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The case of the EU ETS

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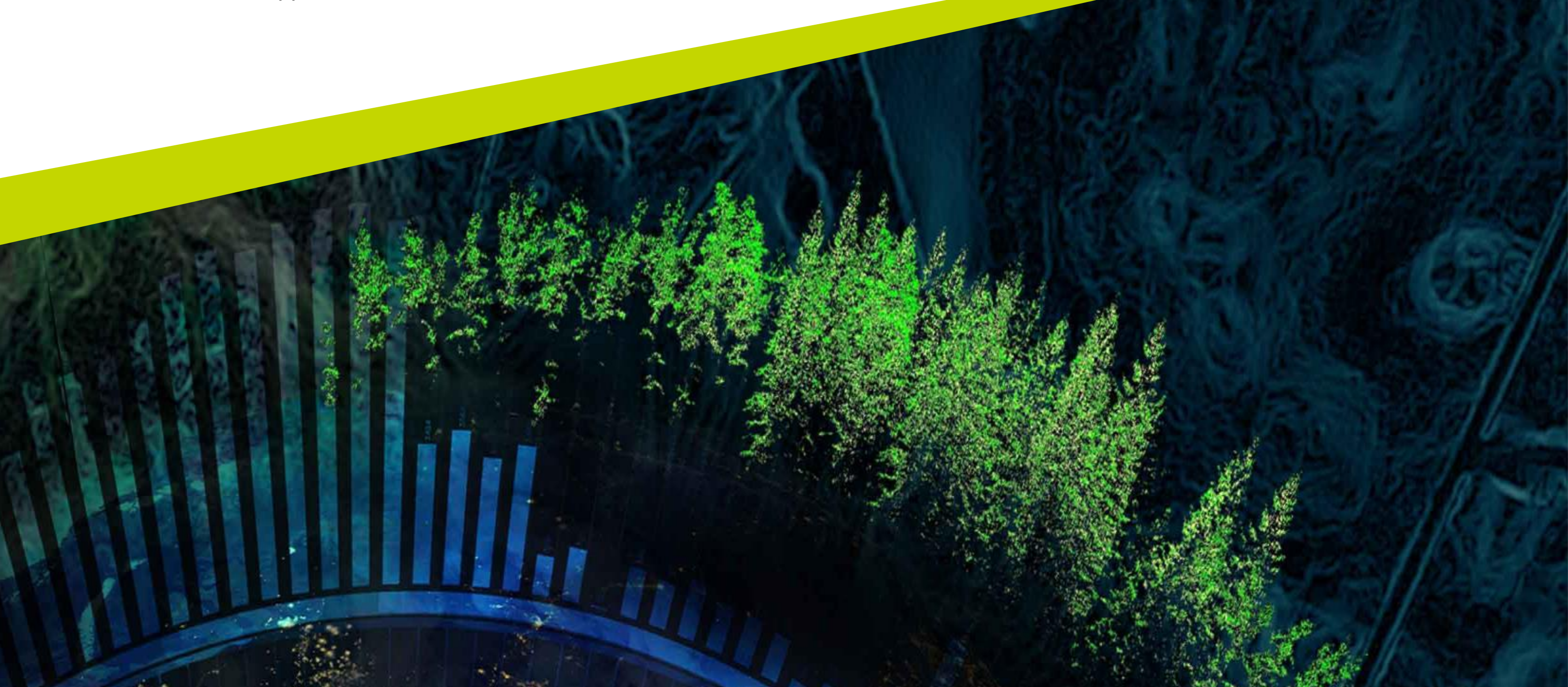

How the duration of a cap-and-trade scheme with an adjustable emissions cap affects cumulative emissions. The case of the EU ETS

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Abstract

The European Union Emissions Trading System (EU ETS) is a cap-and-trade scheme, whose adjustable supply of allowances is determined by a quantity mechanism, as opposed to a price mechanism. This paper quantifies the reduction in cumulative emissions that arises from bringing the final year of a cap-and-trade scheme that operate a quantity mechanism, such as the EU ETS, forward in time. Using a dynamic simulation model of the EU ETS, the paper shows that bringing the final year forward in time will lead to cumulative emissions reductions, if the duration is sufficiently or drastically shortened. On the other hand, shortening the duration of the scheme to a lesser extent will lead to increased cumulative emissions. Moreover, the intuition behind the result is described through a three-period theoretical model of emissions trading. These results have implications not only for emissions in the EU, when the EU ETS is complemented by other policies such as the European Green Deal, but also for the design of overall quantity-based policy instruments for cap-and-trade schemes. The paper concludes by stating that careful consideration should be considered for future reforms of the EU ETS and for broader climate policies.

Keywords: Emissions trading, EU ETS, Market Stability Reserve, Policy design.

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Abbreviations

ETS	Emissions Trading System
EU	European Union
GHG	Greenhouse gas
$GtCO_2$	Billion tonnes of carbon dioxide
LRF	Linear Reduction Factor
MSR	Market Stability Reserve
$MtCO_2$	Million tonnes of carbon dioxide

1. Introduction

Cap-and-trade schemes have emerged as a prominent policy tool in addressing the challenge of reducing greenhouse gas (GHG) emissions and mitigating the impacts of climate change. By placing a limit, or “cap”, on the total amount of emissions and creating a market for trading emission allowances, cap-and-trade schemes offer a market-based approach to incentivize emissions reductions while aiming at maintaining economic efficiency.

Under a cap-and-trade scheme, firms are given allowances that represent the right to emit a certain amount of pollution, and which add up to the cap. If a firm emits more than its allowances permit, it must buy extra permits from other firms that have emitted less. Hence, cap-and-trade schemes represent a market where allowances can be bought and sold.

The aim of this paper is to investigate how cumulative emissions are affected by the duration of a cap-and-trade scheme. Understanding how cap-and-trade schemes influence emissions is important, as it enables policymakers to craft well-designed policies that incentivize emission reductions.

Most cap-and-trade schemes today have adjustable caps. This implies that the supply of allowances in the scheme is determined by observable market conditions. In this regard, the adjustable cap in such schemes is typically determined by one of two prominent designs: *price* or *quantity* mechanism. The difference between these two is important to consider, as they have distinct implications for emissions reduction outcomes and how the schemes operate in general. On one hand, under a price mechanism, the supply of allowances is mainly determined through their price. Examples of existing cap-and-trade schemes where the adjustable cap depends on price mechanisms include the California ETS, and the Regional Greenhouse Gas Initiative (RGGI) in north-eastern USA. On the other hand, the adjustable cap of allowances under a quantity mechanism is instead determined by the level of banked allowances of firms (i.e., unused allowances that are saved for later use). The most common example of a scheme that operates under a quantity mechanism is the European Union Emissions Trading System (EU ETS), whose cap is determined by its Market Stability Reserve (MSR)[1].

A notable distinction between the two mechanisms is that price mechanisms use observed price levels to adjust and stabilize the quantity of allowances, hence functioning like a hybrid policy between price and quantity. Quantity measures, on the other hand, ignore the market price to instead adjust the cap based solely on the

[1] The MSR is explained in detail in section 3 of this paper.

number of allowances, thus being a pure quantity policy (Fell and Morgenstern, 2010).

This paper investigates the case of the largest cap-and-trade scheme to date, that is the EU ETS, and the focal point is hence that of quantity mechanisms. Specifically, the research question is: *how are emissions affected by the duration of a cap-and-trade scheme when the adjustable cap of allowances is determined through a quantity measure?*

The study addresses the research question in two ways. Fistly, by using an already established model that was developed in Heijmans (2022) and using its result as a starting point, the current paper uses a similar model that describes emissions trading under three time-periods. Secondly, the results from the theoretical model are quantified numerically in a simulation model of the EU ETS. Through the numerical model, the paper presents two main results. Firstly, shortening the duration of a cap-and-trade scheme with a quantity-based cap could lead to a significant increase in cumulative emissions. In total, this increase in emissions could rise to 7.44 percent. Secondly, there exist conditions for emissions reductions if the duration of the scheme is strongly shortened. These two results are the contribution of this paper.

The intuition behind the results can be explained by two counteracting effects that are drawn from the theoretical model. Firstly, by bringing the end year of the scheme forward in time, the supply of allowances that would have been supplied if the scheme had not been shortened are permanently eliminated. This acts as a direct cut in allowances. Secondly, by anticipating a shortening in the duration of the scheme, firms will shift their demand to earlier periods to offload their unused banked allowances before the new final year. This leads to a decrease in aggregate banking in earlier periods. Due to the design of quantity mechanisms, the decrease in early-period banking causes less supply of allowances to be eliminated, thus effectively increasing emissions. Hence, whether cumulative emissions increase or decrease from a shortening of the scheme depends on which one of these two effects is the strongest.

Furthermore, as mentioned in Heijmans (2022), the duration of a cap-and-trade scheme can be understood in numerous ways. Two separate interpretations are discussed briefly. Firstly, the scheme could simply end, decidedly by the hand of a social planner. This causes an abrupt end to the scheme starting from a certain year. Secondly, an exogenous supplementary policy such as a ban on emissions, could *effectively* end the scheme. In this case, the duration of the scheme does not end by its own means, but rather by an overlapping policy that turns the scheme obsolete starting from a given year.

The findings of this paper have implications not only for the future emissions trajectory of the EU ETS but also for the design of quantity-based permit markets in general. More precisely, the results indicate that the timing of emissions, or how overlapping policies that affect the timing of emissions, do not easily combine with quantity-based cap-and-trade schemes. This also holds true for the case of the EU ETS as it may overlap with the European Green Deal, which aims at reaching net zero emissions in 2050. Taking this into consideration, the paper raises concerns about the EU's ability to achieve its climate ambitions.

This study contributes to the body of literature that examines permit schemes under quantity mechanisms, and their impact on emissions when combined with overlapping climate policies (see Gerlagh et al., 2021; Perino et al., 2021; Heijmans, 2022).

The structure of the paper is as follows. The next section presents a literature review of relevant studies. Section 3 gives an overview of the EU’s climate ambitions, the EU ETS, and the MSR that was introduced as a means of stabilizing the EU ETS market. Thereafter, section 4 demonstrates the three-period model that explains the mechanisms of a quantity-based scheme. Section 5 illustrates the stylized model of the EU ETS. Section 6 displays the results from the numerical model. Section 7 discussed these results as well as highlights the limitations of the study. The final section concludes.

2. Literature review

The literature on carbon pricing as a way to control pollution and reduce GHG emissions dates back to Weitzman (1974) and Roberts and Spence (1976). Carbon pricing instruments are typically characterized by either price or quantity mechanisms. The effectiveness of price mechanisms, usually in the form of a tax, versus quantity mechanisms, typically as a cap-and-trade scheme, have been comprehensively debated.

Weitzman (1974) drew attention to the distinctions between price and quantity instruments. He concluded that uncertainty regarding abatement costs can lead to different welfare outcomes depending on the instrument used.[2] Complementing and extending Weitzman's conclusions, Roberts and Spence (1976) introduced the idea of combining quantity-based cap-and-trade schemes with a price ceiling that adjusts the number of permits: hence allowing permit schemes to act as a sort of hybrid system of both price and quantity instruments. They demonstrated that under cost uncertainty, a hybrid policy can be more advantageous than price or quantity mechanisms taken separately (Roberts & Spence, 1976).

To date, there exists an extensive literature that examines the various characteristics and impacts of cap-and-trade schemes with adjustable caps, similar to the ones discussed in Roberts and Spence (1976). This includes schemes that operate under both price and quantity mechanisms.

