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Abstract

For any emission trading system (ETS) with quantity-based endogenous supply of allowances, there exists a negative demand shock, e.g. induced by abatement policy, that increases aggregate supply and thus cumulative emissions. We prove this green paradox for a general model and then apply it to the details of EU ETS. In 2018, new rules for a Market Stability Reserve (MSR) were agreed on and implemented. We show that abatement policies announced in early periods but realized in the future, are inverted by the new rules and increase cumulative emissions. We provide quantitative evidence of our result for a model disciplined on the price rise in the EU ETS that followed the introduction of the MSR.

JEL-Codes: D590, E610, H230, Q500, Q540, Q580.

Keywords: emissions trading, green paradox, EU ETS, environmental policy, dynamic modeling.

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1 Introduction

In order to reduce greenhouse gas (GHG) emissions, emissions pricing has long been advocated by economists, either as a tax or via an emissions trading system (ETS) (c.f. Aldy et al., 2010; Golosov et al., 2014) . Where a tax fixes the price of emissions, a standard ETS fixes the overall emissions level while leaving the emissions price endogenous. Policy makers around the world have mostly favored ETSs over emission taxes, typically allowing for banking (and possibly borrowing) between periods. With banking, short-run emission levels can flexibly adjust to changing market conditions even if the short-run supply of emission allowances is fixed. Long-run emission levels are still given, however, as long as the long-run supply of allowances is fixed.

Due to uncertainty, the ETS price may exceed, or fall short of, expected prices (Weitzman, 1974). To avoid too high or too low emissions prices, supplementary measures have been implemented or proposed, such as price collars and floors (Roberts and Spence, 1976; Abrell and Rausch, 2017) or endogenous allocation of allowances to individual firms (e.g., output-based allocation, cf. Fowlie et al. (2016); Böhringer et al. (2017a)). In the EU ETS, the world's largest operating carbon market, alternative measures have recently been implemented, involving market-induced cancellation of allowances. Hence, the long-run supply of allowances is no longer fixed — the emissions cap is endogenous (Perino, 2018).

In this paper we show, first analytically in a general model and then numerically in the context of EU ETS, that any emission trading system with a quantity-based endogenous cap, as in the EU ETS, induces a green paradox. That is, for any such ETS there exists an abatement policy that increases aggregate emissions. When calibrating and simulating a model of EU ETS, we find that this green paradox may be substantial, especially if demand for emission permits is reduced several years from now but anticipated today. Our results unequivocally show that the announcement of future abatement policies can invert the long-run effects from a reduction to an increase in emissions.

The intuition behind our result can be understood by considering the history of EU ETS. Due to the economic slowdown that started in 2008, demand for allowances decreased, a large amount of banked allowances accumulated, which put a downward pressure on the EUA price. The price of emission allowances (EUAs) dropped below 10 €/tCO_2 from 2012 onwards. In response, the EU implemented a Market Stability Reserve (MRS) in 2015, deciding that if aggregate banking in the market exceeds a certain threshold, part of next year's allowances enter the MSR rather than the market (Fell (2016); Kollenberg and Taschini (2019)), to be released back into the market at a future stage. That is, the MSR reduced the short-run but not the cumulative supply of allowances – the long-run cap on emissions remained untouched.

As the backloading of allowances did not succeed to push up prices, the EU further adapted the workings of the MSR in 2018: when the size of the MSR is above the annual auctioning, all allowances above this threshold are permanently canceled. The new rules effectively reduce the long-run cap, supporting higher prices, but the amount of cancelling has been made endogenous; it depends on the allowances banking that determines the flow into the MSR. The intertemporal supply and demand has become an intricate balance.

Whereas demand-reducing policies had no effect on cumulative emissions under the old rules that supported a fixed cumulative cap, Perino (2018) finds that the new rules give back some leverage to abatement policies. A one ton demand reduction in 2018 reduces cumulative emissions (i.e., the long-run emission cap) by 0.4-0.8 tons. The reasoning is that reduced demand in 2018 increases banking and a bigger inflow into the MSR, which eventually cancels more allowances. That is, the new MSR rules have 'punctured the waterbed'. The magnitude of the effects depend on the timing of the demand reduction, and the time window over which the MSR takes in allowances.

Gerlagh and Heijmans (2019) extend the analysis by Perino (2018) considering changes in equilibrium prices and second-order effects on banking and allowance cancellation. Here, we add one further element, and examine the effects of future demand reduction measures that are anticipated today. If the market foresees a future demand reduction, such depresses the banking of allowances. Fewer allowances then enter the MSR, fewer allowances are canceled, and cumulative supply increases. Hence, anticipating future abatement efforts may increase cumulative emissions!

The mechanism is reminiscent of the green paradox (Sinn, 2008; Bauer et al., 2018): anticipated future climate policies incentivize fossil fuels producers to speed up extraction and increasing current emissions. In our context, it is not current but cumulative emissions that increase following well-intended climate policies. The green paradox we consider is worse than the classic one.

The structure of the paper is as follows. We first present the general model in which we prove our Theorem that any quantity-based ETS with endogenous cap suffers from a Green Paradox. The next section illustrates the general model by adding some details of the EU ETS, and shows that the new rules for the MSR introduce multiplicity of equilibria, and that the Green Paradox specifically arises for demand decreasing policies that affect future demand. The third section adds a numerical calibration to the model and calculates the size of the green paradox in the EU ETS.

2 General Model

Consider an emission cap system regulating emissions in a finite number of (temporal or spatial) jurisdictions i, where demand for emission allowances is denoted $\boldsymbol{d}(p, \boldsymbol{\lambda})$ and depends on one price (through Hotelling if temporal) p and demand shifting policies $\boldsymbol{\lambda}$ normalized so that $\partial \boldsymbol{d}/\partial \boldsymbol{\lambda} = \boldsymbol{u}$, where $\boldsymbol{u}$ is the transposed all-ones-vector with 1 everywhere. We assume the law of demand holds, so demand decreases in prices $\boldsymbol{d}' \equiv \partial \boldsymbol{d}/\partial p < 0$, and express aggregate demand as $D = \boldsymbol{u}^T \boldsymbol{d}$.[1] For convenience of presentation, we will refer to jurisdictions i as 'periods', but all results in this section carry over to spatially linked markets.

Our model considers emission cap systems where the aggregate supply of allowances S depends on the demand vector for allowances, such as the one recently implemented in the EU ETS, and we refer to this as quantity-based cap:

Definition 1 (Quantity-based cap)**.** *Aggregate supply S is dependent on the spread of demand:*

$$S = s(\boldsymbol{d}). \tag{1}$$

Note that an emission cap system with price collars, where aggregate supply depends on the emission price, is not a quantity-based cap and hence not considered here.

Equilibrium in this market is defined in the usual fashion, when excess demand equals zero:

Definition 2 (Equilibrium)**.** *In equilibrium, prices adjust so that aggregate demand equals aggregate supply:*

$$D = \boldsymbol{u}^T \boldsymbol{d}(p, \boldsymbol{\lambda}) = s(\boldsymbol{d}(p, \boldsymbol{\lambda})) = S. \tag{2}$$

[1]When vectors are over time, aggregate demand and supply equal cumulative demand and supply.

When deemed convenient, we denote equilibria by a superscript asterisk. It is natural to study the equilibrium through the response of the equilibrium condition with respect to prices p^*, but it is useful to take one step back and consider the response of the equilibrium condition with respect to the demand vector $\boldsymbol{d}$. By construction, the equilibrium in demand space $\boldsymbol{d}$ is characterized by $\boldsymbol{u}^T\boldsymbol{d} - s(\boldsymbol{d}) = 0$. The gradient of the equilibrium demand space (in short: demand space gradient) is given by $\boldsymbol{u} - \boldsymbol{s}'$. We label the cap system as exogenous or fixed if $\boldsymbol{s'} = 0$, or more generally, if supply is proportional (but not equal) to the all-ones-vector, $\boldsymbol{s'} \propto \boldsymbol{u}$.[2] A fixed cap means that aggregate demand D is constant. We label a cap system 'endogenous' if the cap is not fixed. By $\Delta\boldsymbol{d} > 0$ we mean a situation where no demand change is negative, and at least one element is strictly positive. We consider non-trivial cap systems that do not allow a 'free lunch':

Assumption 1 (No free lunch)**.** *There does not exist a non-zero increase (or decrease) in emissions $\Delta\boldsymbol{d} > 0$ that is feasible, that is, for which $(\boldsymbol{u} - \boldsymbol{s}')^T\Delta\boldsymbol{d} = 0$ holds. We write this as a gradient condition: $\boldsymbol{u} - \boldsymbol{s}' > 0$.*

Definition 3 (Policy-induced price and demand change)**.** *We define changes in the equilibrium price due to demand-rudction in period i, $d\boldsymbol{\lambda}_i$:*

$$\boldsymbol{\alpha}_i = dp^*/d\boldsymbol{\lambda}_i. \tag{3}$$

Similarly, we define the policy-induced demand change

$$\boldsymbol{\gamma}^i = d\boldsymbol{d}^*/d\boldsymbol{\lambda}_i, \tag{4}$$

with $\boldsymbol{\gamma}^i_j$ denoting the demand change in period j from a policy-induced demand change in period i.

