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Reviewing the Market Stability Reserve in light of more ambitious EU ETS emission targets

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ABSTRACT

The stringency of the EU's Emission Trading System (ETS) is bound to be ratcheted-up to deliver on more ambitious goals as formulated in the EU's Green Deal. Tightening the cap needs to consider the interactions with the Market Stability Reserve (MSR), which will be reviewed in 2021. We analyse these issues using the model LIMES-EU. First, we examine how revising MSR parameters impacts allowance cancellations. We find that varying key design parameters leads to cancellations in the range of 2.6–7.9 Gt – compared to 5.1 Gt under current regulation. Overall, the bank thresholds, which define when there is intake to/outtake from the MSR, have the highest impact. Intake rates above 12% only have a limited effect, and cause oscillatory intake behaviour. Second, we analyse how more ambitious climate 2030 targets can be achieved by adjusting the linear reduction factor (LRF). We find that the LRF increases MSR cancellations substantially up to 10.0 Gt. This implies that increasing its value from currently 2.2% to only 2.6% could be consistent with an EU-wide target of −55% by 2030. However, MSR cancellations are subject to large uncertainty, which increases the complexity of the market and induces high price uncertainty.

1. Introduction

Being reformed only recently, the Emission Trading System (ETS) of the European Union (EU) is yet again bound for another major reform. In 2018, the EU strengthened the ETS cap in order to deliver on the 40% emission reduction target by 2030. However, this target will likely be ratcheted-up in the near future: the EU Commission aims for a reduction of 50% or 55% by 2030 to eventually reach emission neutrality in 2050 (European Commission, 2019). As the EU ETS covers more than 40% of total EU emissions, its stringency needs to be ramped up to reach this target. The regulatory entry point is the review of the Market Stability Reserve (MSR) planned for 2021. The MSR started operating in 2019 and is a mechanism that reduces the total number of allowances in circulation (TNAC[1]) and ultimately cancels allowances based on a complex mechanism, i.e., allowances are no longer valid and thus are not released into the market through auctions. As such it affects the overall cap and therefore should be considered when increasing the stringency of the EU ETS.

The purpose of this paper is twofold: (*i*) to analyse which MSR parameters have a significant effect on the cap size by affecting MSR cancellations; (*ii*) to show which linear reduction factor (LRF[2]) would achieve a given 2030 emission targets when considering the interaction with the MSR. This is of importance for the MSR review in 2021 and in particular for reforming the EU ETS towards higher stringency. We conduct our analysis in four steps.

First, we provide the policy background and briefly review the main results of the quickly growing literature on the MSR. We find that there is a broad range of MSR cancellation estimates from the literature (from 1.7 Gt to 13 Gt, making up 4%–32% of the total pre-MSR budget[3]), these

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[1] In literature one could also find the terms “allowances bank” or “surplus”, but we use TNAC as it is used in the official EU reports.

[2] The LRF sets the level of ambition of the EU ETS. It is the percentage of the average total quantity of allowances issued annually in 2008–2012 at which the cap decreases each year. In phase 3, the LRF being 1.74%, this amounts to a reduction of 38,264,246 allowances each year (European Commission, 2016).

[3] We calculate the total budget (ignoring MSR cancellations) from 2018 until the last allowances are issued (2057 if the LRF stays 2.2% after 2030) to be 40.1 Gt.

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Acronyms;

EU ETS	EU Emission Trading System
LRF	Linear Reduction Factor
MAC	Marginal abatement cost
MSR	Market Stability Reserve
TNAC	Total Number of Allowances in Circulation

results being driven mainly by the assumed discount rate and the marginal abatement cost (MAC) curves considered.

In a second step, we conduct our own analysis relying on the highly detailed electricity sector and industry model LIMES-EU with an endogenous representation of the MSR mechanism. In our reference scenario, we find moderate cancellations of about 5.1 Gt.

Third, we analyse the effect of a broad range of key MSR parameters which potentially are adjusted in the upcoming MSR review in 2021: intake and outtake rates of allowances into the MSR, TNAC thresholds that determine when in- and outtake begins, and auction shares for newly issued allowances. We show that cancellation is more sensitive to the upper than to the lower TNAC threshold. Moreover, increasing the intake rate has a rather limited effect on cancellations but it could induce an oscillatory behaviour on the TNAC due to a discontinuous MSR intake. Increasing the auction share as envisaged by policy makers reduces cancellations and thus also needs to be considered when calibrating the MSR.

Fourth, we analyse the effect of increasing the LRF in order to comply with the more ambitious 2030 targets that arise from the EU Green Deal. We find that a higher LRF not only directly decreases the cap, but also leads to significantly more MSR cancellations. Under our default assumptions, the LRF would therefore only need to be increased from currently 2.2%–2.4% and 2.6% to bring 2030 emissions in line with an overall 50% and 55% emission reduction target by 2030, respectively.

To the best of our knowledge the only other work in this direction is Quemin (2020). In the same vein as our analysis it assesses both potential changes in the MSR parameters in light of the 2021 review, and how to raise ambition through the LRF and the MSR. The main difference to our work is that Quemin (2020) assumes that firms have a rolling horizon rather than an infinite horizon as in our model, and conducts simulations based on stylized cost function rather than a detailed sectoral as ours. Notably because of the former he finds that combining the MSR and the LRF is more efficient than solely relying on the LRF, which stands in contrast to our recommendation that assess regulatory complexity more broadly.

In the next section we review the latest two ETS reforms and the scientific literature that analyses them. In Section 3 we describe the model, show the results of the reference scenario that uses current ETS parameters and examine alternative parameters. In Section 4 we discuss the results and conclude.

2. The EU ETS and its recent reforms

In this section we shortly present the policy background, review previous work that has analysed the effects of the MSR and provide an overview about cancellation estimates.

The EU ETS covers the power sector, energy intensive industry and aviation which made up more than 40% of GHG emissions in 2017 in the regulated regions – the EU, Iceland, Liechtenstein and Norway (EEA, 2019a, 2019b). Firms are allowed to bank EU allowances (EUA) between years without restriction.[4] This implies that allowances prices are linked over time and, according to theory, they should rise at the discount rate due to intertemporal arbitrage (Rubin, 1996). Yet, in practice prices remained very low (between 3 and 9 €/t) until the beginning of 2018. The low price is attributed to several reasons as for example the economic downturn (e.g. Ellerman et al., 2016; Fuss et al., 2018; van Renssen, 2018). At the same time the TNAC grew continuously between 2008 and 2013 up to 2.1 Gt, which was interpreted as "structural supply-demand imbalance" (European Parliament and Council of the European Union, 2015).

In order to tackle these imbalances, increase the resilience regarding future imbalances and to bring the ETS on track to reach the 2030 emission targets, the MSR was implemented in 2015 to start its operation in 2019 (European Parliament and Council of the European Union, 2015). Basically, the MSR reduces the supply of allowances if the TNAC reaches a certain upper threshold and transfers them into the MSR instead. Allowances are released from the MSR if the TNAC drops below a certain lower threshold. Since this initial version of the MSR was cap-neutral it was expected to have only a weak effect on the EUA price (Perino and Willner, 2016) and may even deter clean long-term investments (Perino and Willner, 2019). In addition, the MSR might also raise the price volatility (Kollenberg and Taschini, 2019; Mauer et al., 2019; Perino and Willner, 2016; Richstein et al., 2015), although Fell et al. (2016) find the opposite.[5]

Facing this criticism and since the price indeed did not increase significantly, the European Parliament and Council of the European Union (2018) agreed to reform the MSR even before it came into effect in 2019: first, if the amount of allowances in the MSR exceeds the amount of auctioned allowances, allowances are permanently cancelled from 2023 onwards and, second, the intake into the MSR is increased until 2023. In addition, it was agreed to raise the LRF from 1.74% to 2.2% for phase IV of the EU ETS (2021–2030) which significantly reduces the cap. The price surged and stabilized in the range of 20–30 €/t from 2019 to 2020, which suggests that the reform indeed created the expectations of a more stringent ETS. Since autumn 2020, EUA prices increased further to reach a price range of 50–60€/t in mid-2021. This increase can likely be explained by the tightening of the overall EU emission targets for 2030 from −40 to −55%, which implies a tighter EU-ETS targets and thus much higher EUA prices in 2030 and beyond (Pietzcker et al., 2021).

The 2018 MSR reform has evoked a wave of studies on the new MSR version and especially on the cancellation mechanism.[6] Table 1 provides an overview of cancellation estimates from the literature ordered from highest to lowest. A crucial reason for the large range from less than 2 to 13 Gt is the variety of assumed discount rates. Since allowance banking is a provision to reduce costs in the future, firms bank less if they discount at a higher rate. Put differently, 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. Table 1 indeed indicates that cancellations tend to go up if the discount rate is low.

However, the discount rate can only partly explain the cancellations. Another feature that might matter is the level of model detail. Unlike Bruninx et al. (2020) and our work, the papers in Table 1 use stylized MAC curves rather than a detailed electricity sector model. This affects the timing of the abatement path, which again affects the TNAC and thus the transfers into the MSR. Notably, in a detailed model mitigation costs change over time depending on technology and fuel costs.

The important role of MAC may also explain the highest estimate (13 Gt) as calculated by Bruninx et al. (2020). They assume strongly

[4] However, borrowing from future periods is not allowed.

[5] The difference might be explained by different underlying shock process, which, however, needs more research.

[6] In doing so, several papers also examine how MSR cancellations are affected by additional policies such as RES support (Beck and Kruse-Andersen, 2020; Burtraw et al., 2018; Carlén et al., 2019; Gerlagh et al., 2021; Pahle et al., 2019; Perino et al., 2019; Quemin and Trotignon, 2019; Silbye and Sørensen, 2018).

Table 1
Comparison of certificate cancellations in the literature.

Source	Cancellation (Gt)	Discount rate
Bruninx et al. (2020)	13	10%
Quemin and Trotignon (2019) [a]	10	3%
Quemin (2020) [a]	8.7	3%
Tietjen et al. (2021) [b]	7.6	3%
Beck and Kruse-Andersen (2020)	6	5%
Gerlagh et al. (2021)	5.5	5%
Silbye and Sørensen (2018)	5	7.4%
Quemin and Trotignon (2019) [a]	5	7%
Quemin (2020) [a]	4.2	7%
Carlén et al. (2019)	3.4	3.5%
Bocklet et al. (2019)	2	8%
Perino and Willner (2017) [c]	1.7	10%
Mauer et al. (2019) [d]	1.2	10%

Notes: these values correspond to the central, standard or reference scenario of the respective study. Some numbers are taken from figures and thus might not be perfectly accurate. We only include scientific papers with a model horizon longer than 2030 to increase the comparability.

[a] No single standard scenario. 10 and 5 Gt (Quemin and Trotignon, 2019) and 8.7 and 4.2 Gt (Quemin, 2020) refer to scenarios with rolling horizon and infinite horizon of market agents, respectively. Both scenarios include anticipation of MSR effects though.

[b] Tietjen et al. (2021) consider only the electricity sector. They assume that the not covered sectors (mainly energy-intensive industry) receive all permits they require for free as approximately happened in the past. The numbers correspond to the risk-neutral case.

[c] Perino and Willner (2017) assume that the cap decreases exponentially by 2.2% instead of using the 2.2% as a linear reduction factor (as determined by the EU) resulting in a total emission budget of 53.8 Gt, i.e. 33% higher than in our assumptions.

