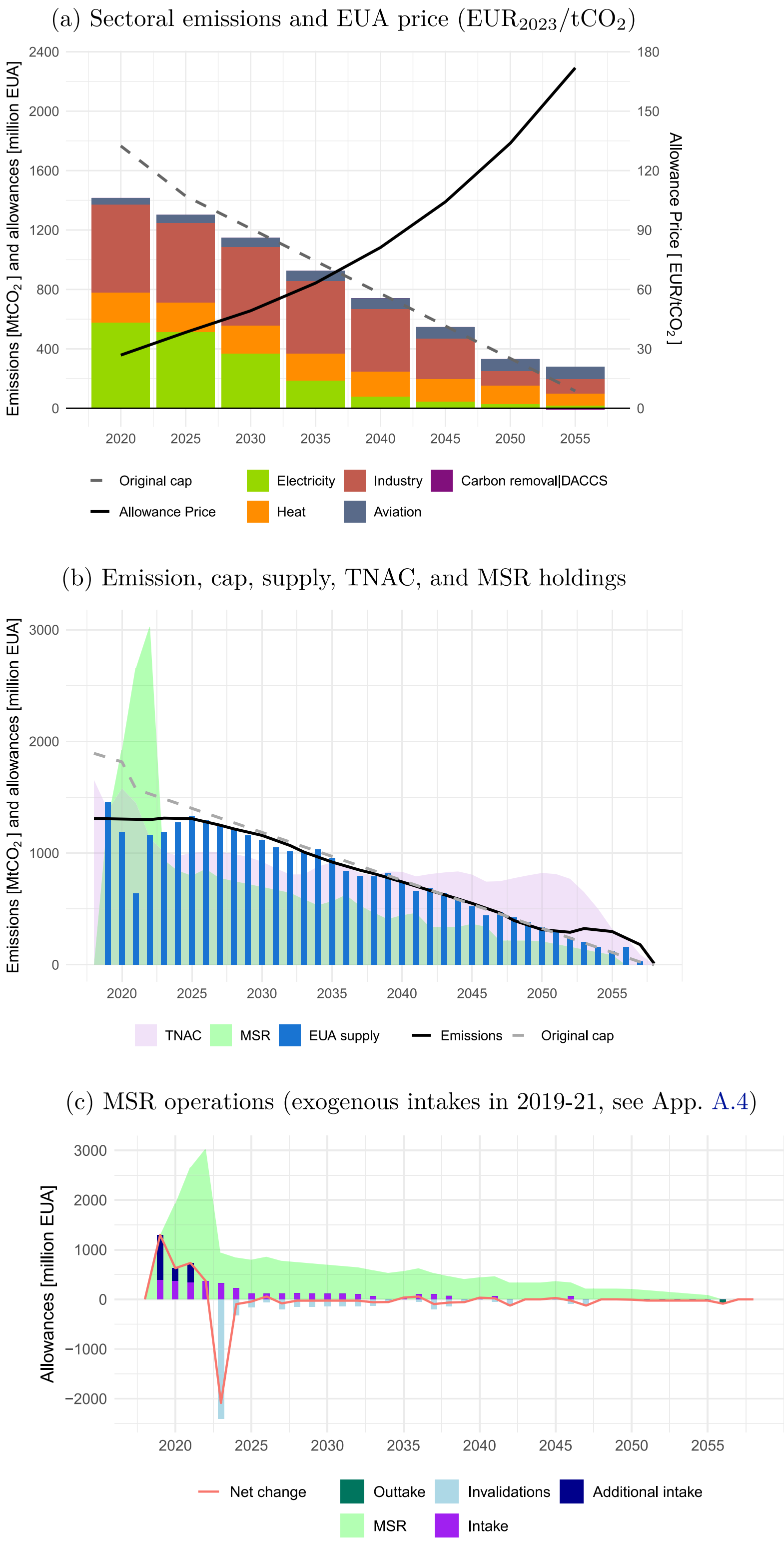

Fig. 1. Market dynamics in the Reference scenario.

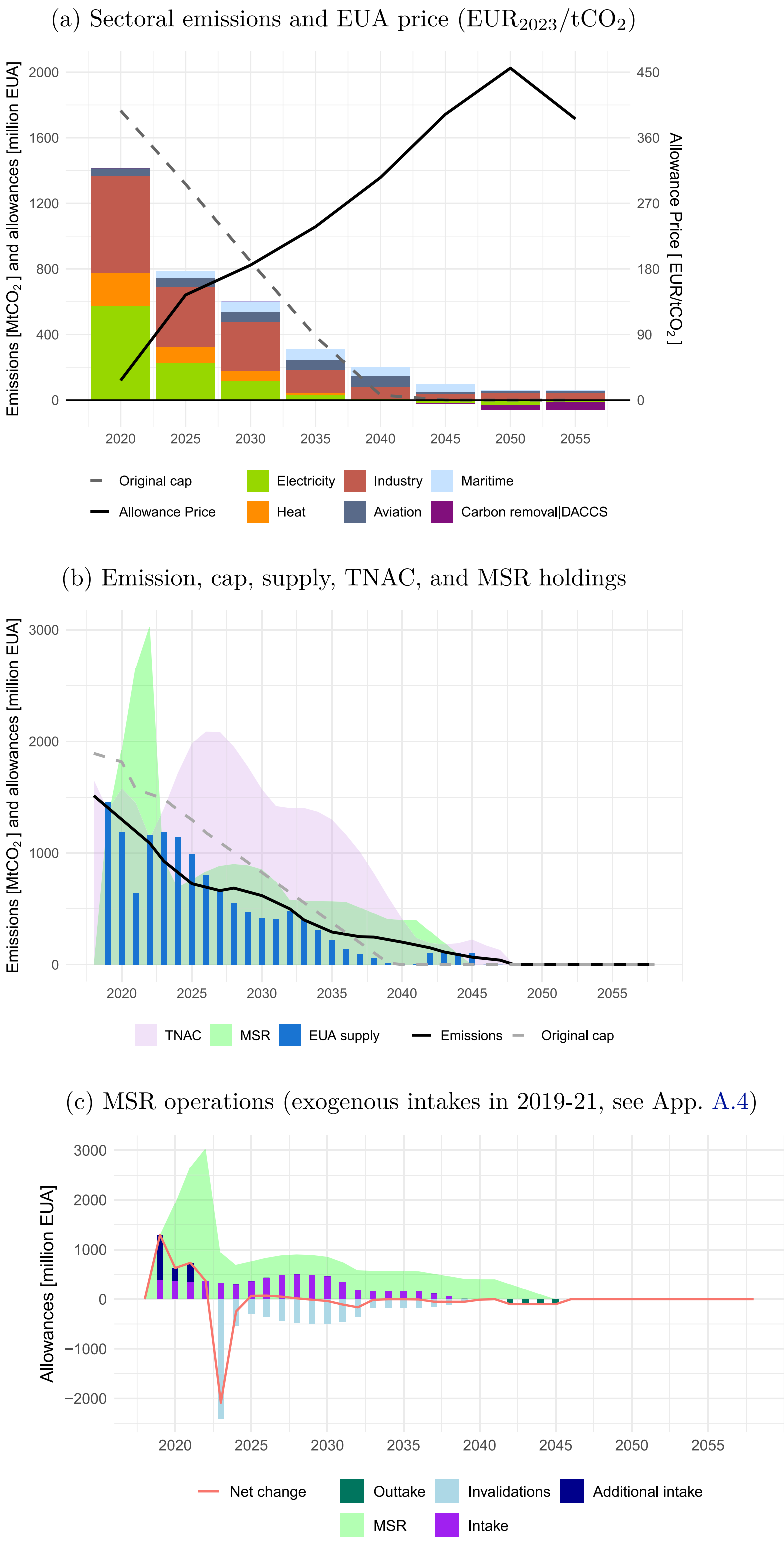

Fig. 2. Market dynamics in the reform scenario.

reducing supply (intake rule), and place less priority on situations that may require supply expansion (outtake rule). More generally, we also foresee that setting relevant quantity parameters will be structurally more difficult as market size and other quantities get increasingly smaller. Overall, this may call for more timely and agile supply adjustments and for the use of a more accurate scarcity metric than the MSR currently provides for, which may reinforce other economic arguments in favor of price-based controls (Perino et al., 2022b; Borghesi et al., 2023).

3. Qualitative analysis of potential frictions

In this section, we use the insights from the above numerical analysis as a backdrop to consider key qualitative differences in the economics of the current ETS versus future ETS with supply closing in on zero. We seek to illustrate whether — and if possible, how — different market conditions may create new or exacerbate existing market frictions and policy failures. This is a useful first step to help overcome the limits of current modeling frameworks in capturing endgame or terminal market dynamics.[13] Where possible, we further discuss some potential adjustments in both ETS design and modeling to overcome these limits. These considerations are intended to raise conceptual and policy-relevant questions and to delineate avenues for future research rather than to provide definite answers and policy recommendations.