As to our notation, we let $\boldsymbol{x}_i$, subscript, denote the i^{th} element of vector $\boldsymbol{x}$, so a scalar; $\boldsymbol{x}^i$, so superscript, denotes a vector. Hence, $\boldsymbol{x}^i_j$ denotes element j of vector i.

Furthermore, we refer to the matrix of all policy-induced changes as Γ so that with a slight abuse of notation we can write $\Gamma\boldsymbol{e}^i \equiv \boldsymbol{\gamma}^i$, where $\boldsymbol{e}^i$ is the unit vector with zeros everywhere but 1 at the i^{th} place. Basic algebra gives the important feature that any

[2]To see this, consider the case $S = S_0 + \beta\boldsymbol{u}^T\boldsymbol{d}$, so that $\boldsymbol{s'} = \beta\boldsymbol{u}$. This is equivalent to fixed aggregate supply $D = S_0/(1-\beta)$.

policy induced demand change is orthogonal to the demand space gradient for all i:

$$(\boldsymbol{u} - \boldsymbol{s}')^T \boldsymbol{\gamma}^i = 0. \tag{5}$$

An immediate implication is that any linear combination of the set $\{\boldsymbol{\gamma}^i\}_i$, that is, any combination of demand policies, will also satisfy the orthogonality property, or $(\boldsymbol{u} - \boldsymbol{s}')^T \Gamma = \mathbf{0}$.

The equilibrium satisfies intuitive conditions on price and demand responses to policy shifts:

Lemma 1. *Prices increase with demand-increasing policies,*

$$\boldsymbol{\alpha} = -\frac{(\boldsymbol{u} - \boldsymbol{s}')^T}{(\boldsymbol{u} - \boldsymbol{s}')^T \boldsymbol{d}'} > 0 \tag{6}$$

and own-period demand increases, while other-period demand decreases:

$$\boldsymbol{\gamma}_i^i > 0 \tag{7}$$

$$\boldsymbol{\gamma}_j^i < 0 \textit{ for } j \neq i. \tag{8}$$

The proof of this and further results, if not mentioned in the main text, are stated in Appendix A.

The aim of this study is to establish that for any system with quantity-based endogenous cap, there exists a policy that induces a green paradox. Loosely speaking, a green paradox occurs when a policy-induced reduction of demand in some jurisdiction i, $d\boldsymbol{\lambda}_i < 0$, leads to an increase in aggregate emissions, $dD > 0$.

Definition 4 (Green Paradox)**.** *There is a Green Paradox if a demand-decreasing policy, $d\boldsymbol{\lambda} < 0$, leads to increasing aggregate emissions, $dD = d(\boldsymbol{u}^T \boldsymbol{d}^*) > 0$.*

We can then state our main result:

Theorem 1. *For every quantity-based endogenuous cap system without a free lunch, there exists a policy $d\boldsymbol{\lambda} < 0$ that induces a green paradox, $d(\boldsymbol{u}^T \boldsymbol{d}^*) > 0$.*

Though the proof is tedious and relegated to the appendix, the mathematical intuition is not too hard. Half of the equilibrium hyperplane in demand space has increasing aggregate emissions, while the other half has decreasing aggregate emissions.

One only needs to establish that policy induced changes Γ are not restricted to one half of the hyperplane.

With this formal result in mind, we can now move on to the analysis of a specific application of our model: EU ETS. There, we will see the compelling economic intuition behind the mechanics governing Theorem 1.

3 EU ETS analytical model

In this section, we apply the techniques developed for the previous, general model to the specificities of a real-world cap-and-trade system with endogenous cap, the European Union's Emissions Trading System (EU ETS). We first briefly revisit EU ETS.

EU ETS is the largest market for carbon to date and as one of the first such instruments, it has experienced many difficulties since its conception. Firms under EU ETS at risk of relocating have led the EU to adopt (too) generous compensation mechanisms (Martin et al., 2014). The price of allowances has been consistently low and highly volatile, carrying along some counter-intuitive implications for firms' profit (Bushnell et al., 2013). The low price of carbon in EU ETS can be traced back to interactions with substite climate policies as well as the general economic recession during part of its existence. The cap on emissions has been considered set too loosely, as evidenced by a strong accumulating 'bank' of unused allowances, privately stored by firms for future use, despite the low prices. In response, the EU introduced a Market Stability Reserve (MSR) and set the new rules in 2018. From 2019 the MSR takes in allowances that are otherwised autioned, the amount of which equals 24% (12% as of 2024) of banked allowances, every year the (cumulative) bank exceeds 833 $MtCO_2$.[3] These allowances, taken from the volumes otherwise auctioned, will return to the market later: in years when the bank has shrunk to below $400MtCO_2$, an additional $100MtCO_2$ is auctioned from the MSR. However, if too many allowances end up in the MSR (i.e. when the bank remains too large for too long), all MSR-held allowances in excess of the volume auctioned in the previous year are canceled permanently. In this sense, the MSR with canceling effectively makes the cap on emissions in EU ETS endogenous. The workings of post-reform EU ETS have been chronicled in Perino (2018) and Gerlagh and Heijmans (2019).

[3] The EU has introduced the term "Total number of allowances in circulation (TNAC)" (EU (2019)), which for our purpose is equivalent with private banking of allowances.

For our analytical model of EU ETS, we consider time periods $t \in \{1, ..., T\}$ and refer to the entire time window if not stated otherwise. We use capitals for stocks at the end of a period (so that a stock at the start of the first period has index 0), and lower case variables for flows. The MSR is defined through the following mechanical rule:

$$M_t = \min(\beta s_{t-1}, M_{t-1}) + m_t - n_t, \tag{9}$$

where

$$(m_t, n_t) = \begin{cases} (0, \min(M_{t-1}, \Gamma)) & \text{if } B_{t-1} < \underline{B} \\ (0, 0) & \text{if } \underline{B} \leq B_{t-1} < \overline{B} \\ (\alpha B_{t-1}, 0) & \text{if } \overline{B} \leq B_{t-1} \end{cases}, \tag{10}$$

with s_t the maximum (exogenous) number of allowances issued in period t, B_t banking from period t to $t+1$, and m_t and n_t flows into and out of the MSR, respectively. The model can be parametrized to EU ETS by setting $\beta = 0.57$, $\Gamma = 100$, $\underline{B} = 400$, $\overline{B} = 833$, $\alpha = 0.24$ (0.12 from 2024). If M_t exceeds βs_t, the difference is shaved off, and these allowances are canceled permanently.

Equilibrium is characterized through demand d_t, supply s_t, and flows into and out of the MSR. Excess supply is added to the bank of allowances available for future use B_t.

$$B_t - B_{t-1} = s_t - d_t(p_t; \lambda_t) - m_t + n_t \tag{11}$$

As before, the one-dimensional parameter λ_t is a demand shifter, through which we study comparative dynamics. It captures the structure of the economy, also describing changes brought about by climate-oriented or other policies. We slightly abuse notation in our model and normalize the parameter λ_t such that $\partial d_t / \partial \lambda_t = 1$.[4] By means of notation, we will abbreviate $\partial d_t / \partial p_t$ as d'_t, so $d'_t < 0$. We define cumulative emissions as $E = \sum_t d_t$.

As allowances are complementary mostly to fossil fuel use, demand is bound from above and well-defined for zero prices. We also assume a finite choke price, where no emissions are profitable anymore (e.g., fossil fuels are replaced by renewables)[5].

[4] We could, for example, specify $D(.) + \lambda_t$ as residual demand, but we like to think of policies in a more generic framework.

[5] The prices at which emissions become unprofitable may not be as excessively high as previously

Furthermore, we assume scarcity of allowances in each period.

Assumption 2.

$$1. \qquad \forall t : s_t < d_t(0) \equiv \overline{d}_t < \infty \tag{12}$$

$$2. \qquad \exists \overline{p} < \infty : \forall t : d_t(\overline{p}) = 0. \tag{13}$$

Definition 5. *An Emissions Trading System (ETS) is defined by its duration T, first-period state variables for banking B_0 and the MSR M_0, entry threshold $\overline{B}$ and entry share α, exit threshold $\underline{B}$ and flow Γ, shave parameter β, the supply sequence $\boldsymbol{s} = (s_t)_t$, and demand functions $d_t(.)$.*

Private borrowing is not allowed in EU ETS, so we impose the constraint that $B_t \geq 0$; however, we assume that sufficient allowances are allocated to early periods, i.e. that the constraint is never binding.[6] Furthermore, we assume that equilibrium moves from a first stage $t \in 1, ..., t_1$ during which allowances enter the MSR, to a second stage $t \in t_1 + 1, ..., t_2$ during which no emissions enter or leave the MSR, to a third stage $t \in t_2 + 1, ...t_3$ in which emissions flow from the MSR back into the market. There possibly is a final stage in which the MSR is not active either. Finally, there is some last period t^* for which the size constraint on the MSR is binding.