[d] Mauer et al. (2019) consider only the electricity sector. They multiply all MSR parameters by the electricity sector share.

increasing industry MAC, and in consequence firms bank a large amount of allowances in order to prevent having to pay high costs for deep emissions reductions later. In contrast, our implied total MAC curve, which results from the detailed power sector modelling in combination with our assumed MAC curve for the industry, is much flatter and therefore we find significantly fewer cancellations despite assuming a discount rate of 5%.

In the following section we elaborate on the model assumption, conduct our own cancellation estimation and assess to what extent it varies depending on the MSR configuration.

3. Model analysis

In this section we examine the ETS and, in particular, the MSR. We first describe the model and scenarios and then show the results of the reference scenario which includes the current regulation. Thereafter the impact of parameters that might be adjusted during the upcoming MSR review is analysed. Finally, we assess in section 3.4 the cancellations triggered by a tighter cap and under which LRF the 2030 emission targets of the EU can be reached.

3.1. Model and scenario description

We use the long-term model for the EU electricity sector (LIMES-EU). It simultaneously optimizes investment and dispatch decisions for generation, storage and transmission technologies, and abatement alternatives for the energy-intensive industry in a 5-year time step, from 2010 to 2070 and covers all EU ETS countries except Cyprus, Iceland, Liechtenstein and Malta, but includes Switzerland and the Balkan region. The model captures the variability of supply (namely wind and solar) and demand by modelling each year through 6 representative days, which are calculated through a clustering algorithm (Nahmmacher et al., 2016). For each day, eight blocks of 3 h are assumed. The model contains 32 generation and storage technologies, including different vintages for lignite, hard coal and gas. The energy-intensive industry is included through a MAC curve, which is derived from (Gerbert et al., 2018). We implement the EU ETS with intertemporal banking according to Rubin (1996). This implies that the ETS price grows at the interest rate (assumed to be 5%) as long as the TNAC is positive. More detail on data sources, parameters and the model equations is available in the LIMES-EU documentation (Osorio et al., 2020).

In the reference scenario, we set all ETS parameters to their current values and assume that they remain at these values after 2030 (current regulation only defines values until 2030). The LRF determines by how much the issued allowances are reduced each year. The LRF is 1.74% until 2020 and increases to 2.2% as of 2021 which implies that allowances would be supplied until 2057. See Appendix A for an elaborated description of the cap estimation. Due to a lack of real world guidance we assume in all scenarios that allowances cannot be banked after 2057 and thus we constrain emissions from the EU ETS sector to zero after 2057. We feel this assumption is appropriate when policy targets are analysed since the EU aims for emission neutrality in 2050. Hence it seems to be implausible that firms bank certificates for decades after 2050 when emission should be zero. We elaborate on the implications of this assumption in Appendix C. The initial TNAC (end of 2017) is 1.65 $GtCO_2$ (EEA, 2018) and we assume that the MSR has an extra intake in 2019 and 2020 of 1.55 Gt in total.[7] In the reference scenario the share of allowances to be auctioned is set to be 57% over the entire model horizon, while the remaining 47% are allocated for free.[8]

The MSR is modelled based on its operation rules: (*i*) allowances are withheld from auctioning and transferred to the MSR when the TNAC of the previous year, is higher than 833 Mt, the intake to the MSR equalling a share of the TNAC level (24% until 2023 and 12% afterwards); (*ii*) allowances are transferred back from the MSR to the market when the TNAC of the previous year is lower than 400 Mt; the outtake from the MSR (available through auctions) equals 100 Mt (unless the level of the MSR is lower); and (*iii*) when the size of the MSR stock is higher than the number of certificates auctioned in the previous year, the difference between both is cancelled from the MSR. Given the non-linearity of the MSR conditions, it is not possible technically to embed such equations directly in LIMES-EU. In addition, directly embedding the MSR into an optimization model as LIMES-EU would be inconsistent with the perfect competitiveness assumption in the model. Competitive firms do not consider the impact of their decisions on the MSR, which would be violated if the MSR is represented as a constraint in an optimization model. We thus couple LIMES-EU with a simulation of the MSR, pursuing an iterative approach described in detail in Appendix B. In this way, the effects of the MSR are exogenous to firms' decision problem.

Table 2 summarizes the parameter values used in the reference scenario (current values) and additionally shows the range used in our analysis. All the variations are implemented after 2023 because we consider this as a plausible first year for new parameters since the MSR review is in 2021.

In the next sections we present the results focussing on cumulative emissions and MSR cancellations. In our model cumulative emissions are always equal to the pre-MSR cap (resulting from the LRF) minus the MSR

[7] This corresponds to 900 Mt that were not auctioned between 2014 and 2016 (backloading) which go directly into the MSR (European Parliament and Council of the European Union, 2015). The remaining 650 $MtCO_2$ (350 $MtCO_2$ in 2017 and 300 $MtCO_2$ between 2018 and 2020) are the estimated unallocated certificates until 2020 (European Commission, 2015). We assume that 250 $MtCO_2$ are transferred in 2019 and 1300 $MtCO_2$ in 2020, as suggested by Burtraw et al. (2018).

[8] The targeted auction share from 2021 onwards is 57% (European Parliament and Council of the European Union, 2018). Notice that the auction share before 2021 is not relevant for our analysis as the difference between auctioning and free allocation only affects the functioning of the MSR.

Table 2
Overview of analysed ETS parameters.

Parameter	Current values (reference)	Analysed range (after 2023)
Linear Reduction Factor (LRF)	Until 2020: 1.74% After 2020: 2.2%	1.7–6.0% (step of 0.1%)
Thresholds[a]	Lower threshold: 400 Mt Upper threshold: 833 Mt	0-1500 $MtCO_2$ (step of 100 $MtCO_2$)
Intake rate	Until 2023: 24% After 2023: 12%	0–100% (step of 2%)
Outtake parameter	100 Mt per year	0-1000 $MtCO_2$ (step of 100 $MtCO_2$)
Auction share	57%	0–100% (step of 10%)

[a] We evaluate all possible combinations within that range (in step of 100 $MtCO_2$).

cancellations. Hence for a given LRF, cancellations determine cumulative emissions. However, from policy perspective annual targets are often of greater importance. We thus also present emissions and carbon prices for 2030 as this year is the current focal point of EU climate policy.

3.2. Reference scenario

Fig. 1 shows the main variables determining the long-term dynamics of the EU ETS, including the MSR. While (a) shows the TNAC and MSR levels as well as parameters and variables that influence them, (b) shows the MSR level and the flows that determine it. The TNAC changes as a result of the annual difference between emissions and supply of certificates as well as the TNAC level in the previous time step. The supply consists of freely allocated allowances (43% of the original pre-MSR cap) and auctioned allowances. The actual auctioned volume in turn depends on the TNAC level: fewer certificates are auctioned and instead are injected into MSR (intake) when the TNAC is higher than the upper threshold, while additional certificates from the MSR (outtake) are auctioned when the TNAC is below the lower threshold. The two thresholds are indicated by the dotted lines in part (a) of Fig. 1.

While the TNAC decreases until 2022, the MSR level quickly rises, achieving a maximum of 2853 $MtCO_2$ in 2022, mainly explained by the extra intake of the not issued allowances before the MSR has started (1550 Mt). There is ongoing intake to the MSR between 2019 and 2042 (except for 2023 and 2025). During the same period, the MSR still progressively decreases due to the higher cancellation of certificates, which takes place from 2023 to 2043 (except for 2024 and 2026) and later between 2047 and 2055.

Such a prolonged cancellation can be partly explained by the MSR rules itself. Since cancellation is determined by the difference between the MSR level and the auction volume of the previous year, cancellation reinforces itself: cancellation implies a lower total cap and thus higher allowance prices. Consequently, emissions are lower and the TNAC is higher which in turn increases the inflow into the MSR. If more allowances flow into the MSR, first, the MSR level is higher and, second, the auction volume is lower, while both imply more cancellations. In addition, the TNAC increase between 2023 and 2033 is caused by a faster decrease of emissions in this period (see Fig. 1). As a result, the TNAC remains above the upper threshold (833 $MtCO_2$), which in turn triggers the intake to the MSR and later the cancellation.

The TNAC remains between both thresholds from 2042 to 2053, i.e., there are no transfers from or to the MSR. When the bank falls below the lower threshold (400 $MtCO_2$) in 2054 and triggers the outtake from the MSR, the MSR level is already at a very low level (125 $MtCO_2$), which limits the reinjection of certificates into the market (outtake only takes place in 2055).[9] In total, from the 5243 $MtCO_2$ certificates withdrawn from the market (including the extra intake in the beginning), 5143 $MtCO_2$ are cancelled, i.e., 98%, with the majority of the cancellation occurring before 2030 (2787 $MtCO_2$, i.e., 54% of total cancellation). As a result, cumulative EU ETS emissions from 2018 until 2057 amount to 34.9 Gt.

We perform a sensitivity analysis on key assumptions in Appendix C. We show that the amount of cancellation is relatively robust towards changes in the abatement costs (fuel prices, electricity demand, technology costs). However, we confirm the strong effect of the discount rate found in the literature: at a level of 10%, only 1.4 Gt instead of 5.1 Gt are cancelled.

Additional robustness checks also show that the EU ETS time horizon, i.e., the time during which banking and inter-temporal trading is allowed, has a strong effect on cancellations. Allowing banking for the entire model horizon (2070) rather than only to 2055 would double cancellations (10.4 Gt) as energy-intensive industries would bank more certificates so as to avoid paying very large abatement costs (up to 650 EUR/tCO2). At the same time, a high discount rate (10%) “compensates” this effect in the sense that cancellations would not change compared to the scenario where banking is only allowed until 2057, i.e., total cancellations reach 1.4 Gt. This makes clear that the time horizons of both policy settings and firms matter considerably for the size of the effect.

3.3. Analysis of MSR parameters

In this section we show how the MSR parameters, namely the thresholds, intake rate, outtake rate and auctions share, affect cancellations. Recall that changes in these parameters are assumed to take place from 2023 onwards. Until then, we assume the parameters to be according to current regulation, i.e., upper and lower thresholds are 400 and 833 Mt, respectively; intake rate is 24%, outtake rate is 100 Mt and the auction share is 57%.

3.3.1. Thresholds

Fig. 2 shows the impact of the lower (currently 400 Mt) and upper (currently 833 Mt) thresholds on EUA cancellation. Cancellation is highest when the lower and upper thresholds are lowest and vice versa. For the evaluated thresholds, cancellation remains within the range of 3.1–7.9 Gt, meaning that between 8% and 20% of the total pre-MSR budget since 2018 is cancelled.

It can be observed that the cancellation is more sensitive to the upper threshold than to the lower threshold: total cancellations decrease on average 93 $MtCO_2$ for every 100 $MtCO_2$ increase of the lower threshold, while total cancellations decrease on average 226 $MtCO_2$ for every 100 $MtCO_2$ increase of the upper threshold. To understand why, recall that the upper threshold mainly affects the intake to the MSR and the lower threshold the outtake from the MSR. Since the inflow into the MSR occurs in the cancellation phase (see Fig. 1(b)), almost all allowances that go into the MSR are cancelled. The reason is that cancellation is the difference between the MSR level (higher due to more inflow) and auctioned certificates (lower due to more inflow) if it is positive. Hence additional inflow (due to a lower upper threshold) is more or less immediately cancelled.

The lower threshold, in contrast, plays only a role later on when the

[9] Importantly, there might be cancellations even when the TNAC is below the lower threshold. Recall that cancellations depend on MSR level and auction volume. In the BAU scenario, despite the TNAC triggering outtake from the MSR in 2055, the MSR level is higher than auctions from previous year, thus leading to cancellations in 2054 and 2055 (28 and 25 Mt, respectively).