Banking constraints, market thinness, and trading frictions. In the short term, the numerical analysis suggests that an allowance bank of a large size will accumulate quickly in anticipation of future allowance scarcity. This notably allows for smoothing out the transition to zero supply over time by prolonging the period of availability of allowances in the market. Yet at least two constraints that are not modeled may lead to suboptimal (lower) banking levels, possibly mitigating the size of the positive banking-MSR feedback effect. First, limited foresight combined with risk-management practices of compliance firms may deviate from full rationality (Venmans, 2016; Fuss et al., 2018; Quemin and Trotignon, 2021), notably in the industry sector that has hitherto only scarcely engaged in trading and hedging (Baudry et al., 2021; Abrell et al., 2022; Quemin and Pahle, 2023).[14] Second, limited access to capital and financial constraints may be magnified by the impact of rising prices and transition risks on firms' creditworthiness (Carradori et al., 2023; De Haas et al., 2024). Up to the mid term, additional impacts on banking, and more generally constraints on allowance availability, may originate from trading strategies of non-compliance actors, such as temporary 'buy and hold' (ESMA, 2022; Quemin and Pahle, 2023), that we do not represent in the model.[15]

In the longer term, the allowance bank will gradually decrease and eventually shrink to zero. This feature is a necessity that occurs by design, and the question of whether this occurs earlier or later than in the numerical analysis is not essential for the following argument.[16] Specifically, a structurally diminishing bank is of economic importance because a shrinking market size (bank + auction volumes) entails the risk of thin trading. This may markedly alter market operations and functioning compared with those we have observed and modeled as of today. For instance, as allowances become scarcer, market participants may become reluctant to trade and may instead cling on to their allowance holdings, so that trading costs and illiquidity may increase (Liski, 2001).[17] The potential of banking to mitigate such trading frictions (Toyama, 2024), as well as its associated benefits for intertemporal efficiency and shock smoothing (Schennach, 2000) and price buoyancy (Lintunen and Kuusela, 2018), may be severely impaired as the bank is gradually drawn down and ultimately depleted.[18]

Information frictions, regulatory uncertainty, and coordination failures. In the short to mid term, the numerical analysis suggests that market fundamentals will become increasingly dominated by the marginal costs of abatement technologies in the industry sector. By contrast, fuel switching in electricity production, which has been a pivotal (short-term) allowance price driver, will become less and less relevant as first coal and then gas will be phased out.[19] This has implications for allowance price formation, because information about industrial abatement is more fine-grained and dispersed (technologies differ considerably by firm and facility) and their fundamentals are less readily observable (underlyings are less transparently traded) than for fuel switch.[20] In other words, information about costs will increasingly become private. Yet efficient information aggregation through the market price as a sufficient statistic breaks down in an allowance market where abatement costs are private information (Cantillon and Slechten,

[13] As the endgame draws closer, we reiterate that using the market's terminal phase as a mere boundary condition to set an endpoint from which to solve for equilibrium paths backwards — as we do in the numerical analysis — will become less and less relevant. What could then arguably be deemed a modeling edge effect when focusing on early to middle market phases must now become an object of study in and of itself.

[14] More generally, risk preferences influence banking decisions and thereby affect the outcomes of supply adjustment mechanisms (Kollenberg and Taschini, 2019; Tietjen et al., 2021).

[15] Compliance enforcement is another constraint we do not model (we implicitly assume full compliance) that may become more prevalent with higher allowance scarcity and prices. See Calel et al. (2023) for a recent analysis and discussion, and Stranlund (2017) for a literature review on enforcement mechanisms.

[16] The banking dynamics hinge on modeling assumptions and, with perfect foresight, notably on the chosen endpoint beyond which allowances are worthless. Ceteris paribus, postponing the endpoint would lead to a longer banking period with higher banking levels, and vice versa.

[17] Trading costs, which capture the wedge between the market price and firms' shadow values of allowances, have been shown to be prevalent in the EU ETS, especially for small firms (Baudry et al., 2021; Zaklan, 2023).

[18] Note that market scope extension through linking to other systems or integration of emission removals certificates may ease quantitative constraints on allowance supply and banking.

[19] The allowance price will be reflected in marginal power generation costs in a decreasing number of hours as power prices become increasingly set by low-carbon and storage technologies (Mallapragada et al., 2023).

[20] Hedging is another important determinant of allowance demand and price formation. Whereas electricity generators have actively engaged in hedging their allowance needs a few years ahead (e.g., Quemin and Pahle, 2023), whether and how industrials will hedge their compliance cost forward remains uncertain.

2018). Information frictions may thus increase, making it more difficult to distinguish fundamentals from noise in market prices.[21]

If trading and information frictions increase, the role of the allowance price as a decentralized coordination and information signal may be undermined. For instance, a lower signal-to-noise ratio may give rise to noise trading that could further exacerbate noise (De Long et al., 1990), an issue which tends to be more prevalent in small markets (Palomino, 1996).[22] Relatedly, price formation may become more erratic if higher noise makes pursuing fundamentalist trading strategies more costly (Hommes et al., 2005).[23] At a more conceptual level, if noise intrinsic to the trading process becomes large enough (i.e., excessive), the trend of a stochastic Hotelling price process can become statistically indiscernible from the price series (Lamberton and Lapeyre, 2011; Bouleau, 2012). This may undermine the scarcity signal conveyed by the market price — and with it, perhaps, the relevance of the Hotelling paradigm — precisely at a time when allowance scarcity becomes of material importance.

In the longer term, price formation may undergo a more fundamental change dictated by the need to offset or even exceed residual emissions with removals (ESABCC, 2023), possibly to a greater extent than in our numerical analysis where a relatively small amount of BECCS is considered. To the extent that allowance prices reflect long-term expectations, they may in part be driven by the anticipation of the still uncertain costs of removal technologies before removals effectively clear the market or are used to compensate for residual emissions separately (Buck et al., 2023; Sultani et al., 2024). There is a crucial regulatory aspect to this transition as existing regulations need to be revised to spur removal deployment. But the nature and timeline of these revisions are still highly uncertain, notably given the novelty and complexity of the subject.[24] Still, this begs the question of how regulatory uncertainty can be resolved fast enough to mitigate associated noise that is inherently prevalent in policy-driven markets such as allowance markets (Salant, 2016; Quemin and Pahle, 2023).

In the absence of such clarification, long-term and regulatory uncertainties may exacerbate the limits of carbon pricing as a coordination mechanism for long-term investment and innovation that are reflected in the tension between short-term cost effectiveness and long-term efficiency and technological improvement (Driesen, 2014; Lukas and Welling, 2014; Tvinnereim and Mehling, 2018; Vogt-Schilb et al., 2018).[25] This tension reflects a general trade-off between short-run and long-run efficiency in the design of property rights (Weyl and Zhang, 2022). In addition, significant long-term uncertainty may lead market actors to overweigh shorter-term and less risky outcomes in their decision-making, further impairing the long-term coordination potential of the allowance price.[26] These issues are even more prevalent when — as is arguably the case for the net-zero transition — investment and transformational change must be coordinated across sectors and along new supply chains due to technological lock-ins and interdependencies (Agi et al., 2021; Driesen and Mehling, 2024; Hoarau and Meunier, 2023).

Trade-offs between efficiency and equity. The numerical analysis suggests that continually rising allowance prices over time are bound to exacerbate pre-existing acceptability, distributional and equity issues. This holds for both regulated entities and end-consumers (Känzig, 2023). In fact, policymakers and stakeholders are increasingly aware of and attentive to the distributional impacts of energy transition policies (Armitage et al., 2024).[27] These issues have historically been addressed through free allocation and auction revenue use (e.g., to finance other decarbonization or targeted fiscal relief policies). However, these levers will become less and less actionable as both allowance supply volumes and auction revenues decrease over time (auction revenues peak around 2025 in the numerical analysis, see Appendix B).[28] Yet, as allowances become scarcer and more expensive, both the pre– and post-trading distribution of allowances across market actors and sectors may still become more relevant for the regulator—e.g., because some sectoral or firm-level emissions are harder or costlier to abate than others, or because firms' ability to respond to higher allowance prices also depends on their financial leverage (Carradori et al., 2023). In other words, various criteria other than market forces may become increasingly relevant in determining who may 'rightfully' hold and use increasingly scarcer allowances.[29]

Inevitably decreasing allowance availability and increasing concerns about allowance distribution may warrant trading off efficiency with equity and distributional considerations—just like environmental effectiveness, the mainspring of allowance markets,

[21] See Cantillon and Slechten (2023) for a review and discussion of the challenges of producing stable and informative price signals in allowance markets.

[22] That is, markets with small turnaround or capitalization. According to these indicators, the ETS is small relative to other commodity markets (ESMA, 2021), a fact that will be exacerbated in the endgame. Small markets may also be less robust to manipulation and churning (Pirrong, 2009; Quemin and Pahle, 2023).

[23] Perino (2024) finds that rational arbitrage (noise trading) is further disincentivized (incentivized) under a banking-based supply adjustment mechanism like the MSR, and vice versa under a price-based mechanism.

