The Emerging Endgame: The EU ETS on the Road Towards Climate Neutrality*

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This version: February 2023

Abstract

The EU Emissions Trading System was recently reformed to make it ‘fit for 55’ by 2030, with the cap on emissions designated to go down to zero by 2040. It is thus widely believed that the next decade will mark the ‘ETS endgame’: when supply approaches zero, the market will undergo fundamental changes and may even cease to function at all. We address the question of which endgame challenges may arise for the ETS with the reformed design. First, we conduct a ceteris paribus analysis based on the numerical ETS model LIMES-EU in a bid to identify anticipation effects. Second, going beyond the numerical modelling, we reflect on and discuss new developments and economic considerations, drawing on the emerging literature and identifying research gaps. The vast range of possible developments suggests that the ETS may as well not be in an endgame, implying ambiguity about the long-term nature of the market that further exacerbates long-term price uncertainty. This puts into question whether the ETS is fit for climate neutrality, and raises the issue of how governance and stability mechanisms must be adjusted to account for it.

Keywords Emissions trading, Climate neutrality, Policy design and evaluation, EU ETS.

JEL classification H23, Q52, Q58.

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1 Introduction

In 2021 the EU adopted more ambitious climate targets, and it is now in the final stages of reforming its climate and energy policies to align them accordingly. The new long-term target of the EU is to reach climate neutrality (net-zero) by 2050. As an intermediate step, it aims to reduce GHG emissions by 55% relative to 1990 by 2030. The reform process was kicked-off in summer 2021 with the publication of the so called Fit-for-55 package by the European Commission. About a year later in summer 2022 the European Parliament and Council proposed amendments to this package, and contentious negotiations between the three institutions followed. Arguably, the most challenging one was to agree on the reform of the ETS, which is front and centre to EU climate policy efforts.

In December 2022 a provisional agreement was reached to substantially tighten the emissions cap of the ETS so that by 2040 the supply of allowances will be zero. Specifically, the annual linear reduction factor (LRF) of supply, expressed as a percentage of the 2005 emission level, will increase from currently 2.2% to eventually 4.4% from 2028 on. Other changes include a reform of the Market Stability Reserve (MSR), the creation of a second ETS (ETS2) for fossil fuels not regulated under the ETS accompanied by a Social Climate Fund (SCF), and a Carbon Border Adjustment Mechanism (CBAM) to address carbon leakage concerns. While the overall package is thus very comprehensive and includes many elements, the tightening of the cap stands out because it implies that the ETS may 'come to an end' as soon as seventeen years from now. In that regard, the reform can be said to usher in the 'ETS endgame'.

Anticipating this endgame begs a number of questions regarding the economic impacts and broader policy ramifications of the emissions cap going down to zero. First of all, how will price formation work when supply becomes very scarce? Will the market continue to function as it currently does or not, will there be a new equilibrium and what will the transition to it look like? Relatedly, market design and other policy developments need to be considered. For instance, will the MSR work properly under different or changing conditions? And how could emerging linking, and potential inclusion of negative emissions through carbon dioxide removals (CDR) change the picture?

So far there is relatively little work that analyses the EU ETS or emissions trading in general from the angle of the cap going down to zero. The related literature is by and large influenced by Hotelling's conceptual framework (e.g., Rubin, 1996; Schennach, 2000; Fuss et al., 2018).[1] Yet the endgame is not formally treated in such works, but rather only the endpoint

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[1] A more detailed literature review can be found in Section 5.

from which an optimal price path can be constructed on the basis intertemporal arbitrage. Similarly, a number of papers using numerical models including the MSR have analysed the EU ETS through 2050 and beyond, see for example Quemin & Trotignon (2021) and Osorio et al. (2021b) for an overview. Yet again they do not specifically consider the endgame issue. Theoretical work by Newell & Stavins (2003) has also looked at the role of cost heterogeneity, which may arguably decline through the endgame. This would imply lower cost savings from market-based policies like an ETS. In contrast, if marginal abatement cost uncertainty remains high as the market becomes smaller in breadth, considering corner outcomes may lead to more volatile pricing (Goodkind & Coggins, 2015). Moreover, detrimental speculation may rise when the cap gets tighter (Quemin & Pahle, 2023). Other strands concern changes in the supply through linking to other ETSs (Verde & Borghesi, 2022) or CDR certificates (Rickels et al., 2022; Franks et al., 2023). While they are all related to the endgame question, none address it head on.

In this paper, we conduct a first analysis of the endgame question. We use the numerical model LIMES-EU to analyze market behavior in a deterministic ceteris-paribus setting, and going beyond immediate results also discuss broader market and policy design issues. To the best of our knowledge, we are the first to conduct such an analysis.

2 Methodology

In this section, we describe the numerical model LIMES-EU along with its core assumptions and parameters. Thereafter, we outline the the Reference and Reform scenarios, which represent the EU ETS design before and after the Fit-for-55 reform in the model analysis.

2.1 LIMES-EU model

LIMES-EU is a linear dynamic cost-optimization model with a focus on the electricity sector, covering all emissions of the EU ETS. Because of its wide sectoral and geographical coverage, it can be used to analyse comprehensive scenarios for the cost-efficient future development of the European electricity sector and the EU ETS. While the electricity sector is modelled in detail, emissions from the other sectors covered by the EU ETS, namely energy-intensive industry and heat from district heating, are represented in a stylised way. The geographical coverage includes all EU countries (excluding Cyprus and Malta) as well as the Balkan region, Norway, Switzerland and the United Kingdom[2].

LIMES-EU simultaneously optimizes investment and dispatch decisions for generation, storage and transmission technologies in five-year time steps from 2010 to 2070. The model covers 35 generation and storage technologies, including different vintages for lignite, hard coal and gas. A total of 33 abatement options are included, whose costs decrease over time due to technological progress. The investments in generation, storage and transmission capacities are optimized endogenously for each of the 5-year time steps. 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 modelled using six representative days, comprising 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. The energy-intensive industry is represented by a step-wise linear marginal abatement cost curve for each country.

Specifically to analyze the EU ETS, LIMES-EU accounts for the emissions of all covered sectors for both the demand and supply side. The EU ETS allowance price is determined endogenously, by means of a constraint (cap) on emissions. The MSR is included as a separate simulation module, implying that computing the long-term equilibrium requires an iterative approach. A comprehensive description of the LIMES-EU model is provided in the documentation available from the models website (Osorio et al. (2021a)).

2.2 Assumptions

A first set of assumptions relates to market aspects, i.e. costs, prices and trading behavior (see Table 1). For fuel prices, we draw on results of the REMIND model[3] and Strefler et al. (2021). The prices of natural gas and coal, though temporarily at very high levels due to the Ukraine crisis, roughly remain at their pre-crisis level in the long run. 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 (see Figures 7-9).

For investment and intertemporal trading decisions, we assume perfect foresight and a dis-

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[2] A market linkage between UK and EU ETS is assumed going forward.

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

count rate of 5% in line with many energy market optimization models. For the carbon market (EU ETS), it is often questioned if perfect foresight is appropriate to capture market dynamics. In other research (Sitarz et al., in preparation) we looked into this issue conducting a back-casting analysis. It turns out that using limited foresight in LIMES-EU explained allowance prices pre-2018 quite well, but for allowance prices post-2020 using 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. This can be translated as traders using longer time horizons. What is more, new non-compliance traders like investment banks entered the market, which engaged in long speculative trading like buy-and-hold strategies (Quemin & Pahle, 2023). This increases trading activities that consider the further away future. Hence, while we do not model these traders explicitly, we do so implicitly by assuming perfect foresight.

In line with current ETS regulation, banking of emission allowances across years is allowed and cost-efficiently modelled. A key uncertainty for the ETS is how long regulated entities can bank allowances and use them to cover their emissions. We assume this can be done until 2057, when the cap would have reached zero under the previous market rules.