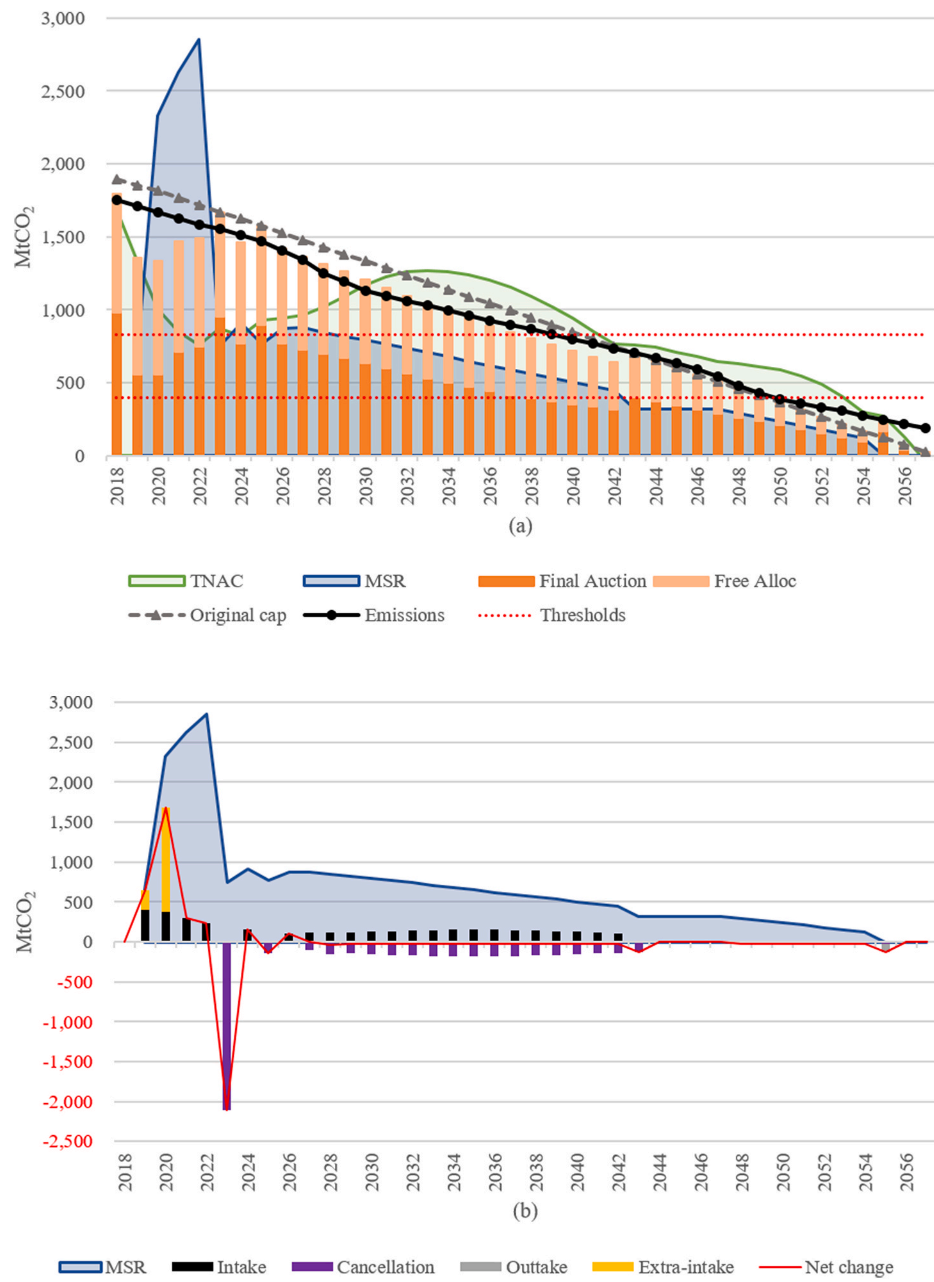

Fig. 1. EU ETS dynamics. (a) TNAC and MSR levels as well as parameters and variables that determine influence them; (b) MSR level and its flows.

TNAC is low enough (recall Fig. 1(a)). However, at this time many allowances have already been cancelled such that not many allowances actually can leave the MSR. Essentially, the MSR level cannot be higher than the auction volume because of the cancellation mechanism. Therefore there is only little room for the lower threshold to have an effect on cancellations.

In addition, price effects reinforce the effect of varying the thresholds. With more intake (lower upper threshold), there is more cancellation and hence a higher price. This in turn leads to a higher TNAC, and thus to more intake and eventually more cancellation. A reduced lower threshold has in principle a similar effect as it leads to lower prices and eventually to less cancellation and vice versa. Yet, again after cancellation takes place not many allowances are left such that outtake generally is relative low in our model.

3.3.2. *Intake and outtake rates*

Fig. 3 shows the impact of the intake rate on cancellations. Notice that even when the intake rate after 2023 is 0%, cancellation still equals 2.6 Gt because 2.7 Gt are transferred to the MSR before 2023 and outtake equals 0.1 Gt. While cancellation increases sharply for rates between 0 and 12% (from 2.6 to 5.1 Gt), it is hardly affected between 12% and 50% (5.1 ± 0.1 $GtCO_2$) and only slightly increases when the rates are higher than 50% and remains within the range of 5.0–5.9 Gt. The maximum cancellation (5.9 $GtCO_2$) occurs when the intake rate is 58%. Hence compared to current regulation (12% after 2023) that leads to a cancellation of 5.1 Gt (reference scenario) a higher intake rate only has a moderate effect on the overall cap.

Moreover, for rates higher than 12% the effect on cancellation is non-monotonic. On the one hand, a higher intake rate raises the transfers to the MSR in years with intake. On the other hand, the TNAC cut-backs are severer and thus a higher rate leads to fewer years in which certificates are transferred to the MSR because the upper threshold is less often reached. If the first effect dominates a higher rate leads to more cancellations and if the second effect is stronger cancellations go down.

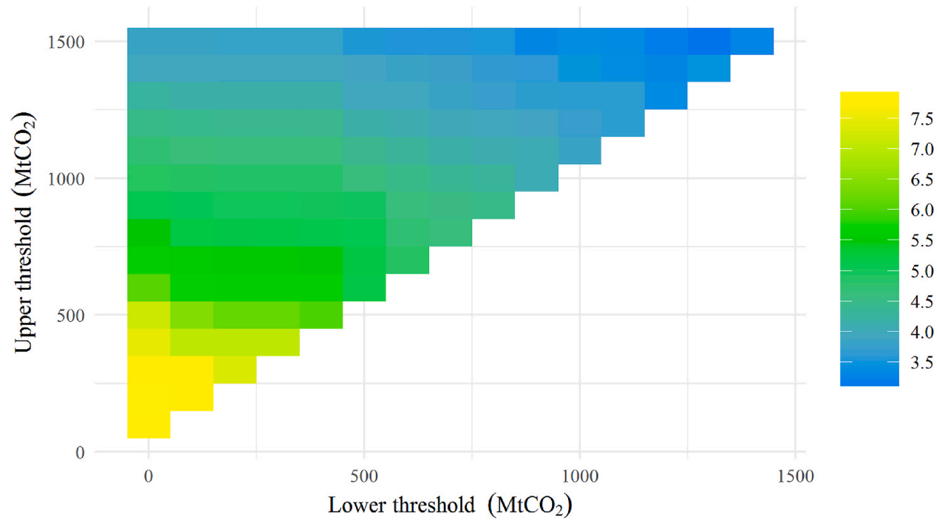

Fig. 2. Impact of MSR thresholds on total certificate cancellations (Gt).

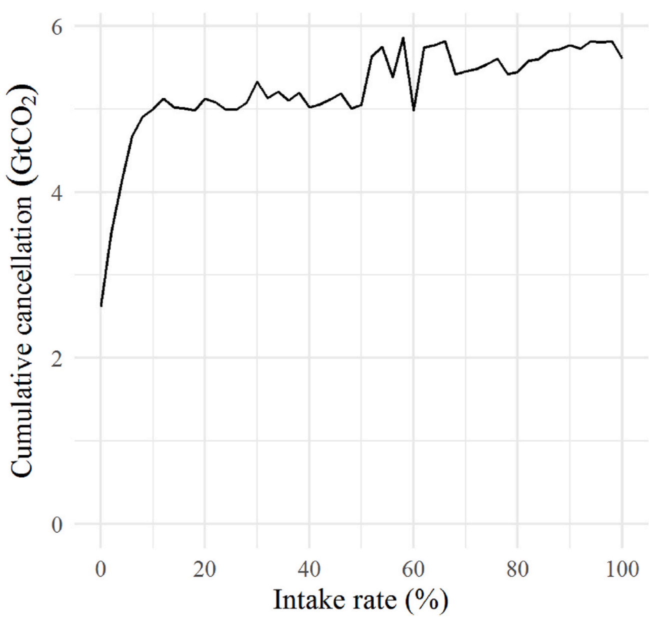

Fig. 3. Impact of MSR intake rate on total certificates cancellations.

Taking a closer look to the intake volumes and TNAC levels in Fig. 4 shows these effects. When the rates are 12%, 24% and 36% the maximum annual intakes are respectively 157, 231 and 340 Mt during the period 2024–2043. Within the same period there are respectively 1, 9 and 12 years in which transfers to the MSR do not occur. This is because the TNAC oscillates around the upper threshold (red dashed line at 833 $MtCO_2$) more frequently when the intake rate is high whereas it is constantly above the threshold when the rate is low (see Fig. 4).

This unveils a potential risk posed by high intake rates. While aggregate cancellation it not much affected (see above), moderately higher intake rates may induce some instability. Although we do not model this explicitly, it is plausible that under uncertainty a TNAC that is slightly below or above the upper threshold may cause some additional price jumps or higher price volatility because only a very little change in emissions and thus TNAC levels, may imply that the threshold is reached or not. If it is reached, significant fewer allowances are issued in the next year and potentially cancelled implying a higher price and vice versa. Moreover, even small firms relative to the market size could try to affect the market outcome because only a relative small amount of allowances is needed. For example, increasing emissions may reduce the TNAC such that the upper threshold is not reached, implying that more allowances are issued in the future.

That said, it is an open question if this behaviour will actually materialize, and – if so – it will be considered as problematic. For one, other market participants interested in lower prices (e.g. polluting firms) could ty to manipulate the price in the other direction, or try to counteract such manipulation in the first place. Accordingly, the net effect is not clear. Furthermore, even if a net effect would occur, it would most likely only impact price volatility in the short run. If this volatility is small compared to the market's baseline volatility, the differential effect would be rather negligible. The main risk is probably a reputational one: speculating against design features of an allowance market may in general be seen as a flaw of its design, raising concerns about the functionality of the MSR – or even the allowance market as such. In any case, our intention here is not to assess the related risk, but only to bring to the attention of policy makers that such a risk may exist.

The outtake parameter is an absolute value (currently 100 Mt) that determines the outflow from the MSR when the TNAC is below the lower threshold. However, as explained in the previous section, the cancellation mechanism leaves only a small amount in the MSR. Accordingly we find that the outtake parameter plays only a very limited role (not shown). When the outtake rate is 0 Mt, cancellation reaches 5.3 Gt, while outtake rates higher than 200 Mt lead to cancellations slightly lower than 5.1 Gt.