[24] For instance, the fundamental paradigm shift from one public issuer of allowances to (possibly) multiple private sellers of removal certificates creates various economic, legal, governance and political issues (Rickels et al., 2022; Edenhofer et al., 2023; Franks et al., 2023). A key issue is whether and how removals should be integrated into the ETS or deployed separately, see notably (Sultani et al., 2024) for a discussion.

[25] Carbon pricing is good at encouraging the optimization of compliance costs for existing technologies, but not as good at driving technological costs down and encouraging technological innovation (Driesen, 2014). For instance, in the presence of long-lived capital and stringent long-term emission targets, optimal investment levels in sectors with relatively more expensive abatement capital or with larger abatement potential can be higher than those dictated even by an optimal carbon price (Vogt-Schilb et al., 2018). Relatedly, there are also debates on the effect of emissions trading vs. individually binding emission targets (Malueg, 1989; Kerr and Newell, 2003) and on the adequate combination of policies to address the co-existence of market failures (e.g., pollution, innovation) and spillover effects (Jaffe et al., 2005; Fischer and Newell, 2008).

[26] Similar results of inefficient, short-term equilibrium selection occur in a situation of strategic uncertainty where agents are uncertain about others' strategies (Van Huyck et al., 1990; Carlsson and Van Damme, 1993).

[27] Armitage et al. (2024) provide a useful literature review of distributional concerns, as well as coordination failures and financial frictions, associated with the energy transition.

[28] Mazzarano and Borghesi (2024) estimate a 'carbon Laffer curve' whereby auction revenues are found to follow an inverted-U relationship in both the allowance price and the auction volume.

[29] As discussed above, a related issue is allowance trading and holding by non-compliance actors, who may increasingly use allowances as financial assets for hedging transition risks or other purposes not immediately related to compliance, and may thereby exert additional pressure on allowance availability.

may warrant supply adjustments or trading restrictions when needed.[30] Potential measures include the introduction of allowance holding limits (Shobe et al., 2014), or some form of non-linear pricing or price control like price caps that can be tailored to specific entity characteristics (Akbarpour et al., 2024).[31] In fact, such approaches share some similarities with the well-known result that non-uniform carbon pricing can be justified due to the public good nature of emission reductions or in the presence of pre-existing inequalities and distortions (Chichilnisky and Heal, 1994; Abrell et al., 2018; Fleurbaey et al., 2023). On a more fundamental level, the increasing scarcity of allowances resonates with the general economic question of the most adequate instrument to allocate a resource subject to strong availability constraints (Weitzman, 1977; Condorelli, 2013), e.g. a free-floating market, price control or even rationing. These issues deserve more attention and require further research.

4. Conclusion and implications for the EU ETS

Our analysis has revealed key insights that could be crucial for market functioning in the ETS endgame. A few of these have straightforward implications, particularly the need to reform the MSR to better address market stability and liquidity issues as the ETS transitions from a state of historical allowance surplus to one of ever-increasing allowance scarcity. However, at this stage, most of the findings have less clear, yet potentially more profound, ramifications for market functioning and design. Ultimately, they also raise the question of the efficiency of the ETS as a policy instrument for attaining climate neutrality. Answering this question is clearly beyond the scope of this work, and arguably also hinges on the following aspects that extend beyond ETS design and modeling in the (narrow) sense considered above: (*i*) broader rule-based governance including the potential implementation of a carbon central bank (Carradori et al., 2023; Edenhofer et al., 2023; Jeszke and Lizak, 2023),[32] (*ii*) the relative role of other policies and their impact on allowance price formation (Armitage et al., 2024; Blanchard et al., 2023; Driesen and Mehling, 2024; Grubb et al., 2023),[33] and more generally, (*iii*) the relative efficiency of market-based policies vs. traditional regulations, depending on how cost heterogeneity across technologies evolves over time (Newell and Stavins, 2003).

Accordingly, no immediate policy recommendations for the long-term design of the EU ETS follow from our analysis. Yet an important implication is that the market may fundamentally change in nature, and that proper market functioning cannot be taken for granted without appropriate adjustments. This holds true especially if the failures and frictions discussed in this paper become more severe and difficult to address as the market gets smaller. It follows that an important direction for further research is the empirical identification of the frictions as theorized above and of their effects on price formation and market efficiency.

CRediT authorship contribution statement

Michael Pahle: Writing – original draft, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Simon Quemin:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Sebastian Osorio:** Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **Claudia Günther:** Writing – original draft, Visualization, Investigation, Data curation. **Robert Pietzcker:** Writing – original draft, Software, Methodology, Formal analysis, Data curation.

Declaration of competing interest

None

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[30] Indeed, in environmental policies like politically-created allowance markets, trading is a policy expedient, not a policy objective per se. As an example of efficiency-equity trade-off, trading restrictions are under consideration in the California ETS to limit the detrimental impact from trading-driven emission redistribution to disadvantaged areas due to pre-existing inequities in pollution exposure (Burtraw and Roy, 2023).

[31] Holding limits are in use in California. Holding and position limits can also be used to mitigate risks of market power or manipulation, which are typically higher in small markets. Free allocation can be seen as a limiting case of non-linear pricing whereby the price paid per allowance is zero (the market price) below (above) the allocation level. Carbon contracts for difference can be seen as a two-way version of price caps, although they are primarily seen as a de-risking tool (Richstein and Neuhoff, 2022; Hoogsteyn et al., 2023).

[32] Calls for such a body (or a functional equivalent thereof) are probably as old as the ETS itself, especially for allowance supply management (de Perthuis and Trotignon, 2014; Grosjean et al., 2016), but the endgame arguably puts them in a different light. Notably, it may have the potential to reduce information frictions, to ensure suitable financing for all firms to be able to curb emissions in the face of increasing allowance prices, and to manage a net-zero-cap market, i.e. balance (residual) emissions with the use of removals

[33] Carbon pricing always brings about short-term efficiency gains (Dimanchev and Knittel, 2023; Bistline et al., 2024), but its role and place within the wider policy package may vary. For instance, it can be conceived as the main policy driver (Edenhofer et al., 2021) or, alternatively, as supplemental to other policies (Driesen and Mehling, 2024), with an emphasis on mitigating possible adverse policy interactions (e.g., green paradox, waterbed effect) and raising revenues to fund those (as well as financial relief and acceptability) policies.

Appendix

In the Appendix, we first elaborate on the model structure and scenario assumptions, and then provide more detail on the results and sensitivity analysis.

Appendix A. Model and scenario description

In this Section, we describe the structure of the numerical model LIMES-EU, its core assumptions and parameters, and the Reference and Reform scenarios. These scenarios represent the EU ETS design before and after the Fit-for-55 reform, respectively.

A.1. LIMES-EU model

LIMES-EU is a linear dynamic cost-optimization model with a focus on the electricity sector, covering all emissions regulated under the EU ETS. While the electricity sector is modeled in detail, emissions from the other sectors covered by the EU ETS — namely energy-intensive industry, heat from district heating and intra-EU aviation and maritime — are represented in a stylized way. The geographical coverage includes all EU countries (excluding Cyprus and Malta) as well as the Balkan region, Norway, Switzerland and the United Kingdom.[34]

LIMES-EU simultaneously optimizes investment and dispatch decisions for electricity generation, storage and transmission technologies in five-year time steps from 2010 to 2070. The model covers 38 generation, storage and carbon removal technologies, including different vintages for lignite, hard coal and gas. Investment in generation, storage and transmission capacities is optimized endogenously for each of the five-year time step. Since the model is forward-looking, investments are made in anticipation of future developments (resembling rational expectations), and delays and lags are only implicitly considered as part of the anticipation process. Consequently, investments and dispatch (and prices) are gradually evolving over time and there are no jumps. For dispatch, the model ensures that electricity demand and supply are balanced, while taking into account technical characteristics of different technologies, such as minimum load or ramping constraints.

Each year is modeled using six representative days, each of which comprises eight blocks of three hours. The representative days are estimated using a clustering algorithm, which enables the short-term variability of supply — namely, wind and solar — and demand to be captured (Nahmmacher et al., 2016). The energy-intensive industry is represented through a marginal abatement cost curve (MACC), which is derived from Gerbert et al. (2018) and calibrated with data from Enerdata (2020). MACCs are also used for each the district heating sector, aviation and maritime sectors based on literature.

For historical years — i.e., between 2010 and 2020 — exogenous allowance (EUA) prices are fixed at historical average levels. For the following (modeled) years, the EUA price is determined endogenously, by means of a constraint (or cap) on emissions with intertemporal flexibility through allowance banking. The reason we assume exogenous prices for historical years is mainly motivated by the need to represent more accurately the historical electricity generation mix. Indeed, EUA prices in a model like LIMES-EU are mainly driven by the anticipation of future scarcity, and thus discount rates have a strong impact (see Table B.1). However, there are many factors such as speculation and firms' reaction to regulatory changes that are not captured by LIMES-EU. Furthermore, historical prices might be explained rather by a combination of a 'high' surplus with firms' shortsightedness (Quemin and Trotignon, 2021; Sitarz et al., 2024). Our default assumption of perfect foresight may thus not suitable to explain historical prices, but might do better when analyzing future prices since the last ETS reforms have led firms to become more farsighted (Sitarz et al., 2024).