Table 1: Market related assumptions

Market related assumptions	
Fuel prices	Based on REMIND model, also see Figure 6
Carbon price (EUA)	Determined endogenously
Investment costs	Decreasing costs for RES, batteries and electrolysers, also see Figures 7 to 9
Time horizon	2010 - 2070
Foresight	Perfect foresight (discount rate = 5%)
Allowance banking	Banking allowed (no borrowing)
Non-compliance trading	Implicit

With regard to policy-related assumptions (Table 2), we consider selected overlapping technology policies on the EU member state level. They influence prices by reducing the demand for allowances. A first group of such policies we consider are mandated coal phaseouts according to Europe Beyond Coal (2022) and RE support measures. For nuclear power we consider the phaseout decisions and respective timetables by Germany, Belgium and Switzerland.

Furthermore, regarding the scope, we mainly extrapolate the regulatory status quo. Over the full time horizon we consider no linking to other carbon markets, whether compliance markets, voluntary markets, or offset crediting under Article 6 of the Paris Agreement. An exception is the UK ETS, which used to be part of EU ETS before Brexit. We therefore assume a de-facto linkage between the two markets[4]. For other non-EU countries such as Switzerland and the Balkan countries we assume an exogenous allowance price. 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 modelled 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. This includes both fossil fuels as well as biomass energy CCS. The reason for doing so is that we think such integration could happen already in the next years. However, we do not consider carbon removal (CR) through carbon farming and storage in long-lasting products and materials as an additional source of supply, because this inclusion seems feasible only further down the road.

It must be mentioned though that both linking and inclusion of CR 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. This linking should not necessarily be physical, it could also be financial. Moreover, the EU has recently published a proposal for a Regulation on an EU certification for carbon removals[5]. This is a first important step that could eventually lead to integrating respective 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.

Table 2: Policy related assumptions

Policy related assumptions	
Complementary policies	RE target (DE) and coal phase-outs (EU-wide)
Nuclear power	Phase-out decisions by DE, CH and BE
Scope/linking	No linking to other ETS considered
Fossil fuel carbon capture and sequestration (CCS)	Considered
Carbon removal (CR)	Bioenergy CCS considered, carbon farming and storage in long-lasting products and materials not considered

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[4] Technically we aggregate emissions caps. For the UK ETS the cap is set only until 2030. For the years after we assume the cap decreases at the same pace as the EU ETS, reaching zero certificates by 2040.

[5] https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7156

2.3 Scenarios

We use two scenarios for the model analysis: a "Reform" scenario in line with the current reform, and a "Reference" scenario based on previous legislation. An overview of the policy settings is provided in Table 3.

Table 3: ETS settings in the different scenarios

Reference	**Reform**
Cap: 43% emission reduction with respect to 2005 • Annual reduction of allowances by 2.2%	**Cap: 62% emission reduction with respect to 2005** • Annual linear reduction of allowances by 4.3% from 2024-27 and 4.4% from 2028 onwards • One-off reduction of allowance supply of 90 Mt in 2024 and 27 Mt in 2026
MSR: • Intake rate: 24% until 2023 and 12% afterwards • Thresholds: Upper threshold of 833 Mt and lower threshold of 400 Mt • Outtake rate of 200 Mt until 2023 and 100 Mt afterwards • Cancellation: the EUA in the MSR exceeding the volume of EUA auctioned in the previous year are invalidated	**MSR:** • Intake rate: 24% until 2030 (assumed at the same value afterwards) • Thresholds: Upper threshold of 833 Mt and lower threshold of 400 Mt. There is also an adaptative threshold of 1096, which implies that when the TNAC lies between the upper and adaptative threshold, the difference between the TNAC and the upper threshold is transferred to the MSR • Outtake rate of 200 Mt until 2023 and 100 Mt afterwards • Cancellation: the EUA in the MSR exceeding 400 Mt are invalidated

We compute the cap in both scenarios as shown in Figure 1 as follows: For both scenarios, we start with historical emissions, and adjust the cap in 2021 to reflect the exit of the UK from the EU ETS. For the "Reference" scenario we annually deduct 43 Mt, which corresponds to a LRF of 2.2%. For the "Reform" scenario, we adjust this value to an LRF of 4.3% and 4.4% respectively for the years after 2023. Moreover, we deduct the one-off reductions in 2024 and

2026 from the annual caps (rebasing). Consequently, the cap in the Reform scenario reaches zero in 2039.

Regarding the MSR, the major changes are (a) continued intake of 24% through 2030, (b) adaptive upper threshold to avid oscillatory effects, and (c) cancellation only up to 400 Mt. This corrects some of the known problems of the original design (see Perino et al. (2022), Willner & Perino (2022), Borghesi et al. (2023), Tietjen et al. (2021)). For the type of analysis here (not considering shocks), the most relevant aspect is the continued intake of 24%, implying a substantial tightening of the cap due to higher cancellations (see Osorio et al. (2021b)).

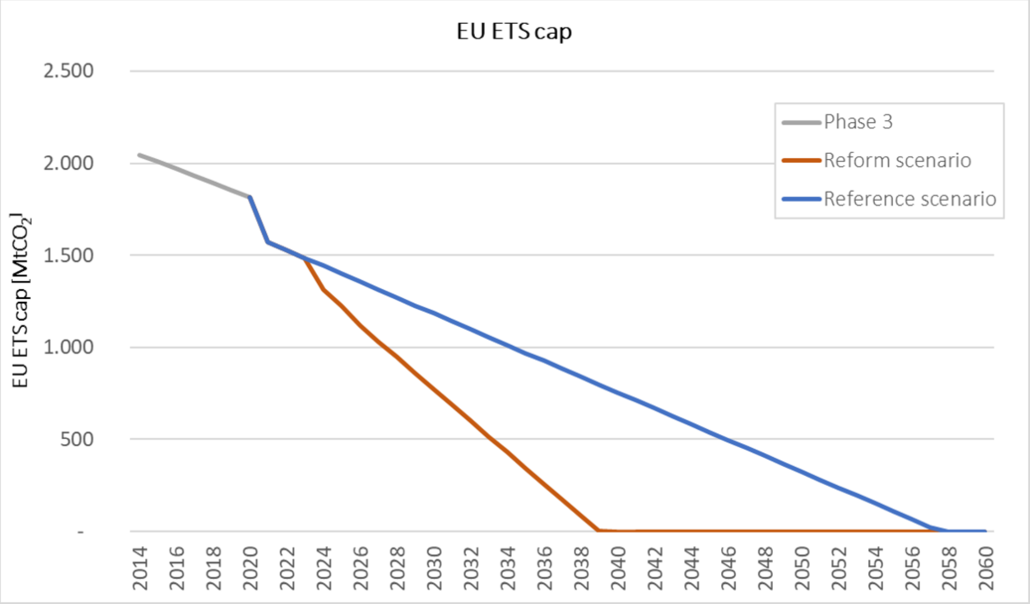

Figure 1: Cap in Reform scenario (adjusted to sectoral scope of LIMES-EU)

3 Results

3.1 Reference scenario

Figure 2 shows the development of sector emissions and the CO_2 price in the Reference scenario. The CO_2 price increases only moderately to 39 EUR/tCO_2 by 2030, and it reaches a level of 106 EUR/tCO_2 by 2050. The corresponding reductions of emissions account to to 1037 Mt by 2030, and are mainly due to reductions in the energy sector. Significant emission reductions in industry are achieved only in the 2040s due to relatively higher abatement costs. More specifically, compared to 2020, industrial emissions only decrease by 2% by 2030 and 22% by 2040, while by 2050 there is a large emission cut larger than 80%.

The evolution of the MSR and TNAC can be seen in Figure 2 (b) and (c). Displayed values are computed as follows: The annual number of allowances in circulation ('TNAC') depends on the realised emissions ('Emissions'), allowance supply ('EUA supply') and the previous year's level of TNAC. The supply of allowances comprises allowances allocated for free and those auctioned by the member states, the latter in turn depending on the TNAC level. The MSR work as follows: If the TNAC exceeds 833 million allowances, fewer allowances are auctioned (24% of the TNAC until 2023, 12% from 2024 onwards) and are instead transferred to the MSR. If the TNAC falls below 400 $MtCO_2$, 100 $MtCO_2$ additional allowances from the MSR are added to the auction volume.