Cap-and-trade schemes operating under price mechanisms have been the subject of numerous academic research papers and policy analyses (Pizer, 2002; Abrell and Rausch, 2017; Borenstein et al., 2019 *on the California ETS*; Friesen et al., 2022 *on the RGGI*).

For this paper however, it is more relevant to review the literature that focuses on cap-and-trade schemes that operate under quantity measures. In this field, economists have typically examined the existing case of the EU ETS, under which the MSR is adjusting its cap (Hepburn et al., 2016; Kollenberg and Taschini, 2016; Perino and Willner, 2016; Lintunen and Kuusela, 2018). For example, Chaton et al. (2019) and Kollenberg and Taschini (2019) evaluate the implications of the adjustable EU ETS cap on allowance prices and banking decisions of firms under uncertainty. By using different stochastic general equilibrium models of intertemporal emissions trading, they both find support for the implementation of the adjustable cap of the EU ETS. Both studies conclude that the adjustable cap of the EU ETS would likely contribute to increased short-run prices as well as long-run market stability.

[2] Specifically, Weitzman (1974) argued that a quantity instrument performs better that a price instrument if the marginal benefit curve of abatement is steeper than the marginal cost curve. In the opposite scenario, a tax perform better.

Osorio et al. (2021) advance this discussion and show that, although the MSR might lead to stabilizing the EU ETS price, emissions and cancellation of allowances are still highly sensitive to the complexities of the MSR design and the linear reduction factor (LRF).[3] To summarize, these studies mostly agree that although the EU ETS cap adjusted by the MSR is a complex design, it seems to fulfill its purpose of market stability.

Other papers have tried to quantify the direct effect of the MSR mechanisms on EU ETS emissions. Among such papers, Bruninx et al. (2020) analyze emissions reductions under the early reforms of the MSR after 2018. Using a long-term investment model with a focus on the electric power sector, they illustrate that the implementation of the MSR could result in cumulative emissions reductions within the EU ETS of up to 21.3 $GtCO_2$, compared to the cumulative cap of 52.2 $GtCO_2$ without any MSR. Moreover, the authors conclude that the effectiveness of the MSR could be sensitive to overlapping climate policies.

The conclusion of Bruninx et al. (2020) has further been confirmed by additional studies, such as Perino (2018), Gerlagh et al. (2021), and Perino et al. (2021). These papers argue that the intervention of the MSR together with overlapping climate policies is a reason for concern for the climate ambitions of the EU. Assessing the risks that arise from the MSR's design, Perino et al. (2021) highlight that the MSR, when supplemented with other climate policies, may even act in a counterproductive way and produce a so-called 'green paradox' that causes emissions to increase. This is also what Gerlagh et al. (2021) conclude and quantify. Using a stylized two-period model and doing a quantitative assessment, they show that, depending on the announcement year of the policy, an overlapping demand-reducing policy that corresponds to a reduction of 1 $MtCO_2$ emissions may cause a significant net increase in cumulative EU ETS emissions by up to 0.86 $MtCO_2$. The intuition behind their result is that firms, anticipating a reduction in future demand, will reduce the amount of banked allowances and thus demand more allowances in present time. Under a quantity mechanism, the reduction in banked allowances leads to less inflow into the MSR, and hence fewer allowances are cancelled.

If these papers have quantified the change in emissions when overlapping policies are introduced, they don't examine how the overall duration of the EU ETS might impact emissions reductions. To the knowledge of the author, there exist no studies that have attempted to quantify the impact on emissions due to overlapping policies that directly affect the time horizon of the EU ETS. A paper that intuitively addresses this topic, without however trying to quantify the change in emissions realized by shortening the duration cap-and-trade schemes, is Heijmans (2022). By using a theoretical model of emissions trading, the author presents two main results

[3] The linear reduction factor is what determines the annual reduction in the supply of allowances. Eventually in the future, annual supply will reach zero because of the LRF.

that are of interest to the current analysis. Firstly, emissions reductions are bounded from above under a quantity mechanism. Secondly, under certain conditions, cumulative emissions increase under a quantity mechanism.

Although Heijmans (2022) shows that these results hold under a general cap-and-trade scheme, there is no telling how large these effects might be under existing permit schemes, such as the EU ETS. The current paper acknowledges this gap in the literature, and argues that this gap, if overlooked, could imply negative repercussions for the EU's climate targets. To this end, this may be the only paper that quantifies the change in cumulative emissions that arises from a shortening in the duration of any existing cap-and-trade scheme, including the EU ETS.

3. Climate ambitions of the EU

To address the challenges of climate change and transition to a low-carbon economy, the EU has set ambitious climate goals. These include a clean energy transition towards renewables, improved energy efficiency, the European Green Deal, and the EU ETS (EU Commission, 2022). The latter two are briefly discussed in this section.

3.1 The European Green Deal

Introduced in December 2019, the European Green Deal is a broad policy roadmap that is aligned with the Paris Agreement's objective of limiting global warming to below 2 degrees Celsius above pre-industrial levels. The goal of the green deal is for the EU to reach net zero GHG emissions by 2050, with the interim target of reducing emissions by 55% below 1990 levels by 2030 (EU Commission, 2021).

3.2 The EU ETS and its Market Stability Reserve

The EU ETS is the largest emissions trading system to date, and it covers various sectors from stationary installations (i.e., industry and power generation) to aviation. Since its establishment in 2005, the scheme has faced challenges which have led it to undergo numerous structural reforms.

A primary example of challenges under the EU ETS is the price of allowances which has been consistently low and highly volatile for most of the duration of the scheme. This is illustrated in figure 1. The reason for the low price is partly due to the mismatch between the scheme and compensating climate policies, as well as the economic recession that hit Europe in 2008. Furthermore, the loosely set cap has led to an oversupply of allowances in the market and the accumulation of banked allowances that firms save for later use, despite the low price (Gerlagh et al., 2021).

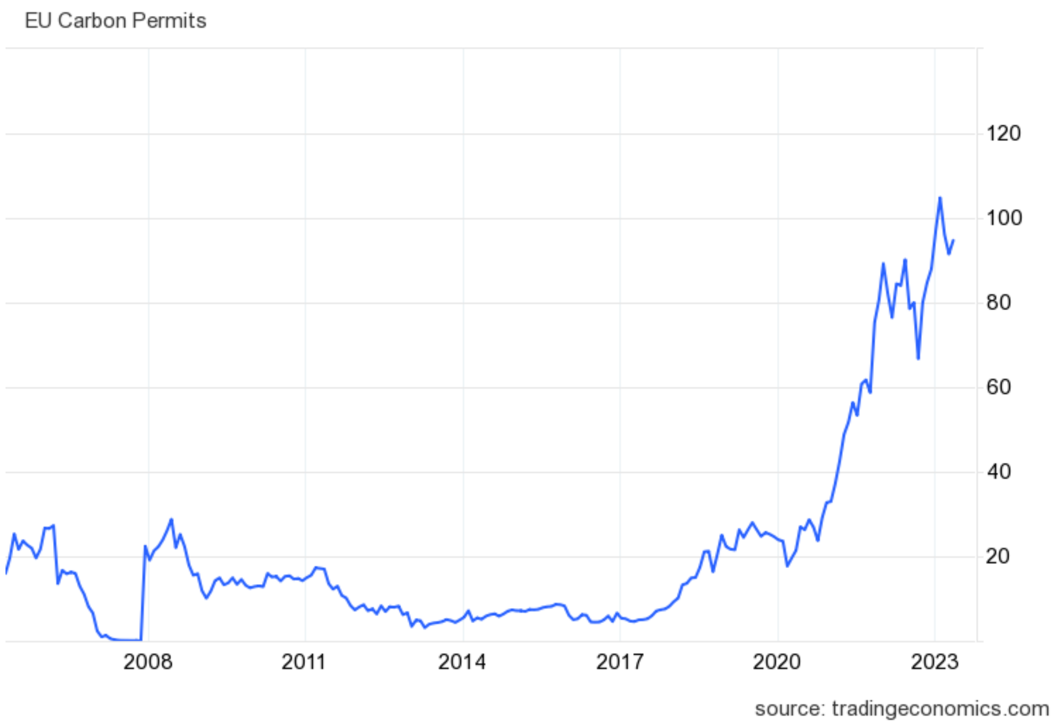

Figure 1. EU ETS carbon permit price 2005-2023 (Trading Economics, 2023).

The EU's reaction to these challenges has been twofold: firstly, by gradually tightening the annual cap of allowances through the so-called linear reduction factor (Pahle et al., 2023), and secondly, by implementing the MSR that takes in and withholds a portion of unused allowances that otherwise would have been banked for later use (Quemin, 2022).

The purpose of the MSR is to address any significant imbalances between the supply and demand of emission allowances, thereby helping to stabilize the carbon price and promote emission reductions. Since the MSR does this through predetermined mechanisms that are set in place, the need for any direct manual adjustments of supply through policymaking has been avoided.

3.3 MSR mechanisms

The mechanisms of the MSR are explained in detail below. The intuition behind these mechanisms is important for the understanding of the stylized EU ETS model presented in section 5.

Allowances move through the MSR in three distinct ways: through inflow, outflow, and cancellation. Starting from 2019, it is set that each year, the amount of *inflow* of allowances into the MSR will be strictly equal to 24% of banked allowances (12% as of 2024), if the aggregate number of banked allowances that same year surpasses 833 $MtCO_2$ (Osorio et al., 2021).

In addition, a portion of withheld allowances in the MSR is later returned to the market. When the amount of banking has decreased to below 400 $MtCO_2$, a level of 100 MtCO2 allowances *flows out* of the MSR and back into circulation (Osorio et al., 2021).

Lastly, *cancellation* works in the following way: starting from 2023, allowances in the MSR that exceed the previous year's auctioned volume are permanently cancelled (Osorio et al., 2021). Cancellation was not part of the MSR when it was first announced in 2015, and as such, the MSR only affected the short-run supply of allowances (while the long-run cap on emissions was untouched). Since this failed to tighten the cap on emissions and push up prices, the MSR was reformed in 2018 to also include the cancellation of allowances (Gerlagh et al., 2021).

With these features considered, the MSR adjusts the quantity of allowances absorbed, released, or cancelled based on predetermined rules and prevailing market conditions. Hence, the cap on allowances in the EU ETS is effectively adjustable (Gerlagh et al., 2021).

4. Model

This section presents a model of emission allowances in a cap-and-trade scheme that operates a quantity mechanism. The aim of this model is to describe the key mechanics of the scheme, which will help to further explain the main results of this paper. The model presented here builds on the framework created by Heijmans (2022), who designed a model of emission allowances in a general cap-and-trade scheme, but we add specific functional forms to their model.

4.1 Building blocks

Consider a dynamic market that amounts to a set N = {1, 2, …, n } of polluters, n > 1, called firms for simplicity. For each period $t \geq 0$, let abatement of firm *i* be written as $a_{it} = q_{it}^0 - q_{it}$, where q_{it}^0 is the level of business-as-usual (BAU) emissions (i.e. the level of emissions in absence of any policy), and where q_{it} is the actual level of emissions of firm *i*. Abatement costs are determined by the abatement cost function $C(a_{it})$, that is given by

$$C(a_{it}) = \alpha a_{it} + \frac{\beta}{2} a_{it}^2, \tag{1}$$

which satisfies $C_{it}'(a_{it}) \coloneqq \frac{\partial C_{it}(a_{it})}{\partial a_{it}} > 0$, and $\frac{\partial^2 C_{it}(a_{it})}{\partial a_{it}^2} \geq 0$, and where α and β are constants. In each period, firms choose their emissions simultaneously, and the abatement cost functions are further assumed to be common knowledge.

