

PYSEUS: Modelling the Mechanisms of the EU ETS in the Decarbonisation of the European Electricity Market

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Abstract— This paper presents a model analyzing long-term impacts of the EU ETS I on the European power sector, focusing on how the Market Stability Reserve (MSR) shapes certificate availability. Based on a large-scale Mixed-Integer Linear Programming (MILP) approach, the model captures CO₂ constraints, price formation, and investment decisions. The detailed modeling covers country-specific spatial resolution and up to 500 time steps per period over 12 modeled periods up to 2050. An integrated time series aggregation ensures efficient computation despite high detail, while capturing seasonal effects. By showing that the MSR drastically reduces freely available allowances, the analysis reveals major implications for capacity expansion, system dispatch, and overall decarbonization pathways. The model provides robust insights into how regulatory adjustments shape future climate policies. As a specialized long-term tool, it opens new perspectives for effective decarbonization strategies and contributes to achieving climate targets.

Index Terms—Market Stability Reserve, Energy System Modelling, EU Emissions Trading System, Mixed-Integer Linear Programming, Power Sector Decarbonization

I. INTRODUCTION

In order to achieve the European climate neutrality targets by 2050, the European Emissions Trading System (EU ETS) is a key instrument for reducing emissions. The EU ETS I, which focuses on emission-intensive sectors such as electricity generation, generates strong incentives to reduce emissions due to its quantity-based certificate restrictions and the associated pricing. At the same time, the volatility of CO₂ prices poses uncertainties for long-term investment decisions, particularly with regard to low-emission technologies [1]. In order to analyze the interactions between the mechanisms of the EU ETS I and the transformation requirements of the electricity sector, a model is needed that maps the specific dynamics of the EU ETS I precisely and in detail.

A wide range of established energy system models already incorporates CO₂ emissions within their respective system boundaries, including Balmorel [1], DIETER [2], ELMOD [3], ETHOS.FINE [3], IKARUS [4], Markal [5], NEMO [6], PYPASA [7], REMIX [8], TIMES [9], URBS [10], and

LIMES[11]. These models collectively offer broad coverage of emissions and sector-specific decarbonization strategies, yet the representation of specific regulatory instruments—such as the Market Stability Reserve (MSR)—varies considerably. For example, while some approaches adopt overall emission caps, they do not explicitly incorporate dynamic MSR mechanisms (e.g., Balmorel, IKARUS, Markal, NEMO, PYPASA, TIMES). Other models focus on enforcing minimum shares of renewable generation (DIETER, URBS, REMIX) or assume an exogenous CO₂ price trajectory (ELMOD, URBS), thereby capturing alternative policy dimensions rather than the internal market adjustments characteristic of the EU ETS I. Among these methodologies, LIMES offers an iterative approach to integrate the MSR. Although its five-year time steps and subsequent subdivisions into representative days [12] allow for medium-term analysis, the aggregation of time slices may limit the resolution needed to capture short-term operational decisions. This issue can be relevant for power systems with high shares of intermittent renewable resources, where fine-grained modeling of fluctuations informs more accurate investment and capacity-expansion strategies [13].

In response to these challenges, the present paper introduces an endogenous, non-iterative modelling framework that comprehensively reflects EU ETS I regulations—particularly the Market Stability Reserve—while supporting a high degree of temporal resolution. As an illustrative example, up to 500 time slices per analysis period are employed; however, this figure is not a strict upper bound. Additionally, the length of each analysis period is determined in accordance with regulatory developments occurring after 2020, ensuring that significant policy interventions are reflected in a timely and precise manner. To preserve computational tractability while maintaining analytical detail, each period is capped at a maximum of three years. Rather than presenting definitive modelling outcomes, the paper positions the proposed approach as a methodological foundation for examining the electricity sector's evolution under evolving EU ETS I rules.