3.3.3. Auction share

Lastly, we analyse the effect of the auction share which is under current regulation targeted to be 57%. The auction volume is relevant for two reasons: first, cancellation is determined as the difference between the MSR level and the auction volume of the previous year when this difference is positive; second, the intake to the MSR is subtracted from the auction volume and thus the auction volume constrain the annual intake. Therefore, increasing the auction share allows for more intake to the MSR eventually increasing cancellations, but it also leads to less cancellations for a given MSR level. It is worth noting that the auction volume might be smaller than the calculated intake. In such cases of 'missing intake', we assume for sake of simplicity that just the available auction volume is transferred to the MSR[10]. In fact, this only occurs in rather extreme scenarios with an auction share below 10%.

[10] In principle the regulator could also run auctions with negative quantities, i.e. where governments buy allowances from the market.

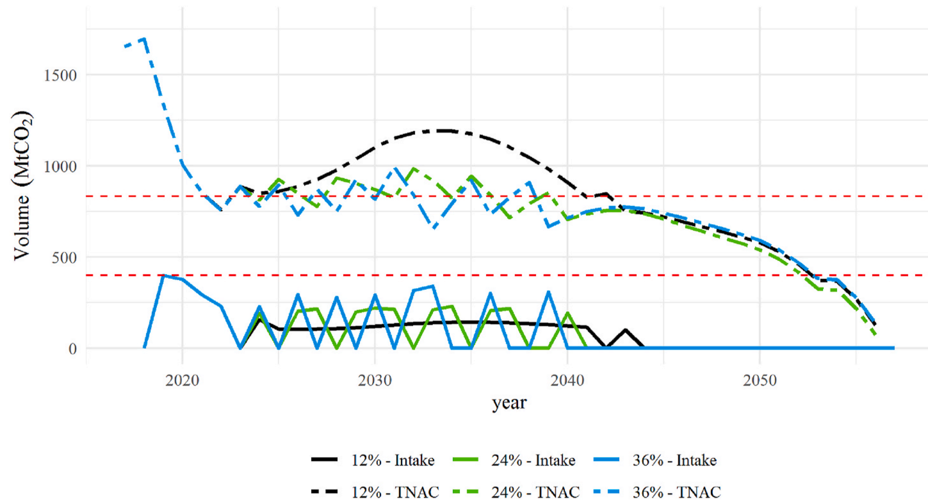

Fig. 4. Effect of the intake rates on yearly transfers to the MSR (intake volumes). The red dashed horizontal lines represent the MSR thresholds. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

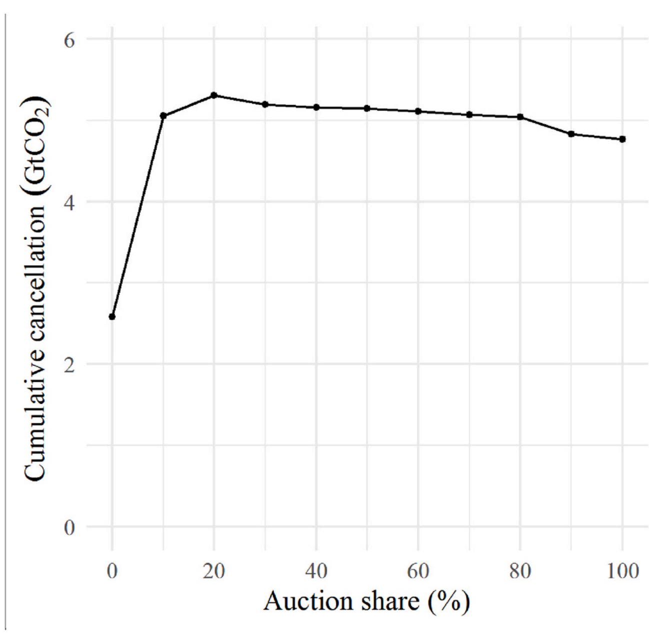

Fig. 5. Impact of auction shares on total certificates cancellations.

As shown in Fig. 5, the relationship between cancellation and auction share is non-monotonic. In the hypothetical case when the auction share is zero (i.e. all certificates are freely allocated instead), cancellation is limited to the total intake to the MSR of the 2018–2023 period. Increasing the auction share to 20% raises cancellations because it softens the constraint on the annual intake (see above) and therefore more allowances flow into the MSR. For auction shares above 20% the other effect dominates: the difference between the MSR level and the auction volume is lower in many years, implying fewer cancellations. Overall, cancellation is highest when the auction share is 20% (5.3 $GtCO_2$) and lowest when it is 0% (2.6 $GtCO_2$). Moderate deviations from the current auction share of 57%, however, only have small impact on cancellations.

3.4. Achieving more ambitious climate targets: The interaction of the MSR with increased LRFs

The EU Green Deal contains a tightening of the 2030 GHG emission targets to −50 or −55% vs. 1990 compared to current −40%. This will in turn require an update of the ETS cap, determined by the LRF. However, the effective cap not only depends on the LRF, but also on cancellations through the MSR. Accordingly, the interplay between LRFs and MSR needs to be considered, which we do in the next section. Based on this, we subsequently analyse how the LRF should be adjusted to reach the 2030 targets.

3.4.1. Interaction between LRF and MSR

The net budget of allowances depends on MSR cancellations in a non-trivial manner. This can be seen in Fig. 6, which depicts cumulative emissions and cancellations as a function of the LRF. The sum of both reflects the total gross (pre-MSR) budget of allowances. Looking at cancellations, they increase substantially when the LRF increases from 1.7% (2.6 $GtCO_2$) to 2.6% (9.8 $GtCO_2$). The reason is a reinforcement mechanism between the LRF and the cancellations, which can be disentangled into two effects. First, a higher LRF implies lower supply of certificates, and thus higher prices, with an equal percentage-wise increase in each time step. At the same time, the changes in the LRF have only a small effect on near-term caps, but a large effect on caps in 2040 and 2050 due to the basic linear rule for calculating the cap for any year. Thus, emissions in the first decade decline due to increased prices but annual caps are hardly reduced, which leads to an increase of TNAC, which in turn increases the inflow into the MSR and results in more

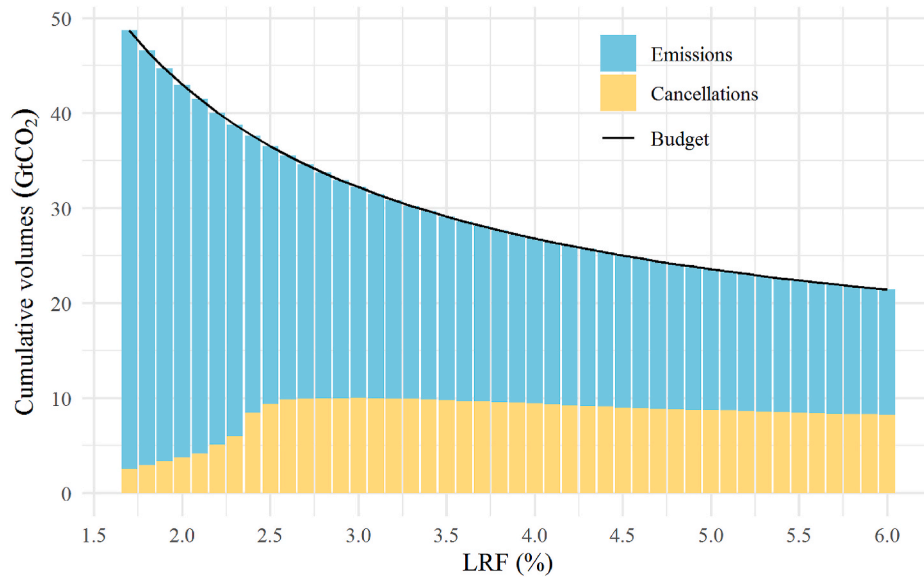

Fig. 6. Impact of the LRF on total certificate cancellations and emissions.

cancellations. Second, a higher LRF raises cancellations because they depend on the number of auctioned allowances: in each year allowances in the MSR above the auction volume of the previous year are cancelled.

Assuming the continuation of the MSR as currently implemented, the interaction effect is particularly sensitive to changes in the LRF in the range of 2%–2.6%. For example, increasing the LRF from 2.2 to 2.6% reduces the overall net allowances budget by 4.6 Gt due to the lower LRF itself and additionally by 4.7 Gt due to more cancellations, leading to overall 9.3 Gt lower cumulative emissions.

However, for LRFs larger than about 2.6% the reinforcing effect between the LRF and the MSR cancellation becomes significantly weaker and even reverses the sign: the highest cancellation is reached when the LRF is 3.0% (10.0 Gt), and afterwards cancellation decreases to 8.2 Gt when the LRF is 6.0%. The reason for this declining effect is that the transfers to the MSR are constrained by the certificates to be auctioned. Put differently, if the cap becomes smaller, auctions decline, and therefore the amount of certificates that could potentially be cancelled also decreases. Still, the share of cancellations from the total pre-MSR budget (the sum of cumulative emissions and cancellations) increases from 5% to 39%.

We also analyse a simultaneous modification of the LRF, TNAC thresholds and intake rate. We find that the intake rate has a larger impact and the TNAC thresholds a lower impact when the LRF is increased. However, the degree of interaction between the LRF and the MSR parameters is limited and the main qualitative insights do not change. We elaborate on these mechanisms in Appendix D.

3.4.2. Readjusting the LRF to achieve more ambitious climate targets

We contrast two types of approaches for setting the LRF in order to achieve more ambitious emission targets. In the “conservative approach”, policy makers simply calculate the LRF that would be needed to make the annual cap in 2030 equal to the 2030 target as derived from the Green Deal targets. This approach ignores the effects of banking and MSR cancellations on resulting 2030 emissions: if firms use allowances in 2030 banked from previous years, the actual emissions could exceed the target. Vice versa, if firms bank allowances in 2030 in expectation of higher decarbonization challenges after 2030, emission would be lower than the 2030 cap. Moreover, the MSR endogenously adjusts the issued allowances and cancels an unknown number. Since cancellations are ignored we consider this as a conservative approach as emissions very likely will not exceed the target. In the “sophisticated approach”, the expected effects of banking and MSR cancellations are considered when evaluating whether a given LRF is sufficient to reach the envisaged 2030 targets. In other words, (estimated) emissions in 2030 are compared to the target for 2030 emissions. This approach minimizes the LRF required to achieve a given emission target, while at the same time increasing the risk that the 2030 target will be missed if cancellations or banking turn out smaller than expected.

For each LRF, we calculate the resulting emissions using our model (keeping the current MSR parameters). Fig. 7 shows emissions in 2030 as a function of the LRF, for which we evaluate values ranging from 1.7% to 6.0%. The figure also includes the different 2030 targets: the current −40% target, and the potential new −50% and −55% targets which translate to −43% (1352 $MtCO_2$), −56% (1044 $MtCO_2$) and −63% (878 $MtCO_2$) for the EU ETS, respectively, if the current split of efforts between ETS and Effort Sharing Regulation is kept constant.[11]

First note that the current 43% target is reached even with a LRF of 1.7% (minimum evaluated), i.e., it is clearly achieved with the current cap. With a LRF of 1.7% emissions reach 1300 Mt in 2030, below the current 2030 target of 43% reduction, i.e., 1352 Mt. This implies that the current LRF (2.2%), which is indeed set to reach a level in 2030 equivalent to the target (i.e., conservative approach) allows reaching further emission reductions. Emissions reach 1112 Mt in 2030, i.e., 53% reduction with respect to 2005 level, much lower than the current target.