Figure 2 (b) shows that the TNAC, the MSR and the supply of EUA more less co-evolve in the coming decades. All the indicators go down relatively smoothly to (near) zero by around 2055. The only exception is the MSR spike in 2022, when it reaches a volume of 2945 $MtCO_2$. This is primarily due to the special intake of allowances and, to a lesser extent, because of the regular intake of allowances from the auction volumes. This special intake of allowances corresponds to the 900 $MtCO_2$ of allowances that were not auctioned under the backloading decision between 2014 and 2016 (European Commission, 2014) and are instead transferred directly to the MSR (European Parliament and Council of the European Union, 2015). In addition, there are 650 $MtCO_2$ of allowances that the Commission (2015) estimates were not allocated between 2016 and 2020. In both scenarios, it is further assumed that 250 $MtCO_2$ were transferred to the MSR in 2019 and 1300 $MtCO_2$ in 2020, based on Burtraw et al. (2018).

The corresponding activity of the MSR can be seen in Figure 2 (c). The MSR continuously takes in allowances until 2038, thus tightening the supply in the market. After 2038, the TNAC falls below the upper limit (833 $MtCO_2$), such 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 every year until 2038, the MSR volume decreases because more allowances are cancelled than transferred into it. In total, the MSR takes up around 5204 $MtCO_2$ of allowances between 2018 and 2057, of which 5117 $MtCO_2$ are cancelled. Most EUAs are cancelled in 2023 (2444 $MtCO_2$), due to the high MSR volume after the special inflow in 2022. Thereafter, annual cancellations decrease to a level below 200 $MtCO_2$ after 2024.

In summary, the Reference Scenario is characterised by emissions reductions at a moderate pace and relatively low carbon prices. Banking activity is quite low due to high allowance supply, and the MSR cancels only around 5 $GtCO_2$ over the entire period. In particular, there is no strong anticipation effect that characterizes the emerging endgame, as will become clear from comparison with the Reform scenario.

3.2 Reform scenario

The Reform scenario stands in contrast in many ways. To begin with, emission reductions are considerably accelerated and carbon prices considerably higher, compared to the Reference scenario. Notably, most of the reductions occur already in the current decade; emissions by 2030 are 65% lower than in 2020. The rate of reduction is thus around twice as fast than in the Reference Scenario.

Going into details, large parts of the electricity sector are already decarbonised by 2030, and coal is basically phased-out across Europe by then; just 30 TWh of coal generation remain. Industrial emissions also already fall by 36% between 2020 and 2030. The CO_2 price rises to 126 EUR/tCO_2 by 2030, more than three times higher than in the Reference Scenario. In the long term, the CO_2 price even rises to over 400 EUR/tCO_2 after 2050.

Figure 3 (b) shows the development of MSR, TNAC and allowance supply. In the short term, the MSR volume develops similarly to the Reference scenario and reaches a maximum of 2.8 $GtCO_2$ in 2022. In the medium term though, the MSR volume is much higher due to the increased intake rate of allowances (24% vs. 12% of TNAC). However, the TNAC is also significantly higher. The reason for this is the stronger banking behaviour of regulated entities in anticipation increasing allowance scarcity. This has important implications: A substantial volume of allowances is transferred to the MSR each year in the 2020s and 2030s. Another noteworthy observations is that the TNAC is above the upper threshold for allowance intake until 2040 and does not oscillate around it afterwards. This is in part due to the adaptative threshold, which smoothens the intake into the MSR. Therefore, the oscillations reported in Osorio et al. (2021b) for scenarios with high intake rates are not present because of the improved threshold design.

The cancellation of EUAs through the MSR is shown in Figure 3 (c). Overall cancellation amounts to 7.5 $GtCO_2$, significantly more (47%) than in the Reference scenario. Moreover, in the Reform scenario the MSR is active until completely empty by 2048, seven years earlier than in the Reference scenario. The reason for this is that the TNAC falls below 400 million earlier due to the lower allowance inflow.

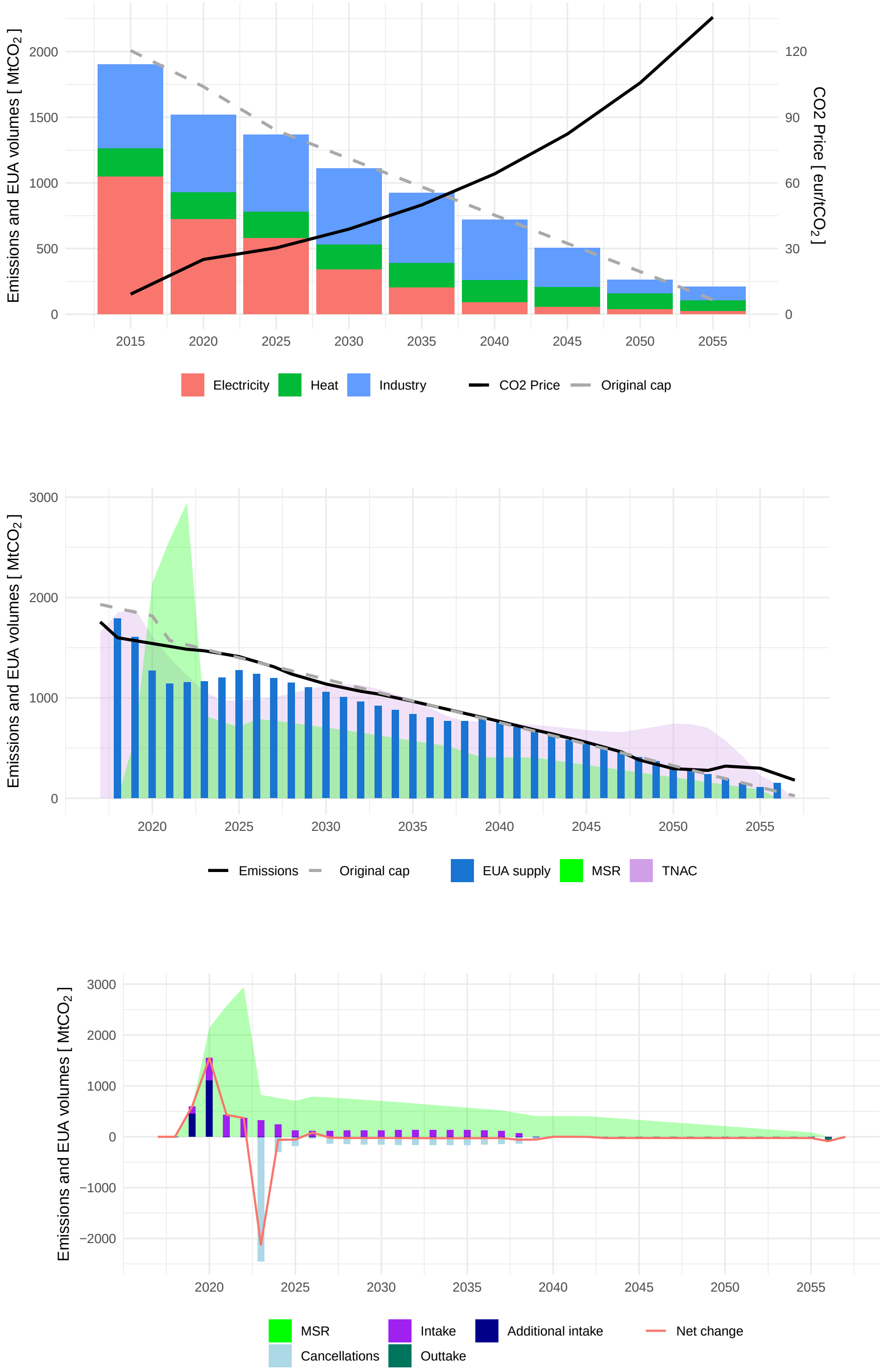

Figure 2: EU ETS development in the Reference Scenario. (a) Sectoral emissions and EUA price; (b) ETS emissions, cap as well as TNAC and MSR volumes; (c) MSR operation.

To summarize, the Reform scenario is characterised by a substantial acceleration of the need to reduce emissions. Because allowance supply becomes tighter much faster, and firms anticipate this, they bank more. Importantly, this effect arises not in the far away future, but already in the years to come, constituting the emerging endgame. Exacerbating this is the relatively high cancellation of allowances through the MSR, which is one of several aspect we will discuss in 5.

