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EU ETS and the new green paradox

Abstract

With the new rules of the EU ETS, involving cancellation of allowances, cumulative emissions are no longer fixed but depending on the market outcome. Perino (2018) showed that additional abatement effort can reduce cumulative emissions if it occurs within a few years. This article shows that Perino's result will be reversed, i.e., cumulative emissions increase, if the abatement effort is at a later year, or permanent. Thus, a new green paradox has emerged.

JEL-Codes: H230, Q540, Q580.

Keywords: emissions trading, green paradox, EU ETS, MSR.

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Introduction

Emissions trading has become the most important climate policy instrument around the world (Wettestad and Gulbrandsen, 2018), with the EU Emission Trading System (EU ETS) as the most prominent. Emissions trading ensures, at least in theory, that an emission target is reached in a cost-effective way. On the other hand, the price of emission allowances (EUAs) is determined in the market, and may become higher or lower than desired by policy makers.

The EUA price has been below 10 Euro per ton of CO_2 since 2012 – that is, until 2018. The price has been considered too low by many politicians in the EU, and also far below CO_2 prices consistent with the 2 degrees target (IPCC, 2014; Ricke et al., 2018). The main reason is the financial crisis in 2008, followed by economic recession in the EU (Ellerman et al., 2016). In addition, supplementary policies such as renewables support have been implemented, which tends to depress the CO_2 price (Böhringer and Rosendahl, 2010). A huge surplus of emission allowances have thus accumulated. From 2017 to 2018, 2.6 billion allowances were banked or "back-loaded", amounting to about 140% of annual ETS emissions (EU, 2018).[1]

The EU has introduced various measures attempting to tighten the ETS and increase the EUA price. Most notably, a Market Stability Reserve (MSR) was established in 2015 (EU, 2018; Fell, 2016; Perino and Wilner, 2016). When the total number of banked allowances is sufficiently large, parts of next year's allowances are put into the reserve instead of being auctioned. When banking becomes sufficiently low, allowances in the MSR will be released into the market. Thus, initially the MSR was expected to reduce the *short-term* supply of allowances, but not the long-run supply. In April 2018, a new, crucial rule was adopted, stating that when the MSR exceeds a certain threshold, allowances exceeding the threshold become permanently canceled. Hence, the *long-term* supply of allowances is also decreased.

As pointed out by Perino (2018), this new MSR rule temporarily punctures the waterbed effect of the ETS. The waterbed effect denotes the phenomenon that if some emissions are abated, e.g., due to some supplementary policy such as renewable support or phase-out of coal (Bertram et al., 2015), total emissions will not change because the emission cap is fixed. Instead, other emissions regulated by the ETS increase, and the leakage rate is 100%. In the market, this will happen via a reduction in the price of emissions (see e.g. Böhringer and Rosendahl, 2010).

Perino calculates that one ton of additional abatement within the EU ETS in 2018 will lead to a net long-term emission reduction of 0.4-0.8 tons (see also Burtraw et al., 2018). Hence, the leakage rate drops to 20-60%. The outcome depends on how long the MSR continues taking in allowances (again depending on the future banking of allowances). The intuition is that lower current emissions imply more banking and therefore increased input of allowances into the MSR, and subsequently increased cancellation of allowances. Perino's calculations do not take into account, however, that a change in emissions in say 2018 will alter the allowance market and hence the banking of allowances into the future. Moreover, he does not consider the effects of *future* abatement, except emphasizing that the puncture of the waterbed is temporary.

The main finding in this article is that Perino's result is reversed if an additional abatement is instead expected sufficiently long into the future. Thus, announcing today that a supplementary policy or

[1] 1 654 million allowances were banked in the market, so-called TNAC (Total number of allowances in circulation) (EU, 2018). Further, 900 million allowances were "back-loaded" in 2014-16, which means that auctioning of these allowances was postponed (implicitly banked by the regulator). Initially, the "back-loaded" allowances were supposed to be auctioned in 2019-20 instead, but later it was decided that they should enter into the MSR (see next paragraph). For more details on the MSR, including the new rules described below, see: https://ec.europa.eu/clima/policies/ets/reform_en

measure will be imposed later on can have detrimental effects by *increasing* cumulative emissions, meaning a leakage rate above 100% and possibly much higher. The intuition is that if market participants today anticipate a less tight future market (compared to their previous views), banking becomes less profitable. Less banking implies fewer allowances enter into the MSR, and hence fewer allowances are canceled. I also find that a current but permanent abatement effort increases cumulative emissions.

The effect described here shares some similarities with the green paradox discussed extensively in the economics literature, where anticipated climate policies in the future can give fossil fuel suppliers incentives to accelerate their extraction of reserves (see e.g. Gerlagh 2011; Sinn 2008). Hence, current emissions may increase ("weak paradox"), and net present value of climate damages may potentially increase ("strong paradox"). However, cumulative emissions will typically *not* increase. This is different from the result shown in the current article, where a (supplementary) future climate policy can lead to higher cumulative emissions.

In the next section, a stylized, dynamic model of an ETS incorporating the features of the MSR is specified. In the subsequent section, the model is parameterized based on the EU ETS and the rules of the MSR. Then I show the simulated impacts of an additional abatement in one or more future years. A number of sensitivity analysis are performed, before I close the article with some discussion and conclusions.