The MSR is included as a separate simulation module, hence solving for the equilibrium requires an iterative approach with year-on-year interpolation within each five-year time step. For coherence, the MSR operation is thus also simulated for the two years after the final five-year time step. A comprehensive description of LIMES-EU and the MSR module is provided in the documentation available from the model's website (Osorio et al., 2024).

A.2. Modeling assumptions and parameters

A first set of assumptions relates to market aspects, i.e. production and technology costs, input prices and trading behavior (Table A.1). For natural gas and coal prices, although temporarily at very high levels due to the Ukraine war, we assume they roughly going back to their pre-crisis level and thus in the long run their level is expected to remain at the level of pre-crisis estimations, according to the EU Reference Scenario 2020 (European Commission, 2021). For biomass prices, we draw on the results from the REMIND model[35] and Strefler et al. (2021) (Fig. A.1). For investment costs, we assume moderate cost reductions for renewable energy generation technologies, electric batteries and electrolysers, while costs of fossil generation technologies remain constant (Figs. A.2–A.4).

For investment and intertemporal trading decisions, we assume perfect foresight with a discount rate of 5%. This aligns with many other energy market optimization models. In the EU ETS it is often questioned if perfect foresight is appropriate to capture market dynamics. In a different analysis using LIMES-EU, we looked into this issue by conducting a back-casting analysis (Sitarz et al.,

[34] We assume that the EU and UK ETSs are linked in our analysis.

[35] The detailed harmonized model documentation for REMIND is available from the Common IAM documentation: https://www.iamcdocumentation.eu/Model_Documentation_-_REMIND.

Table A.1
Market-related assumptions in LIMES-EU.

Market-related assumptions	
Fuel prices	Fig. A.1
Investment costs	Figs. A.2–A.4: Declining costs for RE, batteries & electrolysers
Time horizon	2010–2070
Foresight	Perfect foresight
Time preference	Discount rate of 5%
Intertemporal trading	Banking is allowed and cost efficient (no borrowing)
Non-compliance trading	Not explicitly modeled
Allowance price	Determined endogenously

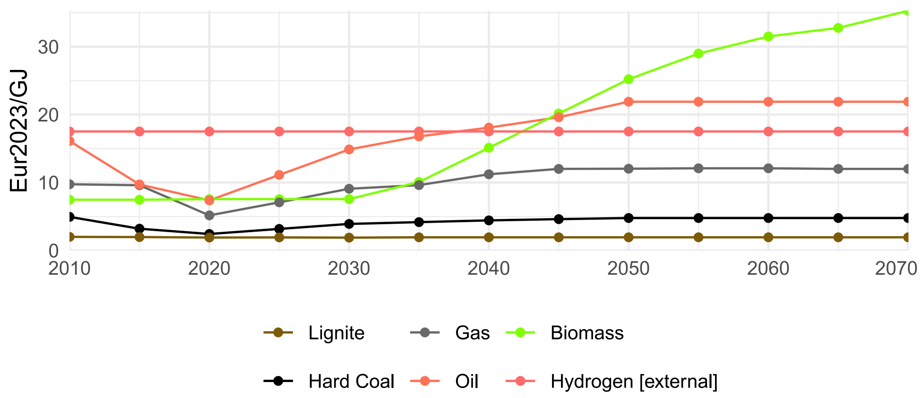

Fig. A.1. Fuel prices assumptions. *Source:* European Commission (2021), REMIND model, Strefler et al. (2021); own assumptions.

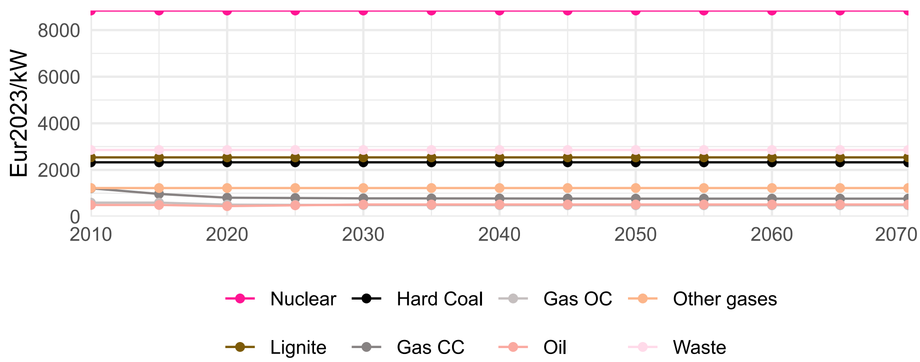

Fig. A.2. Turnkey capital costs assumptions for fossil-based and nuclear generation. *Source:* European Commission (2021); own assumptions. Includes financing during build time.

2024). We found that limited foresight explains pre-2018 allowance prices quite well, but after 2020 perfect foresight performs better. A potential explanation for this is that the 2018 reform (re)instilled trust in the market and increased the credibility of the cap in the long term. This can be translated as market actors using longer time horizons. Additionally, perfect foresight can also implicitly capture long-term speculative trading by non-compliance actors like investment funds and banks that re-entered the market *en masse* after the 2018 reform (Quemin and Pahle, 2023). Finally, as per current regulation, unlimited allowance banking of allowances across years is allowed while borrowing is prohibited. A key regulatory uncertainty in that regard is how long entities can use banked allowances to cover their future emissions. We assume banking is allowed until 2057 in the Reference scenario and 2047 in the Reform scenario, when the cap has reached zero in both the Reference and Reform scenarios described below.

A second set of assumptions relates to broader policy aspects (Table A.2). First, we consider a selection of the main overlapping technology policies at the EU member state level. These influence EUA prices by reducing emissions and thus the demand for allowances. Specifically, we consider mandated coal phase-out decisions (Beyond Fossil Fuels, 2024b) and renewable energy (RE) support measures. For nuclear power, we consider the phase-out decisions and respective timetables by Germany, Belgium and

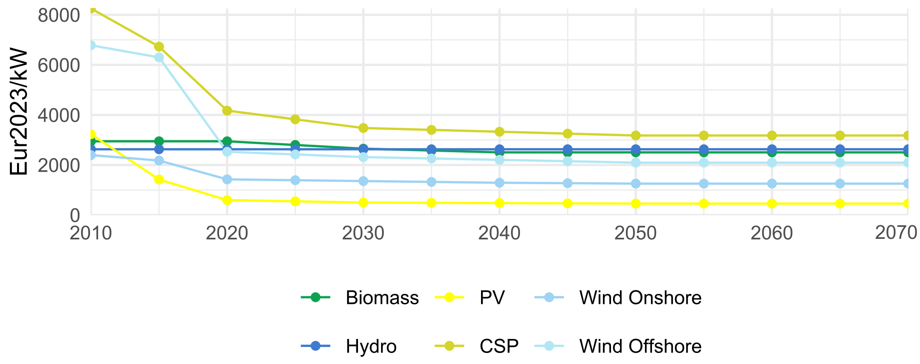

Fig. A.3. Turnkey capital costs assumptions for renewables. *Source:* European Commission (2021). Includes financing during build time.

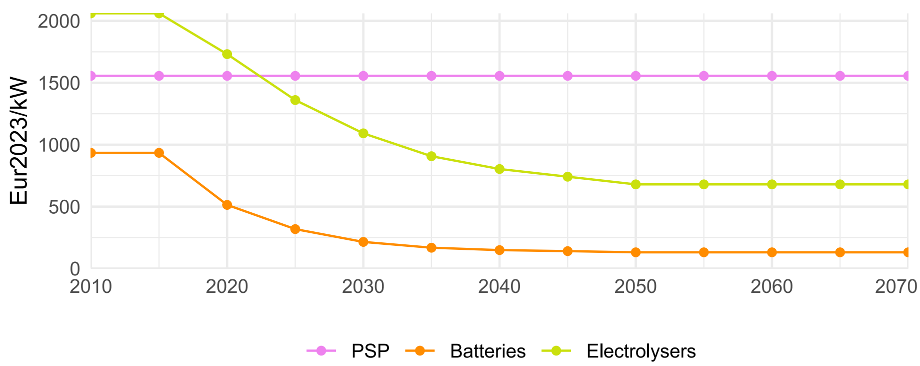

Fig. A.4. Turnkey capital costs assumptions for storage technologies. *Source:* Saba et al. (2018) and Schmidt et al. (2019); own assumptions. Includes financing during build time.

Table A.2
Policy-related assumptions in LIMES-EU.

Policy-related assumptions	
Complementary policies	RE target (DE) and coal phase-outs (EU-wide)
Nuclear power	Phase-outs by DE, CH and BE
Scope/linking	Linking to the UK ETS not considered
Fossil-fuel carbon capture and sequestration (CCS)	Considered
Carbon dioxide removal (CDR)	Biomass energy CCS and Direct air CCS considered; carbon farming and storage in long-lasting products and materials not considered
Limit to EUA banking	Allowances can only be banked until 2057 in the Reference and 2047 in the Reform scenarios. Afterward, all emissions need to be balanced by CDR[a]

[a] When CDR are not available, a change to the ETS design is required. From a modeling point of view, all residual emissions for which there is no abatement cost, namely in aviation, are removed from the EU ETS after the banking limit is reached.