What happens when tightening the 2030 targets? Under the “conservative approach”, policymakers would choose a cap equivalent to the desired reduction, implying LRFs of 4.1% and 5.2% for −50% and −55%, respectively. Due to banking and the MSR cancellations, the emissions in 2030 resulting from such LRFs would be substantially lower than the targets, as Fig. 7 shows. The effective emission reduction in

[11] The current target establishes an EU-wide reduction of 40% with respect to 1990 emission level. Accordingly, the EU sets a target of 43% reduction for the EU ETS (i.e., 1018 $MtCO_2$) and of 30% reduction for the Effort Sharing Regulation (ESR) (i.e., 857 $MtCO_2$) with respect to 2005 emissions (2368 and 2855 $MtCO_2$, respectively). This implies that the ETS is expected to contribute 54% of emissions reduction by 2030. If the EU-wide target increases to 55% (i.e., 15% more), then 859 $MtCO_2$ additional reductions are required in 2030. Assuming the same contribution as for the current policy, we estimate that emissions in the EU ETS would need to reduce additionally by 467 $MtCO_2$, i.e., 1485 $MtCO_2$ in total. Such volume implies a 63% reduction compared to the 2005 value. Likewise, an EU-wide reduction of 50% would imply a reduction of 1249 $MtCO_2$ in the EU ETS in 2030, i.e., 56% reduction with respect to 2005.

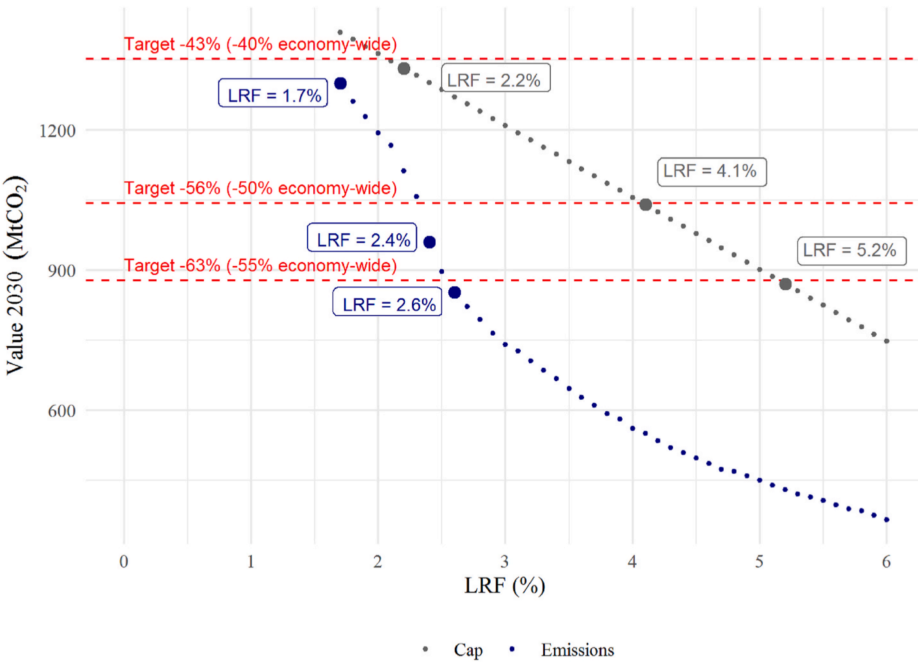

Fig. 7. Impact of the LRF on emissions in 2030. The required LRF to reach 2030 targets (red dashed lines) under the 'conservative' (grey labels) and 'sophisticated' (blue labels) approaches are shown. Under the 'conservative' approach, the LRF is calculated so that the cap reaches a level equivalent to the target in 2030. Under the 'sophisticated' approach, MSR cancellations and banking are accounted for, so actual emissions in 2030 differ from the cap, and thus the cap can be much larger than the desired emission target in 2030. The bigger dots highlight the scenarios that minimise the required LRF to reach the target under both the 'conservative' and 'sophisticated' approaches. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Emissions and prices implied by 2030 targets.

Approach	EU-wide target 2030	ETS target 2030	Target 2030 emissions	Implied LRF	2030 cap	2030 emissions	CO2 Price in 2030
			$MtCO_2$/yr		$MtCO_2$/yr	$MtCO_2$/yr	€/tCO_2
Conservative	−40%	−43%	1353	2.2%	**1353**	1112	27
	−50%	−56%	1044	4.1%	**1044**	550	67
	−55%	−63%	878	5.2%	**878**	429	76
Sophisticated	−40%	−43%	1353	1.7%[a]	1410	**1300**	16
	−50%	−56%	1044	2.4%	1302	**960**	37
	−55%	−63%	878	2.6%	1271	**853**	43

Note: Numbers in bold and underlined highlight the values that are brought as close to the target emissions as possible under a given approach by varying the LRF. For the "conservative" approach, the LRF can be directly calculated; in the "sophisticated" approach, the implied LRF correspond to that of the scenarios in which the resulting emissions in 2030 are closest (and below) the corresponding target, thus the resulting emissions do not exactly match the target emissions.
[a] The lowest LRF examined is 1.7%, for which −43% target is largely achieved. Hence, the implied LRF for achieving such target could be lower.

2030 would be 77% and 82%, respectively, with respect to 2005.

For the "*sophisticated*" approach, required LRF increases are much lower. The −56% target (1044 Mt) is reached by increasing the current LRF from 2.2% to 2.4%. The −63% target (878 Mt) is reached by increasing the LRF to 2.6%. Hence, due to the positive effect on cancellations, only a relative modest increase of the LRF is necessary to reach significantly more ambitious targets.

Table 3 summarizes the emission targets in 2030, the LRFs derived from the two approaches, as well as the resulting emissions and CO_2 prices. Note that the required EUA price in 2030 to reach the 63% target (accounting for MSR cancellations) more than doubles compared to the price required to achieve the current target, but still remains far below the 2030 economy-wide CO_2 price levels of 61–169 €/tCO_2 that were found by Knopf et al. (2013) in a multi-model comparison study as being in line with a 40% reduction vs. 1990 of economy-wide EU emissions in 2030. In contrast, the 2030 EUA price connected to the "conservative" implementation of the −63% target would be in the lower half of this range.

4. Conclusion and policy implications

In this paper we analyse key EU ETS parameters with a view on the upcoming MSR review and a potentially broader reform of the EU ETS to reach more ambitious emission targets. We find that under the current regulation the reduction of the cap through cancellations of allowances amounts to 5.1 Gt.

Analysing the MSR parameters we find that especially the upper threshold of the TNAC has a significant impact on cancellations and thus on the cap: when the threshold is decreased from the current 833 Mt to 100 Mt, about 2.8 Gt more certificates are cancelled because a lower threshold implies more inflow to the MSR. Since a high share of the allowances in the MSR is always cancelled, more inflow ultimately implies more total cancellations. This also implies that the lower threshold, which determines the outflow from the MSR, is of lower relevance: since a high share of allowances that go into the MSR is cancelled anyway, only a low share can actually leave the MSR regardless the lower threshold level.

Furthermore, we find that cancellation would strongly decrease (from 5.1 Gt to 2.6 Gt) if the intake rate were decreased from 12% to 0%. However, intake rates above 12% only have a small additional effect but may lead to discontinuous cancellation and intake because the TNAC fluctuates around the upper threshold relevant for intake. This may have undesirable side effects because small deviations in the TNAC decide whether the threshold is reached or not, potentially implying higher price volatility and a larger impact of firms applying market power. A dedicated analysis of uncertainty and market power in the context of the MSR is left to future research, and should in particular consider myopic firms, for which this effect would be more pronounced.

We further show that the MSR has another so far under acknowledged side effect, as the share of auctioned certificates has an impact on the cap. In total we find that increasing the auction share raises cancellations up to an auction share of 20% and reduces cancellations in the range of 20%–100% (currently targeted to be 57%). However, in the practically most relevant range above 20% the effects are relative weak (less than 0.5 Gt difference in cancellations).

We further show that cancellations may vary significantly when the LRF is increased. Beyond the direct cap decreasing effect, a higher LRF also indirectly affects the cap through MSR cancellations. Up to a LRF of about 2.6% (currently 2.2%) we find a strong positive feedback between the LRF and cancellations. However, this effect declines with higher LRF and becomes negative from a LRF of about 3% onwards, though the negative effect is weak. We additionally find that – keeping all other parameters fixed – a LRF higher than 2.4% and 2.6% could be in line with the potential new 2030 EU emission targets of 50% and 55%, respectively, if banking and cancellations turn out as our model suggests.

However, the actual number of cancelled allowances can vary considerably depending on key design parameters set by policy makers, but also on market actors' time horizons and discount rates, as well as their expectations about the future costs of abatement. For instance, increasing the discount rate from 5% to 7% leads only to 2.1 Gt cancellations and decreasing it to 3% leads to 10.0 Gt compared to 5.1 Gt in our reference scenario, and the banking horizon proves to be a critical assumption for cancellations under low discount rates (+5 Gt). Put more succinctly, the (unpredictable) *expectations* of market actors about future CO_2 prices and costs will – via the MSR – influence the size of the cap. Investors expecting higher future abatement costs will bank certificates, thereby increasing cancellations and thus increasing abatement costs. This feedback effect to expectations makes it hardly possible to tune the ETS and MSR parameters to reach a certain emission target.

In light of this observation, and given that the aim of the MSR was to stabilize the ETS, make it more resilient against shocks and increase planning certainty, a more profound reform of the MSR seems to be recommendable. A promising way forward would be to trigger in- and outtake from the MSR by prices rather than emissions, developing it into what could be called a "Price Stability Reserve". Such a reserve would turn the ETS into a classical hybrid instrument, which is typically considered to be more efficient (e.g. Roberts and Spence, 1976; Weitzman, 1978). In particular it would consolidate expectations about future CO_2 prices and thus increase planning security for development of and investments into decarbonization technologies.

CRediT authorship contribution statement

Sebastian Osorio: Conceptualization, Methodology, Software, Writing – original draft, Visualization. **Oliver Tietjen:** Conceptualization, Methodology, Writing – original draft. **Michael Pahle:** Conceptualization, Writing – original draft, Funding acquisition. **Robert C. Pietzcker:** Conceptualization, Writing – original draft. **Ottmar Edenhofer:** Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

A. Construction of annual caps

The cap (before the impact of the MSR) for the stationary sector (i.e. all but aviation) has decreased since 2013 (beginning of Phase III) at a rate of 1.74% (of the average cap during phase II, i.e. 38.3 $MtCO_2$ per year). The resulting cap in 2020 is 1816 $MtCO_2$ and is set to decrease at a rate of 2.2% (i.e. 48.4 $MtCO_2$ per year) until 2030. We assume the cap keeps decreasing afterwards at the same rate.

Since we do not model the heating-related and aviation emissions explicitly in LIMES-EU, we assume exogenous emissions as follows:

Heating: The combustion sector emissions added up to 1163 $MtCO_2$ (66% of stationary sector emissions) in 2017, accounting mainly for power plants. To differentiate electricity- and heat-related emissions, we estimate them using the primary energy consumed from power plants (Eurostat, 2019) and the emission factors from the IPCC's guidelines (Gomez et al., 2006). We allocate the emissions from cogeneration heat and power (CHP) plants according to the power plants output. We estimate that heating-related emissions added up to 11% of the total stationary sector emissions in 2017. We thus assume exogenous emissions accounting for 11% of the cap for the entire modelling period.