Stylized model of the EU ETS

Consider a dynamic emission trading system with n periods. Supply of allowances in each period is initially fixed and given by S_t. Demand for allowances is denoted D_t, and depends on the allowance price P_t. Demand in period t should here be interpreted as emissions in period t. Banking is allowed, and B_t denotes the number of allowances banked at the end of period t (in the EU ETS, banking is referred to as "total number of allowances in circulation").

The regulator then introduces a market stability reserve (MSR), where M_t refers to the size of this reserve at the start of period t. It has the following characteristics: If banking B_{t-1} exceeds a certain threshold λ, the supply of allowances in the following period t is reduced, and the withdrawn allowances instead enter into the MSR as M_t^{IN}. That is, we have:

(1) $$M_t^{IN} = \alpha_t B_{t-1} \quad \text{(if } B_{t-1} > \lambda \text{)}$$

where α_t is a parameter between 0 and 1. Further, if banking drops below a certain threshold η ($\eta < \lambda$), up to γ units of allowances are taken out of the MSR and fed into the ETS (by increasing the supply of allowances in the following period). That is, we have for M_t^{OUT} :

(2) $$M_t^{OUT} = \text{Min}\left(M_{t-1}; \gamma\right) \quad \text{(if } B_{t-1} < \eta \text{)}$$

Moreover, if the size of M_t exceeds a certain share β of S_t (the supply of allowances), all these excess allowances are permanently canceled (in the EU ETS, this takes place from 2024 onwards):

(3) $$C_t = M_t - \beta S_t \quad \text{(if } M_t > \beta S_t \text{)}$$

Thus, we have the following equation of motion for M_t:

(4) $$M_t = M_{t-1} + M_t^{IN} - M_t^{OUT} - C_{t-1}$$

The market balance in the allowance market is then given by:

(5) $$S_t - M_t^{IN} + M_t^{OUT} = D_t\left(P_t\right) + B_t - B_{t-1}$$

Last but not least, I disregard uncertainty, and assume that banking takes place up to the point where there is no more arbitrage possibilities at the market interest rate r:[2]

(6) $$P_t = \delta P_{t+1}$$

where $\delta = 1/\left(1+r\right)$ is the discount factor.

Model parametrization

Next, I parameterize the model in the context of the EU ETS (including aviation emissions), applying the rules of the MSR. I consider a constant elasticity of demand function:

(7) $$D_t(P_t) = \Gamma_t \left(P_t\right)^{\sigma}$$

where σ is the price elasticity and Γ_t is a time variant constant.

The parameter specifications are shown in Table 1. Here I give a brief explanation of how the model is parameterized. For more details and discussion of the calibration and corresponding assumptions, see Appendix A.

Several of the parameters are either specified by the policy, or based on historic observations (i.e., emissions and banking). Four of the parameters, however, are both uncertain and crucial (the last four in Table 1). Thus, I perform sensitivity analysis using alternative assumptions.

For the demand function, the parameters are disciplined using historic evidence. That is, I require that the following three features are fulfilled: i) The *level* of demand should be consistent with the observed price and demand combination in 2018; ii) the simulated Base Case scenario, which includes the MSR rules, should have an *initial price* in 2019 at 21.0 Euro per ton; and iii) a simulated scenario that does *not* include the MSR rules, should have an *initial price* in 2019 at 7.5 Euro per ton. That is, the model should be able to reproduce both the current ETS prices, but also the prices before the MSR was introduced.

The calibration leads to a price elasticity of -0.12 and a linear annual reduction factor in the demand function of 1.9%. Further, for the (real) interest rate, 5% is chosen. Last but not least, the EU ETS is assumed to continue until 2050, and I require that banking in the last period is zero.

[2] Strictly speaking, for this to hold more generally, borrowing should also be allowed ($B_t < 0$). However, in the current context, borrowing is not allowed in the EU ETS and is also not desired by the market participants in the model simulations due to the huge initial surplus. Regarding uncertainty, I return to this issue in the discussion at the end of the article.

Table 1. Specification of parameter values*

Parameter name	Parameter description	Parameter value	Comment
λ	Threshold for inflow into MSR	833 Mt	
α	Withdrawal rate (Pace of inflow into MSR)	0.24 (2019 - 2023) 0.12 (from 2024)	
η	Threshold for outflow from MSR	400 Mt	
γ	Outflow from MSR	100 Mt	
β	Threshold for canceling allowances	0.57	The threshold is βS_t
S_{2019}	Supply of allowances in 2019	1 893 Mt	
	Linear reduction factor of S_t	1.74% (until 2020) 2.2% (from 2021)	Multiplied with average annual supply in phase 2
B_{2018}	Assumed banking from 2018	1 654 Mt	Banking from 2017 – assumed no change in 2018 (EU, 2018)
	Additional transfer of EUAs into MSR (back-loading + unallocated)	1 525 Mt	
	First year of cancellation	2024	
σ	Demand elasticity	-0.116	Cf. discussion in the text
	Calibrated linear annual reduction factor in demand function	1.86%	Cf. discussion in the text
r	Real interest rate	5%	Cf. discussion in the text
n	Number of periods	32 (2019-2050)	Cf. discussion in the text

* This is mostly based on European Commission (https://ec.europa.eu/clima/policies/ets/reform_en and https://ec.europa.eu/clima/policies/ets/cap_en) and Perino (2018).