Assumption 3 (Distinct Stages)**.** *For all equilibria considered, supported by a price sequence p_t, there are $0 < t_1 < t_2 < t_3 \leq T$ such that for $t \leq t_1$ there is an inflow in the MSR $m_t > 0$ and $n_t = 0$, for $t_1 < t \leq t_2$ and $t_3 < t$ we have no flows from and to the MSR, $m_t = n_t = 0$, and for $t_2 < t \leq t_3$ there is an outflow from the MSR into ETS, $m_t = 0$ and $n_t > 0$. We also assume that the size contraint for the MSR is binding, $\exists t : \beta s_t < M_t$, with a last period at which it is binding $t_1 < t^* = \max\{t | \beta s_t < M_t\} < T$; there is no cancellation of allowances for $t > t^* + 1$.*

Figure 1 presents the time line for the MSR.[7]

Equilibrium is then defined by the model dynamic equations, with no left-over unused allowances, $B_{T+1} = 0$. We assume allowances have constant assets return δ

believed, see e.g. Wilson and Staffell (2018) and Gillingham and Tsvetanov (2019).

[6] Which has been the case for EU ETS; the assumption is innocent.

[7] Note that t^* in principle could come before or after t_2. However, since the annual cap in the EU ETS is reduced over time, the cancellation threshold βs_{t-1} is declining over time. Hence, we must have $t^* \geq t_2$, and most likely $t^* = t_2$ (cf. the numerical results below).

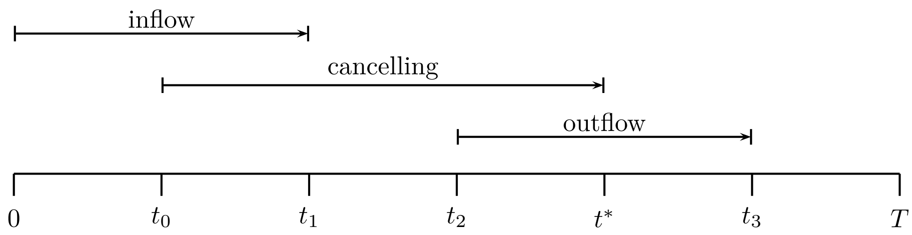

Figure 1: Time line for MSR

leading to the Hotelling rule for prices:

$$p_{t+1} = \delta p_t. \tag{14}$$

If the MSR is emptied before the end of the ETS, $M_T = 0$, cumulative emissions are given by cumulative supply minus cancelled allowances. Given the stages of equilibrium (assuming that t_1, t_2, t_3, t^* does not change), all additions to the MSR before t_1 are cancelled one-to-one at t^*. In other words, if some economic changes (e.g. innovations, or policies) as captured by λ_t move demand from early periods before t_1 to late periods after t_1, so that banking in early periods increases, without changing the stage periods, such a change in the demand path reduces cumulative emissions:

Observation 1. *Conditional on $M_T = 0$, and the stages as denoted by t_1, t_2, t^*, t_3 remaining unaffected, the change in cumulative emissions equals the change in banking in the early periods, before t_1, multiplied by the shaving parameter:*

$$dE = -\alpha \sum_{t \leq t_1} dB_t \tag{15}$$

The condition of constant stages mentioned in the statement of the result points at an important property of the equilibrium. When prices go up, demand goes down. Lower demand means banking goes up and so the MSR increases. However, though demand is a continuous function of prices, both the flow into and the flow out of the MSR are discontinuous functions of banking, and thus demand. When banking decreases below $\overline{B}$, the flow into the MSR is suddenly and discretely reduced by an amount $\alpha\overline{B}$, and fewer allowances are canceled due to the mechanics of canceling, equation (10). That is, the number of allowances available cumulatively jumps up while demand goes down.[8] In other words, EU ETS introduces a, presumably unintended, side-effect: the MSR generates multiplicity of equilibria and thus ambiguity in equilibrium selection.

Proposition 1 (Multiplicity)**.** *For any ETS characterized by* $(\alpha, \beta, B_0, M_0, T, \underline{B}, \overline{B}, \Gamma, \boldsymbol{s})$*, there exists a (vector) demand function* $d_t(.)$ *such that at least two distinct equilibria, by prices* $p_1^* < p_2^*$*, exist supported with cumulative emissions* $E_1^* < E_2^* - \alpha\overline{B}$*.*

For the calibrated model, we will show that, indeed, multiplicity is an issue of concern. We say an equilibrium is (strictly) interior if the bank levels B_t are strictly separated from the thresholds $\underline{B}, \overline{B}$. For (sufficiently) small changes in demand λ_t, continuity is then preserved and we can state sharp conditions for a green paradox:

Proposition 2 (Carbon Leakage)**.** *Consider an interior equilibrium. A (small) shock in demand is dampened by the MSR if the shock is 'early':*

$$0 < \frac{dE}{d\lambda_1} < 1. \tag{16}$$

A (small) shock in demand is reversed (Green Paradox) if it occurs in a 'late' period:

$$\frac{dE}{d\lambda_t} < 0 \text{ if } t \geq t_1. \tag{17}$$

The proposition makes explicit that the timing of demand shocks is important for the final effect on emissions. Early demand reductions, while not 100% effective, still lead to a strictly positive fall in emissions in the aggregate; this is what Perino (2018) calls the puncturing of the waterbed, since with a classic waterbed effect, one would observe $dE/d\lambda_t = 0$. Late shocks, on the other hand, when anticipated today, lead to an increase in emissions. The logic is as follows. When firms today foresee a decline in demand (or value) of emissions allowances in the future (e.g. due to the implementation of some pre-announced policies), the price of allowances in the future will be lower and the incentive for banking reduced. However, in equilibrium, prices follow the Hotelling rule, and so allowance prices in fact decrease in *every* period. Lower prices today, in turn, lead to higher demand today. Hence, the demand (and use) of allowances will be higher in all periods leading up to the anticipated fallout of demand. Since this higher use means less allowances will be banked, the bank will shrink, and so will the MSR. However, since the MSR was assumed at some point to be so large that part of it

[8] Although the flow out of the MSR is also discontinous, as can be seen in the same equation, this does not affect cumulative supply as long as $t^* \leq t_2$, as is the case in our calibrated model.

will be shaved off, the increase in demand in early periods is effectively taken from the allowances otherwise canceled from the MSR. Thus, net emissions increase relative to the case where no future reduction in emissions demand had occured. A Green Paradox arises. We will come back to the importance of anticipation in the next section (see Figure 4).

If the shock in demand takes place after period 1 but before period t_1, the effect on aggregate emissions is in general ambiguous. As we will see in the simulations, if t is sufficiently early, aggregate emissions intuitively decline. However, if t is sufficiently close to t_1 (but still $t < t_1$), aggregate emissions increase.

4 Quantitative assessment

In the previous section, we showed analytically that under certain conditions, a demand-reducing policy in early periods ($t << t_1$) reduces cumulative emissions, while it increases cumulative emissions if it takes place later on ($t > t_1$). That is, as long as there exists a policy that reduces cumulative emissions, there exists a similar policy (but at a different point in time) that increases cumulative emissions.

One important condition for the latter result is that the demand-reducing policy is anticipated early on ($t < t_1$), so that forward-looking agents take this into consideration when they make decisions about banking. If the policy comes as a surprise, the result no longer holds. This illustrates the importance of policy announcement, that is, *when* the policy is announced. It is not only the timing of the policy that matters, but also the timing of announcement.

In this section, we first calibrate a stylized model for the EU ETS, and then use this model to quantify the effects discussed above. In the last subsection, we return to Proposition 1 and investigate whether there indeed are multiple equilibria in EU ETS.

4.1 Model calibration

The model is given by the equations in the previous section. We further specify the demand function as follows:

$$d_t(p_t; \lambda_t) = \Omega_t (p_t)^\sigma + \lambda_t, \tag{18}$$

where σ is the price elasticity and Ω_t is a time variant constant. We further assume that the demand function shifts by a constant linear factor $\omega = (\Omega_t - \Omega_{t-1})/\Omega_{2018}$. The parameter specifications are shown in Table 1 in the appendix. Here we give a brief explanation of how the model is parameterized. For more details and discussion of the calibration and corresponding assumptions, see the Appendix.

For the demand function, the parameters σ and ω are disciplined using historic evidence. That is, we 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 €/tCO_2; and iii) a simulated scenario that does not include the MSR rules, should have an initial price in 2019 at 7.5 €/tCO_2. That is, the model should be able to reproduce both the current ETS prices and those before the MSR was introduced.

The calibration leads to a price elasticity of -0.14 and a linear annual shift factor in the demand function of -1.7 percent. Further, for the (real) interest rate, 5 percent is chosen. Last but not least, the EU ETS is assumed to continue until 2050, requiring that banking in the last period is zero.

4.2 Quantitative results: Baseline scenario

The model described above can easily be simulated to derive the EU ETS market equilibrium for the period 2019-2050.[9] The outcome is shown in Figures 2-3, where we also display the time stages introduced in Figure 1.[10] Note that this should not be taken as a forecast of the EU ETS market. The purpose of this analysis is to examine the effects of demand-reducing policies at different points of time, given a possible but fairly realistic scenario for the future EU ETS market.

Figure 2 shows that supply exceeds demand until 2040 – which then reverses. Annual demand is equivalent with annual emissions, while supply refers to gross supply (s_t), i.e., before taking into account interaction with the MSR. Initially, net supply is significantly below gross supply (see Figure 2), and also well below demand, due to a large inflow into the MSR.