Switzerland. More details are provided in the following subsection.

Regarding the scope, we essentially extrapolate the regulatory status quo. Over the entire time horizon, we consider no linking to other carbon markets, whether compliance markets, voluntary markets, or offset crediting schemes under Article 6 of the Paris Agreement. For instance, the UK ETS is modeled separately after the year 2020, i.e., UK emissions are weighted in the EU ETS in 2020 when estimating the TNAC, and afterward accounted as part of a separate system, with its own emission cap and bank. We assume an exogenous allowance price for non-EU countries such as Switzerland and the Balkan countries. Norway, which is non-EU, but part of the EU ETS, is included in the model. Other countries that are part of the EU ETS, such as Malta, Cyprus, Liechtenstein, and Iceland are not included in the model for technical reasons. But given that their emissions in 2021 were less than 1% of total EU ETS emissions, the impact on modeled allowance prices is negligible.

Regarding carbon management, we do consider carbon capture and sequestration (CCS), even though it is not yet integrated into the EU ETS in the form of exemption from compliance or generating new allowances, i.e., full fungibility of emission allowances and

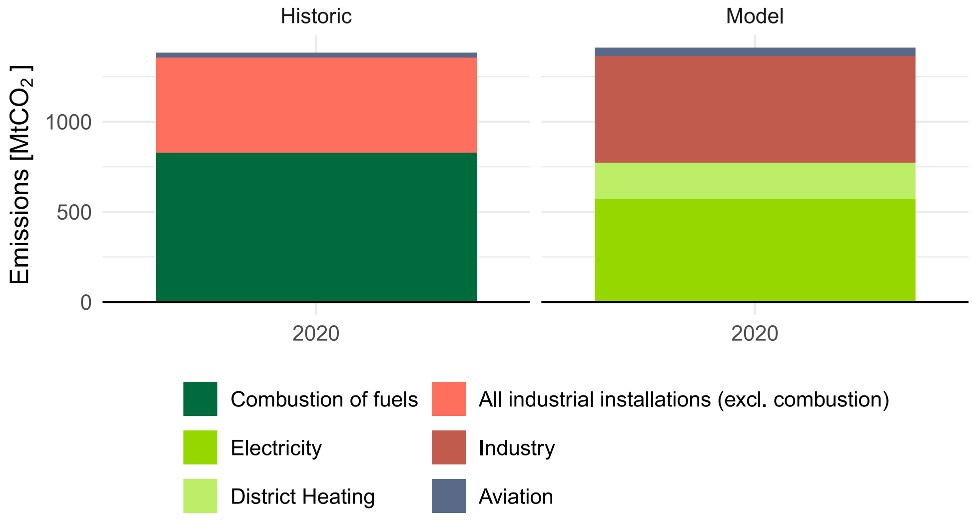

Fig. A.5. Comparison of historical and modeled EU ETS emissions in 2020.
Source: Historical data compiled from EEA (2024); own modeling results.

removal certificates. This includes fossil-fuel and biomass energy CCS (BECCS), and three technologies for direct air carbon capture (DACC). The reason for doing so is that we think such integration could happen already in the next years. However, we do not consider carbon dioxide removal (CDR) technologies related to carbon farming and storage in long-lasting products and materials as an additional source of supply, as this inclusion seems feasible only further down the road.

It is worth noting though that both linking and CDR inclusion may become integral features of the ETS in the next decade. To begin with, linking seems more and more of an option, also within the EU—namely to the new ETS2 to be established by 2027. Such linking should not necessarily be physical, it could also be financial. Most recently, the European Council gave the green light to the EU certification framework for permanent carbon removals, carbon farming and carbon storage in products (European Union, 2024). This is a first important step that could eventually lead to integrating CDR certificates into the ETS. Accordingly, model results must be interpreted with care, and should first of all be considered as exploring the effects of the reform in isolation under 'ceteris paribus' conditions.

A.3. Calibration to historical market data and prospective technology phase-ins and phase-outs

We calibrate the model by fixing electricity, storage and transmission capacities from 2010 to 2020 based on historical data, and scale levels if required to align with historic electricity generation. In contrast, electricity dispatch, and thus emissions, remain completely endogenous in the model. To validate the calibration, we compare modeled emissions with historical emissions in 2020, as shown in Fig. A.5. As can be seen, both modeled and historical emissions are approximately equal in 2020. The sectoral split of emissions differs somewhat, but this is only because the source for historical emissions (EEA, 2024) uses slightly different categories (sectoral scopes). More specifically, in the EEA report smaller industrial plants are subsumed under 'Combustion of fuels' that in our categorization fall under 'Industry'.[36]

Next, we calibrate future capacity evolution by considering implemented or announced phase-ins and phase-outs for certain technologies. Regarding the latter, we impose upper bounds on future nuclear capacities in countries where nuclear phase-out decisions are in place or seem likely, namely Germany, Belgium and Switzerland. Likewise, we impose upper bounds on coal capacity and future investments in unabated coal (i.e., non-CCS) according to existing phase-out plans as compiled by Beyond Fossil Fuels (2024b). We further fix investments in coal and nuclear power to those currently expected to start operation in the short term (data from Beyond Fossil Fuels (2024a) and World Nuclear Association (2024)).

Regarding phase-ins, we constrain investments in 'novel' technologies such as CCS — both thermal generation coupled with CCS, such as BECCS, and direct air capture — and hydrogen-based generation. These technologies are not available until 2030, and bounded until 2040. Other technologies are constrained by resource endowments, namely by wind (NREL, 2013), solar (Pietzcker et al., 2014), hydropower (Eurelectric, 2018), and biomass potentials (Ruiz et al., 2019; Eurostat, 2024; European Commission, 2024a). Given the absence of data for other thermal technologies such as waste, their future use is constrained such that it does not exceed the maximum primary energy used between 2010 and 2020 plus a margin of 20%.

[36] The category 'Combustion of fuels' (830 $MtCO_2$) comprises power sector emissions (including both heat- and electricity-related emissions) as well as some industry emissions. The rest of industry emissions are reported as 'All industrial installations (excl. combustion)' (526 $MtCO_2$). Therefore, historic (overall) industry emissions are higher than the ones reported in 'All industrial installations (excl. combustion)'. Since the modeled industry emissions (590 $MtCO_2$) are higher than the reported 'All industrial installations (excl. comb)' value, our modeled emissions align with historical ones. Moreover, the modeled total emissions (1408 $MtCO_2$) are in line with historical ones (1381 $MtCO_2$).

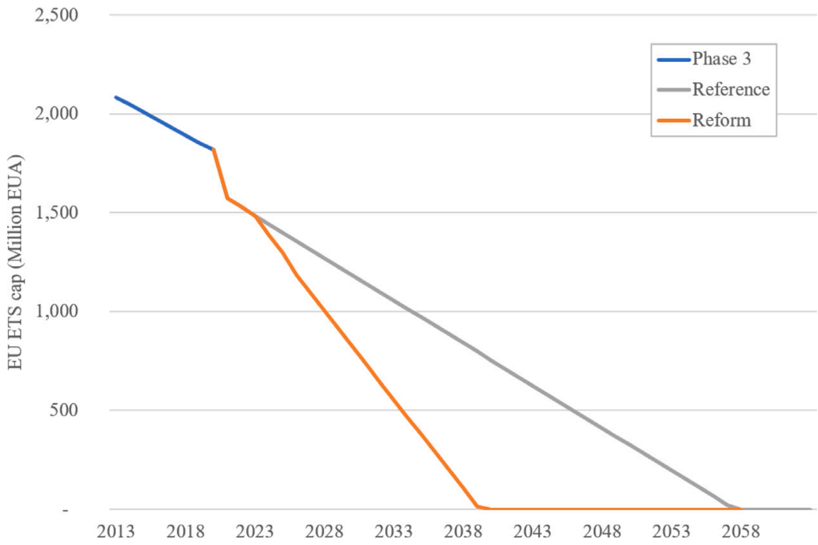

Fig. A.6. Emissions cap trajectories (adjusted to LIMES-EU's sectoral scope).

A.4. Scenarios

We consider two scenarios for the numerical analysis: A 'Reform' scenario in line with the Fit-for-55 package, and a 'Reference' scenario based on previous legislation. An overview of the policy settings is provided in Table 1 in the main text.