Numerical results for the EU ETS

Base Case scenario

Given the model in equations (1)-(6) and the specification of parameters in Table 1, we can easily simulate the model and derive market equilibrium values for the years 2019-2050.[3] This Base Case scenario is shown in Figures 1a-c. Note that this is not a forecast of the EU ETS market until 2050 – the market development will clearly be less smooth due to unexpected events as well as expected variations in supply and demand that are not incorporated into the model. The purpose of this analysis

[3] The model is simulated using the MCP solver in GAMS (Brooks et al., 1996). The GAMS program is provided in Appendix B.

is to examine the effects of an (anticipated and additional) abatement effort in some future year(s), given a possible but fairly realistic scenario for the future EU ETS market.

We see from Figure 1a that the price starts at 21 Euro per ton in 2019, and reaches 95 Euro in 2050 (all prices are measured in real terms). The price path follows directly from the calibration procedure and the chosen interest rate. Supply exceeds demand until almost 2040 – then demand becomes higher than supply, cf. Figure 1b. As explained above, annual demand is the same as annual emissions. Supply here refers to gross supply (S_t in equation (5)), i.e., before taking into account that net supply is also affected by input into or output from the MSR. Initially, net supply is significantly below gross supply (see Figure 1b), and also well below demand, due to a large inflow into the MSR.

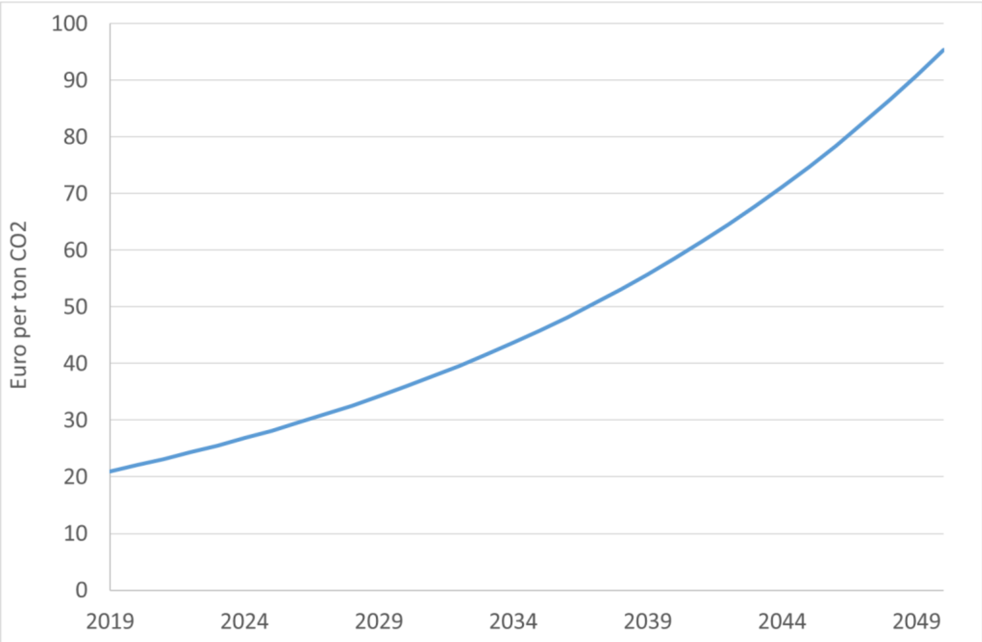

Figure 1a. Allowance price in Base Case scenario (2019-2050). $Euro_{2018}$ per ton CO_2.

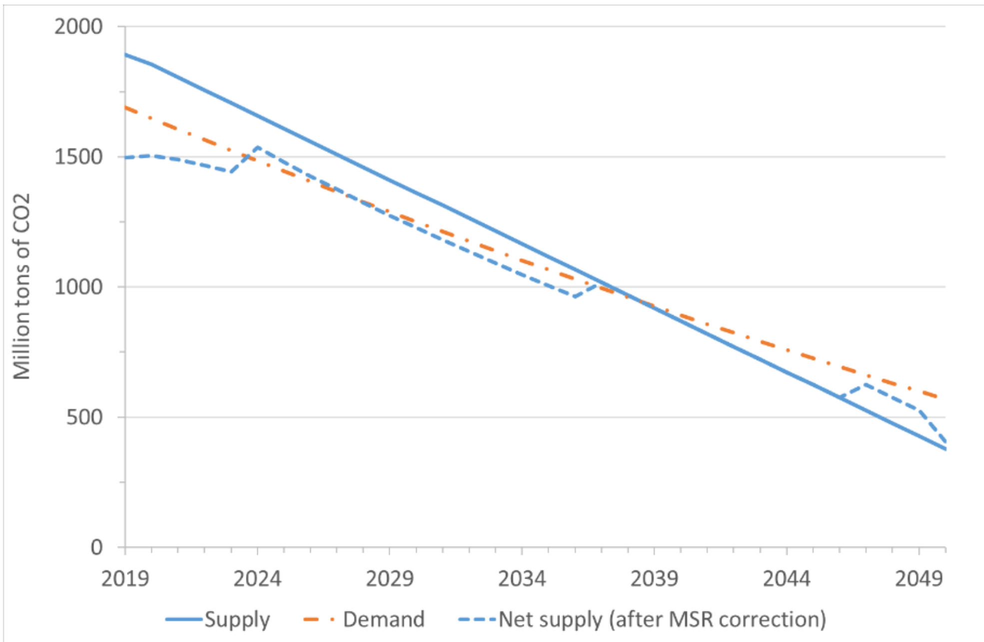

Figure 1b. Market balance in Base Case scenario. Annual figures for the period 2019-2050.