Figure 3 shows the stocks of allowance reserves, both privately held ("banking")

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

[10] By assumption, the ETS price starts at 21 Euro per ton in 2019, and reaches 95 Euro in 2050 (due to equation 15).

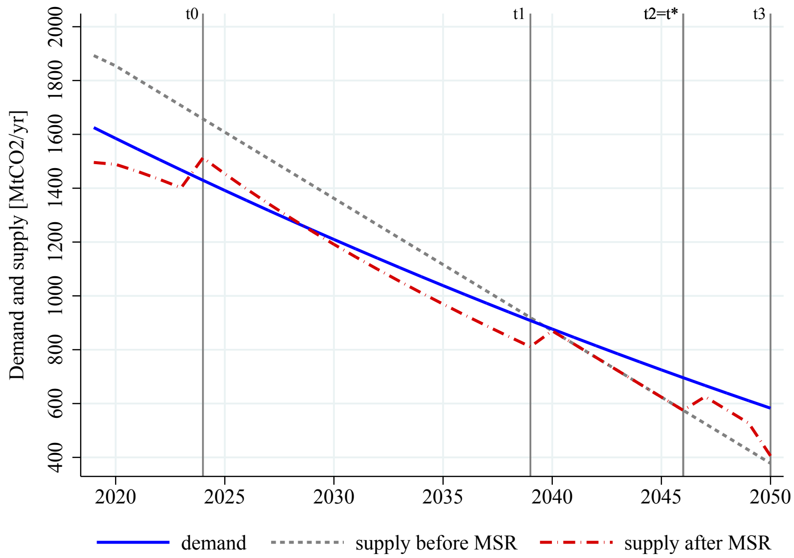

Figure 2: Market balance in Baseline scenario. Annual figures for the period 2019-2050.

and in the MSR. It also displays how allowances enter into, or are taken out of, the MSR, as well as the canceled allowances. There is a notable change in 2024, due to two important factors that year: Cancellation of allowances begins (t_0), and the withdrawal rate drops from 24 to 12 percent. The latter explains the increased net supply in 2024 (Figure 2), as well as the decline in m_t (labeled "MSR-in") (Figure 3). In this scenario, the MSR stops taking in allowances after 2039 (t_1), increasing net supply the next year (Figure 2). Cancellation of allowances is clearly biggest in 2024, but continues for two decades in this scenario. In total, 5.5 Gt of allowances are canceled until cancellation ends in 2046 ($t^* = t_2$), of which 3.7 Gt are canceled by 2030.[11]

4.3 Quantitative results: Effects of demand-reducing policy

We now turn to the main purpose of the numerical analysis, which is to examine the effects on cumulative emissions of a demand-reducing policy. We consider policies that reduce demand in a given year t ("reduction year") by one million EUAs (corresponding to 1 Mt of CO2). Moreover, the announcement of the policy can take place in any year s ("announcement year") up to the year when the demand reduction takes place

[11] As a comparison, Refinitiv Carbon (2018) 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.

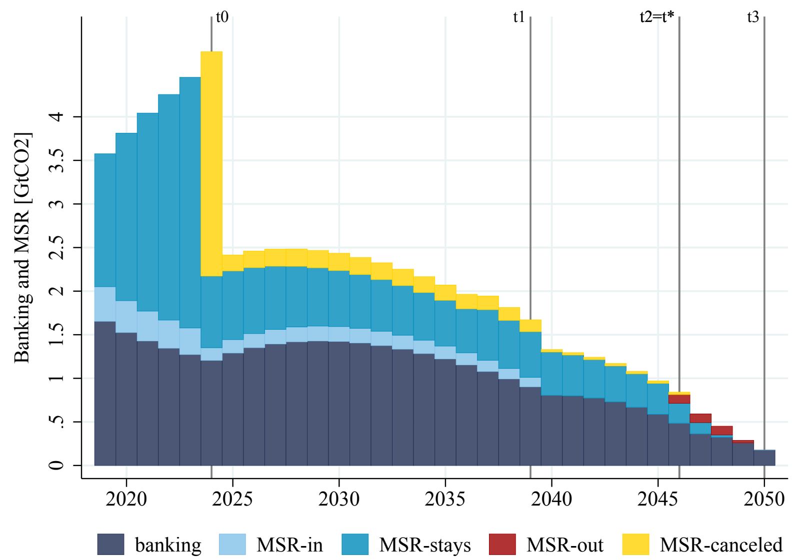

Figure 3: Stocks of allowances. The MSR is divided into the following four contents (cf. eq. 4): Input of allowances into MSR this period (m_t, "MSR-IN"); other allowances that remain in the MSR next period ("MSR stays"); allowances that leave MSR next period (n_t,"MSR-OUT"); and allowances that are canceled ("MSR Canceled"). Annual figures for the period 2019-2050 in Baseline scenario.

$(s \leq t)$.

Figure 4 shows the effect on cumulative emissions of such a demand-reducing policy. On the horizontal axis, we have the reduction year t. The curve "Announcement 2020" shows the effects on cumulative emissions of announcing the policy in 2020 ($s = 2020$), and we have similar curves for $s = 2025$ and $s = 2030$. The fourth curve shows the effects of announcing the policy the same year ($s = t$).

We first notice that a demand-reducing policy announced and realized in 2020 will reduce cumulative emissions quite substantially (relatively speaking). A decrease in emissions in 2020 by 1 Mt CO2 will reduce cumulative emissions by 0.9 Mt. The intuition is, as explained by Perino (2018), that less emissions in 2020 lead to more banking, which further increases the inflow into the MSR, and subsequently more cancellation of allowances.

Next, we see from the fourth curve that we get a similar but less pronounced effect as long as the demand-reducing policy is announced the same year, that is, until 2039 (t_1). Afterwards, the MSR does not take in more allowances (in our scenario, cf. Figure 3), which means that from 2039 onwards the supply of allowances is fixed. The reason

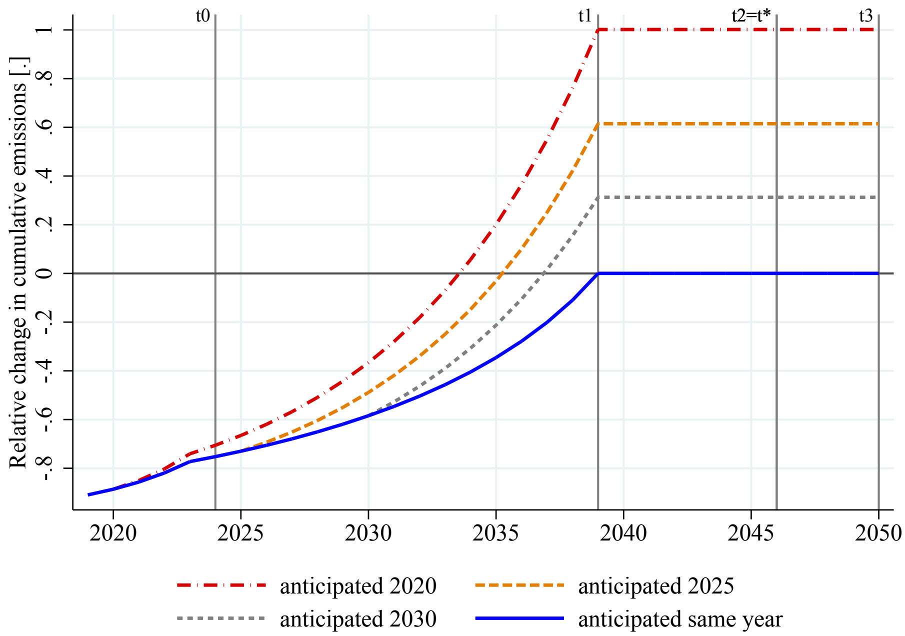

Figure 4: Effects on cumulative emissions of a demand-reducing policy that reduces demand by one million EUAs (1 Mt CO2) in the "reduction year" t, with the policy announced in year $s \leq t$.

why the effect on cumulative emissions is biggest in the early years is that there are more years with additional inflow into the MSR when banking is increased early on.

If the demand-reducing policy is announced years before it is realized, the effects are quite different though. For instance, if the policy is announced in 2020, but realized in 2039 or later ($t \geq t_1$), the net effect of the policy is to increase cumulative emissions by around 1.0 Mt (according to our simulations). That is, the policy has quite the opposite effect of what is intended as it increases rather than decreases total emissions. Hence, a green paradox. The intuition is that when agents in the ETS market foresee a less tight market in the future, it becomes less profitable than before to bank allowances from the preceding periods. With less banking, fewer allowances enter the MSR, and thus fewer allowances become canceled. Moreover, when fewer allowances are taken out of the market, this further reduces the market tightness – hence there is a multiplier effect which is bigger the longer the MSR is taking in allowances.

If the announcement is made in 2025 (or 2030), the effects on cumulative emissions are still perverse, but to a lesser degree as banking before 2025 (or 2030) is not affected. This illustrates the importance of policy announcement. It is not only the timing of the policy that matters, but also the timing of announcement.