Consider a cap and trade scheme in which emissions are regulated over a total of 3 periods so that *t = {0, …, T}*, where *T = 2* is the duration of the scheme. Let s_{it} be the number of allowances supplied to firm *i* at the start of period *t*. Allowances can be traded on a secondary market at price p_t, which the firms take as given for the respective period. Let m_{it} denote the number of allowances that firm *i* buys on the secondary market in period *t*. Additionally, the total number of allowances bought must also be sold, so that

$$\sum_i m_{it} = 0\,, \tag{2}$$

for all *t*. Allowances can be traded over time, so that unused allowances that were supplied in one period may be carried over to the next period, i.e. banking. Banking of firm *i* during period *t* is given by $b_{it} := s_{it} + m_{it} - q_{it}$. Hence, the bank of allowances held by firm *i* at the start of period *t* is

$$B_{it} \coloneqq \sum_{s=0}^{t-1} b_{is} = B_{it-1} + b_{it-1} = B_{it-1} + s_{it-1} + m_{it-1} - q_{it-1}, \tag{3}$$

and where the total amount of banking at the start of period t is denoted as $B_t := \sum_i B_{it}$. Furthermore, it is assumed that banking is not allowed to be negative, i.e. borrowing of allowances is not allowed. In other words,

$$B_{it} \geq 0, \tag{4}$$

for all i and t. This is not a necessary assumption, albeit a realistic one. Hence, total emissions may not exceed the total supply of allowances, and thus the effective constraint on firm i's emissions is given by

$$\sum_{s=0}^{t} q_{is} \leq \sum_{s=0}^{t} s_{is} + m_{is}\,, \tag{5}$$

In this regard, allowances can only be used to cover emissions during the scheme. Therefore, any leftover allowances lose their value after the scheme ends.

4.2 Demand-side: firms' problem

In any period t, the respective firm i minimizes the discounted sum of total costs, that is given by abatement a_{it} and allowances m_{it},

$$\min_{a_{it}, m_{it}} \quad \sum_{t=0}^{2} \left(\frac{1}{1+r}\right)^{t} [C_{it}(a_{it}) + p_t m_{it}], \tag{6}$$

subject to (2)-(5). The Lagrangian is for the firms' problem is specified as follows:[4]

$$\mathcal{L}_{\mathrm{i}} = \sum_{t=0}^{2} \left(\frac{1}{1+r}\right)^{t} \left[\alpha a_{it} + \frac{\beta}{2} a_{it}^{2} + p_t m_{it}\right] + \lambda_i \left[\sum_{t} q_{it} - s_{it} - m_{it}\right] +$$
$$\sum_{t} \left(\frac{1}{1+r}\right)^{t} \mu_t \left[\sum_{i} m_{it}\right] + \omega_{it}[B_{it} - B_{it-1} - s_{it-1} - m_{it-1} + q_{it-1}] + \left(\frac{1}{1+r}\right)^{t} \psi_{it} B_{it}. \tag{7}$$

[4] Note that in the lagrangian, $q_{it} = q_{it}^{0} - a_{it}$.

Taking partial derivatives of (7) with respect to a_{it}, m_{it}, and B_{it} yields the following first-order conditions:

$$\frac{\partial \mathcal{L}_i}{\partial a_{it}} = \left(\frac{1}{1+r}\right)^t \alpha + \left(\frac{1}{1+r}\right)^t \beta a_{it} - \lambda_i - \omega_{it+1} = 0, \tag{8}$$

$$\frac{\partial \mathcal{L}_i}{\partial m_{it}} = \left(\frac{1}{1+r}\right) p_t - \lambda_i + \left(\frac{1}{1+r}\right)^t \mu_t - \omega_{it+1} = 0, \tag{9}$$

$$\frac{\partial \mathcal{L}_i}{\partial B_{it}} = \omega_{it} - \omega_{it+1} + \left(\frac{1}{1+r}\right)^t \psi_{it} = 0. \tag{10}$$

Rearranging (8) and (9) gives the level of abatement for firm *i* in period *t*:

$$a_{it}(p_t) = \frac{p_t + \mu_t - \alpha}{\beta},$$

Hence, the level of emissions for firm *i* in period *t* is:

$$q_{it}(p_t) = q_{it}^0 - \frac{p_t + \mu_t - \alpha}{\beta}, \tag{11}$$

For a vector of prices $p = (p_t)$, let $q_{it}(p_t)$ (that is given above) represent the firms' solution to the minimization problem. Furthermore, the convexity of abatement costs C_{it} implies:

$$\frac{\partial q_{it}(p_t)}{\partial p_t} \leq 0, \tag{12}$$

for all $t \leq T$. The inequality in (12) is strict in all cases when $q_{it}(p_t)$ is not a corner solution. For a given period *t*, the cost-minimizing level of emissions for firm *i* is decreasing in the allowance price for that period. This is stated in *Observation 1*.

Observation 1. *In each period $t \in \{0, \dots, T\}$, aggregate demand for emissions $q_{it}(p_t)$ is decreasing in the price for emission allowances p_t.*

Observation 2. *For all $t \in \{0, \dots, T-1\}$, allowance prices co-move between periods:*

$$\frac{\partial p_{t+1}}{\partial p_t} > 0, \tag{13}$$

For the sake of simplicity however, it is assumed for the remainder of the model that the allowance price rises with the interest rate *r*, that is:

$$p_{t+1} = (1 + r)p_t, \tag{14}$$

This condition has been commonly used in similar models of dynamic emissions trading (*c.f.* Gerlagh et al., 2021; Heijmans, 2023). Intuitively, firms adjust their levels of borrowing and banking so that prices rise at the rate of return *r*.[5] On one hand, if prices rise faster than the interest rate, firms and investors would buy allowances in the present period, and then sell them in the next period for a positive net return. However, as more investors do this, the price starts to increase at a slower rate, until it rises at the interest rate in equilibrium. On the other hand, if prices rises below the interest rate, firms would sell allowances for a higher return in the bank. This would lead to the price rising at a higher pace, until it rises with the interest rate.

4.3 Supply-side

As previously mentioned, the supply mechanism considered in this paper is a quantity mechanism. Let the supply of allowances under this mechanism be denoted as s_t^Q. By definition, a cap and trade scheme is operating a quantity mechanism if the supply of allowances in period t is decreasing in the number of banked allowances at the start of that period. That is,

$$s_t^Q\big(B_t(p_t)\big) = \begin{cases} \overline{s_t} - \delta B_t, & if\ \ \overline{s_t} \geq \delta B_t \\ 0, & otherwise \end{cases}, \tag{15}$$

where $\bar{s}$ is the exogenous number of allowances given to firms, and B_t is banking at the start of period *t*. Moreover, the parameter $0 < \delta < 1$ by definition. Taking the interaction of banking into account, the supply cap of allowances effectively becomes endogenous.

The timeline of events is the following: at the start of period *t*, the amount s_t allowances are supplied to firms in accordance with (15); allowances are thereafter traded between firms on the secondary market, as firms choose their level of emissions q_t, and where unused allowances are banked; lastly, markets clear and period $t + 1$ starts.

[5] This paper sets r = 0.05 in the analysis. One may argue that other values are more appropriate for the interest rate. Nevertheless, this value is consistent with previous literature, such as Gerlagh et al. (2021).

4.4 Equilibrium

Equilibrium is reached when overall demand of emission allowances is equal to supply, for which prices adjust to bring about equilibrium in the competitive market.

The aim is to establish how equilibrium emissions are affected by the duration of a cap-and-trade scheme. The first step in doing so is to determine the equilibrium price in the model. The equilibrium price allows one to procedurally solve for the equilibrium levels of emissions $q_t^Q(p_t)$, banking $B_t^Q(p_t)$, and supply of allowances $s_t^Q(B_t(p_t))$. The equilibrium solutions are consequently needed to help explain how emissions are affected when the scheme ends in period $\bar{T}$ rather than T, for which $\bar{T} < T$.

The equilibrium price p_t^Q is found by solving the equality:

$$q_0^Q(p_0) + q_1^Q(p_1) + q_2^Q(p_2) = \bar{s_0} + s_1^Q(B_1) + s_2^Q(B_2), \qquad (16)$$

The left-hand side of (16) can be characterized by the demand solution from (11) for respective period, and the right-hand side is given by (15). Hence, the term can be rewritten as:

$$q_0^0 + q_1^0 + q_2^0 + \frac{3\alpha - (\mu_0 + \mu_1 + \mu_2)}{\beta} - \frac{(p_0 + p_1 + p_2)}{\beta} = \bar{s_0} + \bar{s_1} + \bar{s_2} - \delta B_1 - \delta B_2, (17)$$

From (3), define $B_1 = \bar{s_0} - q_0(p_0)$, and $B_2 = B_1 + \bar{s_1} - q_1(p_1)$, assuming that the number of allowances, m_{it}, bought is also sold in the same period. The above expression can thus be simplified as follows:

$$q^0 + \frac{1}{\beta}(3\alpha - \mu) - \frac{p_0}{\beta}[(2+r) + (1+r)^2] = \bar{s} - \delta(2\bar{s_0} + \bar{s_1} - 2q_0 - q_1), \quad (18)$$

Thereafter, plugging in the expressions for q_0 and q_1 from (11) allows one to solve for equilibrium allowance price for period 0 under a quantity instrument, p_0^Q. Using p_0^Q, a straightforward solution for p_1^Q and p_2^Q can be reached.

$$p_0^Q = \frac{\beta(q^0 - \bar{s}) - \delta\beta(2q_0^0 + q_1^0 - 2\bar{s_0} - \bar{s_1}) + 3\alpha - \mu - \delta(3\alpha - 2\mu_0 - \mu_1)}{(2+r) + (1+r)^2 - \delta(3+r)}, (19)$$

$$p_1^Q = (1+r)\left[\frac{\beta(q^0 - \bar{s}) - \delta\beta(2q_0^0 + q_1^0 - 2\bar{s_0} - \bar{s_1}) + 3\alpha - \mu - \delta(3\alpha - 2\mu_0 - \mu_1)}{(2+r) + (1+r)^2 - \delta(3+r)}\right], (20)$$

$$p_2^Q = (1+r)^2 \left[\frac{\beta(q^0 - \bar{s}) - \delta\beta(2q_0^0 + q_1^0 - 2\overline{s_0} - \overline{s_1}) + 3\alpha - \mu - \delta(3\alpha - 2\mu_0 - \mu_1)}{(2+r) + (1+r)^2 - \delta(3+r)}\right], \quad (21)$$

The price solutions can be simplified further by assuming that $r = 0$. This is a reasonable assumption, given that the observed interest rate in the Euro area for the years 2015-2022 has been close to (if not even below) zero. Setting $r = 0$ yields the same price in each period. The solution thus becomes:

$$p_0^Q = p_1^Q = p_2^Q$$

$$= \frac{\beta(q^0 - \bar{s}) - \delta\beta(2q_0^0 + q_1^0 - 2\overline{s_0} - \overline{s_1}) + 3\alpha - \mu - \delta(3\alpha - 2\mu_0 - \mu_1)}{3 - 3\delta}, \quad (22)$$

Additionally, the equilibrium price allows one to solve for given equilibrium levels of emissions $q_t^Q(p_t)$, banking $B_t^Q(p_t)$, and supply of allowances $s_t^Q(B_t(p_t))$ for the respective period. For these solutions, see appendix 2. The next section focuses on the key mechanics behind the analytical solution, and how they relate to the research question.