II. METHODOLOGY

In this study, we present an integrated framework for modeling the EU ETS I with a particular emphasis on auction volumes,

the MSR, and the overall circulation of allowances. The approach captures both the demand-driven aspects of the EU ETS I and the regulatory mechanisms governing allowance inflows and outflows. The framework is based on a set of variables and parameters, each of which is introduced below, followed by the key equations that formalize these relationships. This study uses key components of the model PERSEUS-EU model described in [14] to minimize total discounted system costs, maintain nodal and storage balances, enable capacity expansion for conventional and renewable generation (with transmissions fixed at NTCs), and satisfy exogenously specified demand trajectories. It has been extended using the equations outlined below to mathematically represent the regulatory framework of the EU ETS I. Furthermore, the methodology introduced in [15] was applied to enhance the original implementation of time series aggregation using [16], allowing for the inclusion of seasonal storage systems. The underlying power system model is an optimization framework with 30 nodes that permits capacity

Variables	
AV_p	Auction volume of allowances in period p
AD_p	Demand of allowances in period p
C_p	Circulation vol. of allowances in period p
DV_p	Deletion of allowances in period p
MI_p	Allowances input into MSR in period p
MO_p	Allowances output out of MSR in period p
MV_p	MSR Volume
$PRL_{pr,p,tp,t}$	Process level of process pr in period p in typical period tp in timestep t
DAC_p	Usage of direct air capture in period p
Parameter	
cl_p	Circulation volume lower limit in period p
cm_p	Circulation volume mid limit in period p
co_p	Circulation volume old limit in period p
cu_p	Circulation volume upper limit in period p
$co2_e$	Specific co2 emissions of energy carrier e
d_p	Duration of period p
ec_p	Max output of allowances in period p
$eff_{pr,p}$	Efficiency of process pr in period p
mip_p	Percentage intake of MSR in period p
mul_p	Upper limit of MSR output in period p
$tpf_{p,tp}$	Frequency of occurrence of type period tp in period p
Sets	
$e \in E$	Energy carrier
$p \in P$	Period
$pr \in PR$	Process
$t \in T$	Timestep
$tp \in TP$	Typical period

Figure 1 Variables, parameters and sets of the ETS I module

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expansion across 12 periods, with each period consisting of up to 500 timesteps.

A. Modelling EU ETS I

Equation (1) defines the volume MV_p of the MSR in period p . It is composed of the reserve volume from the previous period MV_{p-1} , plus all inflows of CO2 allowances MI_p , minus any outflows MO_p and the number of canceled allowances DV_p during the period under consideration [17].

$$MV_p = MV_{p-1} + MI_p - MO_p - DV_p \quad \forall p \in P \quad (1)$$

For clarity, the subsequent sets of (2),(3),(4),(6) are presented in piecewise form. In the model's implementation, however, a Big-M formulation is used. Detailed variable definitions are provided in Figure 1.

Equations (2) and (3) determine the number of allowances MI_p entering the MSR. From its introduction in 2019 through 2023, allowances were added to the reserve once more than 833,000,000 allowances (hereafter co_p) were in circulation (see (2)) [18]. In 2024, this mechanism was reformed under the Fit for 55 decision [19]. While the minimum threshold for transferring allowances into the MSR was untouched to 833,000,000 (hereafter cm_p), the inflow mechanism was modified as follows:

- If the circulating volume exceeds 1,096,000,000 (hereafter cu_p), 24% of the total circulating allowances are deducted from the next auction volume and transferred into the MSR.
- If the circulating volume lies between cm_p and cu_p , only the portion exceeding cm_p is transferred [17].

$$MI_p = \begin{cases} mip_p \cdot C_{p-1} \cdot d_p & \text{if } C_{p-1} \geq co_p \\ 0 & \text{otherwise} \end{cases} \quad p \in [2020, 2021, 2023] \quad (2)$$

$$MI_p = \begin{cases} 0 & \text{if } C_{p-1} \leq cm_p \\ (C_{p-1} - cm_p) \cdot d_p & \text{if } C_{p-1} \in [cm_p, cu_p] \text{ and } \frac{ec_p}{d_p} \geq C_{p-1} - cm_p \\ mip_p \cdot C_{p-1} \cdot d_p & \text{if } C_{p-1} > cu_p \text{ and } \frac{ec_p}{d_p} \geq mip_p \cdot C_{p-1} \\ ec_p & \text{otherwise} \end{cases} \quad (3)$$

$p \in [2024, 2027, 2030, 2033, 2036, 2039, 2042, 2045, 2048]$

Outputs from the MSR in period p MO_p occur only when the circulation volume C_p falls below a predefined threshold cl_p of 400.000.000 allowances in circulation. In such cases, up to 100.000.000 (hereafter mul_p) allowances may be released, or the entire MSR volume if fewer allowances are available [17] as shown in (4).