We compute the cap in both scenarios as follows (Fig. A.6). In both scenarios, the cap is adjusted in 2021 to reflect the exit of the UK from the EU ETS. For the Reference scenario, the cap's annual linear reduction factor (LRF) of 2.2% applies as of 2020, corresponding to annual reductions of 43 million EUAs. For the Reform scenario, an annual reduction of 43 million EUA applies in 2022 and 2023 (corresponding to a LRF of 2.2%), but the 2023 ETS revision modifies this value. According to the European Commission (2023), in 2024, the Union-wide quantity of allowances shall be increased by 78.4 million EUA for maritime transport. The LRF shall be 4.3% from 2024 to 2027 and 4.4% from 2028 onward. As a result, the annual reduction volume in 2024–2027 is 87.9 million EUA. Moreover, there is a cap rebasing that decreases the cap by 90 and 27 million EUAs in 2024 and 2026, respectively. Thus, the cap for stationary installations reaches 825 million EUA in 2030 and zero in 2040 in the Reform scenario. The aviation sector, with a cap of 29 million EUA and reduction of 1.4 million EUA in 2025 (corresponding to the same LRF as of the stationary + maritime sectors, i.e., 4.3%), reaches zero in 2044. Since there is full fungibility between stationary + maritime and aviation allowances, the total ETS cap will reach zero by 2044. However, the availability of allowances post 2040 is very limited (17 million EUAs).

Regarding the MSR, its main operating rules remained unchanged with the reform, namely transferring allowances to (from) the MSR when there is a large (low) 'surplus' of allowances and invalidating allowances held in the MSR above a certain threshold. Specifically, the MSR utilizes the total number of allowances in circulation (TNAC) as a proxy for allowance availability/scarcity and functions as follows: If the TNAC exceeds 833 million EUAs, fewer EUAs are auctioned and are instead transferred to the MSR (a volume equivalent to a share of the TNAC); if the TNAC falls below 400 million EUAs, a predefined volume of EUAs is transferred from the MSR and added to the annual auction volume. An exogenous intake of EUAs occurred in 2019 when the MSR started operations as it was seeded with the 900 million EUAs that were not auctioned under the backloading decision between 2014 and 2016 (European Commission, 2014; European Union, 2015) and another volume of 637 million EUAs resulting from unsold EUAs between 2020 and 2021 minus some that were extracted directly from the MSR to be auctioned and others that were placed in the New Entrants Reserve.[37] The changes in MSR parameter values as per the reform are described in Table 1.

Appendix B. Detailed numerical results

Here we provide additional detail on the numerical results presented in the main text for the Reference and Reform scenarios. First, we give simulated market dynamics a closer look, in particular MSR operations and cross-scenario differences. Second, we provide an analysis of the sensitivity of the numerical results to policy and techo-economic assumptions as well as different ETS policy settings.

[37] Data compiled from the annual Publications between 2017 and 2024, available in the Documentation/Market Stability Reserve indicator(TNAC) in European Commission (2024b).

B.1. Reference scenario

Further explanation for Fig. 1(a): This figure shows the developments of emissions by sector and of the EUA price. The EUA price increases only moderately to 49 EUR/tCO_2 by 2030 and reaches 134 EUR/tCO_2 by 2050. Total emissions in 2030 amount to 1148 MtCO_2, a reduction of 47% compared to 2005 (accounting only for stationary sectors) which is mainly driven by abatement in the electricity sector. Large emission reductions in the industry sector are achieved only in the 2040's due to relatively higher abatement costs. Specifically, compared to 2020, industrial emissions only decrease by 2% and 22% by 2030 and 2040 respectively, while by 2050 emission reduction is larger than 80%.

Further explanations for Fig. 1(b): This figure shows the co-evolution of the TNAC, MSR holdings, and EUA supply.[38] These quantities go down relatively smoothly to (near) zero by around 2055. The only exception is the spike in MSR holdings in 2022 at 3026 million EUAs. This is due to the exogenously given intake of allowances until 2022.

Further explanations for Fig. 1(c): This figure shows MSR operations in detail. The MSR continuously takes in allowances until 2041 (with interruptions in 2034 and 2039), thus tightening annual auction volumes. After 2039, the TNAC falls below the upper threshold of 833 million EUAs, only going slightly above (835 million EUA) in 2044, so that no more allowances are transferred to the MSR. There is no outtake of allowances from the MSR over the entire time horizon, except for the last year (2056). Although the MSR takes in EUAs almost continuously until 2039, MSR holdings decrease over time, as more allowances are invalidated than transferred to it. In total, the MSR takes in 5.1 billion EUAs between 2018 and 2057, 5.0 billion of which are invalidated. Most EUAs are invalidated in 2023 (2.4 billion EUAs). After 2025, annual invalidations decrease to a level below 0.2 billion EUAs.

In addition, Fig. B.1 provides auction volumes and revenues over time. The former decrease steadily from 664 million EUAs in 2025 to 80 million EUAs in 2055. Because the EUA price increases from 38 to 172 EUR/tCO_2 in parallel, auction revenues remain rather stable between 25 and 32 billion EUR between 2025 and 2050. In 2055, revenues amount to 14 billion EUR.

B.2. Reform scenario

Further explanations for Fig. 2(a): This figure shows that emission reductions are considerably accelerated and carbon prices considerably higher compared to the Reference scenario. Notably, most of the reductions occur already in the 2020's. By 2030, emissions are 57% lower than in 2020 and 77% lower than in 2005, which is substantially below the -62% target. The rate of reduction is almost three times as fast as in the Reference Scenario. Going into details, large parts of the electricity sector are already decarbonized by 2030. For instance, coal is nearly completely phased out across Europe by then: just 10 TWh per year of coal generation remain, an almost hundred-fold reduction compared to the 2000's. This strong reduction is mostly in line with accelerated coal phaseout plans in many (but not all) EU member states that led to a 45% of coal-based generation in the five years from 2018 to 2023 (Ember, 2024) - although LIMES cannot incorporate political economy effects, e.g., in Poland or Germany, that may slow down the transition away from coal. Industrial emissions already fall by 45% in the 2020's. In parallel, the EUA price rises to 185 EUR/tCO_2 by 2030, almost four times higher than in the Reference Scenario. In the long term, the price rises to over 400 EUR/tCO_2 after 2050.

Further explanations for Figs. 2(b,c): These figures show that the MSR holdings are much higher in the medium term than in the Reference scenario. This is due to the combination of a higher intake rate (24% vs. 12% of TNAC) and a higher TNAC which remains above the intake threshold until 2037. The reason for this is stronger banking incentives in anticipation of increasing allowance scarcity over time. Thus, a larger volume of allowances is transferred each year to the MSR in the 2020's and 2030's. As a result, total invalidations amount to 7.3 billion EUAs, a 46% increase relative to the Reference scenario. Additionally, the MSR becomes empty by 2045, eleven years earlier than in the Reference scenario. The reason for this is that the TNAC falls below the outtake threshold earlier due to lower allowance supply.

Compared to the Reference scenario, as shown in Fig. B.1 auction volumes decrease by a third between 2020 and 2025 (from 572 to 390 million EUAs) and then drop sharply to 76 million EUAs in 2030 due to the continuous MSR operation. Because of steadily increasing EUA prices, auction revenues remain high over 2020–2035, above 13 billion EUR, with a remarkable peak at 53 billion EUR by 2025. Because some allowances are released from the MSR to the market in the form of auctions between 2042 and 2045 (TNAC below outtake threshold), auction revenues reach 22 billion EUR in 2045.

B.3. Sensitivity analysis

We split the sensitivity analysis into two subsections. In the first one, we focus on the impact of varying policy and techno-economic parameters for both the Reference and Reform scenarios. We focus on parameters that could be expected to have a strong influence on EUA prices. In the second one, we focus on the impacts of alternative (counterfactual) EU ETS policy settings, namely the cap and MSR parameters, focusing on the Reform scenario.

[38] TNAC in year y is computed as: TNAC in year $y-1$ plus EUA supply in year y minus realized emissions in year y. EUA supply comprises allowances allocated for free and those auctioned by member states, with the total volume of the latter being a function of TNAC in the previous two years due to the timeline the allowances are transferred to the MSR (from January to August of year y depending on the TNAC in year $y-2$ and from September to December of year y depending on the TNAC in year $y-1$) .

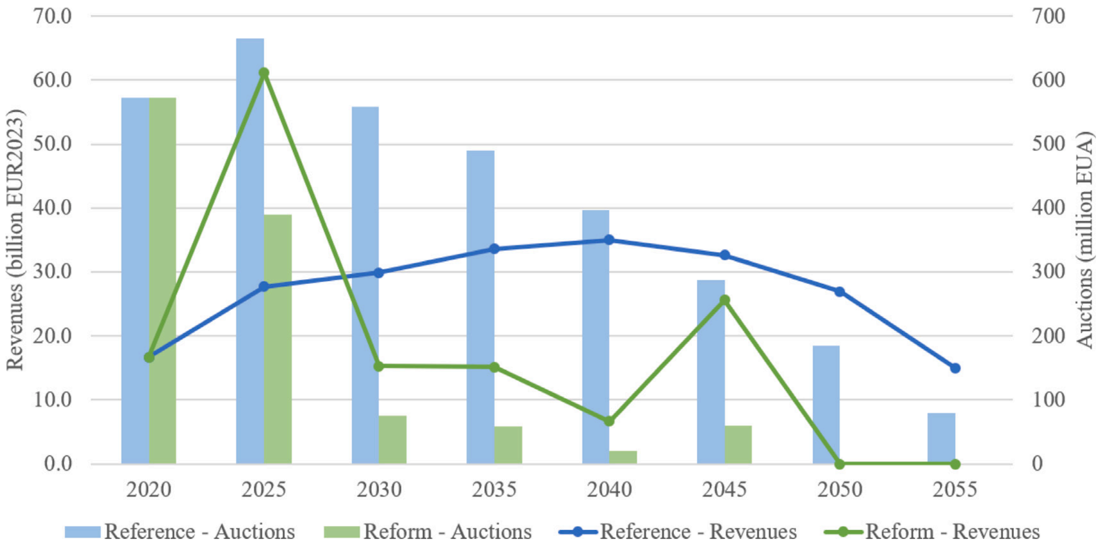

Fig. B.1. Annual auction volumes (right axis) and revenues (left axis) in different scenarios.