4.5 Equilibrium results

The intuition behind the mechanics of the model and how they relate to the research question is explained below. Firstly, it is important to consider the interplay between the equilibrium price and the banking choice of firms. Since allowances have no use after the scheme has ended, firms will be inclined to offload any unused allowances before the final period. Because of this, equilibrium banking will be weakly less when the scheme ends in an earlier period $\bar{T}$, compared to T. This drop in banking can only occur due to an increase in demand, which per se is explained through a decrease in the period $\bar{T}$ price. By Hotelling's rule, prices co-move between periods so that the decrease in period $\bar{T}$ price trickles down to earlier periods, thus causing the price to fall in all periods. Lastly, the price reduction in all periods causes equilibrium banking to also fall in respective periods. This relationship between allowance price and banking is demonstrated through Observation 3:

Observation 3. *Consider a cap-and-trade scheme that operates under a quantity instrument. For any two periods* $\tau, t < T$, *for* $\tau > 0, t \geq 0$, *banking of allowances is explained as a positive function of price, such that:* $\frac{\partial B_t^Q(p)}{\partial p_\tau} > 0.$[6]

4.5.1 Effect on emissions from shortening the duration of the scheme

This section explains the change in emissions realized by shortening the duration of the scheme. The main effect is described by Propositions 1 and 2, but first some notations need to be explained. Firstly, given a price vector *p*, define the number of allowances supplied between two periods t_1 and t_2, for which $t_1 \leq t_2$, as:

$$S^Q(t_1, t_2 | \, p) \coloneqq \sum_{t=t_1}^{t_2} s_t^Q \left(B_t^Q(p)\right), \tag{23}$$

where supply s_t^Q is determined by the bank of allowances B_t^Q, which in turn falls under a price vector *p*. Secondly, recall that the aim of the paper is to study how emissions are affected when the duration of the scheme is shortened. To do this, the paper compares emissions from two scenarios. In one scenario, the scheme ends in period T, while in the other the scheme ends in $\bar{T}$, for which $\bar{T} < T$. The reduction in equilibrium emissions is thereafter the difference between the two scenarios. Therefore, denote R^Q as the reduction in equilibrium emissions when the scheme ends in $\bar{T}$ rather than T:

$$R^Q(\bar{T}, T) \coloneqq \sum_{t=0}^{T} q_t(p_t^Q) - \sum_{t=0}^{\bar{T}} q_t(\bar{p}_t^Q), \tag{24}$$

where $q_t(p_t^Q)$ denotes equilibrium emissions when the scheme ends in T, and $q_t(\bar{p}_t^Q)$ for when the scheme ends in $\bar{T}$.

If supply is determined through a quantity mechanism, the reduction in equilibrium emissions that occur from having the scheme end in period $\bar{T}$, rather than T, is bounded from above. This is formally described in proposition 1:

[6] The proof for the observation has already been provided in Heijmans (2022). This proof has also been included in Appendix 1 of this paper.

Proposition 1. *Consider a cap-and-trade scheme that operates a quantity mechanism. The reduction in equilibrium emissions from having the scheme end in period $\bar{T}$, rather than T, satisfies the following:*

$$R^Q(\bar{T},T) \leq S^Q(\bar{T},T\;|p^Q), \tag{25}$$

i.e., emissions are bounded from above by the level of supplied allowances.

Under a quantity mechanism, shortening the duration of a cap-and-trade scheme has two opposing effects on cumulative emissions. Firstly, there is a direct reduction in emissions, since any allowances that would have been supplied starting from period $\bar{T}$ and after are removed. Secondly, as implied from Observation 3, firms shift their emissions (i.e., demand) to earlier periods to prevent them from holding any allowances by the final period of the scheme. The increase in early-period demand (which can only be realized through a fall in the price) corresponds to a decrease in banked allowances. As implied by (15), this reduction in banking leads to an increase in adjustable supply prior to period $\bar{T}$. As discussed in Heijmans (2022), the ensuing increase in overall emissions from the second effect offsets most, if not all, of the emissions reductions from the first effect. This implies that there is an upper bound on emissions reductions from shortening the end year of the scheme.

4.5.2 Adverse changes in cumulative emissions

There is a possibility that the reduction in equilibrium emissions is strictly negative (i.e., so that cumulative emissions increase) as the duration of the scheme is shortened. Principally, two conditions need to be satisfied for such a scenario to arise. These two conditions are given by (26) and (27):

$$q_{\bar{T}}\left(p^Q_{\bar{T}}\right) > 0, \tag{26}$$

And

$$f^Q(p^Q) \leq \bar{T}. \tag{27}$$

When the scheme ends in period T, suppose there exists another year T^* at which (1) equilibrium demand is strictly positive, while (2) equilibrium supply has already reached zero. If such a year exists, set $\bar{T} = T^*$. Given this, condition (1) is expressed by equation (26), and (2) is represented by (27) above. If both conditions are fulfilled, equilibrium emissions strictly increase if the duration of the scheme is shortened from T to $\bar{T}$.

Proposition 2. *Consider a cap-and-trade scheme that operates a quantity mechanism. For all $\bar{T}$ and T such that $\bar{T} < T$, and for which $\bar{T}$ satisfies (26) and (27), then equilibrium emissions strictly increase when the duration of the scheme is shortened from $\bar{T}$ to T:*

$$R^Q(\bar{T}, T) < 0. \tag{28}$$

It is important to highlight that since there is no supply of allowances from period $\bar{T}$ and onwards, then shortening the duration of the scheme won't cancel any allowances that conceivably would have been supplied after $\bar{T}$.

In the previous section, this paper identified two mechanisms that describe whether cumulative emissions increase or decrease as the duration of the scheme is shortened. The fact that no emissions are supplied after $\bar{T}$ implies that the first mechanism (which explains how total emissions decrease) is approximately non-existent in this case. Meanwhile, since emissions are strictly positive in $\bar{T}$ by (26), this implies that any emissions after $\bar{T}$ must be entirely covered by banked allowances. Therefore, when the duration of the scheme is shortened, this causes firms to exhaust their banked allowances earlier, and as explained by (15), less banking in early periods procedurally leads to increased supply. Thus, on one hand, no supply after period $\bar{T}$ is eliminated, while on the other hand, supply before period $\bar{T}$ increases. Hence, cumulative emissions increase when the scheme is shortened from T to $\bar{T}$.

5. Stylized model of the EU ETS

In this section, the paper develops a stylized version of the EU ETS that illustrates the mechanisms of the MSR in detail. The aim of this model is to numerically quantify how cumulative EU ETS emissions are affected by a shortening of the scheme. The model was initially created by Gerlagh et al. (2021), and it is from this study that the model presented here is inspired. For the present analysis, parameter values and mechanics of the scheme have been updated due to recent reforms made in the EU ETS. For more information about this, see table 1 in appendix 3.

5.1 Model calibration

The first step of the stylized model is to calibrate the demand function. Demand is expressed as a decreasing function of allowance price p_t:

$$d_t(p_t) = \alpha - \beta p_t, \tag{29}$$

where d_t is demand of allowances in year *t* and p_t is the price of allowances. The two parameters α and β are calibrated using OLS estimation based on observed annual average allowance prices and EU ETS verified emissions for the years 2018-2021. More intuitively, α/β represents the choke price (i.e., the constant price in which demand equals zero), and $1/\beta$ is the slope of the inverse demand function. Furthermore, the demand function expressed above can be considered equivalent to the demand solution in (11) from the theoretical model by setting $\mu_t = 0$.

Equation (14) is repeated, and thus it is assumed that prices rise according to the rate of return, also known as Hotelling's rule:

$$p_{t+1} = (1 + r)p_t \tag{30}$$

Lastly, in the calibration there are two requirements that need to be satisfied. Firstly, since the first year of the simulated model is 2020, the level of demand should be consistent with observed levels of EU ETS emissions for 2020. Secondly, the model price for 2020 should reflect observed prices for the initial years.

The calibration leads to a choke price of 208.7 €/tCO_2, while the initial price in the simulation is set at 38.63 €/tCO_2. The initial price is equal to the annual average of 2020 and 2021 observed levels. This value has been chosen to reflect the vast increase in allowance price that happened after 2020, while still remaining consistent with the observed 2020 price. Taking the price into consideration, demand becomes zero in the year 2054 according to the calibration. Moreover, the supply of allowances dries out in 2050. Hence, 2054 is treated as the endogenous final year of the EU ETS.

The EU ETS is in equilibrium when two conditions are fulfilled: first, when there are no banked allowances that remain in the market, and second, when all allowances in the MSR have been emptied in the final period. Accordingly, cumulative emissions are defined as the aggregate demand over all periods that do not exceed cumulative supply and aggregate bank of allowances.

An essential condition of the model is that the duration of the EU ETS is common knowledge for all firms at the beginning of the scheme. In other words, agents update their beliefs and decisions on banking depending on the final year of the scheme. If the duration of the scheme would be reduced by a regulator, this would cause firms to adjust their market behaviour accordingly, which would bring about a new equilibrium path of the EU ETS. Lastly, the duration of the EU ETS is assumed not to change after the scheme has started. Taking this into account, firms decide on their present and future levels of optimal banking and demand.

5.2 Baseline scenario

The outcome of the simulated EU ETS model is presented below. Figures 2 and 3 show the market equilibrium when the EU ETS ends in 2054. Note that the two figures display the EU ETS for when the scheme ends endogenously, and not for when the final year is set exogenously by a regulator.

Figure 2 shows the supply and demand of allowances in the EU ETS. The curve “supply (no MSR)” in green is equivalent to gross supply without the MSR interactions, and “supply (with MSR)” in red describes net supply with the MSR considered. Net supply is significantly lower than gross supply for most of the scheme due to the fact that the MSR takes in allowances and withholds them from the market. Furthermore, net supply exceeds demand up to the year 2027, and thereafter demand exceeds adjustable supply. Since supply is lower than demand for these years, firms use their previously banked allowances to satisfy their high level of demand. This trend continues until 2047 when supply exceeds demand for the rest of the scheme. This implies that there is a surplus of used allowances after 2047, and this surplus will be banked by firms.

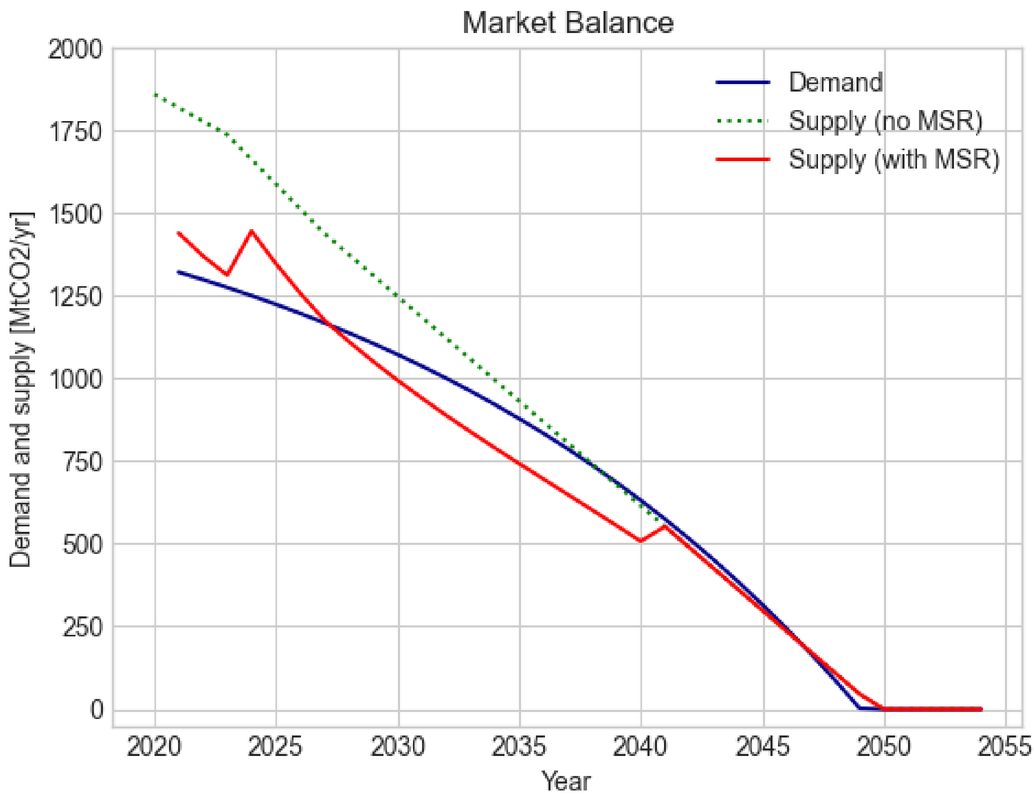

Figure 2. Market balance of demand and net supply in the EU ETS for the baseline scenario, that is for the years 2021-2054.