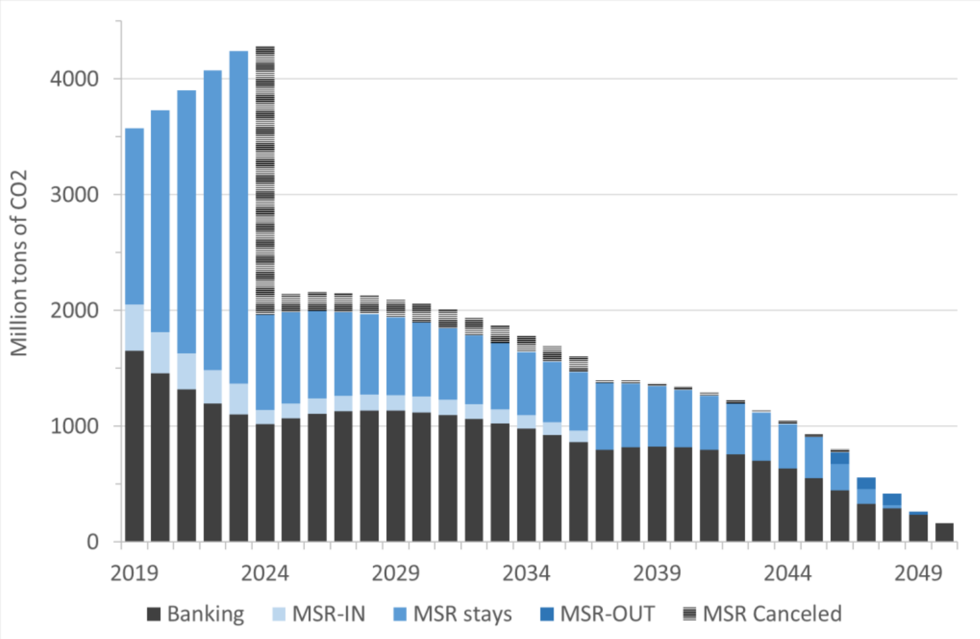

Figure 1c. Stocks of allowances. The MSR is divided into the following four contents (cf. eq. 4): Input of allowances into MSR this period ("MSR-IN"); other allowances that remain in the MSR next period ("MSR stays"); allowances that leave MSR next period ("MSR-OUT"); and allowances that are canceled ("MSR Canceled"). Annual figures for the period 2019-2050 in Base Case scenario.

The stocks of allowance reserves, both privately held ("banking") and in the MSR, are shown in Figure 1c. The figure also displays how allowances enter into, or are taken out of, the MSR, as well as the canceled allowances. Two important things happen in 2024: Cancellation of allowances begins, and the withdrawal rate drops from 24% to 12%. The latter explains the increased net supply in 2024 (Figure 1b), as well as the decline in MSR-IN (Figure 1c). In this Base Case scenario, the MSR stops taking in allowances from 2036, increasing net supply that year (Figure 1b).

Cancellation of allowances is clearly biggest in 2024, but continues for two decades in this scenario. In total, 4.5 Gt of allowances are canceled, of which 3.3 Gt are canceled by 2030.[4]

Effects of additional abatement

Next, we are interested in examining the effects in the ETS market of additional abatement effort, reducing the demand for allowances, in one or more future years. Importantly, the additional abatement is expected by the market already today, and may e.g. be due to some policy or measure that intends to reduce emissions. Examples could be more ambitious targets for renewables or energy efficiency, decisions to phase out coal power, or stricter emission standards in manufacturing industries.

I will mainly focus on the impacts on cumulative emissions over the whole period, or in other words the cumulative cancellation of allowances. I run a series of simulations, where demand for allowances is reduced by 1 million EUAs (corresponding to 1 Mt of CO_2) in a specific year t, where t varies from

[4] As a matter of fact, Refinitiv Carbon (2018) also expects 3.3 Gt to be canceled by 2030, and a total surplus of allowances of 1.6 Gt in 2030 (banking in the market plus MSR) implying further cancellation post-2030, especially since that study predicts a rising surplus in the market between 2025 and 2030.

2019 to 2050.[5] This demand reduction (additional abatement) can either be temporary (i.e., only in year t) or permanent (i.e., all years $s \geq t$).

Figure 2 displays the effect on cumulative emissions as a percentage of the abatement effort in year t (or years $s \geq t$). The blue solid bars show the impacts of a temporary abatement. We see that if the abatement takes place before 2032, the net effect is a reduction in cumulative emissions in line with Perino (2018). As explained before, an early reduction in demand for allowances increases banking and hence also the number of allowances that enter into the MSR, which further leads to a higher number of canceled allowances. If the abatement occurs during the first five years, the effect is particularly strong with leakage rates less than one third.