Aviation: this sector has its own cap (about 37 $MtCO_2$ per year have been allocated since 2013), but is allowed to buy certificates from the stationary sector. Emissions have increased from 53 $MtCO_2$ in 2013 to 64 $MtCO_2$ in 2017, the sector having always a negative balance of EU allowances for aviation (EUAA), i.e. airlines have had to buy allowances from the stationary sector to cover their emissions. The EU forecasts aviation emissions (under the current scope of the EU ETS, i.e. only covering intra- European Economic Area (EEA) flights) to be between 65 and 70 $MtCO_2$ in 2030 (EEA, 2018). However, it is not clear whether the scope will remain, as the current derogation from the EU ETS obligations for flights to and from third countries is extended until 31 December 2023, subject to review. There is also significant uncertainty about the future demand and technical improvements as well as on feasibility of implementing alternative fuels on a large scale (ICAO, 2016). We assume that emissions from aviation remain at 60 $MtCO_2$ per year and the cap – starting in 37 $MtCO_2$ per year in 2020 – decreases at the same pace as the stationary cap. The difference between emissions and the aviation cap are thus subtracted from the stationary cap.

B. Coupling the MSR simulation with LIMES-EU

Since LIMES-EU is a linear model, including the MSR rules as part of the optimization problem would not be possible. Converting the model into a non-linear one risk the non-convergence of the runs given the size of the model. In addition, the MSR rules are stated on an annual basis, while LIMES-EU runs in a 5-year basis. To reconcile these issues, we couple LIMES-EU with a simulation of the MSR through an iterative process, which we summarize in the flow diagram presented in Fig. B1.

We estimate the cap on an annual basis (p_cap_{t2}), based on the assumed LRF. We 'translate' this cap into a 5-year value (v_cap_t), averaging the corresponding 5 year values to each year in LIMES-EU.[12] For instance, the cap in LIMES-EU in 2020 equals the average of the annual cap between 2018 and 2022. In a first iteration, the certificates supply (v_supEUA_t) equals the cap (v_cap_t).

From the LIMES-EU results, we use the total emissions for the EU ETS (v_emi_t) and the bank at the end of 2015 (v_TNAC_{2015}) as input for the MSR. These 5-year-based inputs nonetheless have to be 'translated' into annual values for the MSR simulation. This is necessary because of the MSR operation criteria, e.g., use TNAC from year *t2-1* to estimate the intake into the MSR in *t2*, works on an annual basis. Recall that each year in LIMES-EU corresponds to the 5 years around it. To smoothen the input, we interpolate the emission volumes between LIMES-EU years and then normalize them to ensure that the 5-years average equals the LIMES-EU value. Unlike emissions, which are a flow, the TNAC in 2015 from LIMES-EU (v_TNAC_{2015}) is a stock. This corresponds to the initial TNAC used in the MSR simulation, p_TNAC_{2017} (TNAC at the end of 2017). From the annual cap, we estimate the preliminary auctions ($p\_prelaucEUA_{t2}$, see Eqn B.1) and certificates to be freely allocated ($p\_freeEUA_{t2}$, see Eqn B.2).

Other parameters such as the thresholds ($p\_lower\_threshold_{t2}$ and $p\_upper\_threshold_{t2}$), the intake rate ($p\_rateintakeMSR_{t2}$), the outtake rate ($p\_rateoutakeMSR_{t2}$) and the additional intake ($p\_extraintake_{t2}$) are required to simulate the MSR. Once the MSR is simulated, we are able to estimate the intake (Eqn B.3), outtake (Eqn B.4), cancellation (Eqn B.5), MSR level (Eqn B.6), certificates to be auctioned (Eqn B.7) and TNAC (Eqn B.8) on an annual basis as of 2019.

$$p\_prelaucEUA_{t2} = p\_cap_{t2} \times (1 - p\_sharefreeEUA_{t2}) \tag{B.1}$$

$$p\_freeEUA_{t2} = p\_cap_{t2} \times p\_sharefreeEUA_{t2} \tag{B.2}$$

$$\text{If } p\_TNAC_{t2-1} > p\_upper\_threshold_{t2},\ p\_intake_{t2} = min\left(2/3\, p\_TNAC_{t2-2} \times p\_rateintakeMSR_{t2-2} + 1/3\, p\_TNAC_{t2-1} \times p\_rateintakeMSR_{t2-1}, p\_prelaucEUA_{t2}\right) \text{, in other case } p\_intake_{t2} = 0 \tag{B.3}$$

$$\text{If } p\_TNAC_{t2-1} < p\_lower\_threshold_{t2},\ p\_outtake_{t2} = min(p\_MSR_{t2-1}, p\_rateouttakeMSR_{t2}) \text{, in other case } p\_outtake_{t2} = 0 \tag{B.4}$$

$$p\_cancellation_{t2} = 0\ \forall t2 \leq 2023\ p\_cancellation_{t2} = max(p\_MSR_{t2-1} - p\_prelaucEUA_{t2-1}, 0)\ \forall t2 > 2024 \forall t2 \leq 2023 \tag{B.5}$$

$$p\_MSR_{t2} = p\_MSR_{t2-1} + p\_extraintake_{t2} + p\_intake_{t2} - p\_outtake_{t2} - p\_cancellation_{t2} \tag{B.6}$$

$$p\_aucEUA_{t2} = p\_prelaucEUA_{t2} - p\_intake_{t2} + p\_outtake_{t2} \tag{B.7}$$

$$p\_TNAC_{t2} = p\_TNAC_{t2-1} + p\_aucEUA_{t2} + p\_freeEUA_{t2} - p\_emi_{t2} \tag{B.8}$$

The intake to the MSR (Eq. (B.3)) is modelled in detail, i.e., the exact time in which allowances are removed from the auctions is considered. The European Commission informs each May about the TNAC by the end of the previous year and about the volume of certificates to be transferred to the MSR. A volume calculated on the basis of the TNAC of a year *t-1* is removed from the auctions between September in year *t* and August of year *t+1*. Since the MSR only starts absorbing certificates in January 2019, 16% of the TNAC in 2017, informed in May 2018 (1.65 $GtCO_2$), i.e., 264 $MtCO_2$, will be transfer to the MSR between January and August2019.[13] Likewise, the TNAC at the end of 2018, informed in May 2019 (1.65 $GtCO_2$), determined the amount of certificates being removed from auctions between September 2019 and August 20, 20[14] and transferred to the MSR. Accordingly, it can be assumed that the intake for each year *t* amounts to two thirds of the volume calculated on the basis of the TNAC by the end of *t-2* and one third of the volume calculated on the basis of the TNAC by the end of the year *t-1*, such volume depending on the intake rate.

[12] To distinguish the variables computed in LIMES from those computed in the MSR simulation, we name as v_* for the former and p_* for the latter. In addition, the index t is only used for input from or variables used in LIMES-EU ($t = 2015, 2020 \ldots 2055$), while *t2* is only used for those related to the MSR simulation ($t2 = 2017, 2018 \ldots 2057$).

[13] Communication from the Commission C(2018) 2801 final, available at https://ec.europa.eu/clima/sites/clima/files/ets/reform/docs/c_2018_2801_en.pdf.

[14] Communication from the Commission C(2019) 3288 final, available at https://ec.europa.eu/clima/sites/clima/files/ets/reform/docs/c_2019_3288_en.pdf.

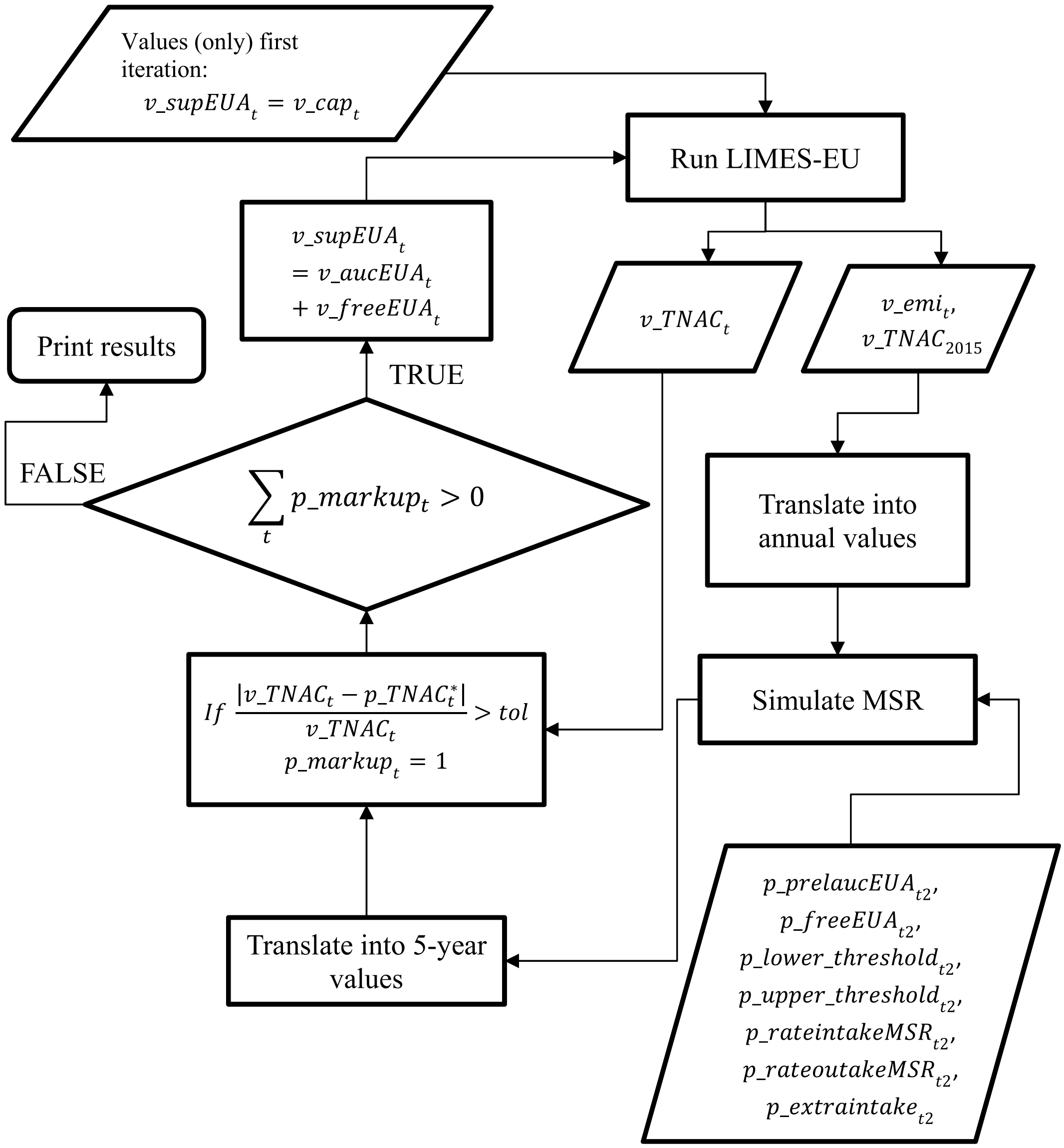

Fig. B1. Iterative process to couple LIMES-EU with the MSR simulation.