$$MO_p = \begin{cases} mul_p & \text{if } C_p \leq cl_p \text{ and } MV_p \geq mul_p \\ 0 \leq x \leq mul_p & \text{if } C_p \leq cl_p \text{ and } MV_p \in [0, mul_p] \\ 0 & \text{otherwise} \end{cases} \quad \forall p \in P \quad (4)$$

Until 2023, no cancellation of allowances from the MSR was envisaged (see (5)). With the Fit for 55 legislative package, the option to cancel allowances took effect from 2024 onward [19]. If at the end of the previous period—accounting for both inputs and outputs—the MSR holds more allowances than cl_p , the difference between the auction volume and the MSR volume is canceled [17]. This mechanism is specified in (6).

$$DV_p = 0 \quad p \in [2020, 2021, 2023] \quad (5)$$

$$DV_p = \begin{cases} MV_p - AV_p & \text{if } MV_{p-1} - cl_p + MI_p - MO_p \geq 0 \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

$$p \in [2024, 2027, 2030, 2033, 2036, 2039, 2042, 2045, 2048]$$

The demand for allowances in period p AD_p is calculated as the sum of emissions across all processes pr , energy carriers e , typical periods tp , and timesteps t . Emissions are determined by the specific CO₂ emissions of each energy carrier co_{2e} divided by the process efficiency $eff_{pr,p}$, weighted by the frequency of occurrence of each typical period $tpf_{p,tp}$, while also accounting for emissions removed by Direct Air Capture (DAC). It is important to note that, within the scope of this paper, DAC is represented in a non-process-based manner, serving primarily as an illustrative mechanism rather than a fully detailed conversion process.

$$AD_p = \sum_{pr \in npr} \sum_{e \in E} \sum_{tp \in TP} \sum_{t \in T} PRL_{pr,p,tp,t} \cdot \frac{co_{2e}}{eff_{pr,p}} \cdot tpf_{p,tp} - DAC_p \quad (7)$$

$$\forall p \in P$$

The auction volume AV_p in period p is determined by the maximum available allowances ec_p [20], [21], adjusted by the interaction with the MSR. Specifically, the net effect of allowances transferred into the MSR MI_p and those withdrawn from the MSR MO_p modifies the auction volume, as shown in (8).

$$AV_p = ec_p - MI_p + MO_p \quad \forall p \in P \quad (8)$$

The circulation volume C_p of allowances in period p , shown in (9), reflects the dynamic balance of market inputs and outputs. It evolves from the previous period's circulation volume C_{p-1} by adding the maximum output ec_p , subtracting the input into the MSR MI_p , adding the MSR outflow MO_p , and subtracting the total demand AD_p .

$$C_p = C_{p-1} + ec_p - MI_p + MO_p - AD_p \quad \forall p \in P \quad (9)$$

These equations complete the core representation of our EU ETS I model. By jointly modeling the demand for allowances, the dynamic auction volume, and the overall circulation, this framework enables an analysis of how policy instruments—particularly the MSR—affect the balance between supply and demand for emission allowances.

B. Data

The following section delineates which elements of the power system are expanded endogenously and which remain exogenously fixed. Specifically, the model allows for

endogenous investment in renewable and conventional power plant capacities, as well as battery storage, while pumped hydro remains at existing levels. Network Transfer Capacities (NTCs) are likewise treated exogenously. The dataset underlying this model integrates multiple sources to comprehensively represent both existing and prospective power sector assets, ensuring a reliable test environment for evaluating the model's fundamental functionality rather than providing prescriptive advice. Conventional power plants currently in operation are based on data from the WEPP database [22]. Utility-scale battery storage facilities, including their capacities and geographic distributions, are drawn from [23]. Residential scale battery storage capacities are approximated using [24]. Existing renewable power plants are catalogued based on publicly available datasets on installed capacities in Europe from Eurostat [25], while electricity demand projections follow the “Distributed Energy” scenario of the 2022 TYNDP [26]. Wind and solar generation profiles are derived from [27]. Investment options for new conventional power plants reference the Danish Energy Agency [28], while cost and performance data for battery storage derive from NREL [29], and for renewable plants from the International Energy Agency [30]. Network Transfer Capacities are consistent with the same TYNDP 2022 scenario [26]. Lastly, renewable energy potential estimates are sourced from recent literature on geospatial assessments of resource availability [31].