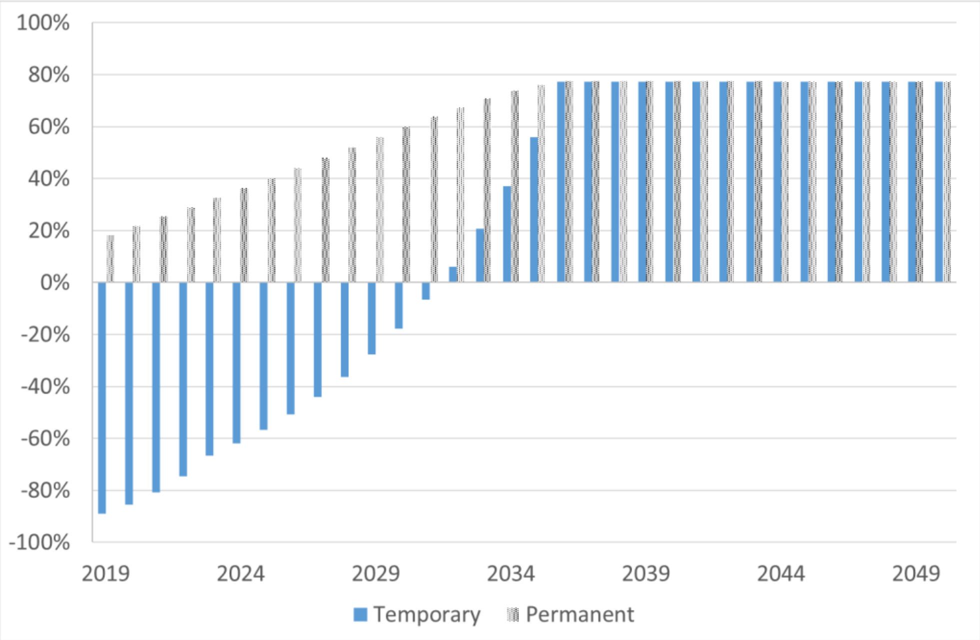

Figure 2. Changes in cumulative emissions as a result of a temporary or permanent additional abatement in the given year. Per cent of the additional abatement (measured in CO_2 emissions). Positive numbers mean a green paradox: Cumulative emissions increase.

On the other hand, if the additional abatement takes place after 2036, that is, after the MSR has stopped taking in allowances, there is a net *increase* in cumulative emissions of 0.8 Mt CO_2, i.e., a leakage rate of 180%. The intuition is that when the market participants expect a less tight allowance market in the future, they will bank fewer allowances from the preceding periods. As a consequence, fewer allowances enter into the MSR, and thus fewer allowances are canceled. Moreover, when fewer allowances are taken out of circulation, this further reduces the tightness of the market – hence there is a multiplier effect which is bigger the longer the MSR is taking in allowances.

If the abatement takes place in the interim period 2032-2036, i.e., shortly before the MSR stops taking in allowances, cumulative emissions also *increase*. Although the reduced demand for allowances leads to more banking and more cancellation of allowances in the subsequent years, there will be less

[5] I have also tested the effects of reducing demand by 10 million EUAs, in which case the relative changes are almost identical.

banking and less cancellation in the preceding years. The latter effect is dominating the former effect from 2032 in these simulations.

The results of a permanent abatement effort, i.e., a permanent reduction in demand for allowances, are even more disturbing. Irrespective of when the abatement takes place, if it is permanent it will be counterproductive. Cumulative emissions will increase by 0.2 Mt or more for every Mt of abatement, cf. the grey (pattern) bars in Figure 2. Thus, the finding in Perino (2018) only holds if the abatement effort is temporary (and occurs early on) – if it is permanent the result may be turned around, at least according to these simulations. Hence, a green paradox.

Sensitivity analysis

To check how sensitive the results are to the uncertain parameters, I run several sensitivity analysis. In each case, I recalibrate the linear annual reduction factor in the demand function so that the price in 2019 remains at 21.0 Euro per ton, i.e., consistent with the observed price (see above).[6] Here I focus on the impacts on cumulative emissions in the following cases: i) A temporary additional abatement in 2019; ii) a temporary additional abatement after the MSR stops taking in allowances (e.g., last period); and iii) a permanent additional abatement from 2019. I will also report the first year when the impact on cumulative emissions of a temporary abatement is positive (2032 in Base Case), and the last year that the MSR takes in allowances (2036 in Base Case).