Figure 3 illustrates the stocks of allowances over time. The stocks describe the number of privately banked allowances ("Banking"), inflow ("MSR-in") and outflow ("MSR-out") of the MSR, allowances that stay in the MSR ("MSR-stays"), and lastly cancellation ("Cancellation").

The first thing to note is the major change in the stocks that occur in 2023-24. This is due to two reasons: cancellation of allowances begins in 2023, and the rate of inflow into the MSR halves from 24 to 12% in 2024. Secondly, inflow stops in 2040, which is a result of banking dropping below 833 $MtCO_2$ the preceding year. Moreover, since inflow stops permanently in 2040, this implies that banking never exceed 833 Mt for the rest of the scheme. Additionally, the decline in inflow can further be seen in figure 2 as an increase in net supply in both 2024 and 2040. Thirdly, the last year of cancellation is 2050.

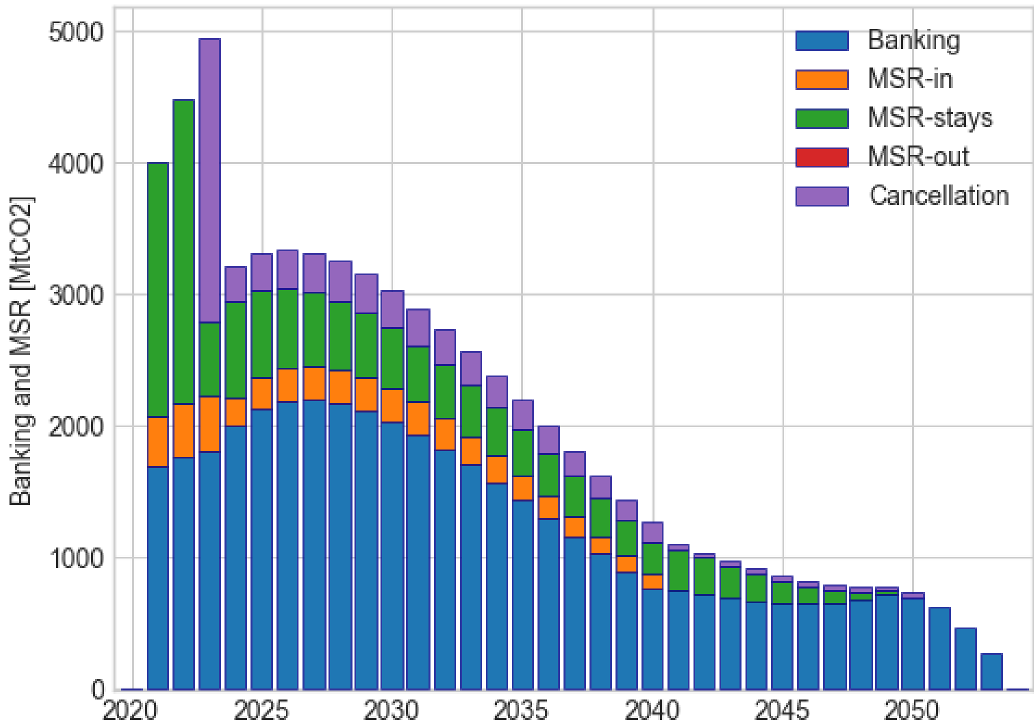

Figure 3. Stocks of allowances over time in the baseline scenario. The MSR is separated into four parts: inflow of allowances into the MSR ("MSR-in"), allowances that stay in the MSR next period ("MSR-stays"), allowances that leave the MSR for next period ("MSR-out"), and cancelled allowances ("Cancellation").

Figure 4 illustrates the equilibrium initial price of the simulation when varying the final year of the EU ETS. The purpose of figure 4 is to show how the equilibrium prices shift as the duration of the EU ETS changes. Intuitively, one may interpret this shift in the final year as if a regulator exogenously sets a different end year of the scheme, or as if a supplementary policy (e.g., a binding emissions target) effectively ends the EU ETS. Furthermore, figure 4 can also be seen as a good illustration of how firms adjust their market behaviour as the final year of the EU ETS changes, and that these adjusting behaviour ultimately affect the equilibrium price.

The initial (2021) price when the EU ETS ends in 2054 is 53.2 €/tCO_2. As the duration of the scheme is increasingly shortened, the price in the first year gradually decreases, to the point where it is close to 0 €/tCO_2 if the scheme ends in 2025. The equilibrium price paths shown in this figure confirm the mechanism already described in sections 4.5 and 4.6 of this paper. Firms have no incentive to keep allowances after the final period since they only serve the purpose of covering emissions. For any final period ($\bar{T}$) that is before 2054, equilibrium banking is thus less compared to when the scheme ends in 2054. Given the level of supply, this fall in banking can only arise through an increase in demand, which consequently is explained through a fall in equilibrium price for period $\bar{T}$. Hence, the equilibrium price level is lower when the duration of the scheme is shortened.

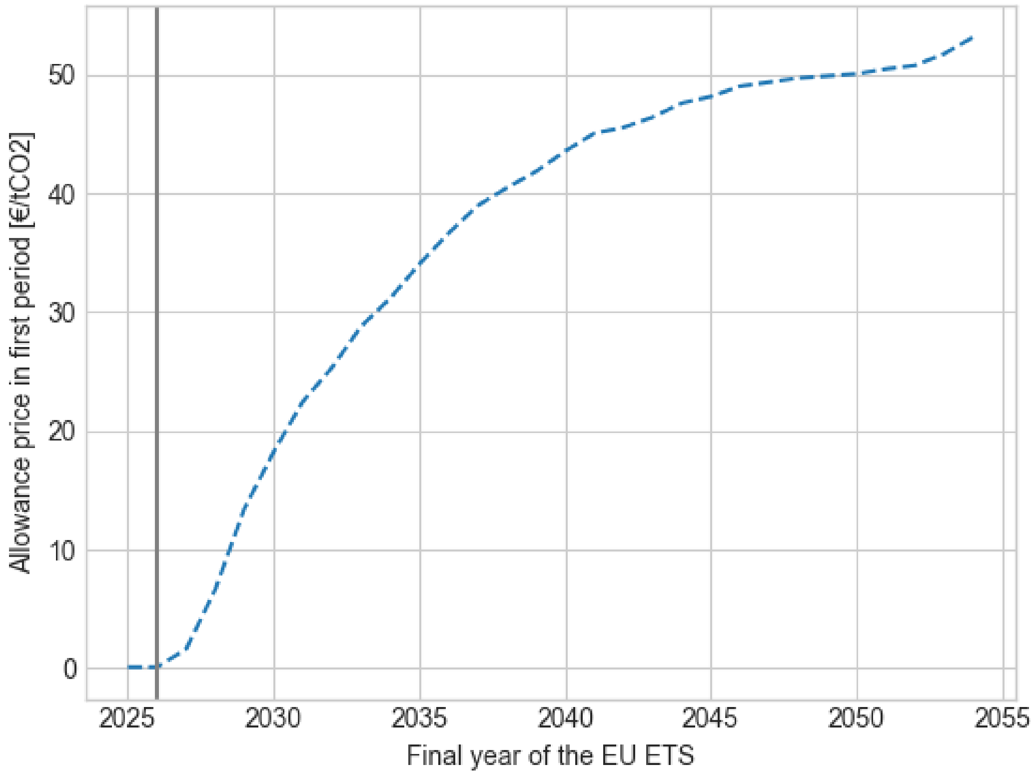

Figure 4. Equilibrium price in the initial period 2021 (vertical-axis) that is realized by varying the final year of the EU ETS (horizontal-axis). The horizontal axis contains the years 2025-2054. The 2021 allowance price is negative for scenarios when the scheme ends before 2025, and has therefore been excluded from the figure.

6. Results

6.1 The effect of bringing the final year of the EU ETS forward in time

The main results are presented in this section. Note that any final year of the scheme that is before 2054 is considered the year in which a regulator or an independent policy (e.g., a binding emissions target) exogenously shortens the duration of the EU ETS. Furthermore, any exogenous end year, $\bar{T}$, of the scheme is anticipated by firms starting from 2020.

Figures 5 and 6 show the effect on cumulative emissions that arises from bringing the end year of the EU ETS forward in time. Figure 5 expresses this effect in terms of percentage change relative to 2054, while figure 6 depicts the effect in absolute values. The horizontal axis in both figures represents any given final year of the EU ETS.

Firstly, cumulative emissions when the EU ETS ends in 2054 are equal to 23200 $MtCO_2$ (figure 6). If the final year of the scheme is set at 2040 or before, then cumulative emissions relative to 2054 decrease. Moreover, starting from 2040, cumulative emissions gradually decrease the more the scheme is shortened. According to the figures, the highest reduction in emissions that could be obtained from a shortening of the EU ETS would be 61.9% which would be achieved by having the scheme end in 2025, compared to 2054. This reduction would represent a total of 14408 $MtCO_2$ (figure 6).

Secondly, and more interestingly, the opposite occurs if the end year of the EU ETS is set between 2041 and 2053. For these final years, cumulative emissions increase compared to 2054. In fact, the increase in cumulative emissions relative to 2054 is, *at its lowest*, exceeding 3%[7] and may increase as much as 7.44% if the scheme ends in 2049 (figure 5). To put the result into perspective, an increase of 7.44% in 2054 emissions corresponds to 1730 $MtCO_2$. This number exceeds the total combined CO_2 emissions of Norway and Sweden since 2004 (Our World in Data, 2023).

[7] To be specific, the increase in cumulative emissions is 3.6% in 2041 and 3.2% in 2053.