4 Sensitivity analysis

4.1 Sensitivity across assumptions

In addition to the two main scenarios, a sensitivity analysis is carried out, in which important model parameters are varied. A total of 26 sensitivity variations are calculated for each main scenario. We focus on the discount rate, CAPEX of renewables, higher electricity demand as a result of enhanced sector coupling, gas prices, unavailability of CCS, limited transmission expansion, and share of free allocation (only for the Reference scenario[6]). The initial selection of parameters was made on the basis of preliminary work with LIMES-EU, through which sensitivities to certain parameters are already known (e.g. discount rate, commodity prices). The list was supplemented based on current political processes and discussions (e.g. rebasing, CCS technology).

Figure 4 shows the carbon price for 2030 in the sensitivity scenarios, grouped by the two main scenarios. The individual data points represent the respective price in 2030 in a single scenario. In the sensitivity scenarios of the Reference scenario, the price ranges between 82 and 147 EUR/tCO_2, exhibiting a wide bandwidth. At the same time, the minimum of EUR 82/tCO_2 is still clearly above the prices of the reference scenario sensitivities (EUR 29-55/tCO_2).

Carbon prices are the result of allowance scarcity. Therefore, lowest prices occur when the emission budget is highest, i.e., when cancellations are also lowest. The parameters having the strongest effect on cancellations are discount rates and CCS (un)availability. Discount rates affect cancellations because allowance banking is a provision to smooth compliance and abatement costs over time. Accordingly, if firms have a higher discount rate they put a lower weight on the future and thus bank less. A lower bank in turn implies that fewer allowances go into the MSR and therefore also cancellations are lower, and thus carbon prices in 2030 are

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[6] In the Reform scenario the shares of free allocation are already defined for the entire time horizon

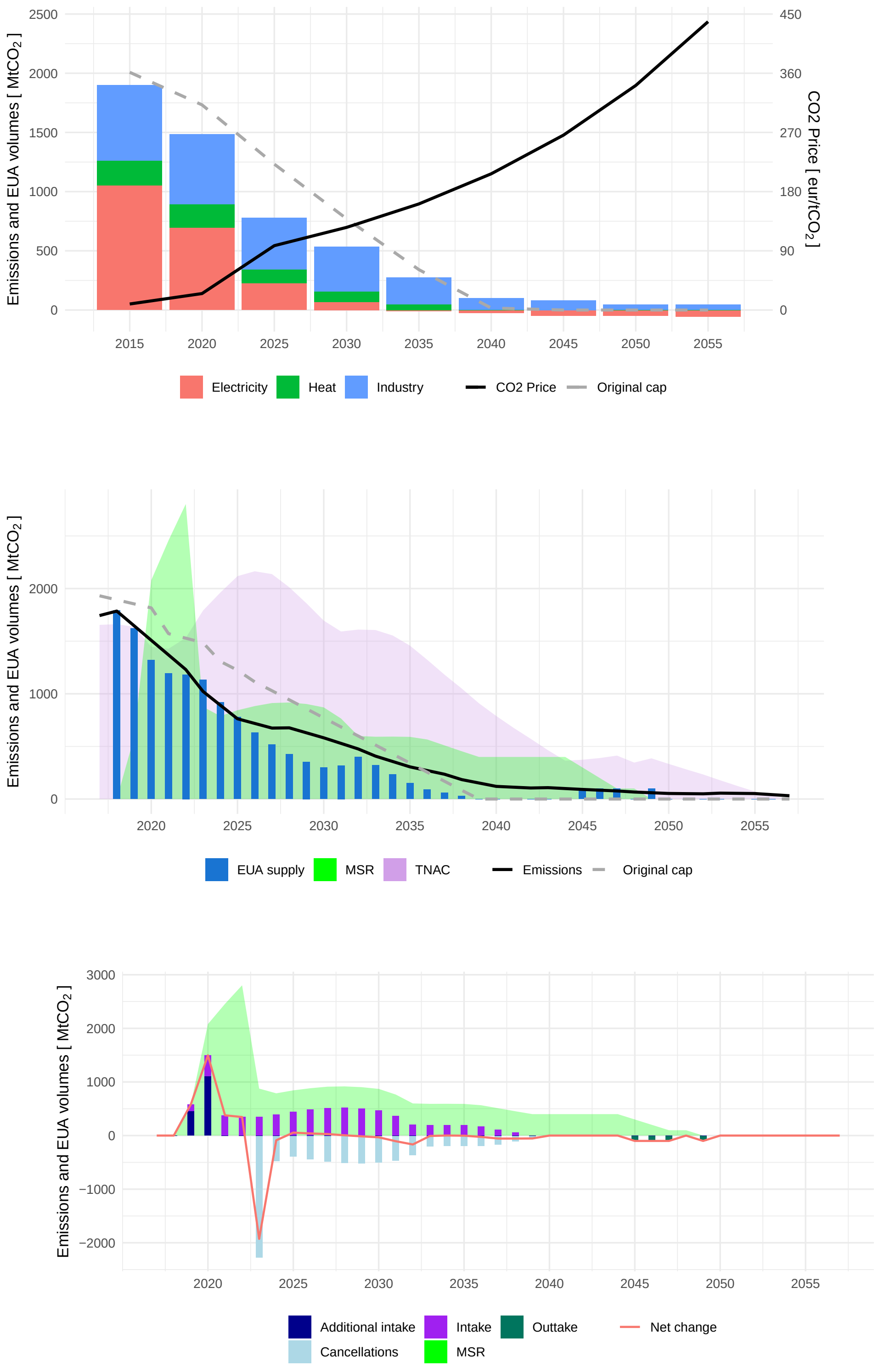

Figure 3: EU ETS development in the Reform Scenario. (a) Sectoral emissions and EUA price; (b) ETS emissions, cap as well as TNAC and MSR volumes; (c) MSR operation.

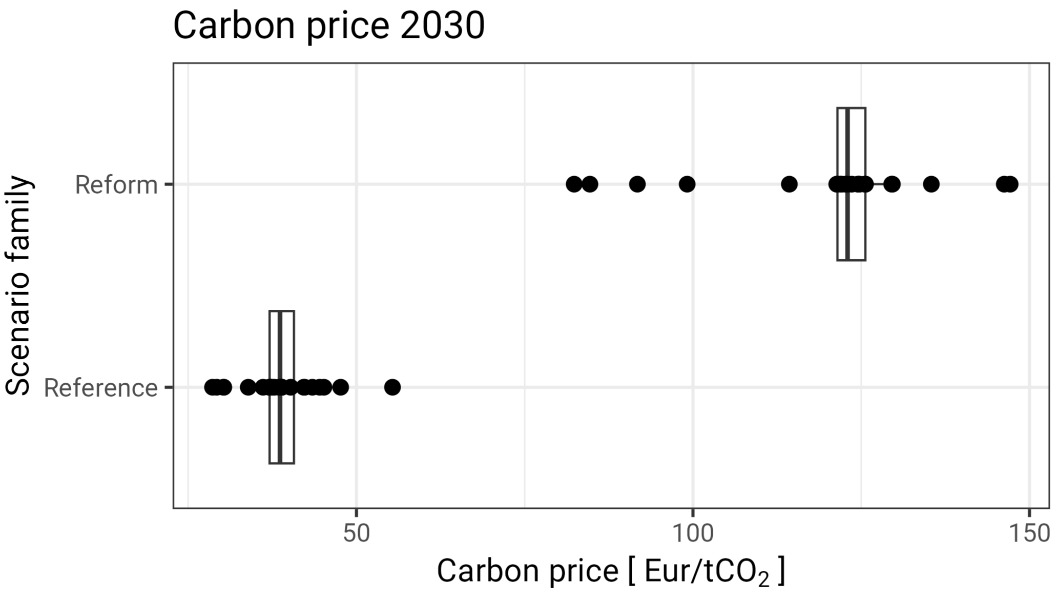

Figure 4: Sensitivity analysis of 2030 EUA price for Reference and Reform scenarios

lower. The opposite effect occurs when discount rates are low. Similarly, the unavailability of CCS triggers more banking to cover long-term emissions and thus lead to higher cancellations and thus higher carbon prices.

Although the range of prices is clearly wider in the Reform scenario, the changes in the corresponding parameters (e.g., discount rate) have the same (qualitative) effect on cancellations, and thus on carbon prices. For instance, a discount rate of 10% leads to the lowest carbon prices in 2030 in both scenarios. The results of the default scenarios can thus be considered robust in the above sense.