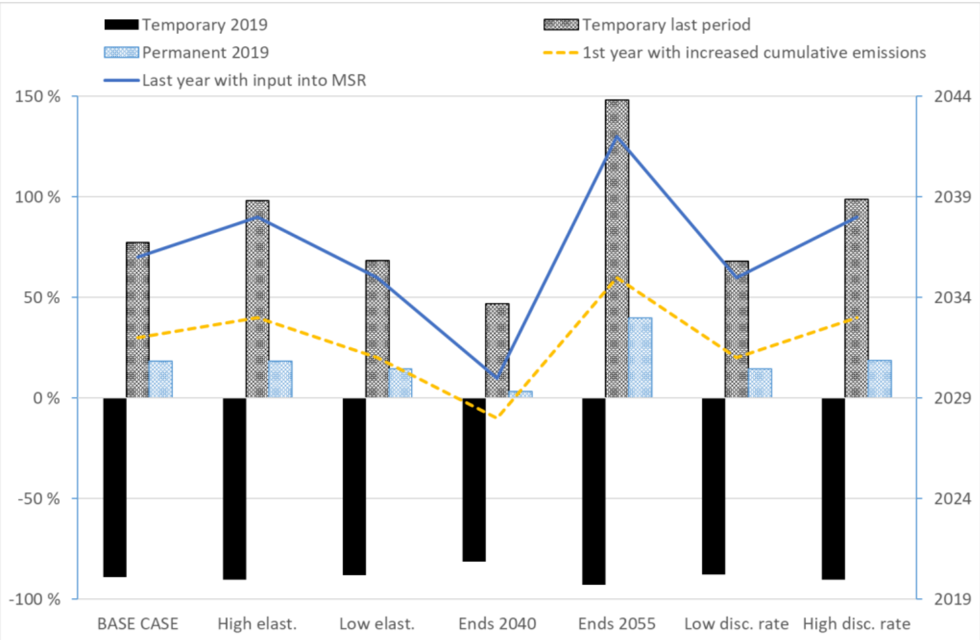

Figure 3. Changes in cumulative emissions as a result of a temporary or permanent abatement in 2019 or in the last period. Per cent of the abatement (measured in CO_2 emissions). High elast. and Low elast. refer to 50% higher and lower elasticities, respectively. Low disc. rate and High disc.rate refer to 3% and 10%, respectively.

[6] Two exceptions are “Low elasticity” and “Ends 2040”, where it was not possible to find a reduction factor that was consistent with an initial price of 21. This is due to the discontinuity in the M^{IN} function in equation (1). Thus, in these two sensitivity cases, the initial price starts a bit higher (25-30 Euro per ton).

Figure 3 shows that the direction of change is consistent across the sensitivity analysis. The size of the effects vary somewhat, but in all seven cases (including Base Case), we notice that an early and temporary additional abatement leads to a profound reduction in cumulative emissions (> 80%) while a late abatement effort leads to a substantial *increase* in cumulative emission (> 45%). In three of the cases, cumulative emissions increase by around 100% or higher (i.e., leakage rates of 200% or higher). Moreover, an early and permanent additional abatement increases cumulative emissions notably in six of the seven cases (14-40%). We also notice that there is a clear pattern that the longer the MSR takes in allowances, the stronger are the effects on cumulative emissions – in both directions.

Discussion and conclusions

The results above have shown that stimulating additional abatement within the ETS sectors can lead to lower net emissions if it is temporary and takes place early on, but not if it is permanent *or* takes place later on. Especially in the latter case, it may have large detrimental impacts on cumulative emissions, with leakage rates in the range of 150-200%. How reliable are these results, and what are the policy conclusions?

As pointed to before, there are several uncertain parameters in the model, and these have been tested in the sensitivity analysis, which largely confirms the main conclusions. A more fundamental objection to the model is that it is deterministic. In reality, market actors take decisions under uncertainty, and this obviously affects their behavior. Nevertheless, the mechanism that drives the main results in this article is still highly relevant. The extensive banking of allowances over the last 5-10 years is a result of overallocation of allowances, but probably also due to an expectation of higher future prices. Whereas smaller firms may take a rather passive approach in this respect, larger companies and financial speculators are to some extent looking ahead and buy or sell allowances depending on their price expectations. This implies that if the market is expected to become less tight in the future, e.g. due to an announced supplementary policy, (some) market participants will expect lower future prices than they did before, and thus become less interested in saving allowances. In other words, the results obtained in the deterministic model is also relevant in a world with uncertainty and different expectations about the future market.

As an example, when the German coal commission delivered its final recommendations in January 2019, the allowance price “tumbled by more than a euro … amid speculation that Germany’s coal phaseout deal would prompt big-emitting utilities to unwind generation hedges” (Carbon Pulse, 2019). The main impacts of the German coal phaseout are expected to occur after 2030 (CarbonBrief, 2019). If so, Figure 2 above may suggest that the policy measure may *increase* rather than decrease cumulative emissions regulated by the EU ETS unless it is followed up with cancellation of allowances, which the coal commission also proposes (Carbon Market Watch, 2019). Cancellation of allowances should then ideally take place after the MSR has stopped taking in allowances so that it doesn’t lead to reduced cancellation via the MSR.

The findings in this article are rather detrimental for progressive policy makers in Europe that want to impose supplementary domestic policies or regulations hoping to further reduce CO_2 emissions. Whereas Perino’s (2018) conclusion was more optimistic when it comes to the effects of immediate abatement, such abatement will often tend to be (semi-)permanent, in which case the conclusion may be reversed. Furthermore, many policies and measures come with a time lag, with the abatement taking place years after the policies have been announced, in which case they may become counterproductive. Continued efforts to strengthen the cap on emissions thus seems to be a more productive approach. At the same time, it should be mentioned that supplementary policies that lead to lower ETS prices can make it politically easier to strengthen the cap in the future. If so, the case for supplementary policies is more ambiguous. In any case, announcing supplementary policies that are not followed up in due course will be particularly detrimental.

Last but not least, this article should not be used to conclude that the new cancellation rule of the EU ETS has been counterproductive. Quite the contrary, according to the Base Case simulations above, the cancellation rule will reduce cumulative emissions until 2050 by 4.5 Gt of CO_2, corresponding to more than two years of EU ETS emissions.