B.3.1. Technological and behavioral parameters

We analyze a total of 44 sensitivities per scenario. The focus is on banking behavior driven by the discount rate, CCS availability, renewables' investment cost, electricity demand, fuel prices, cross-border transmission expansion, and biomass potential.

We consider biomass because BECCS is the only generation technology that can provide negative emissions. As LIMES does not capture the full energy system, it cannot endogenously represent the competition for biomass to be used for the production of liquid fuels, hydrogen, gases, heat and electricity, but rather needs assumptions on the amount of biomass available for the power sector. In the default LIMES setup, these amounts are informed by potentials from the ENSPRESO database (Ruiz et al., 2019), the 2040 target Impact Assessment (European Commission, 2024a), the historical use of biomass in the power sector derived from Eurostat (2024), and prices from full-system modeling with the integrated assessment model REMIND (Baumstark et al., 2021) that captures the competition between usages.

Figs. B.2 and B.3 depict the ranges of 2030 and 2050 EUA prices and cumulative invalidation across sensitivities, grouped by scenario (i.e., each dot represents the value in a given sensitivity case). Table B.1 describes each sensitivity and summarizes the main impacts in terms of EUA prices and invalidations. We also include the default scenario for comparison. In the Reference (Reform) scenario, the full range of price is between 39 (126) and 82 (201) EUR/tCO_2 by 2030, and between 120 (409) and 200 (939) EUR/tCO_2 by 2050. That is, the price range exhibits a larger bandwidth in the Reform scenario, highlighting the extent to which the MSR might further tighten an already ambitious cap. The 2050 price range is particularly large, but there are only a few values above 500 EUR/tCO_2. These correspond to rather extreme scenarios, namely those with no CDR or no biomass. In particular, the unavailability of both biomass and CDR would imply deploying the most expensive abatement measures. Such high prices are not reached in the Reference scenario because there are still allowances available at that time, either because they are still being issued or carried from previous periods (recall that banking is only allowed until 2045 in the Reform scenario).

Overall, our results show a larger price range in the Reform scenario, while there is a larger range of invalidations in the Reference scenario. There is normally some correlation between EUA prices and invalidations—that is, low prices occur when the emission budget is high (i.e., when invalidations are low) and vice versa. However, depending on the parameter variation, higher demand for allowances might lead to lower MSR intakes due to higher emissions. This nonetheless might limit a price increase—e.g., when electricity demand increases, EUA prices remain the same but invalidations decrease. We elaborate on the specific effects below.

The parameter that has the strongest effect on prices and invalidations is the discount rate. Discount rates affect invalidations through banking: When firms have a higher discount rate they put a lower weight on the future and thus bank less allowances. A lower bank in turn implies that fewer allowances go into the MSR and therefore invalidations are lower, and thus carbon prices are also lower. The converse holds when discount rates are low. Furthermore, the discount rate determines the curvature of the Hotelling price path (i.e., the price rises with the discount rate). The high price effect stems from both these channels.

The (partial or full) unavailability of CCS technologies has only limited effects in both scenarios until 2045; only from 2050 onward, does the unavailability of CDR lead to very high prices (> 900 EUR/tCO_2) in the Reform scenario as even the most expensive abatement options have to be implemented in a net-zero system without negative emissions. The unavailability of CCS triggers more banking to cover long-term emissions and leads to higher invalidations and thus higher carbon prices. There is almost no difference between the 'no CDR' and 'no CCS at all' scenarios, neither under Reference nor under Reform climate policy, which shows the very limited role of fossil-CCS. The highest invalidations among the CCS sensitivity runs occur in the Reference scenario when there is no DACCS (5.5 billion EUA), rather as a result of changes in the MSR intakes when the TNAC is just slightly above the upper threshold.

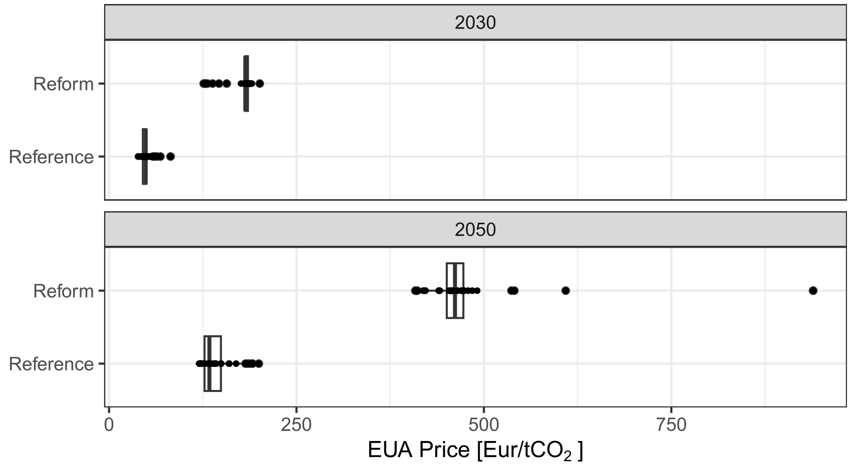

Fig. B.2. Sensitivity range of EUA price in 2030 and 2050 (EUR_{2023}/tCO_2).

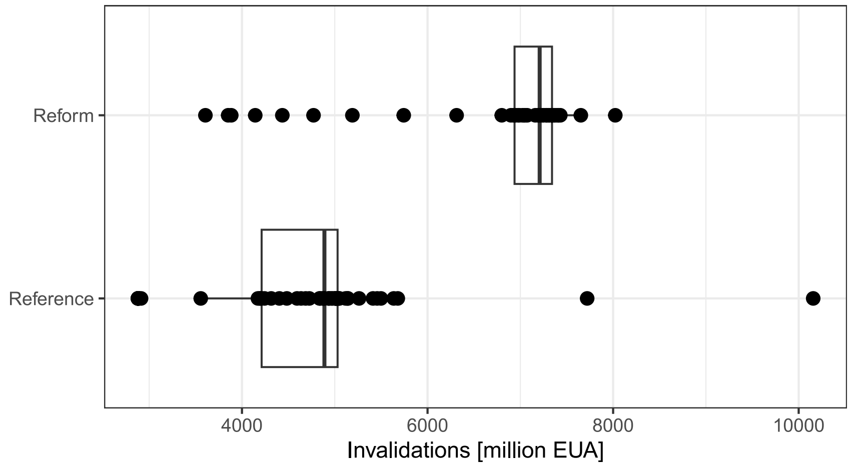

Fig. B.3. Sensitivity range of cumulative invalidations.

Fuel prices have a relatively moderate impact. This is underlined by the coal phase-out, which occurs rapidly (at the latest in 2040 and 2030 in the Reference and Reform scenarios, respectively) and independently of relative fuel prices. Specifically, even when gas prices are low, RES become the dominant technology in the power sector in the medium term. The gas-to-renewables switch impacts EUA prices in the long run. In the case of low gas prices, a market-based gas phase-out requires higher carbon prices, so EUA prices are higher in the low gas price scenarios. At the same time, higher gas generation leads to a higher TNAC, and thus more EUAs get invalidated. Here, a counterintuitive effect arises due to the positive banking–MSR feedback effect: Although low gas prices could allow for cheaper decarbonization, more intensive MSR operations trigger higher decarbonization costs (larger invalidations imply stricter decarbonization efforts).

RES CAPEX have an effect only in the Reference scenario. Unlike the effect of lower gas prices, when RES CAPEX are lower, EUA prices are lower in the Reference scenario. One might think that cheaper RES leading to higher RES generation might increase the TNAC and thus invalidations. Yet the lowering effect of cheap RES on EUA prices also encourages coal generation, at least in the medium term. As a result, there are more emissions than in the default scenarios, and thus lower invalidations. Given the strong pressure of high EUA prices in the Reform scenario, RES CAPEX have a negligible impact in this scenario.

When electricity demand increases, there is higher demand for allowances, and thus EUA prices are higher in the Reference scenario (or remain unchanged in the Reform scenario). However, with a higher demand, there are also more emissions and thus fewer invalidations than in the default scenario. Indeed, lower invalidation allows for limiting price increases in the Reform scenario by allowing for additional emissions.