We also see from the figure that if the demand-reducing policy takes place in year $\widehat{t}$, where $\widehat{t}$ is only a few years before the MSR stops taking in allowances (t_1), it can still have a perverse effect on cumulative emissions (if it is announced several years in advance). In this case, there will be less banking before, and more banking after, year $\widehat{t}$. Hence, fewer allowances enter the MSR before year $\widehat{t}$, whereas more allowances enter after year $\widehat{t}$. If year $\widehat{t}$ is quite close to t_1, the first effect dominates, and hence the net effect on cumulative emissions is positive.

We notice from the figure that all the three first curves have both negative and positive values. This illustrates the main theorem of this paper: If there exists a policy that reduces cumulative emissions, there exists a similar policy (announced at the same time, but realized at a different point in time) that increases cumulative emissions.

4.4 Quantitative results: Multiple equilibria

In proposition 1 we concluded that there exists a demand function such that there exist at least two distinct equilibria given the characteristics of the EU ETS. Here we want to investigate this issue in the context of the numerical model of the EU ETS. As we will see, with the calibrated demand function, there are indeed two distinct equilibria. One equilibrium is the one described in subsection 4.2, the other has a slightly higher price path.

When looking into this, it is useful to consider the level of banking at the end of the last period. In the model we require this to be zero, and we search for a price path that is consistent with this condition. Assume now that we instead consider different exogenous price paths (satisfying the Hotelling rule), and examine the net banking at the end of the last period for the different price paths. This is shown in Figure 5 for the first period price interval 20-25 Euro per tCO2.

At first thought, we would expect net banking to be a monotonically increasing function of the price, as a higher price increases abatement and hence reduces demand for allowances. However, we see from the figure that the net banking is only piecemeal increasing in the price, and then drops down at certain price levels. Moreover, we notice that there are two distinct first period prices where net banking at the end of the last period is zero, one at 21 and one just below 22 Euro per tCO2. In other words, both these prices (price paths) are feasible equilibria given the calibrated demand function.

What is the intuition here? It is useful to first consider the drop in net banking at the price around 21.5. When the initial price is 21.5, the level of banking falls marginally below the threshold of 833 Mt in 2039. Hence, no more allowances enter into the MSR. On the other hand, if the initial price is just above 21.5, banking in 2039 is marginally above 833 Mt. Hence, 100 Mt ($0.12 * 833$) more allowances enter into the MSR (instead of being auctioned) compared to the previous case, and thus fewer allowances are available in the market. Net banking at the end of the last period is therefore lower even though the price is (marginally) higher.

As the size of the MSR increases by 100 Mt in 2040 when the initial price is just above 21.5, but not if it is exactly 21.5, it follows that 100 Mt more allowances are (not) shaved off if the initial price is just above (equal to) 21.5. In Figure 6, we see indeed that cumulative cancellation jumps considerably around the initial price of 21.5, but not as much as 100 Mt. The reason is that the other MSR threshold also plays a role here, i.e., when allowances should return to the market (400 Mt). If the initial price is equal to 21.5, banking in 2046 is above the threshold, while if the price is marginally above 21.5, banking is below the threshold. Only in the latter case are allowances (100 Mt) released from the MSR, in which case there is no more cancellation. In the former case, the size of the MSR is somewhat above the cancellation threshold, and 28 Mt more allowances are canceled. This mitigates to some degree what happens in 2039, and so the net difference in cancellation is 72 Mt ($100 - 28$).

The same story explains the drop in net banking when the initial price is slightly above 23.5. We see that net banking also drops at initial prices around 20.1, 21.4, 22.6 and 24.0, but not as much. In these cases only the 400 Mt threshold plays a role.

5 Discussion and Conclusions

In this paper we have established that an emission trading system with endogenous emission cap, where the supply of emission allowances is responsive to demand, suffers from a green paradox. That is, there always exists an abatement policy that induces a green paradox. We have proven this in a very general framework, and then illustrated it both in an applied theoretical model and a quantitative analysis of the world's largest emission trading system: EU ETS.

Our analysis highlights the importance of anticipation: currently announced policies aiming to reduce emissions in the future run a risk of being severely impaired if not more than overturned. Cumulative emissions may increase rather than decrease as a

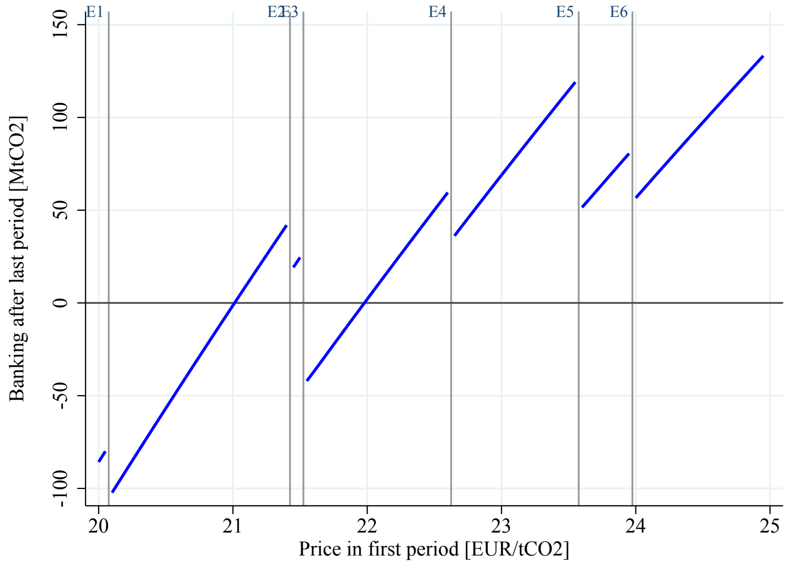

Figure 5: This figure shows banking after the last period as a function of the initial price, and illustrates the multiplicity of equilibria generated by the MSR. By definition, an equilibrium is characterized by the intersection of the banking curves with the horizontal line at 0. In this particular case, two equilibria exist: one at a first-period price of 21, the other at a price of 22. The six dotted lines at discrete jumps in the banking function indicate MSR-events. E1: banking rises above 400Mt in 2045. E2: banking rises above 400Mt in 2046. E3: banking rises above 833Mt in 2039 and drops below 400Mt in 2046. E4: banking rises above 400Mt in 2046. E5: banking rises above 833Mt in 2040 and drops below 400Mt in 2046. E6: banking rises above 400Mt in 2046.

consequence of abatement policies. This green paradox is even stronger than the one previously pointed to in the economics literature (Sinn, 2008).

That pre-announced policies may be less effective than 'surprise' ones is not a new insight, nor is it limited to the case of environmental policy. In fiscal policy, for instance, pre-announcement of policies has been found to substantially decrease their *net* effect (Auerbach and Gorodnichenko, 2012; Mertens and Ravn, 2012). Monetary policy is another such example (Sheehan, 1985). Our finding of a strong green paradox only underlines further the importance of very carefully considering new policies, including how and when to communicate them, especially so if this communication takes place in advance of actual implementation.

We have also shown, both analytically and numerically, that the new rules of the EU ETS imply that multiple equilibria may exist, meaning that two (or more) distinct price paths may both be consistent with the long-run requirement of no net banking

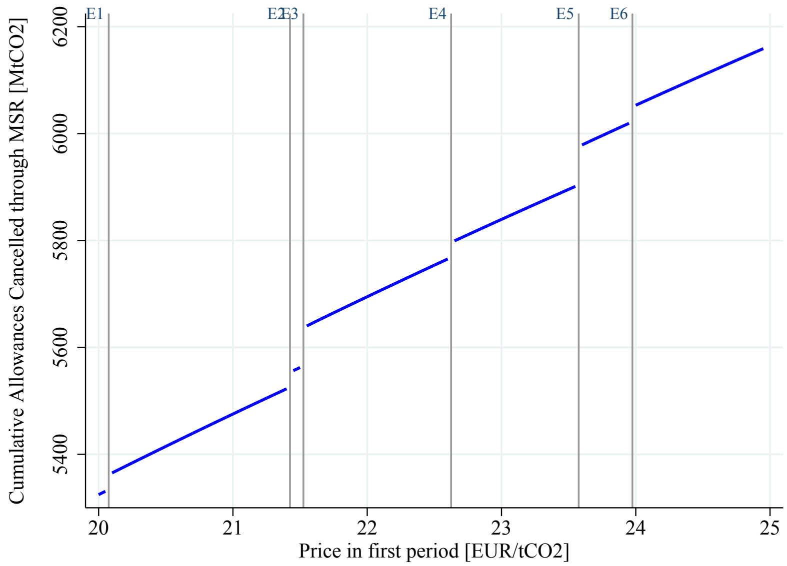

Figure 6: This figure shows the cumulative cancellation of allowances as a function of the initial price, and relates to Figure 5. Whenever one of the MSR thresholds is passed, cumulative cancellation jumps. For explanation of the discrete jumps, see the caption of Figure 5

after the last period of the ETS.

One crucial assumption behind our analysis is that the market has perfect foresight about the future ETS market. This is a strong assumption, but we believe that the mechanism underlying our result is highly relevant also with imperfect foresight. Still, an important question is to what degree market participants let expectations about the future affect their current decisions (Kollenberg and Taschini, 2019). Incorporating different forms of expectations into our model framework would be one interesting avenue for future research.