4.2 Sensitivity across models

In addition to analyzing sensitivities of assumptions within in the LIMES-EU model, it is also insightful to consider sensitivities across different ETS models. To illustrate this, we draw on the results of a workshop conducted in late 2022, which brought together seven ETS modeling teams to discuss their results and projections for the ETS price through 2030 (Pahle et al., 2022). Each team used its own assumptions, specific scenario definition and modelling approach. That is, no harmonization was conducted. Figure 5 shows individual simulated price outputs for the teams' default 'Green Deal scenario'.

The most remarkable result is the convergence of the price paths towards the end of the

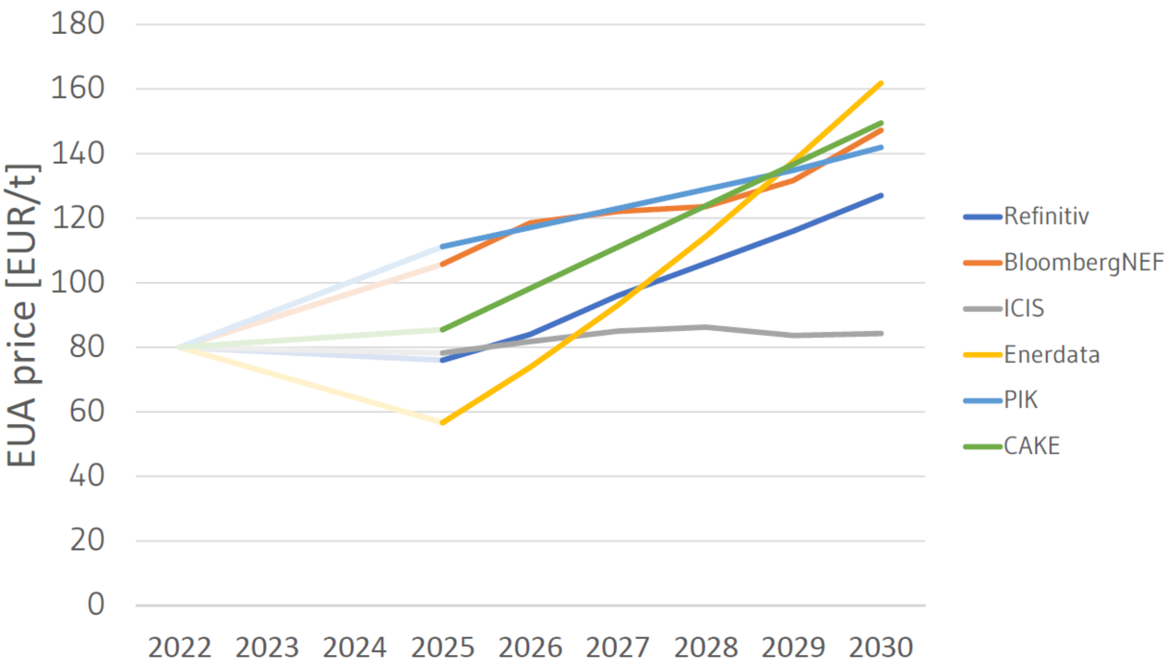

Figure 5: Price projection of different models

Source: Ariadne Workshop (Pahle et al., 2022). Only six out of the seven teams could provided prices.

2020s. Five out of six models yield a price estimate in the range of around 130 to 160 Euro/tCO_2 in 2030, although their short-term predictions differ more widely (between 56 and 111 Euro/tCO_2 in 2025). From the discussion of this convergence emerged that there may be fewer abatement choices in the medium to long term than there are in the short to medium term. In other words, flexibilities become smaller and/or more aligned across different models over time.

Another important insight was gained by inspecting the one ‘outlier’ with considerably lower prices. The discussion suggested that this was due to the comprehensive inclusion of complementary policies in the model, the effect of which is a strong reduction of demand for allowances and thus prices. Consequently, across different modeling approaches the comprehensiveness of overlapping policies considered in the model – and the assumptions regarding their effectiveness – can be considered the most important sensitivity.

5 Policy discussion (beyond ceteris paribus)

In this section we reflect on several climate policy and emissions market design issues on the road towards climate neutrality, with a particular focus on the EU ETS in 2030 and beyond.

These issues have for now largely eluded formal treatment in the literature (e.g., Fuss et al., 2018), but they can no longer be deemed distant considerations and as such should occupy the forefront of academic research in the near future. That an endpoint (i.e., the cap reaching zero) is now 'in sight' and increasingly overlaps with current investment horizons motivates a general reflection on the ETS endgame. In particular, it both enables and compels a backward-induction approach to climate policy and market design for policymakers as well as to trading and investment decisions for market actors (Dolphin et al., 2022). Below we sketch out and discuss different alleys for future research in this direction.

Market stability reserve and supply adjustment. The MSR was designed and implemented to absorb an 'historical surplus' of allowances and to provide resilience against both unanticipated demand shocks and overlapping emission-curbing policies. As the previous sections show and in line with the related literature recently reviewed in Perino et al. (2022) and Borghesi et al. (2023), large MSR intakes and in turn cancellations are expected to continue through this decade. By construction, MSR intakes and cancellations will be higher, the higher and longer banking remains above the intake threshold. Importantly, this may inconsistently run counter to rational banking behavior on the part of market actors in anticipation of fast-approaching net-zero targets, further accelerating the reduction of supply over time, both transitionally and cumulatively.

Additionally, effective MSR impacts on supply volumes are highly uncertain and convoluted, which undermines price predictability and stability. The literature does not provide a robust estimate of the MSR impacts on supply, as these are extremely sensitive to modelling assumptions and intrinsically highly dependent on market behavior and market actors' anticipation of future MSR impacts (Bruninx et al., 2020; Osorio et al., 2021b; Quemin & Pahle, 2023). This is amplified by regulatory uncertainty: First, tapping into the MSR to fund part of the REPowerEU plan may possibly undermine confidence in the system overall (Borghesi et al., 2023). Second, legally speaking, allowances in the MSR are 'invalidated' and not cancelled per se. The absence of a clear definition of the term 'invalidation' leaves some room for future interpretation, and one could envisage a scenario where invalidated allowances would make their way back into circulation should policymakers decide so.

As the policy focus shifts from reducing historical surpluses to efficiently managing the net-zero transition, both the MSR counterproductive effect on supply depletion and induced supply uncertainty call for a reform of how supply adjustment is conditioned. MSR limitations are essentially rooted in the use and misinterpretation of banking as the indicator to adjust supply. Indeed, banking weighs allowance demand today (relative to supply) against anticipated demand tomorrow. However, the MSR reacts to an increase in banking as if it unconditionally signaled a decrease in demand (relative to supply) whereas it can be a rational response to a future increase in demand.[7] In comparison, the market price is robust signal of demand relative to supply overall, and using it as an indicator to adjust supply is both more straightforward and efficient (e.g., Burtraw et al., 2022; Perino et al., 2022). If EU regulators were to stick to banking-based supply adjustments, the MSR parameters should at least be regularly revised in line with hedging volumes and a finer decomposition of allowance holdings for different purposes (Quemin & Pahle, 2023).[8]

Market functioning and price formation in an ETS terminal phase. To the best of our knowledge, there is no literature on market and trading behavior as an ETS nears natural termination (i.e., the cap nears or becomes virtually zero and the market volume becomes tiny).[9] Yet such future market conditions will likely entail different pricing regimes and market dynamics than those observed so far. In this respect, some papers address such issues, although for the generic case of an exhaustible resource or indirectly. Bouleau (2012, 2018) shows how the price of an exhaustible resource can become erratic and increasingly volatile with strong price swings as its depletion progresses, so much so that the deterministic Hotelling trend may even vanish. Importantly, this has not to do with uncertainty about reservoir size and extraction technology cost or performance, but rather with the extent of randomness or noise in the stochastic process that can originate from trading or the market itself.[10] As a result, when the trend is hidden by randomness, the price loses its function as a signal in the Hayekian sense. Other papers shed light, albeit indirectly, on what trading could be like in a 'tiny' market. One could expect the frequency of corner vs. interior equilibrium solutions to become more frequent, increasing price volatility and the dominance of price over quantity regulation (Goodkind & Coggins, 2015). A tiny market could also be prone to

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[7] While banking may indeed well reflect past 'oversupply', it points in the opposite direction for anticipated shifts in demand or supply. That is why the MSR (1) can be effective at reducing historical surpluses and providing resilience against unanticipated demand shocks; (2) reduces the efficacy of overlapping policies, which are bound to play an ever more important role in the future (Perino et al., 2022).