Biomass availability has a larger impact in the Reform than in the Reference scenario due to the higher use of biomass in the former. Higher biomass availability releases some untapped decarbonization potential: As biomass potential is binding in some countries (and only until 2035) in the default scenarios, there is room for cheaper abatement in the power sector. This has a downward effect on emissions, which triggers further MSR intakes. Likewise, when the potential is more constrained, abatement becomes more expensive, thus triggering fewer invalidations. Such changes in the emission budget contain prices, which increase by less than 5% compared to the default scenarios.

In sum, although the price range is wider in the Reform scenario, the changes in the corresponding parameters have the same qualitative effect on prices and invalidations in both scenarios (e.g., the highest discount rate always leads to the lowest carbon price).

B.3.2. EU ETS policy settings

Here we perform an analysis of how different (counterfactual) choices for the cap and the MSR settings would affect results. These choice are relevant because they affect how fast EUA prices are expected to rise and how the cumulative emission budget (cap net of invalidations) will evolve throughout the next decades. Overall, 157 variations are analyzed. The focus is on the Reform scenario to evaluate potential alternatives that may inform upcoming policy reforms, namely the MSR revision in 2026 and potential changes to the EU ETS depending on the 2040 targets.

Specifically, we assess the following variations: We vary the LRF post-2030 between 2% and 5%. Adjusting the LRF directly impacts the annual cap and cumulative caps. Keeping the LRF at 4.4% would lead to a cumulative budget of 3.5 billion EUA post-2030. In contrast, reducing the LRF to 2.2% would more than double it to 7.4 billion EUA. We also vary the MSR parameters, namely the intake rate, lower and upper thresholds and outtake rate.[39] The buffer threshold (currently set at 1096 million EUA), as explained before, aims at smoothening the intake volumes. This is nonetheless a function of the upper threshold and intake rate, and is calculated as follows: $\frac{\text{upper\_threshold}}{1-\text{intake\_rate}}$. All changes are applied after 2030 as we do not expect earlier implementation to be feasible. Table B.2 shows how these variations affect EUA prices in 2030 and 2050, and cumulative invalidations. There is overall little variation of prices in 2050, except when the cap changes, because the MSR is not operational anymore. Even if changes in the MSR lead to different invalidation volumes, allowances do not trade anymore by 2050, and thus prices just depend on removal costs. The little variations thus stem from different CDR deployment rates. When the cap varies, prices as low as 308 EUR/tCO_2 are achieved because lower LRF leads to caps that remain positive beyond 2050, i.e., there are allowances available and thus the MSR remains operational.

Sensitivity to different caps: In general, a higher LRF leads to lower overall emissions. Yet confirming previous findings (Osorio et al., 2021; Quemin, 2022), there is a reinforcing mechanism between the LRF and invalidations, meaning that the LRF disproportionally reduces emissions. This mechanism operates through a primary effect: A higher LRF reduces supply, leading to a higher price. Firms anticipate this by banking more allowances, which increases the TNAC. This, in turn, boosts MSR inflows and subsequent invalidations. In other words, tighter caps trigger more invalidations as firms bank more in anticipation of higher future scarcity. As a result, a tighter cap (i.e., higher LRF) does not only lead to less emissions because of the smaller allowance budget but also because it triggers more invalidations.

Sensitivity to different intake rates: Since the TNAC in the default scenario is at 1570 million EUA in 2030, i.e., the MSR is still active afterward, changes in the intake rate affects prices and invalidations. EUA prices in 2030 range between 168 and 188 EUR/tCO_2 and invalidations between 6.0 and 7.9 billion EUA for intake rates varying between 0% and 30%. Higher intake rates (recall the intake rate is back to 12% in the default Reform scenario) further tighten the cap through more allowance transfers to the MSR, which are eventually invalidated. The opposite effect occurs for lower intake rates. As a result, higher (lower) intake rates lead to more (less) invalidations, which put an upward (downward) pressure on EUA prices. The upward effect is limited because the auction volumes constrain resulting transfers to the MSR. This is why intake rates between 21% and 30% lead to the same amount of invalidations, and thus EUA prices. That is, when the intake rate is kept at 24% after 2030, prices reach 188 EUR/tCO_2 in 2030 and invalidations 7.9 billion EUA over time. In the extreme case where intake is stopped post-2030 (i.e., intake rate set at 0%), total invalidations amount to 6.0 billion EUA and EUA prices to 168 EUR/tCO_2 in 2030.

Sensitivity to different thresholds: Changes in thresholds lead to prices in 2030 ranging between 158 and 188 EUR/tCO_2, and invalidations between 5.2 and 7.8 billion EUA. As expected, high upper thresholds lead to fewer transfers to the MSR, while low upper thresholds lead to more. As a result, EUA prices and invalidations are higher (lower) when the upper threshold is low (high). Likewise, high levels of the lower threshold reduce EUA prices and invalidations not only because there are more transfers from the MSR to the market, but also because the maximum amount of allowances available in the MSR increases. As a result, lowest EUA prices and invalidations occur with high upper and lower thresholds while highest EUA prices and invalidations occur with low upper and lower thresholds.

Sensitivity to different outtake volumes: Finally, changes in the outtake volume have only a marginal effect because the TNAC never oscillates around the lower threshold. Hence, transfers from the MSR only occur at the end of the trading period, and the rate at which they occur has little impact. Indeed, results are identical for outtake volumes higher than 100 million EUA, as the maximum MSR volume (400 million EUA) is released. When the outtake volume is 50 million EUA, only 300 million EUA are transferred back to the market as the MSR operation time ends before the MSR is completely depleted, but this has a negligible impact on prices. In the extreme case when the MSR cannot release allowances back to the market (i.e., outtake volume equals 0), there is only a minor effect on prices and invalidations (188 EUR/tCO_2 in 2030 and 7.4 billion EUA, respectively).

[39] We test all possible combinations for values between 0 and 1500 million EUA, ensuring that the upper threshold remains higher than the lower threshold. The thresholds do not only affect the transfers to and from the MSR, but also when invalidations are triggered. According to the ETS Directive, "the number of allowances in the reserve should, therefore, be fixed at a level of 400 million allowances, which corresponds to the lower threshold for the value of the TNAC". It is therefore safe to assume that a potential new lower threshold will play the same role.

Table B.1
Sensitivity ranges for 2030 and 2050 price levels, and total MSR invalidations.

Sensitivity	Description	2030 EUA price in Reference/Reform (EUR_{2023}/tCO_2)	2050 EUA price in Reference/Reform (EUR_{2023}/tCO_2)	Total invalidations in Reference/Reform (*billion EUAs*)
Default		49/185	134/456	5.0/7.3
Banking behavior	Discount rate between 3% and 15% (step of 1%-points)	39–82/126–201	134–200/411–485	2.9–10.1/3.6–8.0
CCS availability	Five cases: no CCS, no fossil-CCS, no BECCS in the power sector, no CDR, no DACCS	49–51/180–188	133–139/459–939	4.9–5.5/7.2–7.4
Fuel prices	Gas prices vary between −50 and +400% and coal between 0 and 100% of prices in default scenarios	44–55/180–187	120–149/409–474	4.2–5.5/6.9–7.3
RES CAPEX	CAPEX of PV and wind energy vary by −50 and +50% by 2050 relative to default scenarios[a]	47–52/184–185	128–142/409–440	4.9–5.0 /7.2–7.3
Cross-border transmission expansion	No transmission expansion beyond 2020 installed capacity	49/185	133/458	4.2/7.2
Electricity demand	Demand increases by 50%–100% by 2050 with respect to default scenario as a result of increased electrification of other sectors[b]	59–69/188	160–186/440–473	4.2–4.9/6.3–6.9
Biomass availability	Varies between −100 and +100% in terms of maximum primary energy to be used in the power sector as of 2025	49–52/185–188	133–141/454–541	4.6–5.7/7.2–7.4
Overall		39–82/126–201	120–200/409–939	2.9–10.1/3.6–8.0

[a] We interpolate the factor by which demand is scaled for the period between 2020 and 2050.
[b] Due to computational issues, there is no result for the Reform scenario with a DR of 15%.

Table B.2
Sensitivity ranges for 2030 and 2050 price levels, and total MSR invalidations in Reform scenario due to changes in the cap and MSR parameters after 2030.

Sensitivity	Description	2030 EUA price (EUR_{2023}/tCO_2)	2050 EUA price (EUR_{2023}/tCO_2)	Total invalidations (*billion EUAs*)
Default		185	456	7.3
Cap	LRF between 2% and 5% (steps of 0.2%)	113–188	308–481	4.9–7.3
Intake rate	Between 0% and 30% (steps of 3%)	168–188	452–464	6.0–7.9
Thresholds	Values between 0 and 1500 million EUAs (steps of 100 million EUA)	156–188	452–477	5.2–7.8
Outtake volume	Value between 0 and 400 million EUAs (steps of 50 million EUA)[a]	185–188	452–456	7.3–7.4
Overall		113–188	308–481	4.9–7.9

[a] A maximum value of 400 million EUA is defined as this is the maximum of allowances held in the MSR in the default configuration.

Data availability

Data will be made available on request.

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