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A Proofs

A.1 Proofs for Section 2

PROOF OF LEMMA 1:

Proof. We write the full derivatives for the equilibrium equation (2):

$$-(\boldsymbol{u}-\boldsymbol{s}')^T\boldsymbol{d}'dp = (\boldsymbol{u}-\boldsymbol{s}')^T d\boldsymbol{\lambda} \tag{19}$$

We note that the term $-(\boldsymbol{u}-\boldsymbol{s}')^T\boldsymbol{d}'$ on the LHS is a positive scalar (due to Assumption 1 and $\boldsymbol{d}' < 0$); hence (6) follows. The positive price effect implies a negative demand response in all jurisdictions $j \neq i$, and because no free lunch is possible, there must be a positive demand response in the own jurisdiction i. Q.E.D.

PROOF OF THEOREM 1:

Proof. Proof by contradiction. We assume there is no green paradox. We show that we can then construct a demand-reducing policy $d\boldsymbol{\lambda} < 0$ such that demand decreases in all periods $d\boldsymbol{d} < 0$, and then we show that such an outcome violates the 'no free lunch' condition.

If there is no green paradox, then specifically all policies that reduce demand in some jurisdiction i decrease aggregate demand; the matrix Γ is diagonally dominant over columns: $\forall i : \boldsymbol{u}^T\boldsymbol{\gamma}^i \geq 0$.

Define normalized policies and responses. We write $\boldsymbol{\kappa}^i = d\boldsymbol{\lambda}^i/\boldsymbol{\gamma}^i_i < 0$, and $\boldsymbol{\eta}^i = \boldsymbol{\gamma}^i/\boldsymbol{\gamma}^i_i$, for the policy in jurisdiction i and the vector demand response over all jurisdictions, respectively, such that if $\boldsymbol{\kappa}^i = -\boldsymbol{e}^i$, the policy reduces demand by one unit in jurisdiction i. Let H be the matrix of normalized responses, $(H\boldsymbol{e}^i)_j = \boldsymbol{\eta}^i_j$. The matrix H is also diagonally dominant over its columns (inherited property from Γ), with unity elements on the diagonal and negative numbers everywhere else. In this notation, the effect of a policy vector $d\boldsymbol{\lambda} < 0$ on demand can be described through $d\boldsymbol{d} = H\boldsymbol{\kappa}$. Let A be chosen such that any policy directly reducing demand in jurisdiction i by one unit will reduce aggregate demand by at least A units: $A = \min_i\{\boldsymbol{u}^T H\boldsymbol{e}^i\}$. That is, A is the lower bound for the cumulative effectiveness of a policy in any jurisdiction i. Absence of a green paradox implies $A > 0$. We now have all notation in place.

We construct a series of vectors $\boldsymbol{z}^k$, with $k = 1, ..., \infty$, recursively, so that the series converges to $\boldsymbol{z}^k \to \boldsymbol{\kappa} < 0$, and $H\boldsymbol{\kappa} < 0$.

We start for $k = 1$ with $\boldsymbol{z}^1 = -\boldsymbol{e}^1$. That is, the policy $\boldsymbol{z}^1$ decreases demand in the first jurisdiction by one unit, $(H\boldsymbol{z}^1)_1 = -1$, increasing demand in all other periods, $\forall j \neq 1 : (H\boldsymbol{z}^1)_j > 0$, but aggregate demand is decreased, $\boldsymbol{u}^T H\boldsymbol{z}^1 < -A < 0$. This property also implies that the sum of all positive elements is bound from above: $\sum_i \max\{0, (H\boldsymbol{z}^1)_i\} < (1 - A)$.

We now describe the inductive step. We assume that in step k, we have (i) $\boldsymbol{u}^T H\boldsymbol{z}^k < 0$, and (ii) the sum of all positive elements is bound from above by $\sum_i \max\{0, (H\boldsymbol{z}^k)_i\} < (1-A)^k$. We can then construct the next element in the sequence, making sure that the properties (i) $\boldsymbol{u}^T H\boldsymbol{z}^{k+1} < 0$, and (ii) $\sum_i \max\{0, (H\boldsymbol{z}^{k+1})_i\} < (1-A)^{k+1}$ are transferred to the next inductive step.

In the inductive step, consider all positive elements of $\boldsymbol{u}^T H\boldsymbol{z}^k$, that we want to neutralize. Thus, let $\boldsymbol{z}^{k+1}$ be defined by $(\boldsymbol{z}^{k+1} - \boldsymbol{z}^k)_i = -\max\{0, (H\boldsymbol{z}^k)_i\} < 0$. The required properties follow immediately from this construction:

$$\boldsymbol{u}^T H\boldsymbol{z}^{k+1} = \boldsymbol{u}^T H\boldsymbol{z}^k + \boldsymbol{u}^T H(\boldsymbol{z}^{k+1} - \boldsymbol{z}^k) < 0 \tag{20}$$

$$\sum_i \max\{0, (H\boldsymbol{z}^{k+1})_i\} < (1 - A) \sum_i \max\{0, (H\boldsymbol{z}^k)_i\} < (1 - A)^{k+1} \tag{21}$$

Finally, we show that $\boldsymbol{z}^k \to \boldsymbol{\kappa} < 0$ is well defined, because from the construction, we see that we have a Cauchy sequence:

$$\boldsymbol{u}^T(\boldsymbol{z}^{k+1} - \boldsymbol{z}^k) = \sum_i \max\{0, (H\boldsymbol{z}^k)_i\} < (1 - A)^k \tag{22}$$

Any Cauchy sequence defined on a compact set converges to a point in the set. Thus, we want to establish compactness. To this end, recall that in any step κ, the sum of all positive demand-changes, i.e. the increase in aggregate in each step κ, was bound from above by $(1 - A)^\kappa$. The aggregate increase in demand is therefore never larger than $\sum_{\kappa=1}^{\infty}(1 - A)^\kappa = 1/A < \infty$, where the last inequality follows from the fact that $A > 0$. But this means the series of vectors $\boldsymbol{z}^k$ is defined on a closed and bounded set. By Heine-Borel, a closed and bounded set is compact.

Thus, we have $\boldsymbol{z}^k \to \boldsymbol{\kappa} < 0$, and $H\boldsymbol{\kappa} < 0$. We can rewrite before normalization that we have constructed a strict demand-reducing policy $d\boldsymbol{\lambda} < 0$ and associated strict negative emissions response in all jurisdictions, $\boldsymbol{\gamma} = \Gamma d\boldsymbol{\lambda} < 0$. But combine this with the 'no free lunch' assumption, $(\boldsymbol{u} - \boldsymbol{s}')^T > 0$, and we conclude $(\boldsymbol{u} - \boldsymbol{s}')^T \boldsymbol{\gamma} < 0$, which contradicts (5). Q.E.D.

A.2 Proofs for Section 3

To prove Proposition 1, we will make use of the following lemma. We first recall that there is an exogenous emission cap sequence $\boldsymbol{s} = (s_t)_t \gg 0$.

Lemma 2. *For each period t with $1 \leq t \leq T$, and any chosen $\psi_t \in [0, \overline{p}]$, a supporting price vector $(\psi_\tau)_{\tau=1}^{t-1}$ exists, such that the bank at period $\tau \in 1, ..., t-1$ cumulates excess supply for these prices:*

$$b_\tau = b_{\tau-1} + s_\tau - d_\tau(\psi_\tau) \geq 0 \tag{23}$$

with $b_0 = 0$, while the banking market arbitrage holds between all periods:

$$\forall \tau < t : \begin{cases} b_\tau = 0 \Rightarrow \psi_\tau \geq \psi_{\tau+1}, \\ b_\tau > 0 \Rightarrow \psi_\tau = \psi_{\tau+1}. \end{cases} \tag{24}$$

We define

$$\beta_t(\psi_t) = b_{t-1} + s_t - d_t(\psi_t), \tag{25}$$

which is increasing, with $\beta_t(0) < 0 < \beta_t(\overline{p}) = \sum_{\tau=1}^{t} s_\tau$, so that there exists a price ψ_t^* in period t for which the bank in period t becomes zero, $\beta_t(\psi_t^*) = 0$ and $0 < \psi_t^* < \overline{p}$.

Proof. Note that the ψ_τ in this lemma refers to the price sequence that leads to an equilibrium in all markets $\tau = 1, ..., t-1$, given the condition that the price in period t equals ψ_t. The proof uses induction for $1, .., t$.

For $t = 1$, the lemma follows immediately from the assumptions for $d_t(.)$ applied to $t = 1$ (Assumption 2).

The induction step. Assume the lemma holds for $\tau = 1, .., t-1$, implying that ψ_τ^* has been constructed for all $\tau = 1, .., t-1$. By backwards induction we construct the price vector:

$$\psi_{t-1} = \max\{\psi_{t-1}^*, \psi_t\}. \tag{26}$$

If we have $\psi_t < \psi_{t-1}^*$, then we generated $\psi_{t-1} = \psi_{t-1}^*$ and $b_{t-1} = 0$ and the banking market arbitrage (24) holds for $\tau = t-1$. If $\psi_t \geq \psi_{t-1}^*$, then we generated $\psi_{t-1} \geq \psi_{t-1}^*$ and since $\beta_t(.)$ increasing, we have $b_{t-1} \geq 0$ and the arbitrage also holds. By invoking the lemma for the previous period, we have that equations (23) and (24) are thus satisfied for all previous periods as well.