[8] Such decomposition becomes increasingly warranted as the scope of traders (and thus of trading and investment strategies) widens beyond compliance actors (Quemin & Pahle, 2023). At a minimum, one could envisage MSR intake threshold and rates that adjust over time to the market size, e.g., declining based on the linear reduction factor of the cap (Quemin, 2022).

[9] A notable recent exception is Heijmans (2022) who quantifies the reduction in overall emissions realized by shortening the duration of an ETS with a price– or banking-based supply adjustment mechanism. As a signal used to adjust supply, the price is found to outperform banking along several dimensions.

[10] This is not accounted for in standard economic models of intertemporal permit use where the Hotelling's rule holds in expectation (e.g., Rubin, 1996; Schennach, 2000; Fuss et al., 2018).

trading frictions, which can distort market outcomes (Baudry et al., 2021), or to illiquidity issues, which can increase the risk of manipulation (Quemin & Pahle, 2023).

There is also little experience with emissions trading programs in their final stages, or with limited relevance or applicability to carbon dioxide. Perhaps the only relevant example is the US sulfur dioxide emissions trading program (e.g., Schmalensee & Stavins, 2013, 2017).[11] In its first two phases, the program and the downward cap trajectory reduced emissions cost effectively, but since the early 2010s the program, while still nominally in place, has de facto been replaced by ever stricter prescriptive air regulations. Although there are many other factors at play, this experience suggests that the suitability of a cap-and-trade may decrease over time as the phaseout advances. However, drawing a parallel for decarbonization has limits because carbon is more ubiquitous than sulfur in the economy and because of net-zero targets and the need for negative emissions.

Fundamentally, the ETS endgame begs the question of the political acceptance and economic relevance of emissions trading as a climate policy tool. That is, is an ETS useful and effective only during the transitory stages of a phaseout, or can it also be suitable in its terminal phase as the paradigm shifts from driving down emissions to managing a net-zero environment? If, for instance, abatement cost heterogeneity (e.g., abatement options with different costs and investment timelines) decreases over time as the endgame nears and relevant technologies (possibly with increasingly homogeneous costs) have emerged and matured, cost savings from emissions trading compared to non-tradable standards could become small if not negative (Newell & Stavins, 2003). If, however, price volatility becomes higher or excessive, be it due to high cost uncertainty or trading conditions in a tiny market, not only can this jeopardize the political acceptance and support for emissions trading, but the market price may also not be a suitable tool for net-zero management. Specifically, can the market price alone effectively fence off positive emissions (i.e., prevent their re-entry) and remunerate negative emissions, or should more regulation be used to meet both objectives in a stable and predictable manner?[12] We discuss the issue of net-zero management in more detail below.

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[11] An earlier trading system, if not the first experience with emissions trading, was the lead phasedown program from gasoline in the US. The program led to virtual elimination of the pollutant and served as a proof of concept that emissions trading could be both environmentally and cost effective (Schmalensee & Stavins, 2017). Although the program enabled banking, it functioned more as performance standard with trading than as a textbook cap-and-trade system since there was no explicit allocation of allowances, which were instead implicitly awarded based on historical gasoline production levels.

[12] Considerations about the long-term or final price signal become more relevant for price formation as the end of the program nears due to intertemporal arbitrage and backward induction from the final stage.

Net-zero management and scope uncertainty. As the ETS approaches net-zero, its market structure will change dramatically. On the demand side, a wider and more diversified trader ecosystem has already emerged, and this trend can be expected to continue as carbon increasingly becomes an asset class with economy-wide relevance (Quemin & Pahle, 2023). At a minimum, this warrants increased market oversight and transparency. In this regard, the EU financial regulator recently identified data issues and ways of improvement, and also proposed several options for consideration to enhance scrutiny, including allowance holding limits, position limits or position management controls (ESMA, 2022).

Yet a more fundamental change occurs on the supply side, with a shift from one public seller of (positive) emission allowances to multiple private sellers of negative emission certificates. Carbon removal credits are likely to constitute a new source of supply that could be surrendered against compliance – in net terms – in the ETS, de facto loosening the zero cap on positive emissions. It is however unclear how, when and to which extent negative emissions could be integrated in the ETS, see notably Rickels et al. (2021) and Burke & Gambhir (2022) for a discussion of various economic, legal, and political challenges associated with such integration. This creates supply uncertainty which in turn could destabilize the market and induce excessive price volatility. To mitigate this, Rickels et al. (2022) propose that in the transition from positive to net negative emissions trading, an institutional mandate be given to a 'carbon central bank' to (1) procure removals, (2) convert them into fungible credits, and (3) dynamically auction them to the market over time to keep the net emissions path unchanged and ideally to keep prices within a certain dynamic price corridor.[13] The idea of introducing a carbon central bank is not new (e.g., Whitesell, 2012; de Perthuis & Trotignon, 2014) but it may gain traction in the context of net-zero management.

Finally, observe that volume uncertainty on the supply side goes beyond that induced by the sole availability and usability of negative emissions. Specifically, the effective supply size beyond 2040 will essentially be driven by the scope of the ETS, that is (1) the inclusion of additional sectors, possibly through a merging with the second ETS for road transport and buildings (e.g., Pollitt & Dolphin, 2021; Görlach et al., 2022) and (2) the linking to other ETSs beyond the EU, possibly under the framework of the Article 6 of the Paris Agreement (e.g., Rose et al., 2018; Doda et al., 2019; Verde & Borghesi, 2022). Beyond efficiency gains, this

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[13] In this setup, there would be no direct interactions between buyers and suppliers of negative emission credits, as the regulatory authority would – at least transitionally – act as an intermediary. See also Bednar et al. (2021) for a proposal of market-based instruments to address intertemporal issues with carbon dioxide removals in the transition to a net-negative carbon economy. Note also that the pricing of negative emissions should also be a function of inter-jurisdictional leakage and domestic policies (Franks et al., 2023).

would expand the breadth of the market, thus providing more liquidity and stability.[14] Note that the MSR, as a banking-based supply adjustment mechanism unique of its kind, would likely constitute an obstacle to linking to other systems internationally due to compatibility issues with price-based mechanisms (e.g., Borghesi et al., 2023).

6 Conclusion

In this paper we establish that with the recent reform, what can be called the ‘endgame’ of the ETS is emerging. That is, the cap reaching zero is now ‘in sight’ and this prospect increasingly overlaps with current investment horizons, begging the question of how the corresponding anticipation of zero supply affects market and policy functioning. To address these issues, we first conduct a ceteris paribus analysis based on the numerical ETS model LIMES-EU, and find substantial acceleration that is further exacerbated by the MSR. Second, going beyond the numerical modelling we reflect on and discuss new developments and economic considerations, drawing on the emerging literature and identifying research gaps. The vast range of developments that appear possible at this time suggests that the ETS may as well not be in an endgame, implying that ambiguity about the long-term nature of the market further exacerbates long-term price uncertainty. This puts into question whether the ETS is fit for climate neutrality, and raises the issue of how governance and stability mechanisms must be adjusted to account for it.

7 Acknowledgements

The authors would like to thank G. Perino, L. Taschini, D. Burtraw and R. Gerlagh for comments on how price formation could work when supply becomes very tight. Funding from the ENGAGE project of the European Union’s Horizon 2020 research and innovation programme under grant agreement 821471, and from the German Federal Ministry of Education and Research under the Kopernikus-Projekt Ariadne (FKZ 03SFK5A) is gratefully acknowledged. All errors and views expressed in this article are solely those of the authors. This article is neither commissioned by, nor does it reflect the opinions of, Électricité de France.

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[14] Importantly, linking could also be anticipated and reflected in prices before it actually happens.

References

Baudry, M., Faure, A. & Quemin, S. (2021). Emissions Trading with Transaction Costs. *Journal of Environmental Economics & Management*, **108**, 102468.