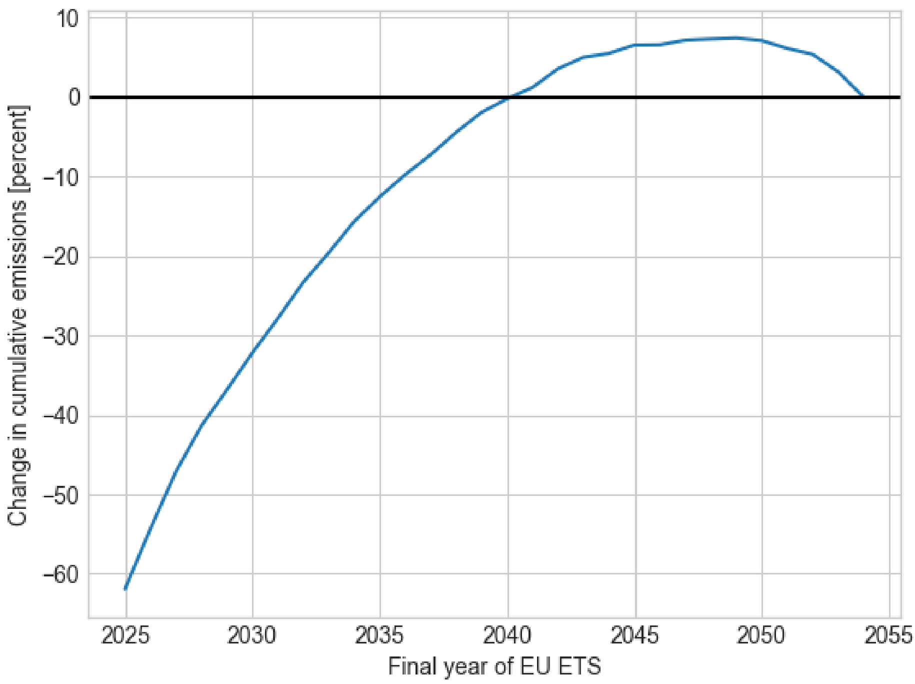

Figure 5. Percentage change in cumulative emissions relative to year 2054. Expressed for each respective final year of the scheme. 2054 is the year in which the EU ETS ends endogenously in the model simulations.

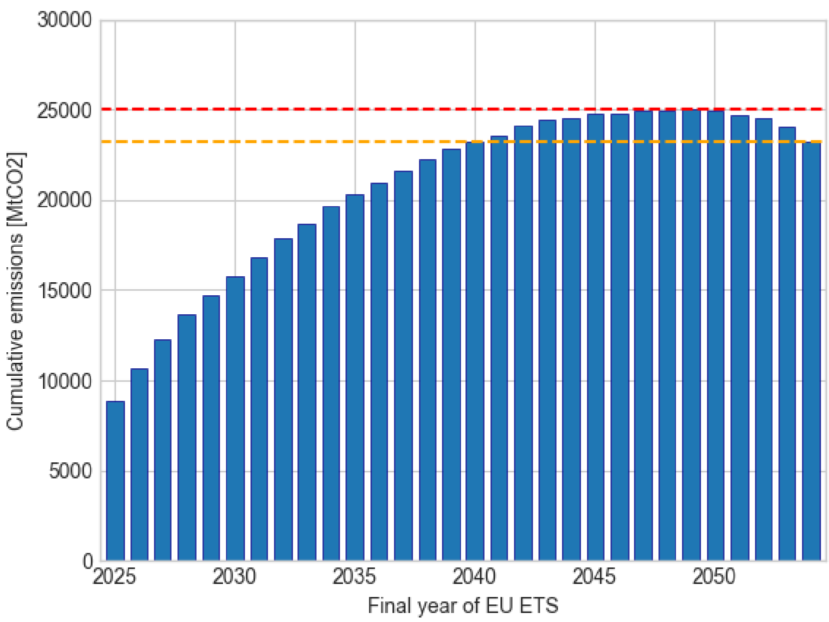

Figure 6. Cumulative emissions of the EU ETS for each respective final year of the scheme. The orange horizontal line symbolizes the level of cumulative emissions when the EU ETS ends in 2054, which is 23264 MtCO2. The red horizontal line illustrates the maximum amount of cumulative emissions, which occurs when the EU ETS ends in 2049. This amount equates to 24995 $MtCO_2$.

The intuition behind these results is explained in twofold. Firstly, concerning scenarios when the EU ETS ends in 2040 or earlier: the increase in adjustable supply that arises from a decrease in banking, and in cancelled allowances, is not large enough to offset the supply that is directly cut from shortening the scheme. Hence, cumulative emissions decrease. Secondly, the intuition for cases when the EU ETS ends after 2040 is the same as already described in this paper (see section 4.5.2). For these years, the reduction in cancelled allowances that follows from shortening the scheme exceeds the direct cut in allowances that would have otherwise been supplied, had the EU ETS ended in 2054. This leads to an increase in cumulative emissions.

6.2 Sensitivity analysis: multiple equilibria

One topic that has not been mentioned thus far is the occurrence of multiple equilibria. As discussed in Gerlagh et al. (2021) and Perino et al. (2021), the MSR mechanics may result in the existence of several equilibrium price paths for which firms succeed in offloading all their banked allowances by the end period. If such multiple equilibria exist for a given end year of the EU ETS, this could have implications for the main results. Since cumulative emissions are determined by the equilibrium price, the existence of other price paths would imply that cumulative emissions may depart from what has already been reported in the main results. The intuition behind this is explained below.

Multiple equilibrias can arise due to the discrete jumps from the inflow and outflow of allowances from the MSR. How so? It has been established from the demand function in (23) that demand decreases *continuously* in the allowance price. On the other hand though, the inflow and outflow of the MSR are *discontinuous* functions of banking, and thus of demand as well (Gerlagh et al., 2021). If banking falls below the inflow threshold of 833 Mt, this leads to an instant decrease of inflow into the MSR, and thus a discrete reduction in cancelled allowances. Less cancellation leads to a discontinuous increase in the number of available allowances, despite demand continuously decreasing. Hence, this may lead to multiple equilibria. The potential occurrence of such equilibria is checked for in figure 7.

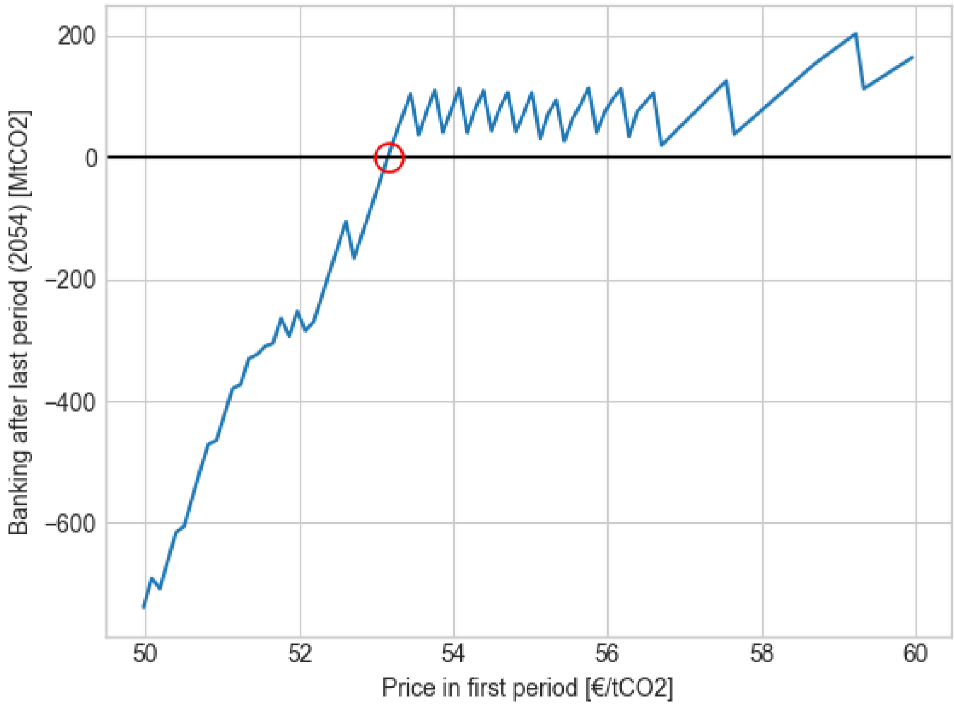

Figure 7. Banking after the last year of the EU ETS (vertical axis) as a function of price in the first period (horizontal axis). This figure illustrates the occurrence of multiple equilibria that is produced by the MSR.

Figure 7 shows the 2021 price in the interval 50-60 €/tCO_2, and its relationship with final-period banking. As previously mentioned, equilibrium is reached when firms successfully offload all their banked allowances by the end of the scheme. In the figure, this is indicated through the intersection of the banking curve and the horizontal line at 0.

The calibrated demand function generates one equilibrium which is found for the initial price of 53.2 €/tCO_2, as indicated by the red circle in figure 7. The figure thus confirms that multiplicity of equilibria is not a issue when the EU ETS ends in 2054. The initial price of 53.2 €/tCO_2 is henceforth the level reported in the results for when the EU ETS ends in 2054 (as also indicated by figure 4). Surprisingly, this price is remarkably close to the actual observed average annual allowance price for 2021, which was 52.5 €/tCO_2 (German Environmental Agency, 2023).

Another remark can be made regarding figure 7. Observation 3 describes banking as increasing in the allowance price. One may therefore naturally think that the price affects banking in a posive and continuous way. However, as displayed in figure 7, there are several discontinuous drops in banking as the price increases to certain levels. The most notable drops take place in the price interval 53-57 €/tCO_2. These discontinuous drops in banking are explained by the banking thresholds of the MSR. Recall that if banking is above 833 Mt, the MSR takes in allowances which, ultimately, reduces the amount of banked allowances in the market for the next year. If this threshold is crossed repeatedly, this implies that fewer banked allowances are available in the market. This leads to final-period banking being lower, even though the price path is at a higher level (which is precisely what is observed in the figure).

For example, for the scenario when the equilibrium price is equal to 53.2 €/tCO_2, banking of allowances falls below the inflow threshold of 833 Mt in year 2040 (see figure 3). After 2040 there is no more inflow of allowances into the MSR for the rest of the duration of the scheme, *since banking never exceed the 833 Mt threshold again*. The first major drop in last-period banking occurs when the initial price is around 53.5 €/tCO_2 (see figure 7). This sudden drop occurs because the higher price level causes banking to exceed the 833 Mt threshold, *after already having fallen below it once*. Since banking exceeds this cutoff more than once, this implies that a greater amount of banked allowances flows into the MSR, which leads to fewer banked allowances available in the market. What follows is that end-period banking is discontinuously lower, despite the higher price level.

It is important to highlight that figure 7 only checks for multiplicity of equilibria when the final year of the EU ETS is 2054. Appendix 5 extends this analysis for other end years of the scheme. In total, multiple equilibria exist for seven distinct years in the model. An analysis has been conducted to see whether any of these aditional equilibria lead to significant differences in the main results from section 6.1. The findings from the multiple equilibria analysis is presented in figure 8 below.