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Appendix A. Model parametrization

Table 1 in the main text displays the specification of parameter values in the model. The main text explains the calibration procedure. Here some more details are provided.

As mentioned in the main text, I require three features to be fulfilled when calibrating the demand function. First, the *level* of demand (emissions) should be consistent with the observed price and demand combination in 2018. The average EUA price in 2018 was 16.0 Euro per ton. Emissions in 2018 are assumed to be the same as in 2017, i.e., 1812 Mt (Refinitiv Carbon, 2018).

Second, the simulated Base Case scenario, which includes the MSR rules, should have an *initial price* in 2019 at 21.0 Euro per ton. This is equal to the average price in the last quarter of 2018 (when adjusting for the interest rate). The EUA price was rising steadily in the three first quarters of 2018, whereas the price *trend* afterwards has been quite flat (the price has been volatile though).

Third, a simulated scenario that does *not* include the MSR rules should have an *initial price* in 2019 at 7.5 Euro per ton. The average price from the start of phase 3 in 2013 to the first half of 2017, i.e., just before the price started to take off, was 5.8 Euro. Adjusting for the (real) interest rate of 5% and inflation rate of 1.5%, this corresponds to 7.5 Euro in 2019.

As mentioned in the main text, the calibration leads to a price elasticity of -0.12. As a comparison, the results in Böhringer et al. (2018) for the EU ETS (Figure 12.3) can be used to estimate a corresponding demand elasticity. Focusing on the price levels 10-50 USD per ton, I find a price elasticity of -0.13, i.e., almost identical to the calibrated elasticity. On the other hand, the marginal abatement cost curve for the EU ETS illustrated in Refinitiv Carbon (2018) (Figure 1) indicates a somewhat lower price elasticity. More generally, there is limited empirical evidence of to what extent the EU ETS has led to emission reductions so far (Dechezleprêtre et al., 2018).

Note that a *linear* change in the demand function has been assumed, similar to the linear reduction in supply of allowances. The reduction factor was calibrated to 1.9% per year, which is of the same size as the reduction factors applied on the supply side. It is difficult to foresee how the demand function will change over time. On the one hand, economic growth tends to push the demand upwards. On the other hand, technological progress and supplementary policies related to renewables, energy efficiency and coal phase-out, tend to push the demand downwards. The calibration might suggest that market participants in aggregate believe the latter to be dominating the former. Notice that the assumed constant elasticity of demand function implies that demand for allowances goes towards infinity as the price goes towards zero. This is of course totally unrealistic, but the functional form may still be useful for prices in the range of observed (or higher) prices.

Regarding the real interest rate, there are arguments for both higher and lower rates than the assumed 5%. Looking at futures prices of EUAs suggest a lower interest rate, even in nominal terms.[7] At the time of writing, the annual futures prices increase by 3-4% in the period 2020-2025. On the other hand, the future of the EU ETS is uncertain, and recurring regulatory changes enhance the future price uncertainty. This suggests a high market interest rate (or a gradually higher interest rate to reflect that regulatory uncertainty increases over time, especially between phases).

Finally, it is difficult to know when the EU ETS will end, and here it is assumed that it continues until 2050. Then the annual supply of allowances is 20% of the current supply, given no change in the linear reduction rate after 2021. Of course, it is difficult to know what will happen around 2050,

[7] https://www.barchart.com/futures/quotes/CK*0/all-futures

which is why I test the effects of ending the ETS in 2040 or 2055 (the supply of allowances will drop to zero between 2055 and 2060, given no changes to the reduction rate.).

Regarding the initial size of banking and MSR, 1 654 million allowances were banked in the market from 2017.[8] 900 million allowances were "back-loaded" in 2014-16, which means that auctioning of these allowances was postponed (implicitly banked by the regulator). Eventually, it has been decided that they should enter into the MSR, together with expectedly 625 million allowances.