Bednar, J., Obersteiner, M., Baklanov, A., Thomson, M., Wagner, F., Geden, O., Allen, M. & Hall, J. W. (2021). Operationalizing the Net-Negative Carbon Economy. *Nature*, **596**, 377–83.

Borghesi, S., Pahle, M., Perino, G., Quemin, S. & Willner, M. (2023). *The Market Stability Reserve in the EU Emissions Trading System: A Critical Review*. Working Paper, EUI.

Bouleau, N. (2012). Limits to Growth and Stochastics. *Real-World Economics Review*, **60**, 92–106.

Bouleau, N. (2018). Le Mensonge de la Finance – Les Mathématiques, le Signal-Prix et la Planète. Les Éditions de l'Atelier.

Bruninx, K., Ovaere, M. & Delarue, E. (2020). The Long-Term Impact of the Market Stability Reserve on the EU Emission Trading System. *Energy Economics*, **89**, 104746.

Burke, J. & Gambhir, A. (2022). Policy Incentives for Greenhouse Gas Removal Techniques: The Risks of Premature Inclusion in Carbon Markets and the Need for a Multi-Pronged Policy Framework. *Energy & Climate Change*, **3**, 100074.

Burtraw, D., Holt, C., Palmer, K. & Shobe, W. (2022). Price-Responsive Allowance Supply in Emissions Markets. *Journal of the Association of Environmental & Resource Economists*, **9**(5), 851–84.

Doda, B., Quemin, S. & Taschini, L. (2019). Linking Permit Markets Multilaterally. *Journal of Environmental Economics & Management*, **98**, 102259.

Dolphin, G., Pahle, M., Burtraw, D. & Kosch, M. (2022). *A Net-Zero Target Compels a Backward Induction Approach to Climate Policy*. Working Paper 22-18, Resources for the Future.

ESMA (2022). *Emission Allowances and Associated Derivatives*. Final Report, 28 March 2022, European Securities and Markets Authority, Paris.

Europe Beyond Coal (2022). Europe's Coal Exit. Overview of National Coal Phase Out Commitments. `https://beyond-coal.eu/europes-coal-exit/`.

European Commission (2021). EU Reference Scenario 2020 – Technology Assumptions.

Franks, M., Kalkuhl, M. & Lessmann, K. (2023). Optimal Pricing for Carbon Dioxide Removal under Inter-Regional Leakage. *Journal of Environmental Economics & Management*, **117**, 102769.

Fuss, S., Flachsland, C., Koch, N., Kornek, U., Knopf, B. & Edenhofer, O. (2018). A Framework for Assessing the Performance of Cap-and-Trade Systems: Insights from the European Union Emissions Trading System. *Review of Environmental Economics & Policy*, **12**(2), 220–41.

Goodkind, A. L. & Coggins, J. G. (2015). The Weitzman Price Corner. *Journal of Environmental Economics & Management*, **73**, 1–12.

Görlach, B., Jakob, M., Umpfenbach, K., Kosch, M., Pahle, M., Konc, T., aus dem Moore, N., Brehm, J., Feindt, S., Pause, F., Nysten, J. & Abrell, J. (2022). *A Fair and Solidarity-based EU Emissions Trading System for Buildings and Road Transport*. Ariadne Report, Kopernikus Projekte.

Heijmans, R. J. R. K. (2022). *Times Horizons and Emissions Trading*. Working Paper, Swedish University of Agricultural Sciences.

Hotelling, H. (1931). The Economics of Exhaustible Resources. *Journal of Political Economy*, **39**(2), 137–75.

Newell, R. G. & Stavins, R. N. (2003). Cost Heterogeneity and the Potential Cost Savings from Market-Based Policies. *Journal of Regulatory Economics*, **23**(1), 43–59.

Osorio, S., Pietzcker, R. & Tietjen, O. (2021a). Documentation of LIMES-EU – A Long-Term Electricity System Model for Europe (v2.37). `https://www.pik-potsdam.de/en/institute/departments/transformation-pathways/models/limes/model-documentation-v2.37`.

Osorio, S., Tietjen, O., Pahle, M., Pietzcker, R. & Edenhofer, O. (2021b). Reviewing the Market Stability Reserve in Light of More Ambitious EU ETS Emission Targets. *Energy Policy*, **158**, 112530.

Pahle, M., Sitarz, J., Osorio, S. & Görlach, B. (2022). *The EU-ETS Price Through 2030 and Beyond: A Closer Look at Drivers, Models and Assumptions*. Ariadne Report, Kopernikus Projekte.

Perino, G., Willner, M., Quemin, S. & Pahle, M. (2022). The European Union Emissions Trading System Market Stability Reserve: Does It Stabilize or Destabilize the Market? *Review of Environmental Economics & Policy*, **16**(2), 338–45.

de Perthuis, C. & Trotignon, R. (2014). Governance of CO_2 Markets: Lessons from the EU-ETS. *Energy Policy*, **75**, 100–6.

Pollitt, M. G. & Dolphin, G. (2021). Should the EU ETS be Extended to Road Transport and Heating Fuels? *Economics of Energy & Environmental Policy*, **11**(2), 125–44.

Quemin, S. (2022). Raising Climate Ambition in Emissions Trading Systems: The Case of the EU ETS and the 2021 Review. *Resource & Energy Economics*, **68**, 101300.

Quemin, S. & Pahle, M. (2023). Financials Threaten to Undermine the Functioning of Emissions Markets. *Nature Climate Change*, **13**, 22–31.

Quemin, S. & Trotignon, R. (2021). Emissions Trading with Rolling Horizons. *Journal of Economic Dynamics & Control*, **125**, 104099.

Rickels, W., Proelß, A., Geden, O., Burhenne, J. & Fridahl, M. (2021). Integrating Carbon Dioxide Removal Into European Emissions Trading. *Fontiers in Climate*, **3**, 690023.

Rickels, W., Rothenstein, R., Schenuit, F. & Fridahl, M. (2022). Procure, Bank, Release: Carbon Removal Certificate Reserves to Manage Carbon Prices on the Path to Net-Zero. *Energy Research & Social Science*, **94**, 102858.

Rose, A., Wei, D., Miller, N., Vandyck, T. & Flachsland, C. (2018). Policy Brief – Achieving Paris Climate Agreement Pledges: Alternative Designs for Linking Emissions Trading Systems. *Review of Environmental Economics & Policy*, **12**(1), 170–82.

Rubin, J. D. (1996). A Model of Intertemporal Emission Trading, Banking and Borrowing. *Journal of Environmental Economics & Management*, **31**(3), 269–86.

Saba, S. M., Müller, M., Robinius, M. & Stolten, D. (2018). The Investment Costs of Electrolysis – A Comparison of Cost Studies from the Past 30 Years. *International Journal of Hydrogen Energy*, **43**(3), 1209–23.

Schennach, S. M. (2000). The Economics of Pollution Permit Banking in the Context of Title IV of the 1990 Clean Air Act Amendments. *Journal of Environmental Economics & Management*, **40**(3), 189–210.

Schmalensee, R. & Stavins, R. N. (2013). The SO_2 Allowance Trading System: The Ironic History of a Grand Policy Experiment. *Journal of Economic Perspective*, **27**(1), 103–122.

Schmalensee, R. & Stavins, R. N. (2017). Lessons Learned from Three Decades of Experience with Cap and Trade. *Review of Environmental Economics & Policy*, **11**(1), 59–19.

Schmidt, O., Melchior, S., Hawkes, A. & Staffell, I. (2019). Projecting the Future Levelized Cost of Electricity Storage Technologies. *Joule*, **3**(1), 81–100.

Strefler, J., Kriegler, E., Bauer, N., Luderer, G., Pietzcker, R. C., Giannousakis, A. & Edenhofer, O. (2021). Alternative carbon price trajectories can avoid excessive carbon removal. *Nature Communications*, **12**(1), 2264.

Tietjen, O., Lessmann, K. & Pahle, M. (2021). Hedging and Temporal Permit Issuances in Cap-and-Trade Programs: The Market Stability Reserve under Risk Aversion. *Resource & Energy Economics*, **63**, 101214.

Verde, S. F. & Borghesi, S. (2022). The International Dimension of the EU Emissions Trading System: Bringing the Pieces Together. *Environmental & Resource Economics*, **83**(1), 23–46.