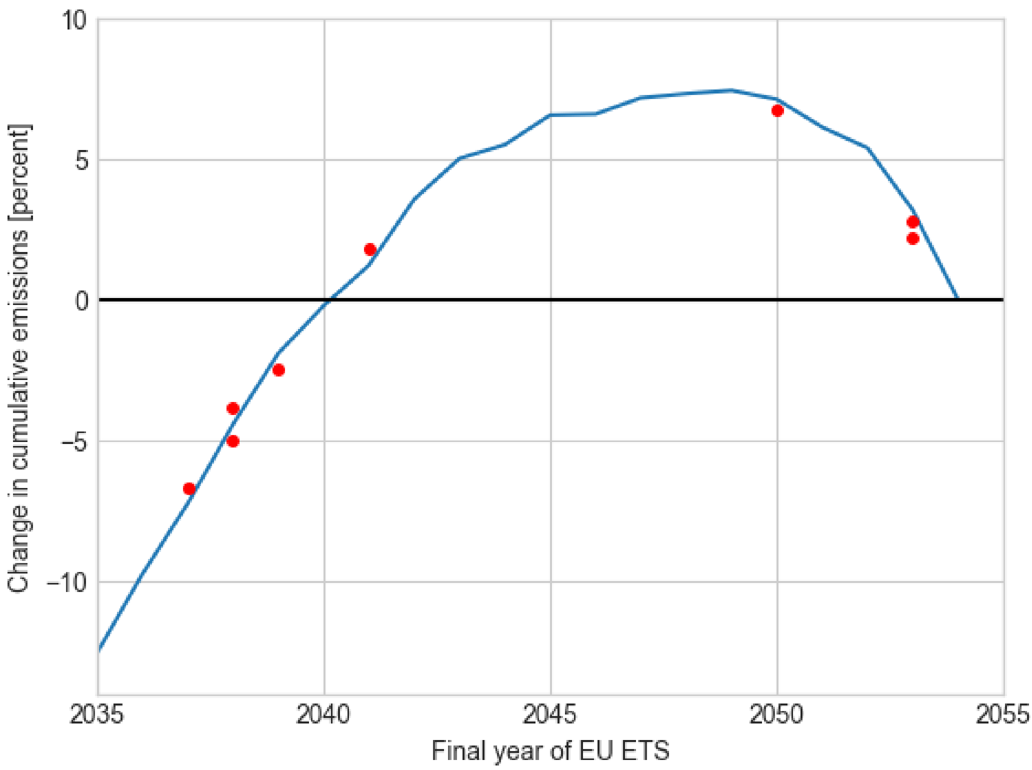

Figure 8. Percental change in cumulative emissions relative to 2054, multiple equilibria included.

Figure 8 shows a zoomed-in version of the main results from figure 6. However, this figure also includes the impact on emissions that occurs when assuming the alternative equilibrium paths. These outcomes are represented as red dots.

As illustrated in the figure, multiple equilibria arise for the years 2037, 2038, 2039, 2041, 2050, and 2053.[8] Furthermore, two separate multiple equilibria can be observed for years 2038 and 2053. For 2038, the two additional equilibria can give rise to either an increase or a decrease in cumulative emissions compared to the change previously observed. Moreover, the two equilibria found for 2053 both point towards a less severe increase in cumulative emissions than what was previously established. However, the observed multiple equilibria over all years remain very close to the main results that are illustrated by the blue curve. Therefore, the distinct equilibria has at most a very minor impact on the main findings of the paper, and hence, one can conclude that the main results are robust to multiple equilibria.

[8] Multiple equilibria moreover occurred for the case of 2030. This year was however excluded from the figure.

7. Discussion

The results of this analysis are in line with those established in Heijmans (2022), who showed that shortening the duration of a cap-and-trade scheme that operates a quantity mechanism could result in increased cumulative emissions under its cap. In this context, the results not only confirm the findings of Heijmans (2022), but also numerically assess them when applied to the specific case of the EU ETS.

Furthermore, these findings expand beyond the case of the EU ETS. The results hold not because of some components specific to the EU ETS alone, but because of the structure that encompasses quantity mechanisms. For example, a price mechanism has a balancing effect on the market, while a quantity mechanism instead misinterprets market signals (Heijmans, 2023). On one hand, the price mechanism would interpret a low price as if there is an oversupply of allowances in the market, and thus adjust the supply accordingly and *decrease* the cap. On the other hand, a quantity mechanism would interpret a low price and reduced banking as if there is an increase in demand. The quantity mechanism's response is to *increase* the cap to meet the rise in demand, regardless if there already is an oversupply of allowances (Heijmans, 2022).

Additionally, the observed results are consistent with the literature that focuses on overlapping policies that interact with the MSR mechanics (Perino et al., 2020; Gerlagh et al., 2021). These studies conclude that the MSR undermines the purpose of the EU ETS, which could lead to an increase in overall EU ETS emissions when it is supplemented by other climate policies that affects demand. In the context of this paper, one may similarly interpret that the duration of the EU ETS is reduced because of an overlapping policy (such as a binding emissions target) that binds emissions to zero.

Moreover, there are a few limitations and considerations of the study that must be addressed.

Uncertainty. In the EU ETS model, present and future abatement costs are assumed to be common knowledge for all firms. However, parts of the literature have highlighted the uncertainty of the allowance price and abatement costs as having possible severe implications for EU ETS outcomes (Lintunen and Kuusela (2018); Kollenberg and Taschini, 2019). As briefly discussed in Heijmans (2022), a similar model of asymmetric information and uncertainty could straightforwardly be included in the analysis by expressing the firms' abatement costs in terms of expected values.

Demand calibration. The values of α and β that arise from the demand calibration are highly uncertain, although important for the analysis. The estimation of these two values is based on historical observations, and as such, the parameters in the demand function will yield different values depending on the annual observations that are considered. Despite the uncertainty of the parameter values, they are in line with previously calibrated values in Gerlagh et al. (2021).

Theoretical model. The theoretical model in section 4 is an approximation of the stylized model of the EU ETS. Equation (15) in the theoretical model explains the adjustable supply as a continuous negative function of banking. This is a broad simplification of most (if not all) cap-and-trade schemes that operate a quantity mechanism. In the actual EU ETS, the reduction in adjustable supply is not continuous, but instead explained by discrete jumps when banking passes certain thresholds. However, despite this broad approximation, the mechanisms that describe cancellation remains relatively similar between the theoretical case and the simulated model. In this sense, the paper shows that the theoretical framework holds in a more practical context of cap-and-trade schemes.

Emissions target. It is assumed in the model that a complementary policy, independent of the scheme, binds emissions to zero starting from an end year $\bar{T}$. However, a complementary emissions target policy need not set annual emissions starting from a certain year to be zero. The binding target can for example be 55% of emissions relative to a certain year, as seen in the case of the 2030 EU emissions target. Although the study doesn't consider such a case, the results presented here should still be robust for binding targets for which annual emissions are above zero starting from $\bar{T}$. As argued in Heijmans (2022), anticipating firms will act in similar ways that affects banking behaviour (and thus cumulative emissions), regardless if an emissions target that is enacted in $\bar{T}$ binds emissions to zero or above zero.

Welfare. The model presented in the analysis simulates equilibrium emissions trajectories of the EU ETS for a given final period. It does not however consider an analysis on optimal emissions paths for mitigating climate change. From a welfare perspective, it might for example be socially optimal for the EU to have very high emissions at the start of the scheme, followed by steep emissions reductions in the next few years. Optimal emissions paths from a social welfare analysis have for example been studied in Dietz and Venmans (2019), where they establish that steep emissions reductions early on would yield optimal outcomes for avoiding climate damages. None of this is however taken into account in the model.

Emissions reductions. It was confirmed in the results that shortening the duration of the EU ETS has an impact on cumulative emissions. Decreases in cumulative emissions may only occur by vastly reducing the duration of the scheme, which would likely require drastically ambitious climate policies in the coming years. A question that arises from this is whether such a drastic tightening of climate policies would be beneficial from a welfare analysis, and whether the implementation of these would be well-accepted in domestic policy.[9]

[9] See for example Oberthür and Roche Kelly (2008), who mention that the implementation of domestic climate policies have historically been one of the most major challenges of EU climate policy.

MSR design. As already mentioned in Osorio et al. (2021), parameter values due to the complexities of MSR mechanics are uncertain, and varying these values could impact the outcome of EU ETS cancellation drastically. Policymaking should take careful consideration as to the design of the MSR mechanisms and the linear reduction factor in future reforms of the EU ETS.

8. Conclusions

This paper has focused on emissions trading schemes whose adjustable cap is determined by a quantity mechanism. In addition to deriving equilibrium conditions under a general permit scheme, it utilizes a stylized model of emissions trading in the EU ETS to examine how the duration of the scheme affects cumulative emissions under its cap.

The paper shows that under sufficient conditions, a shortening of the duration of the EU ETS leads to an increase in cumulative emissions, compared to when the time horizon is not shortened. This increase may be as much as 7.44%, or 1730 $MtCO_2$. To put the result into perspective, this number exceeds what Norway and Sweden have jointly emitted since 2004, which is one year before the establishment of the EU ETS.

Additionally, there exist possibilities for a decrease in cumulative emissions. However, this would require a more drastic shortening of the duration of the EU ETS. A question that arises is whether such a drastic tightening of the cap would be politically and socially feasible to impose.

The results are an extension of the established framework and findings of Heijmans (2022). This paper illustrates that what Heijmans (2022) proved theoretically for a general setting also holds in a practical and specific context (that is the EU ETS). Moreover, this analysis puts a numerical value to the changes in emissions from bringing the end year of the scheme forward in time. That is the contribution of this paper.

Furthermore, this analysis highlights concerns regarding policy implications of the EU ETS and permit schemes in general. What the paper has illustrated is that the duration of the scheme matters. Depending on *when* a binding target may render the EU ETS obsolete, this may result in counterproductive climate policies it the EU. This particularly concerns the European Green Deal, whose final goal is zero net emissions by 2050. Firms, anticipating net zero emissions in 2050, will shift their post-2050 demand to earlier periods, leading to decreased banking and thus less cancellation of allowances. According to the model simulation, this would result in a 6.1% increase in total EU ETS emissions, compared to in the absence of the net zero emissions target.

Compared to the rest of the EU, countries such as Germany and Sweden have set the more ambitious net zero emissions target of 2045. Assuming a scenario where the EU would follow in their example of net zero emissions, this would lead to an increase in cumulative emissions by 6.6%. Achieving net zero emissions in 2045, instead of in 2050, would thus lead to an increase in cumulative EU emissions by 0.5 percentage points. Therefore, shortening the time horizon of emissions trading may be incompatible with strengthened climate ambitions, since such a counterintuitive scenario can arise in the case of the EU ETS.

It is important to emphasize that this is not a direct criticism of the EU ETS nor of the need for stronger climate ambitions, but rather an observation that follows from the MSR-design of the EU ETS and quantity mechanisms in general. It implies that policymakers should take this into consideration when designing climate policies.

Although price instruments are beyond the scope of this study, a large body of literature has already argued for the advantages of price measures over quantity mechanisms (Abrell and Rausch, 2017; Gerlagh et al., 2021; Heijmans, 2022). Price mechanism could hence be a suitable addition to the current quantity-based measures of the MSR due to its ability to stabilize the market through price signals. A proposal has for example been to implement a *"Price Stability Reserve"* that would function similar to a price instrument, in contrast to the existing MSR (Perino et al., 2021).

Lastly, one key assumption behind the analysis is that firms in the EU ETS market have full information regarding the duration of the scheme, as well as abatement costs. A consideration for future research is to examine the implications of the EU ETS under asymmetric information regarding future abatement costs, given the considerably volatile allowance price in recent years.

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Popular science summary

This master's thesis examines what happens to CO_2 emissions if the duration of a cap-and-trade scheme is shortened. First of all, what is a cap-and-trade scheme?

Imagine a group of firms who all produce something that creates pollution, like factories or power plants. A cap-and-trade scheme is a way to control and reduce that pollution. Under a cap-and-trade scheme, firms are given a limited number of allowances that represents the right to pollute, and if they exceed their limit, they must buy permits from others who have emitted less.

What happens if the duration of a cap-and-trade scheme is shortened? This topic has been studied in 2022 by the economist Roweno J.R.K. Heijmans, where he made an interesting discovery. He found that if the duration of a specific kind of cap-and-trade scheme is shortened, then overall emissions are likely to increase. However, we have no idea how large this effect is in numbers. Knowing how large this effect might be is important for climate policies that aim at reducing emissions and mitigating climate change. If the effect from shortening the duration of a scheme is very large, it would mean that we will emit a large amount of unnecessary CO_2 emissions into the atmosphere.