In addition to the parameters outlined above, the emissions-related inputs for this study are based on official EU reports and legislative sources governing the EU ETS I. The maximal output of allowances in period p ec_p is derived from official EU reports, with values for 2020 sourced from [20] and for 2021–2029 from [21]. The maximum Market Stability Reserve fill level cl_p , effective from 2024, follows from [17], which establishes the deletion of allowances in the MSR framework within the EU ETS I. Percentage intake of MSR in period p mip_p for the period 2019–2023 is based on [32], referencing the framework as of April 8, 2018, with subsequent adjustments derived from the same source [17]. The upper limit of MSR output in period p mul_p , applicable from 2019 onwards, is similarly governed by [17]. The old cut-off threshold co_p , valid for 2019–2023, is defined by [32], reflecting the regulatory status as of April 8, 2018. The upper limit of the MSR volume cl_p is established under [17], which sets the upper threshold for MSR holdings. The middle and upper limit of the Circulation volume in period p (cm_p and cu_p), applicable from 2024 onwards, follows the provisions of [17]. Initial values for the total number of allowances in circulation are obtained from [21]. The initial values for the MSR Volume are drawn from [33].

In total, the final model formulation comprises 28.412.713 variables, of which 72 are binary, and encompasses 26.653.522 constraints. The binary variables appear exclusively in the EU ETS I module, where a Big-M formulation is employed to accommodate piecewise definitions of threshold conditions.

III. RESULTS

The optimization results underscore the pivotal role that the Market Stability Reserve plays in shaping the quantity of

allowances available for compliance under the EU ETS I. By regulating both the diversion of allowances from the market into the reserve and their possible reintroduction, the MSR can substantially influence carbon price signals and long-term emissions trajectories in the electricity sector. In what follows, Figure 2 illustrates the dynamics of auction volumes, circulation, and reserve balances, revealing how variations in regulatory thresholds and market conditions alter the flow of certificates over time.

visualizes the MSR's net effect on the supply of allowances. During the early phase of the simulation, the green areas predominate, signalling robust MSR intake as surplus allowances are diverted from the auction schedule whenever the circulation volume surpasses the designated thresholds. This redirection constrains the auction volume well below the nominal cap, tightening supply beyond what a simple linear reduction in the cap would otherwise accomplish. Toward the end of the time horizon, orange patches remain comparatively