This output is 'translated' into 5-year data. For flow-type variables we compute the average for the 5-corresponding years. For instance, the average EUA auctioned (p_aucEUA_{t2}) between 2018 and 2022 is used for the 2020 vol in LIMES-EU (v_aucEUA_{2020}). For stock-type variables, p_TNAC_{t2} and p_MSR_{t2}, we use the value from the last corresponding year. For instance, their level in 2022 would correspond to 2020 in LIMES-EU years. We compute the error between the 'translated' TNAC from the MSR simulation ($p\_TNAC_t^*$) and that from LIMES (v_TNAC_t). If the error is higher than the tolerance margin ($tol = 0.05$) for any t, LIMES-EU is run again with an updated supply of certificates (v_supEUA_t). This equals the sum between the 'translated' free allocated EUA ($v\_freeEUA_t$), which does not change across iterations, and the 'translated' final auctioned EUA (v_aucEUA_t), estimated through the MSR simulation. This process is followed until the TNAC from both LIMES-EU and the MSR simulation converge.

C. *Sensitivity analysis*

We perform a sensitivity analysis to our main assumptions. First we show the impact of fuel prices (±50% by 2050), capital costs of variable renewable energy sources (vRES) as photovoltaics and wind mills (±30% by 2050), electricity demand (+50% by 2050) and the industry abatement costs (between −50% and +100%).[15] Second, we provide more details on the impact of the interest rate on cancellations. Finally, we evaluate the impact of a longer banking horizon which we restrict to 2057 in the main scenarios.

Table C1 shows cancellations for variations in the first set of parameters. Cancellations lie within a range of 4.3–7.3 Gt, i.e., 17% lower and 42% higher than in the reference scenario, only low gas price and low industry abatement costs having a significant effect on cancelations. Considering the large variations assumed, this highlights the robustness of our results.

[15] For all these parameters, except the industry MACC, we assume that they grow linearly between 2020 and 2050 up to the value specified, e.g., electricity demand is 34% higher than in BAU by 2040.

When it comes to fossil fuel prices, cancellation (4.3–6.4 $GtCO_2$) is more sensitive to changes in gas prices (independently of coal prices) because investments in gas plans depend heavily on their marginal costs. When gas prices are low, gas-fired generation displaces that from hard coal, increasing the TNAC and thus cancellation. On the contrary, high gas prices are high result in lower ETS prices, from which industry profits to abate less. With overall higher emissions, the TNAC is lower and thus cancellation too.

A higher electricity demand triggers a higher amount of cancellations (5.9 $GtCO_2$). EUA price increases as a result of the higher electricity demand. As a consequence, industry emissions decrease. However, the rise in electricity emissions, due to larger demand requirements, do not offset such drop. There is thus an overall decrease in emissions, that leads to higher TNAC, and thus to higher cancellations. A similar effect is observed when vRES investment costs vary: more expensive vRES increase the ETS price, which leads to less emissions and thus a larger TNAC in the near-term and overall more cancellations (and vice versa). Hence the MSR tends to amplify the effect of higher abatement costs.

However, in case of the energy-intensive industry this effect is non-monotonic, despite carbon prices showing a monotonic behaviour, i.e., they are higher when industry MAC are higher. When the industry MAC are 50% cheaper, cancellations are also higher (7.3 $GtCO_2$) than in the reference scenario. Similarly, higher industry MAC lead to more cancellations (e.g., 6.1 $GtCO_2$ when +100%). In the former case, industry abate more but the electricity sector profits from lower carbon prices and emit more. In the latter, higher carbon prices encourage more abatement in the electricity sector, but industry emits more. The overall effect is less emissions, and thus more cancellations.

Table C1
Sensitivity analysis. Impact of fuel prices, vRES capital costs, electricity demand and the industry abatement costs on cancellations.

Scenario		Cancellation ($GtCO_2$)
Reference scenario		5.1
Fossil fuel prices	Low	5.9
	High	4.5
	High gas/low coal	4.3
	Low gas/high coal	6.4
	Low gas	6.0
	High gas	4.6
	Low coal	5.0
	High coal	5.1
High electricity demand		5.9
vRES capital costs	Cheap	4.3
	Expensive	5.8
Energy intensive MAC	−50%	7.3
	−25%	5.1
	25%	5.0
	50%	5.3
	100%	6.1

The second part of the sensitivity examines the effect of the discount rate. As explained in Section 2, the discount rate is one of the driving parameters for the wide range of cancellation estimations in the literature. Fig. C1 shows that the discount rate also has a huge impact on our results as cancellations lie within a range of 1.4 and 15.1 Gt, i.e., 73% lower and 196% higher than in reference scenario, respectively. Note that the effect of the interest rate is very strong when the discount rate is lower than 7%. Higher discount rates almost have no effect on cancellations because in the short-term the TNAC can hardly fall below a certain level as emissions are almost fixed until the first cancellation happens in 2023 (if only the discount rate is varied).

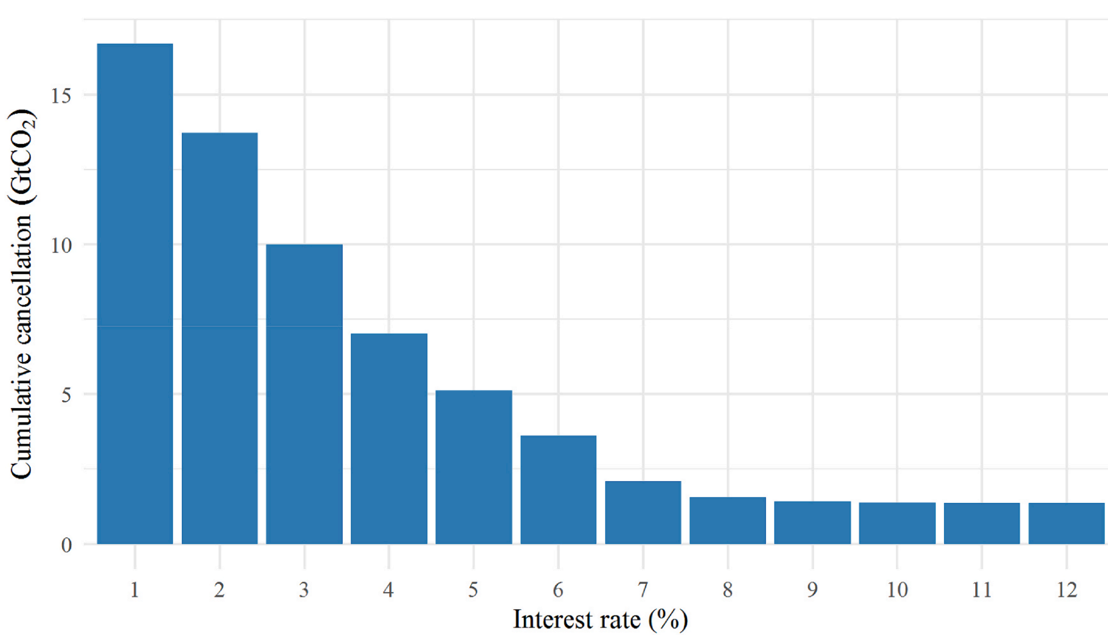

Fig. C1. Impact of interest rate on cancellations.

Another relevant assumption in the model concerns the time horizon for the MSR operation. We assume in all scenarios that certificates cannot be banked after 2057 and thus we constrain emissions from the EU ETS sector to zero after 2057. Table C2 shows cancellations when banking is allowed until 2057 and during the entire model time horizon (2070, i.e., forever). If banking is allowed forever, total cancellations amount to 10.4 Gt. Notice that allowing banking further into the future has significant effects on MSR cancellations in this model framework because firms bank to avoid high MAC in the future. When banking is possible until 2057 there is less banking (and thus fewer cancellations) because MAC after 2057 cannot be reduced through banking. However, when the discount rate is 10%, the banking horizon has no effect on cancellations (1.4 Gt). These results point out that the differences between our estimated cancellations and those from Bruninx et al. (2020) (13 Gt) stem from the assumptions regarding abatement costs and the banking horizon.

Table C2
Impact of discount rate and banking horizon on cancellations (Gt).

	Discount rate (%)	
Banking horizon	5	10
Until 2057	5.1	1.4
Forever	10.4	1.4

D. *Evaluation of simultaneous changes of MSR parameters and LRF*

We analyse a wide range of combinations of the MSR parameters and the LRF. Among the MSR parameters, we choose the TNAC thresholds and the intake rate, as they are of greatest relevance. Figure D.1 shows a grid of 'heat maps', where colour key indicates the total cancellations. Each row of plots refer to a certain LRF and each column of plots refers to a certain intake rate. We evaluate intake rates from 12% to 100% and consider the 'critical' LRFs: a LRF of 2.2% is currently set, the LRF of 3% yields the highest cancellations (keeping the current MSR parameters, see Section 3.4.1) and the LRF of 2.4%, 2.6%, 4.1% and 5.2% were used in Section 3.4.2 to evaluate the achievement of more ambitious 2030 targets under the 'conservative' and the 'expected emissions' approaches. Due to the amount of required runs, we only evaluate lower thresholds between 0 and 1000 Mt, and upper thresholds between 200 and 1400 Mt, with a step of 200 Mt.

From Fig. D1, we observe that small increases in the LRF still have major impact on cancellations. Indeed, highest cancellations (17.5 Gt) occur when LRF equals 2.6%, intake rate 100% and lower and upper thresholds are respectively 0 and 200 Mt.

The figure also highlights that the intake rate gains in relevance when the LRF increases. Cancellations barely varies across different intake rates when the LRF is 2.2% (first row of plots), because the higher intake rate just makes the TNAC oscillates around the upper threshold implying that intake volumes increase but also decrease in certain years (see section 3.3.2). However, when the LRF is 5.2% intake rate yields significantly more cancellations when the intake rate is 100% (11.0 Gt) than when this is 12% (8.7 Gt). The larger LRF implies that the TNAC increases significantly, i.e., there is large short-term abatement in order to withhold certificates for the long-term. Correspondingly, the TNAC exceeds the upper threshold more often, and thus transfers into the MSR increase and cancellations accordingly as well.

Finally, Figure D.1 also shows that the effect of thresholds on cancellations weakens when LRF increases. As mentioned above, a very stringent cap (high LRF) leads to very high TNAC already in the short-term. The TNAC is indeed higher than the upper thresholds evaluated (up to 1400 Mt) during the period in which certificates can be transferred to the MSR, i.e., before the cap reaches 0 Mt (e.g., year 2038 when the LRF is 5.2%). As a result, cancellation does not vary across all combinations of thresholds when the LRF is 4.1% or 5.2%.