We still need to prove that $\beta_t(.)$ is increasing and $\beta_t(0) < 0 < \beta_t(\overline{p})$. We can write the bank in period t as a function of prices $\beta_t(\psi_t) = s_t + \beta_{t-1}(\psi_{t-1}) - d_t(\psi_t)$.

We see that $\beta_{t-1}(.)$ is increasing, $d_{t-1}(.)$ is decreasing, and we note that ψ_{t-1} is a continuous increasing function of ψ_t, directly from (26). It follows immediately that $\beta_t(.)$ is increasing as well.

For $\psi_t = 0$ we have $\psi_{t-1} = \psi^*_{t-1} \Rightarrow b_{t-1} = 0 \Rightarrow \beta_t(0) = s_t - d_t(0) < 0$.

For $\psi_t = \overline{p}$ we have $\psi_\tau = \overline{p}$ for all $\tau \Rightarrow b_t(\overline{p}) = s_t - d_t(\overline{p}) + b_{t-1} = \sum_{\tau=1}^{t} s_\tau$. Q.E.D.

PROOF OF PROPOSITION 1

Proof. Note that we only need to construct an example. Construct an equilibrium sequence $(d^*_t, m^*_t, n^*_t, B^*_t, M^*_t)$ that satisfies the dynamic equations, and for which $B^*_{t_1+1} = \overline{B} - \varepsilon$ with ε small. Say that the corresponding equilibrium price is p^*_1. We can then easily construct a second equilibrium, denoted by hats, with $\widehat{d}_{t_1+1} = d^*_{t_1+1} - 2\varepsilon$, $\widehat{d}_{t_1+2} = d^*_{t_1+2} - \alpha(\overline{B} + \varepsilon) + 2\varepsilon$, and $\widehat{d}_t = d^*_t$ for all other t. That is, the demand function is inelastic everywhere but at $t \in t_1 + 1, t_1 + 2$, when a price increase to $p^*_2 > p^*_1$ exactly results in the alternative demand. To show that the second equilibrium is indeed an equilibrium, first note that $\widehat{B}_{t_1+1} = \overline{B} + \varepsilon$, so that $\widehat{M}_{t_1+2}$ increases by $\widehat{m}_{t_1+2} = \alpha(\overline{B} + \varepsilon)$ $(m^*_{t_1+2} = 0)$. Banking at the end of period $t + 2$ is now $\widehat{B}_{t_1+2} = B^*_{t_1+2} - (\widehat{d}_{t_1+2} - d^*_{t_1+2}) - (\widehat{m}_{t_1+2} - m^*_{t_1+2}) = B^*_{t_1+2}$. Hence, $\widehat{B}_t = B^*_t$ also for $t > t_1 + 2$, which shows that this is indeed an equilibrium. The additional inflow of allowances into the MSR in period $t + 2$ are canceled, which implies that cumulative supply, and thus emissions, drop by $\widehat{m}_{t_1+2} = \alpha\widehat{B}_{t_1+1} > \alpha\overline{B}$. We have thus proved the proposition. Imposing a strictly decreasing demand function (ruling out entirely inelastic demand) can be accommodated by small perturbations. Q.E.D.

Proposition 2 will be proven *as if* only three periods existed, coinciding with the timing variables t_1, t_2, and t_3. This is done for convenience of notation. It is straightforward to extend the proof to more general, non-normalized periods t, but would come at the cost of cumbersome notation.

PROOF OF PROPOSITION 2:

Proof. Note that in the first period, the equilibrium on the market (11) is given by:

$$B_2 = s_1 - d_1(p_1; \lambda_1). \tag{27}$$

The first part of the proof will establish the result for an early positive shock $(d\lambda_1 > 0)$.

Our proof will consist in proving each of the following (in)equalities:

$$\begin{aligned} dE &= dd_1 + dd_2 + dd_3 && (28)\\ &= -dB_2 + (1-\alpha)dB_2 - dB_3 + dB_3 && (29)\\ &= -\alpha dB_2 && (30)\\ &= \alpha dd_1 > 0 && (31) \end{aligned}$$

Step 1. We are interested in dE, which was defined to be $dd_1 + dd_2 + dd_3$. Recall we normalized the demand shift parameter λ_t such that $\partial d_t/\partial\lambda_t = 1$, so we have $dd_t = d\lambda_t + d_t' dp_t$. In the following three steps, we will find expressions for each of the three elements on the right-hand side of equation (28).

Step 2. We recall that s_t is exogenous, meaning $ds_t = 0\ \forall t$. Equation (27) then implies $dd_1 = -dB_2$, which is the first part on the right-hand side of (28).

Step 3. Note that $B_3 = B_2 + s_2 - d_2 + n_2 - m_2$, as given by equation (11). Writing in differences, we have $dB_3 = dB_2 - dd_2 + dn_2 - dm_2$. By assumption, we also have $B_2 > \overline{B}$, and so as a result of the dynamic equation (10) we have $(m_2, n_2) = (\alpha B_2, 0)$ and thus $(dm_2, dn_2) = (\alpha dB_2, 0)$, meaning $dB_3 = (1-\alpha)dB_2 - dd_2$. Hence, the bank at the start of period 3 is increasing in the bank at the start of period 2 (since by definition what is in the bank is carried over to the future if it is not used), but decreasing in demand in period 2. Because $dB_2 = dd_1$ and $dd_2 = d_2' dp_2 = d_2' dp_1/\delta$, we write: $dB_3 = -(1-\alpha)dd_1 - dd_2 = -(1-\alpha)dd_1 - d_2' dp_2 = -(1-\alpha)dd_1 - d_2' dp_1/\delta$. We can conveniently write this as $dd_2 = (1-\alpha)dB_2 - dB_3$, which is the second part on the right-hand side of (28).

Step 4. Note that we assume the Second Coming of our Lord and Savior Christ in the fourth period, which the very devoutly religious agents acting in this model know and anticipate, so that $B_4 = s_4 = d_4 = ... = 0$. The implication, from (11), is: $dd_3 = dB_3 + dn_3 - dm_3$. Now, dB_3 has been derived in the previous step. By assumption $m_3 = dm_3 = 0$ and $n_3 = S_2$, which it already was, so $dn_3 = 0$ also (which, note, implies $(dM_2 + m_2 - s_2)/d\lambda_1 > 0$). Combining we find $dd_3 = dB_3$, which is the third part on the right-hand side of (28).

Step 5. Having derived all three parts on the right-hand side of (28), we can substitute these and rewrite to obtain (30). This can in turn be rewritten as (31), since we know from Step 1 of this proof that $dd_1 = -dB_2$. Our final step will be to prove the inequality in (31), i.e. to show that $dd_1/d\lambda_1 > 0$.

Step 6. (By contradiction) We finally want to show that $dd_1/d\lambda_1 > 0$. Assume not, so $dd_1/d\lambda_1 = 1 + d_1' dp_1/d\lambda_1$, meaning $d\lambda_1 < -d_1' dp_1$. For simplicity we consider $d\lambda_1 > 0$. Since $dB_2/d\lambda_1 = -dd_1/\lambda_1 < 0$ this would imply in response $dB_2 < 0$. Since $dB_3 + dd_2 = (1-\alpha)dB_2$, it follows $dB_3 + dd_2 < 0$. Now, say $dB_3 > 0$, so it must be that $dd_2 < 0$. As $dB_3 = dd_3$ this implies $dp_3 < 0$, implying in turn (by Hotelling) that $dp_2 < 0$, which cannot be as $dd_2 < 0$ implies $dp_2 > 0$ (since $d\lambda_2 = 0$). Consequently, it must be that $dB_3 < 0$. It is known that $dd_3 = dB_3$ and so $dd_3 < 0$, which means $dp_3 > 0$, and by Hotelling we also have $dp_2 > 0$ and $dp_1 > 0$. However, for dp_2 to be positive, we would need $dd_2 < 0$, and since by know $dd_2 = (1-\alpha)dB_2 - dB_3$ combined with the fact that $dB_3 < 0$ by hypothesis, it must be that $dB_2 < 0$. Note then we have previously derived $dB_2 = -dd_1$, so we obtain $dd_1 > 0$. Hence it cannot be that $dd_1/d\lambda_1 < 0$ and so we conclude $dd_1/d\lambda_1 > 0$.