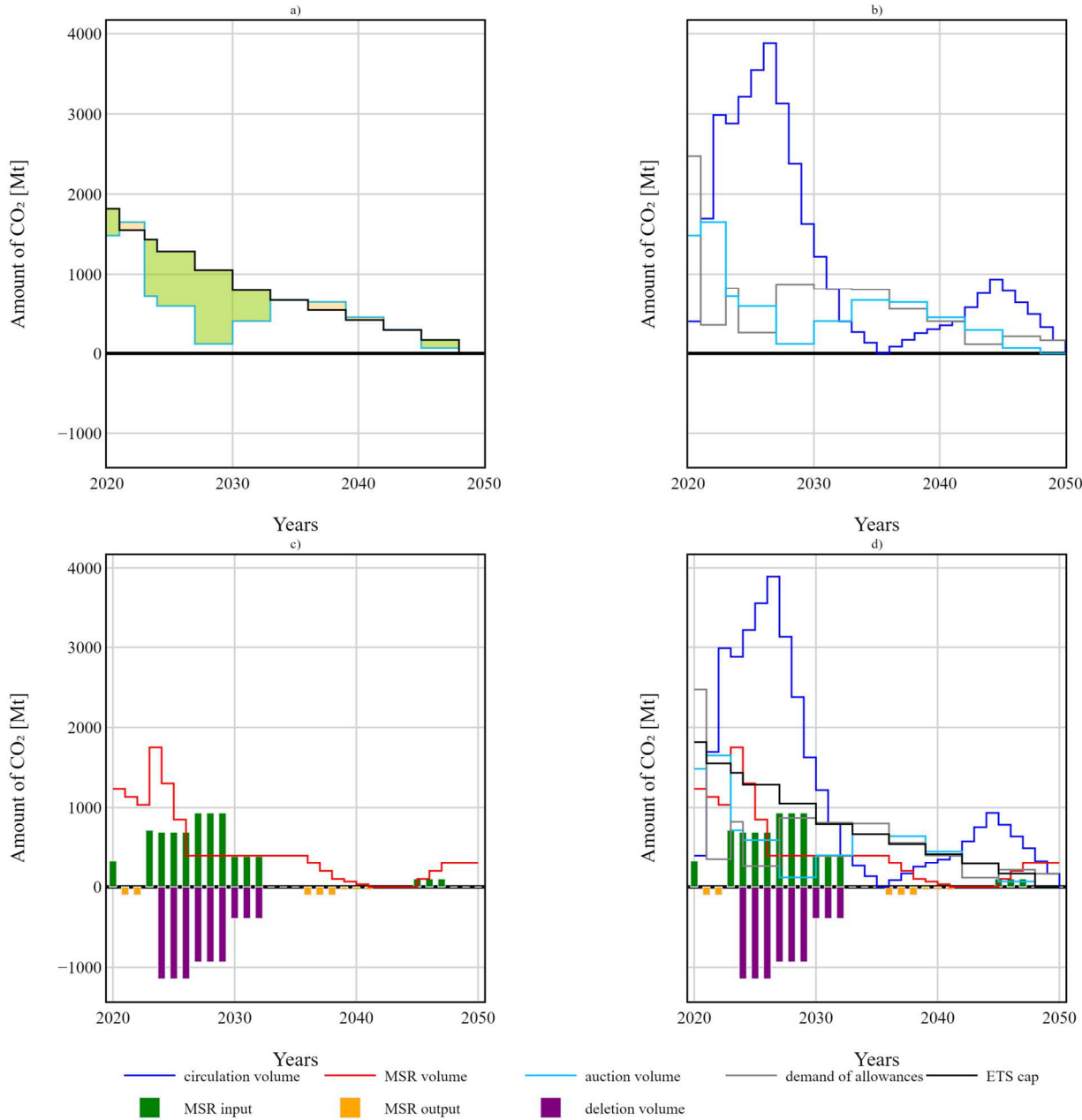


Figure 2 Decomposition of EU ETS I Allowance Allocation: Cap Adjustments, Market Stability Reserve, and Auction Volumes

In Figure 2(a), the black step line indicates the nominal ETS cap, while the solid blue line represents the actual auction volume released to the market. The vertical gap between these lines—shaded green for inflows and orange for outflows—

modest, indicating that far fewer allowances flow back into the market. Consequently, the MSR tends to operate as a net sink, withdrawing more certificates from circulation than it ever reintroduces.

Shifting the focus to Figure 2(b), three lines capture the evolving interplay among circulation, demand, and auction volume. Here, the dark-blue line denotes the total allowances in circulation, the gray line depicts the model’s allowance demand, and the light-blue line indicates the newly issued certificates. Initially, the allowance demand stands well above both the auction volume and the circulation volume, reflecting a substantial surplus carried over from prior periods. As successive rounds of MSR intake occur—occasionally culminating in permanent deletions—the surplus gradually diminishes, causing the circulation volume to draw closer to actual demand levels. By the later years, the newly auctioned allowances and the system’s demand begin to converge, suggesting that the regulatory adjustments introduced by the MSR meaningfully constrain surplus accumulation. This tightening alignment implies more pronounced carbon price signals and, hence, a stronger economic impetus for low-emission investments.

In Figure 2(c), attention turns exclusively to the MSR’s internal mechanisms. The red line depicts the MSR’s volume over time, while the bars show its annual intake (green), outflow (orange), and permanent deletion (purple). In periods of pronounced oversupply—typically when circulating allowances exceed threshold values—inflows surge, causing the MSR to expand. Conversely, the orange bars (outflows) remain modest, underscoring that few certificates withheld from auctions are subsequently released to the market. The purple bars indicate permanent deletions triggered once the MSR volume surpasses legislated caps. By eliminating surplus allowances entirely, these deletion events tighten the system beyond its nominal ETS trajectory, thus raising the effective carbon price signal. The model illustrates how, under ample surplus conditions, the MSR can grow rapidly, only to later engage its deletion mechanism once thresholds are reached, averting prolonged storage of unused certificates.