Whitesell, W. C. (2012). *Climate Policy Foundations: Science and Economics with Lessons from Monetary Regulation.* Cambridge, USA, Cambridge University Press.

Willner, M. & Perino, G. (2022). Beyond control: Policy incoherence of the eu emissions trading system. *Politics and Governance*, **10**(1), 256–264.

8 Appendix

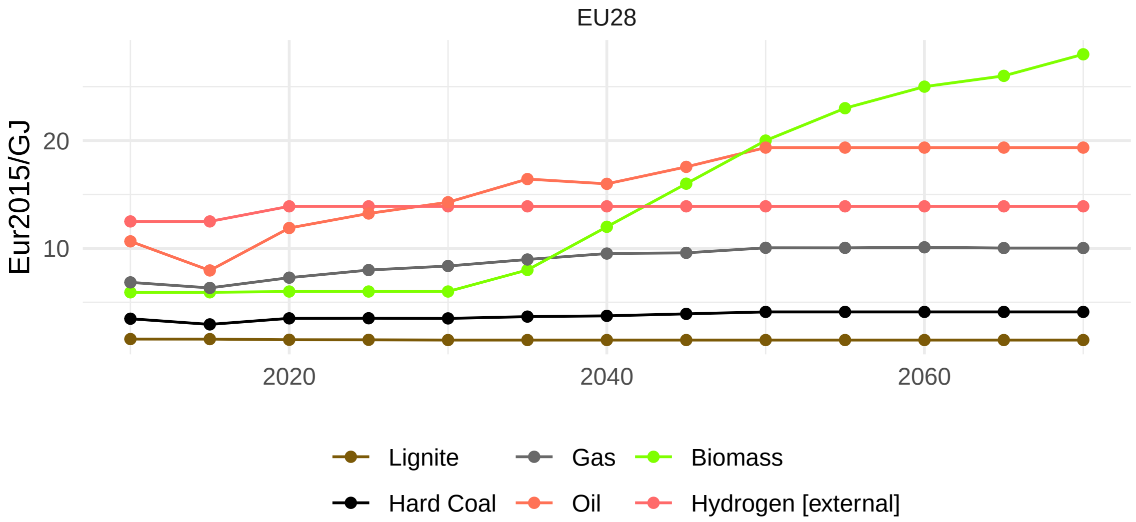

Figure 6: Fuel costs assumptions in LIMES-EU

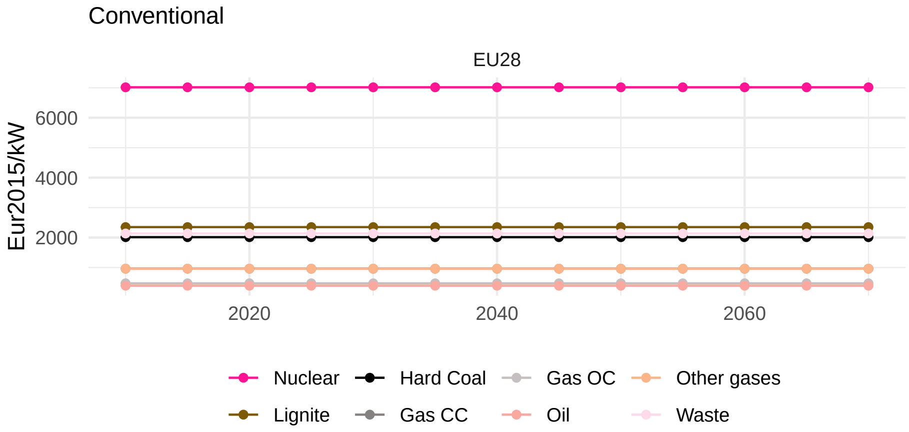

Figure 7: Capital costs assumptions for fossil-based technologies and nuclear power plants in LIMES-EU.

Source: European Commission (2021); own assumptions.

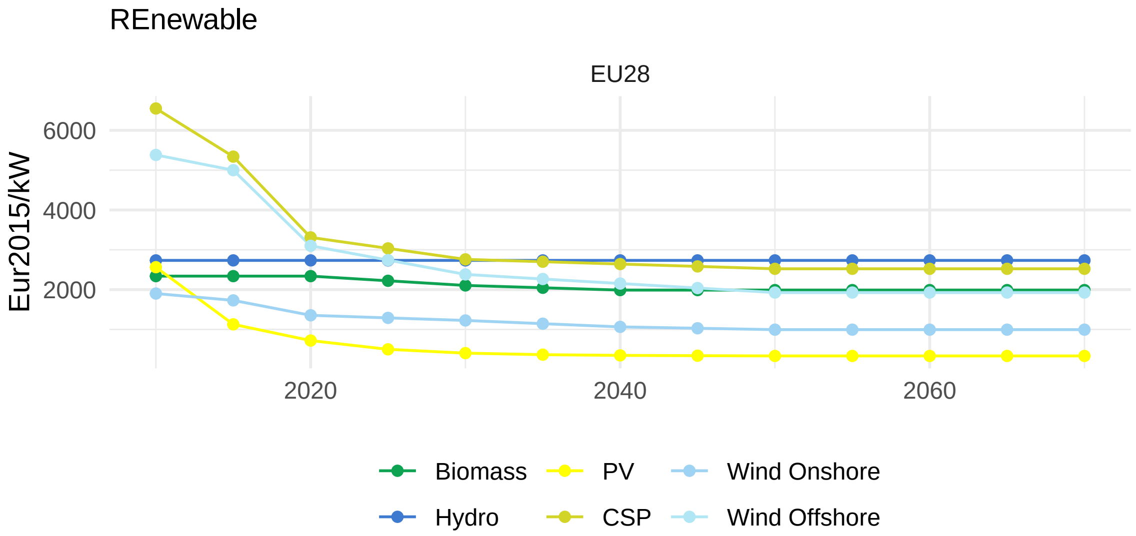

Figure 8: Capital costs assumptions for renewables in LIMES-EU.

Source: European Commission (2021).

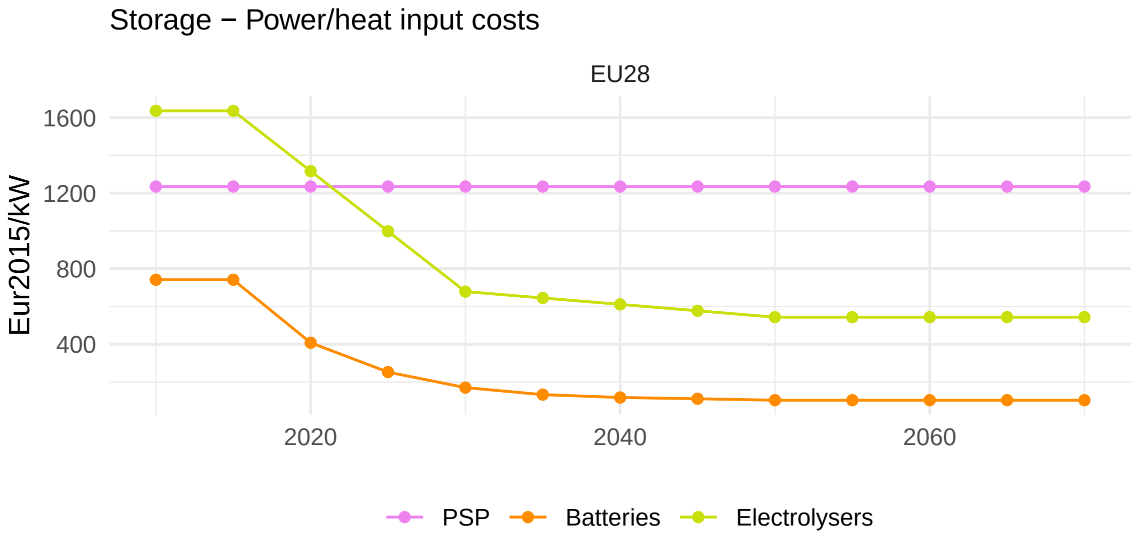

Figure 9: Capital costs assumptions for storage technologies in LIMES-EU.

Source: Saba et al. (2018); Schmidt et al. (2019); own assumptions.