Step 6. (Constructive) Hotelling implies $dp_1 = dp_2/\delta = dp_3/\delta^2$, so we have $dd_1 = d\lambda_1 + d_1' dp_1$, $dd_2 = d_2' dp_2 = d_2' dp_1/\delta$ and $dd_3 = d_3' dp_3 = d_3' dp_1/\delta^2$ (as $d\lambda_2 = d\lambda_3 = 0$). Note we have previously derived $dB_3 = dd_3$ so we have $dB_3 = d_3' dp_1/\delta^2$. We have also seen that $dB_3 = (1-\alpha)dB_2 - dd_2 = (1-\alpha)dB_2 - d_2' dp_1/\delta$ and, since $dB_2 = -dd_1$, we have $dB_3 = -(1-\alpha)dd_1 - d_2' dp_1/\delta = -(1-\alpha)d\lambda_1 - (1-\alpha)d_1' dp_1 - d_2' dp_1/\delta$. Since obviously $dB_3 = dB_3$ we have:

$$d_3' \frac{dp_1}{\delta^2} = -(1-\alpha)d\lambda_1 - (1-\alpha)d_1' dp_1 - d_2' dp_1/\delta \tag{32}$$

$$\Longrightarrow \tag{33}$$

$$\frac{dp_1}{d\lambda_1} = -\frac{1-\alpha}{(1-\alpha)d_1' + \frac{d_2'}{\delta} + \frac{d_3'}{\delta^2}} > 0. \tag{34}$$

The implication is that $dp_2/d\lambda_1 > 0$ and $dp_3/d\lambda_1 > 0$ (by Hotelling). Since $dE = \alpha dd_1$, which we derived earlier, and $dd_1 = d\lambda_1 + d_1' dp_1$, we can plug in equation (34) and obtain:

$$\frac{dE}{d\lambda_1} = \alpha \frac{dd_1}{d\lambda_1} = \alpha \left[1 - \frac{(1-\alpha)\delta^2 d_1'}{(1-\alpha)\delta^2 d_1' + \delta d_2' + d_3'}\right] = \alpha \left[\frac{\delta d_2' + d_3'}{(1-\alpha)\delta^2 d_1' + \delta d_2' + d_3'}\right] > 0, \tag{35}$$

which completes the first part of the proof.

Next we consider an anticipated late shock ($d\lambda_3 > 0$). Remember that by hypothesis $m_1 = n_1 = 0$, $m_2 > 0$, $n_2 = 0$, $m_3 = 0$, and $n_3 = s_2$. Hence, $d_3 = s_3 + B_3 + n_3$ and so $dd_3 = dB_3$, but also $dd_3 = d\lambda_3 + d_3' dp_3$, hence $d\lambda_3 + d_3' dp_3 = dB_3$. Now from Hotelling we have $dp_1 = \delta^2 dp_3$ and $dp_2 = \delta dp_3$. Remember also from equation (11), we know $dB_3 = dB_2 - dd_2 - dm_2$, which gives $dB_3 = -dp_3[(1-\alpha)\delta^2 d_1' - \delta d_2']$. Having derived dB_3 in two different ways, we can set these equal to one another:

$$d\lambda_3 + d_3' dp_3 = -(1-\alpha)d_1'\delta^2 dp_3 - d_2'\delta dp_3 \tag{36}$$

$$\Longrightarrow \tag{37}$$

$$\frac{dp_3}{d\lambda_3} = -\frac{1}{(1-\alpha)\delta^2 d_1' + \delta d_2' + d_3'} > 0. \tag{38}$$

We have so far found that $dd_1 = d_1' dp_1 = d_1'\delta^2 dp_3$ and $dd_3 = d\lambda_3 + d_3' dp_3$. Since we are interested in $dE/d\lambda_3$, and since $dE = dd_1 + dd_2 + dd_3$, we must still find dd_2. To this end, recall that $dd_3 = dB_3$, so we know from (11) that $dB_3 = dB_2 - dd_2 - dm_2 = -dd_1 - dd_2 - dm_2$, and since $dB_2 = dd_3$ it implies: $dd_2 = -dd_1 - dd_2 - dm_2$. Hence, $dE = dd_1 + dd_2 + dd_3 = -dm_2$. Since we assumed $m_1 = n_1 = 0$ and $m_2 > 0$ it follows from (10) that $-dm_2 = -\alpha dB_2$, but this we derived previously is αdd_1. Since we know dd_1 from (36), we may say:

$$\frac{dE}{d\lambda_3} = \alpha\frac{dd_1}{d\lambda_3} \tag{39}$$

$$= \alpha\delta^2 d_1'\frac{dp_3}{d\lambda_3} \tag{40}$$

$$= -\alpha\left[\frac{\delta^2 d_1'}{(1-\alpha)\delta^2 d_1' + \delta d_2' + d_3'}\right] < 0. \tag{41}$$

This concludes the proof. Q.E.D.

B Model parametrization

Table 1 displays the specification of parameter values in the model. Several of the parameters are either specified by the policy, or based on historic observations (i.e., emissions and banking). The last four parameters in Table 1 are uncertain but important. The main text explains the calibration procedure. Here some more details are provided. As mentioned in the main text, we 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

Parameter name	Parameter description	Parameter value
$\overline{B}$	Threshold for inflow into MSR	833 Mt
α	Withdrawal rate (Pace of inflow into MSR)	0.24 (2019 - 2023) 0.12 (from 2024)
$\underline{B}$	Threshold for outflow from MSR	400 Mt
Γ	Outflow from MSR	100 Mt
β	Threshold factor for canceling allowances	0.57
s_{2019}	Supply of allowances in 2019	1 893 Mt
	Linear reduction factor of S_t	1.74% (until 2020) 2.2% (from 2021)
B_{2018}	Banking end of 2018	1 654 Mt
	Additional transfer of EUAs into MSR (back-loading + unallocated)	1 640 Mt
	First year of cancellation	2024
σ	Demand elasticity	-0.14
ω	Linear shift in demand function	-1.73%
δ	Discount factor	1/1.05
n	Number of periods	32 (2019-2050)

* 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), Perino (2018) and Refinitiv Carbon (2018).

Table 1: Specification of parameter values

was 16.0 Euro per ton. Emissions in 2018 were 1749 Mt.[12]

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

[12]https://ec.europa.eu/clima/news/emissions-trading-emissions-have-decreased-39-2018_en

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 percent and inflation rate of 1.5 percent, this corresponds to 7.5 Euro in 2019.

As mentioned in the main text, the calibration leads to a price elasticity of -0.14. As a comparison, the results in Böhringer et al. (2017b) 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, we 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 RefinitivCarbon (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.

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 1.73 percent 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 percent. Looking at futures prices of EUAs suggest a lower interest rate, even in nominal terms.[13] At the time of writing, the annual futures prices increase by 3-4 percent 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).[14]

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 percent of the

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

[14] An alternative approach could be to assume (partly) myopic behaviour by the market participants.

current supply, given no change in the linear reduction rate after 2021. Of course, it is difficult to know what will happen around 2050 (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 2018.[15] 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 740 million allowances (RefinitivCarbon (2018)).

C GAMS Program

```
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);
    alias(t,ttt);

    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 Discount rate
    sigma Demand elasticity
    g Linear annual reduction factor in demand function
    beta Threshold for canceling allowances (as a share of s)
```

[15] https://ec.europa.eu/clima/sites/clima/files/ets/reform/docs/c_2019_3288_en.pdf

```
p0 Average price in 2018 (t=0)
d0 Demand in 2018 (t=0)
;

r = 0.05 ;
sigma = -0.14 ;
g = 0.017339125 ;
* Assumed share of auctioning
beta = 0.57 ;
* Average price in 2018 used to calibrate demand function
p0 = 16 ;
* Demand (incl aviation) in 2018
* https://ec.europa.eu/clima/news/emissions-trading-emissions-have-decreased-39-2018˙en
d0 = 1749 ;

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

* Supply (incl aviation) from 2019 based on https://ec.europa.eu/clima/policies/ets/cap˙en
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 ;
Omega(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
;

Variables
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 the equation 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= Omega(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 + 740 ;

M.fx(t)$tn(t) = 0 ;

* 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;

*Help GAMS find the wanted equilibrium (due to multiple equilibria)
p.up("1") = 21.013 ;

* 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 + 740 ;
```

```
B.fx("0") = 1654 ;

Parameter
CumC˙REP(tt) Reporting CumC for deltaD in different periods
CumCC˙REP(ttt,tt) Reporting CumC for deltaD in different periods (tt) and different announcements (ttt)
;

loop(ttt$(ord(ttt) gt 1 and ord(ttt) lt card(ts)),
deltaD(t) = 0 ;
Solve MSR˙YES using mcp ;
* Fixing historic levels (before time ttt)
B.fx(t)$(ord(t) lt ord(ttt))=B.l(t) ;
M.fx(t)$(ord(t) lt ord(ttt))=M.l(t) ;
d.fx(t)$(ord(t) lt ord(ttt))=d.l(t) ;
C.fx(t)$(ord(t) lt ord(ttt))=C.l(t) ;
ts(t) = yes$(ord(t) ge ord(ttt)) ;
ts2(t) = yes$(ord(t) ge ord(ttt) and ord(t) lt card(ts)) ;

* Inner loop starts here
loop(tt$(ord(tt) ge ord(ttt) and ord(tt) lt card(ts)),
deltaD(t)$(ord(t) eq ord(tt)) = 1 ;
display deltaD;
* Solve the model with reduced demand in one period:
Solve MSR˙YES using mcp ;
* Remembering the effect on CumC in this scenario:
CumCC˙REP(ttt,tt) = CumC.l ;
* Nullifying the reduced demand before next loop
deltaD(t) = 0 ;
);
);

display CumCC˙REP ;
```