Finally, Figure 2(d) consolidates the insights from subplots (a), (b), and (c), offering a comprehensive overview of how nominal caps, auctioned allowances, circulation volumes, and MSR interventions co-evolve. This integrated perspective underscores the tight coupling between the MSR’s design parameters—such as intake thresholds and deletion triggers—and the overall market balance. In periods of moderate demand or rapidly declining caps, MSR inflows escalate, pushing the reserve volume upward and causing a discernible drop in active circulation. Conversely, if demand outstrips the model’s capacity to divert allowances into the reserve, small outflows can occur; however, these remain insufficient to compensate for the cumulative intake and eventual deletions, reinforcing the MSR’s net effect of tightening supply over the long term.

Overall, the model simulation confirms that the MSR plays a decisive role in reconciling short-term market conditions with the EU ETS I’s long-term climate objectives. By bridging the gap between nominal caps and actual auction volumes, the MSR safeguards against oversupply and fortifies decarbonization signals, thereby accelerating the transition to low-emission energy technologies.

IV. LIMITATIONS

The subsequent discussion addresses the limitations and future prospects of this study. Instead of offering a comprehensive analysis of capacity expansion pathways under the EU ETS I, the primary aim is to illustrate the regulatory implications of the Market Stability Reserve. Although the model did perform endogenously determined capacity expansions, these outcomes are not the principal focus here. Rather, the emphasis lies in examining how the MSR affects emissions trajectories, price formation, and broader market behavior. As a consequence, the results should be interpreted primarily as a conceptual demonstration rather than a definitive scenario analysis.

Several additional factors limit the scope and transferability of the findings. First, the analysis is restricted to the electricity sector under EU ETS I, thereby excluding other sectors—such as energy-intensive industry and aviation—that also demand allowances within the same trading system. Consequently, the cap is not proportionally reduced to reflect the absence of these sectors, effectively ignoring their typical share of overall allowance demand. Likewise, the newly introduced ETS II—covering emissions from buildings and transport—remains outside the present framework. Excluding these sectors precludes a more holistic view of the broader decarbonization landscape, including potential cross-sectoral synergies or trade-offs.

A further limitation arises from the choice of a single historical weather year (2012) to capture renewable resource variability. Although this year may reflect typical seasonal patterns, it does not account for interannual fluctuations that could alter system operations—particularly in contexts with high shares of intermittent renewable generation. In addition, the techno-economic parameters used here involve considerable uncertainty, especially for emerging low-carbon technologies whose capital costs and performance metrics may evolve unpredictably. Modest deviations in these assumptions could significantly shift the outcomes.

The representation of DAC is also simplified: rather than a process-based depiction at the country level, the model assumes a dedicated renewable energy supply (“DAC energy island”) that is only accounted for within the cost function. Consequently, local infrastructure requirements, site-specific resource availability, and associated costs are not captured in greater detail.

V. CONCLUSION AND OUTLOOK

This study highlights three key insights. First, the MSR exerts a greater influence on effective allowance supply than the nominal cap alone, owing to its capacity to absorb surpluses and permanently delete allowances. Second, the ability to remove certificates entirely from circulation constitutes a marked escalation in regulatory rigor, making the cap effectively more binding. Third, the degree of MSR-induced tightening hinges on threshold settings: while stringent parameters can enhance decarbonization incentives, they may also induce price volatility, whereas lenient settings can preserve surpluses and weaken mitigation signals.

Looking ahead, extending the model framework to encompass additional sectors under EU ETS I, as well as the newly

introduced ETS II, would offer a more holistic perspective on cross-sectoral interactions and potential synergies. For instance, industrial and aviation allowance demands could initially be removed exogenously and then later integrated endogenously to capture their impact on overall system dynamics. Incorporating multiple historical weather years could better capture variability in renewable energy availability, while updating techno-economic inputs with more recent data would reflect ongoing developments in cost and performance trajectories. Finally, a more refined representation of DAC installations would permit a more accurate assessment of their contribution to reducing residual emissions, thereby further tightening overall climate targets. Together, these advancements would yield a more comprehensive analysis of decarbonization pathways.

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