[8] https://ec.europa.eu/clima/policies/ets/reform_en

Appendix B. GAMS model

```
Sets
* EU ETS is simulated for the years 2019-2050. t=0 is 2018, so t=32 is 2050
t       Time period /0*32/
t0(t)   Period t=0 (before simulation starts)
ts(t)   Simulation periods
ts2(t)  Simulation periods except t=1
tn(t)   Last period
;

alias(t,tt);

t0(t) = yes$(ord(t) eq 1) ;
ts(t) = yes$(ord(t) gt 1) ;
ts2(t) = yes$(ord(t) gt 1 and ord(t) lt card(t)) ;
tn(t) = yes$(ord(t) eq card(t)) ;

Scalars
r       Interest rate
sigma   Demand elasticity
g       Linear annual reduction factor in demand function
beta    Threshold for canceling allowances (as a share of S)
P0      Average price in 2018 (t=0)
D0      Demand in 2018 (t=0)
;

r = 0.05 ;
sigma = -0.116 ;
g = 0.018595598 ;
beta = 0.57 ;
P0 = 16 ;
D0 = 1812 ;

Parameters
S(t)     Fixed allocation of quotas
alpha(t) Withdrawal rate - share of annual auction volume entering into MSR
Gamma(t) Time variant parameter in demand function
deltaD(t) Reduced demand for quotas in year t
;

S(t)$(ord(t) le 3) = 1931 - (ord(t)-1)*38.264 ;
S(t)$(ord(t) gt 3) = S("2") - (ord(t)-3)*49.216 ;
alpha(t)$(ord(t) le 6) = 0.24 ;
alpha(t)$(ord(t) gt 6) = 0.12 ;
Gamma(t) = D0/(P0**sigma)*(1 - ord(t)*g) ;

deltaD(t) = 0 ;

Positive Variables
P(t)     Price
D(t)     Demand for quotas
CumD     Cumulative demand for quotas
M_IN(t)  Number of quotas entering into MSR
M_OUT(t) Number of quotas taken out of MSR and into the ETS market
M(t)     Size of MSR
C(t)     Cancellation of quotas
CumC     Cumulative cancellation of quotas
B(t)     Banking of quotas
;
```

```
Equations
EQ1(t)   Quotas entering into MSR
EQ2(t)   Quotas taken out of MSR
EQ3(t)   Cancellation of quotas
EQ4(t)   MSR stock change
EQ5(t)   Market balance
EQ6(t)   Price movement
EQ7(t)   Demand for quotas

* The following equations sum up cumulative cancellation and demand:
EQ3SUM   Cumulative cancellation of quotas
EQ7SUM   Cumulative demand for quotas

* The following equation is used in the model without MSR:
EQ3NO(t) Without cancellation of quotas from MSR
;

* Due to the discontinuity of the M_IN function, the formulation is somewhat different from eq.1
* in the paper, and a marginal number is added to the denominator to avoid division by zero
EQ1(t)$(ts(t))..        M_IN(t) =E= MAX(0 , alpha(t)*B(t-1)*(B(t-1) - 833))*(B(t-1) - 833)  / ( (B(t-1) -
833)*(B(t-1) - 833) + 0.01 ) ;

* Due to the discontinuity of the M_OUT function, the formulation is somewhat different from eq.2
* in the paper, and a marginal number is added to the denominator to avoid division by zero
EQ2(t)$(ts(t))..        M_OUT(t) =E= MIN(M(t-1),(MAX(0 , 100*(400 - B(t-1)))*(400 - B(t-1)) / ( (400 - B(t-
1))*(400 - B(t-1)) + 0.01 ) ) ) ;

EQ3(t)$(ord(t) gt 6)..   C(t) =E= MAX( 0 , M(t) - beta*S(t) ) ;

EQ4(t)$(ts(t))..        M(t) =E= M(t-1) + M_IN(t) - M_OUT(t) - C(t-1);

EQ5(t)$(ts(t))..        S(t) - M_IN(t) + M_OUT(t) =E= D(t) + B(t) - B(t-1) ;

EQ6(t)$(ts2(t))..        P(t+1) =E= P(t)*(1+r) ;

EQ7(t)$(ts(t))..        D(t) =E= Gamma(t)*(P(t)**sigma) - deltaD(t) ;

EQ3NO(t)..              C(t) =E= 0 ;

EQ3SUM..                 CumC =E= sum(t,C(t)) ;

EQ7SUM..                 CumD =E= sum(t,D(t)) ;


Model MSR_YES
/EQ1.M_IN, EQ2.M_OUT, EQ3.C, EQ4.M, EQ5.P, EQ6.B, EQ7.D, EQ3SUM.CumC, EQ7SUM.CumD /;

Model MSR_NO
/EQ1.M_IN, EQ2.M_OUT, EQ3NO.C, EQ4.M, EQ5.P, EQ6.B, EQ7.D, EQ3SUM.CumC, EQ7SUM.CumD /;

* The initial value of MSR:
M.fx("0") = 900 + 625 ;

* Fixing variables in period 0 (2018):
M_IN.fx("0") = 0 ;
M_OUT.fx("0") = 0 ;
D.fx("0") = 0 ;
B.fx("0") = 1654 ;
B.fx(t)$(ord(t) eq card(t)) = 0 ;
```

```
C.fx(t)$(ord(t) le 6) = 0 ;

* Ensure that prices must be strictly positive:
P.lo(t) = 0.1 ;

option iterlim=100000000;
option reslim=2000.0;
option limrow=10;

* Solve the model including MSR:
Solve MSR_YES using mcp;

********************************
* Without MSR (and backloading)
alpha(t) = 0 ;
B.fx("0") = B.l("0") + M.l("0");
M.fx("0") = 0 ;

* Solve the model excluding MSR:
Solve MSR_NO using mcp;

******************************
* Check the effects of reduced demand (temporary or permanent) in different periods

alpha(t)$(ord(t) le 6) = 0.24 ;
alpha(t)$(ord(t) gt 6) = 0.12 ;
M.fx("0") = 900 + 625 ;
B.fx("0") = 1654 ;

Parameter
CumC_REP(tt)      Reporting CumC for deltaD in different periods
;

loop(tt$(ord(tt) gt 1),

* Temporary reduced demand in period tt:
deltaD(t)$(ord(t) eq ord(tt)) = 1 ;
* Permanent reduced demand from period tt onwards:
*deltaD(t)$(ord(t) ge ord(tt)) = 1 ;

* Solve the model with reduced demand in one or more periods:
Solve MSR_YES using mcp ;

* Remembering the effect on CumC in this scenario:
CumC_REP(tt) = CumC.l ;

* Nullifying the reduced demand before next loop
deltaD(t) = 0 ;

);

display CumC_REP ;
```