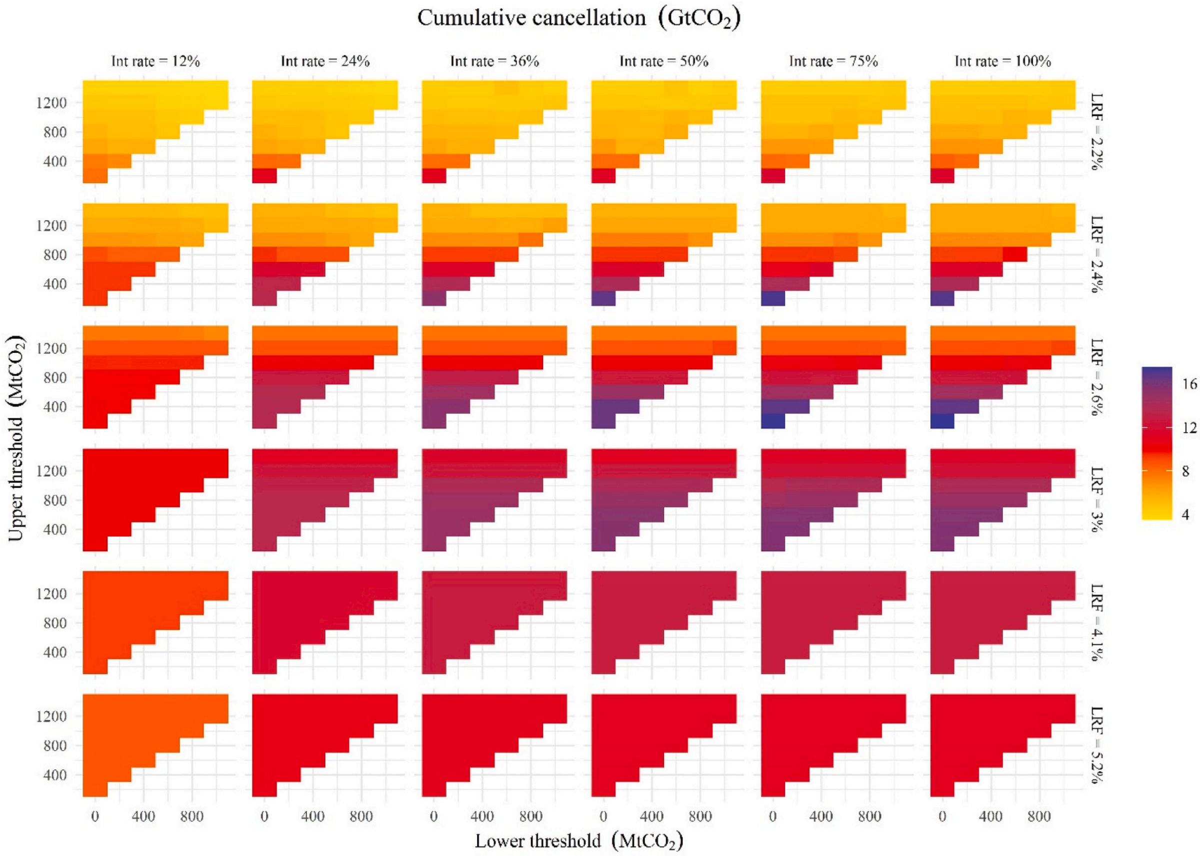

Fig. D1. Impact of simultaneous modifications of thresholds, intake rate and LRF on certificates cancellation.

References

Beck, U., Kruse-Andersen, P.K., 2020. Endogenizing the cap in a cap-and-trade system: assessing the agreement on EU ETS phase 4. Environ. Resour. Econ. 77, 781–811. https://doi.org/10.1007/s10640-020-00518-w.

Bocklet, J., Hintermayer, M., Schmidt, L., Wildgrube, T., 2019. The reformed EU ETS - intertemporal emission trading with restricted banking. Energy Econ. 84, 104486. https://doi.org/10.1016/j.eneco.2019.104486.

Bruninx, K., Ovaere, M., Delarue, E., 2020. The long-term impact of the market stability reserve on the EU emission trading system. Energy Econ. 89, 104746. https://doi.org/10.1016/j.eneco.2020.104746.

Burtraw, D., Keyes, A., Zetterberg, L., 2018. Companion policies under capped systems and implications for efficiency—the north American experience and lessons in the EU context (RFF report). Resources for the Future.

Carlén, B., Dahlqvist, A., Mandell, S., Marklund, P., 2019. EU ETS emissions under the cancellation mechanism - effects of national measures. Energy Pol. 129, 816–825. https://doi.org/10.1016/j.enpol.2019.02.060.

EEA, 2019a. EEA Greenhouse Gas - Data Viewer. Eur. Environ. Agency. https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer. accessed 1.13.20.

EEA, 2019b. EU Emissions Trading System (ETS) Data Viewer. Eur. Environ. Agency. https://www.eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1. accessed 1.13.20.

EEA, 2018. Trends and Projections in the EU ETS in 2018. The EU Emissions Trading System in Numbers (No. 14/2018). European Environment Agency, Copenhagen.

Ellerman, A.D., Marcantonini, C., Zaklan, A., 2016. The European union emissions trading system: ten years and counting. Rev. Environ. Econ. Pol. 10, 89–107. https://doi.org/10.1093/reep/rev014.

European Commission, 2019. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT. THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS The European Green Deal COM/2019/640 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588580774040&uri=CELEX:52019DC0640. accessed 5.14.20.

European Commission, 2016. Emissions Cap and Allowances. Clim. Action - Eur. Comm. https://ec.europa.eu/clima/policies/ets/cap_en. accessed 5.29.18.

European Commission, 2015. COMMISSION STAFF WORKING DOCUMENT IMPACT ASSESSMENT Accompanying the Document Proposal for a Directive of the European Parliament and of the Council Amending Directive 2003/87/EC to Enhance Cost-Effective Emission Reductions and Low-Carbon Investments SWD/2015/0135 Final - 2015/0148 (COD) (Commission Staff Working Document Impact Assessment No. SWD(2015) 135 Final). Brussels.

European Parliament, Council of the European Union, 2018. Directive (EU) 2018/410 of the European Parliament and of the Council of 14 March 2018 Amending Directive 2003/87/EC to Enhance Cost-Effective Emission Reductions and Low-Carbon Investments, and Decision (EU) 2015/1814. off. J. Eur. Union 76, pp. 3–27.

European Parliament, Council of the European Union, 2015. Decision (EU) 2015/1814 of the European Parliament and of the Council of 6 October 2015 Concerning the Establishment and Operation of a Market Stability Reserve for the Union Greenhouse Gas Emission Trading Scheme and Amending Directive 2003/87/EC. off. J. Eur. Union 264, pp. 1–5.

Eurostat, 2019. Energy Balance Sheets - 2017 Data, 2019 edition. Luxembourg.

Fell, H., 2016. Comparing policies to confront permit over-allocation. J. Environ. Econ. Manag., The economics of the European Union Emission Trading System (EU ETS) market stability reserve 80, 53–68. https://doi.org/10.1016/j.jeem.2016.01.001.

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. Rev. Environ. Econ. Pol. 12, 220–241. https://doi.org/10.1093/reep/rey010.

Gerbert, P., Herhold, P., Burchardt, J., Schönberger, S., Rechenmacher, F., Kirchner, A., Kemmler, A., Wünsch, M., 2018. Klimapfade für Deutschland (Study commissioned by the the Federation of German Industries (Bundesverband der Deutschen Industrie – BDI) to the Boston Consulting Group (BCG) and Prognos).

Gerlagh, R., Heijmans, R.J.R.K., Rosendahl, K.E., 2021. An endogenous emissions cap produces a green paradox. Econ. Pol. https://doi.org/10.1093/epolic/eiab011.

Gomez, D., Watterson, J.D., Americano, B.B., Ha, C., Marland, G., Matsika, E., Namayanga, L., Osman-Elasha, B., Kalenga Saka, J.D., Treanton, K., Quadrelli, R., 2006. 2006 IPCC guidelines for national greenhouse gas inventories. Energy 2. Chapter 2: Stationary combustion. IPCC.

ICAO, 2016. On Board. A Sustainable Future. 2016 Environmental Report. International Civil Aviation Authority (ICAO).

Knopf, B., Chen, Y.-H.H., De Cian, E., Förster, H., Kanudia, A., Karkatsouli, I., Keppo, I., Koljonen, T., Schumacher, K., Van Vuuren, D.P., 2013. Beyond 2020 — strategies and costs for transforming the european energy system. Clim. Change Econ 1340001. https://doi.org/10.1142/S2010007813400010, 04.

Kollenberg, S., Taschini, L., 2019. Dynamic supply adjustment and banking under uncertainty in an emission trading scheme: the market stability reserve. Eur. Econ. Rev. 118, 213–226. https://doi.org/10.1016/j.euroecorev.2019.05.013.

Mauer, E.-M., Okullo, S.J., Pahle, M., 2019. Evaluating the Performance of the EU ETS MSR.

Nahmmacher, P., Schmid, E., Hirth, L., Knopf, B., 2016. Carpe diem: a novel approach to select representative days for long-term power system modeling. Energy 112, 430–442. https://doi.org/10.1016/j.energy.2016.06.081.

Osorio, S., Pietzcker, R.C., Tietjen, O., 2020. Documentation of LIMES-EU - A Long-Term Electricity System Model for Europe (v2.36). Model Doc. V236. https://www.pik-potsdam.de/research/transformation-pathways/models/limes/limes-documentation-may-2020.

Pahle, M., Edenhofer, O., Pietzcker, R., Tietjen, O., Osorio, S., Flachsland, C., 2019. Die unterschätzten Risiken des Kohleausstiegs. Energiewirtschaftliche Tagesfr. 69, 1–4.

Perino, G., Ritz, R.A., van Benthem, A., 2019. Overlapping Climate Policies (Working Paper No. 25643), Working Paper Series. National Bureau of Economic Research. https://doi.org/10.3386/w25643.

Perino, G., Willner, M., 2019. Rushing the impatient: allowance reserves and the time profile of low-carbon investments. Environ. Resour. Econ. 74, 845–863. https://doi.org/10.1007/s10640-019-00350-x.

Perino, G., Willner, M., 2017. EU-ETS Phase IV: allowance prices, design choices and the market stability reserve. Clim. Policy 17, 936–946. https://doi.org/10.1080/14693062.2017.1360173.

Perino, G., Willner, M., 2016. Procrastinating reform: the impact of the market stability reserve on the EU ETS. J. Environ. Econ. Manag., The economics of the European Union Emission Trading System (EU ETS) market stability reserve 80, 37–52. https://doi.org/10.1016/j.jeem.2016.09.006.

Pietzcker, R.C., Osorio, S., Rodrigues, R., 2021. Tightening EU ETS targets in line with the European Green Deal: impacts on the decarbonization of the EU power sector. Appl. Energy 293, 116914. https://doi.org/10.1016/j.apenergy.2021.116914.

Quemin, S., 2020. Using Supply-Side Policies to Raise Ambition: the Case of the 2021 EU ETS Review.

Quemin, S., Trotignon, R., 2019. Emissions Trading with Rolling Horizons (Working Paper No. 316). Grantham Research Institute on Climate Change and the Environment, and Centre for Climate Change Economics and Policy. https://www.cccep.ac.uk/wp-content/uploads/2019/08/working-paper-316-Quemin-Trotignon-Aug-2019.pdf.

Richstein, J.C., Chappin, É.J.L., de Vries, L.J., 2015. The market (in-)stability reserve for EU carbon emission trading: why it might fail and how to improve it. Util. Pol. 35, 1–18. https://doi.org/10.1016/j.jup.2015.05.002.

Roberts, M.J., Spence, M., 1976. Effluent charges and licenses under uncertainty. J. Publ. Econ. 5, 193–208. https://doi.org/10.1016/0047-2727(76)90014-1.

Rubin, J.D., 1996. A model of intertemporal emission trading, banking, and borrowing. J. Environ. Econ. Manag. 31, 269–286. https://doi.org/10.1006/jeem.1996.0044.

Silbye, F., Sørensen, P.B., 2018. Towards a More Efficient European Carbon Market.

Tietjen, O., Lessmann, K., Pahle, M., 2021. Hedging and temporal permit issuances in cap-and-trade programs: the Market Stability Reserve under risk aversion. Resour. Energy Econ. 63, 101214. https://doi.org/10.1016/j.reseneeco.2020.101214.

van Renssen, S., 2018. The inconvenient truth of failed climate policies. Nat. Clim. Change 8, 355. https://doi.org/10.1038/s41558-018-0155-4.

Weitzman, M., 1978. Optimal rewards for economic regulation. Am. Econ. Rev. 68, 683–691. September.