This paper looks at the largest cap-and-trade scheme in the world: the EU ETS. Specifically, this paper quantifies, in numbers, how much EU ETS emissions might increase if the duration of the scheme is shortened. This thesis is therefore a direct continuation of the research by Heijmans in 2022.

The study finds two main results. Firstly, if the duration of the EU ETS is shortened sufficiently so that it ends before the year 2040, then total EU ETS emissions will decrease. Secondly, if the EU ETS ends in 2040 or later however, the opposite happens: total EU ETS emissions increases. In fact, total emissions could increase by more that 7% if the EU ETS ends around the year 2050.

Why are these results important? Currently, the EU aims at having net zero emissions in 2050. Indirectly, this would mean that the duration of the EU ETS is effectively shortened to the year 2050. The results suggest that if this happens, then under current EU policy, total emissions could increase by more than 7% compared to if the EU would not aim at net zero emissions. This 7% increase in emissions that the EU might be facing exceeds the combined emissions of Norway and Sweden since 2004. Knowing this, it is important that policymakers are careful when designing cap-and-trade schemes, including the EU ETS.

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Appendix 1: Proofs for the three-period model

Proof of Observation 2:

Observation 2 is proven by equation (8), that is:

$$\omega_{it+1} = \left(\frac{1}{1+r}\right)^{t} \alpha + \left(\frac{1}{1+r}\right)^{t} \beta a_{it} - \lambda_i,$$

which implies the following:

$$\omega_{it} = \left(\frac{1}{1+r}\right)^{t-1} \alpha + \left(\frac{1}{1+r}\right)^{t-1} \beta a_{it-1} - \lambda_i,$$

and thereafter plugging the two expressions above into (10) and rearranging so that

$$C'_{it-1} + \left(\frac{1}{1+r}\right) \psi_{it} = \left(\frac{1}{1+r}\right) C'_{it}, \tag{31}$$

Next, from (11) one can derive the following two expressions:

$$p_t + \mu_{it} = C'_{it},$$

and

$$p_{t-1} + \mu_{t-1} = C'_{it-1}.$$

Inserting these two expressions into (14) and rearranging yields the following:

$$p_t = (1+r)(p_{t-1} + \mu_{t-1}) + \psi_{it} - \mu_t, \tag{32}$$

from which (13), and thus Observation 2, are proven.

Proof of Observation 3:

This proof is split into two sections: first, how first-period banking is affected by an increase in the allowance price, and secondly, how is is affected in any period $t > 1$.

For banking in the first period:

$$\frac{\partial B_1^Q(p)}{\partial p_\tau} = \frac{\partial b_0(p_0)}{\partial p_0}\frac{\partial p_0}{\partial p_\tau} = \frac{\partial\left[s_0^Q - q_0(p_0)\right]}{\partial p_0}\frac{\partial p_0}{\partial p_\tau} = -\frac{\partial q_0(p_0)}{\partial p_0}\frac{\partial p_0}{\partial p_\tau} \geq 0, \quad (33)$$

where (33) is proven to be nonnegative because of (12) and (13). Next, proving Observation 3 for periods $t > 1$ is slightly more complicated. From (3), assume that banking of allowances is given by: $B_t^Q(p) = B_{t-1}^Q(p) + s_{t-1}^Q\left(B_{t-1}^Q(p)\right) - q_{t-1}(p_{t-1})$, where supply s_t is determined by the level of banking because the scheme operates a quantity mechanism. For banking in $t > 1$:

$$\frac{\partial B_t^Q(p)}{\partial p_\tau} = \frac{\partial B_{t-1}^Q(p)}{\partial p_\tau} + \frac{\partial s_{t-1}^Q\left(B_{t-1}^Q(p)\right)}{\partial p_\tau} - \frac{\partial q_{t-1}(p_{t-1})}{\partial p_\tau}, \quad (34)$$

$$= \left[1 + \frac{\partial s_{t-1}^Q\left(B_{t-1}^Q(p)\right)}{\partial B_{t-1}^Q(p)}\right]\frac{\partial B_{t-1}^Q(p)}{\partial p_\tau} - \frac{\partial q_{t-1}(p_{t-1})}{\partial p_{t-1}}\frac{\partial p_{t-1}}{\partial p_\tau}, \quad (35)$$

In (35), the first term $1 + \partial s_t^Q/\partial B_t^Q$ is positive by assumption. The last term is negative because of (12) and (13). The only remaining term, $\partial B_{t-1}^Q/\partial p_\tau$ is known for $t = 2$. For $t = 2$, this term becomes equal to first-period banking in (33), which is already proven to be nonnegative. The overall expression for (35) is thus positive, and thus

$$\frac{\partial B_t^Q(p)}{\partial p_\tau} \geq 0, \quad (36)$$

for all $t, \tau \in [0, T)$.

Proof of Proposition 1:

Since banking must be non-negative, two distinct scenarios can occur: (i) $B_{\bar{T}}^Q(p^Q) = 0$, and (ii) $B_{\bar{T}}^Q(p^Q) > 0$. The two scenarios will be analysed separately. In scenario (i), the price vector p^Q is the same when the duration of the scheme is shortened from T to $\bar{T}$, so that $p_t^Q = \bar{p}_t^Q$. This fact can be proven through contradiction.

Suppose that $p_t^Q \neq \bar{p}_t^Q$, then either (a) $p_t^Q > \bar{p}_t^Q$ or (b) $p_t^Q < \bar{p}_t^Q$ must be true for at least one $t < \bar{T}$. However, Observation 3 implies that for (a) then $B_{\bar{T}}^Q(p^Q) < 0$, whereas for (b) then $B_{\bar{T}}^{Q}(p^{Q}) > 0$, which both contradict the original statement in scenario (i) that $B_{\bar{T}}^{Q}(p^{Q}) = 0$. Therefore, $p_t^Q = \bar{p}_t^Q$. Equilibrium emissions when the scheme ends in $\bar{T}$ are thus given by

$$\sum_{t=0}^{\bar{T}} q_t(p^Q) = \sum_{t=0}^{\bar{T}} s_t(p^Q).$$

If the scheme ends in T instead, emissions are the following:

$$\sum_{t=0}^{T} q_t(p^Q) = \sum_{t=0}^{T} s_t(p^Q).$$

As explained by (24), subtracting the former expression from the latter yields emissions reductions in equilibrium from cutting the duration of the scheme:

$$\begin{aligned} R^Q(\bar{T}, T) &= \sum_{t=0}^{T} q_t(p^Q) - \sum_{t=0}^{\bar{T}} q_t(p^Q) \\ &= \sum_{t=0}^{T} s_t\left(B_t^Q(p^Q)\right) - \sum_{t=0}^{\bar{T}} s_t\left(B_t^Q(p^Q)\right) \\ &= S^Q(\bar{T}, T \mid p^Q). \end{aligned}$$

Similarly, case (i) can additionally be proven by using the more specific functional forms of the equilibrium solution from section 4.4 of the theoretical model. For this, assume that the duration of the scheme is shortened from period t_2 to t_1, and thus

$$\begin{aligned} R^Q(t_1, t_2) &= \sum_{t=0}^{2} q_t(p^Q) - \sum_{t=0}^{1} q_t(p^Q) \\ &= \sum_{t=0}^{2} s_t\left(B_t^Q(p^Q)\right) - \sum_{t=0}^{1} s_t\left(B_t^Q(p^Q)\right) \\ &= s_2^Q + s_1^Q + s_0^Q - (s_1^Q + s_0^Q) = s_2^Q \\ &= S^Q(t_1, t_2 \mid p^Q). \end{aligned}$$

In case (ii), $B_{\bar{T}}^{Q}(p^{Q}) > 0$ for period $\bar{T}$. However, if $\bar{T}$ is set as the final period, then in equilibrium it must be that $B_{\bar{T}}^{Q}(\bar{p}^{Q}) = 0$. From Observation 2, this implies that $p^Q > \bar{p}^Q$ for all $t < \bar{T}$. The reduction in emissions can hence be written as the following:

$$
\begin{aligned}
R^Q(\bar{T},T) &= \sum_{t=0}^{T} q_t(p^Q) - \sum_{t=0}^{\bar{T}} q_t(\bar{p}^Q) \\
&= \sum_{t=0}^{T} s_t\left(B_t^Q(p^Q)\right) - \sum_{t=0}^{\bar{T}} s_t\left(B_t^Q(\bar{p}^Q)\right) \\
&= S^Q(\bar{T},T \mid p^Q) + \sum_{t=0}^{\bar{T}} s_t\left(B_t^Q(p^Q)\right) - \sum_{t=0}^{\bar{T}} s_t\left(B_t^Q(\bar{p}^Q)\right) \\
&< S^Q(\bar{T},T \mid p^Q),
\end{aligned}
$$

where the inequality arises because of $p^Q > \bar{p}^Q$, which futher implies that $B_t^Q(p^Q) > B_t^Q(\bar{p}^Q)$, and thus $s_t\left(B_t^Q(p^Q)\right) < s_t\left(B_t^Q(\bar{p}^Q)\right)$. Combining both cases of this proof thus concludes that $R^Q(\bar{T},T) \leq S^Q(\bar{T},T \mid p^Q)$. Proposition 1 has thus been proven.

Although it is not necessary at this point (since Proposition 1 has already been proven), but case (ii) can similarly be confirmed with the functional forms given in section 4.4. Thus, instead of assuming a shortening of the scheme by using the general terms T and $\bar{T}$, assume that the scheme is shortened from t_2 to t_1. Reduction in emissions would then be given by

$$
\begin{aligned}
R^Q(t_1,t_2) &= \sum_{t=0}^{2} q_t(p^Q) - \sum_{t=0}^{1} q_t(\bar{p}^Q) \\
&= \sum_{t=0}^{2} s_t\left(B_t^Q(p^Q)\right) - \sum_{t=0}^{1} s_t\left(B_t^Q(\bar{p}^Q)\right) \\
&= s_2^Q + s_1^Q + s_0^Q - \sum_{t=0}^{1} s_t\left(B_t^Q(\bar{p}^Q)\right) \\
&= S^Q(t_1,t_2 \mid p^Q) + \sum_{t=0}^{1} s_t\left(B_t^Q(p^Q)\right) - \sum_{t=0}^{1} s_t\left(B_t^Q(\bar{p}^Q)\right) \\
&< S^Q(t_1,t_2 \mid p^Q),
\end{aligned}
$$

where the inequality rises because $\sum_{t=0}^{1} s_t\left(B_t^Q(p^Q)\right) < \sum_{t=0}^{1} s_t\left(B_t^Q(\bar{p}^Q)\right)$, since $p^Q > \bar{p}^Q$.

Proof of Proposition 2:

It has already been established that $R^Q(\bar{T},T) \leq S^Q(\bar{T},T \mid p^Q)$. Furthermore, (27) implies that supplied has already permanently dried out in period $\bar{T}$, and hence $S^Q(\bar{T},T \mid p^Q) = 0$. Moreover, since demand is positive in $\bar{T}$ (by (26)), then this means that any demand must be covered by banked allowances, which implies that banking must also be strictly positive, so that $B_{\bar{T}}^Q(p^Q) > 0$.

The fact that $B_{\bar{T}}^{Q}(p^{Q})$ is strictly positive can also be confirmed through the supply function by (15). From (15), supply in period 2 is given by:

$$\begin{aligned} s_2^Q &= \bar{s_2} - \delta B_2^Q \\ &= \bar{s_2} - \delta(B_1^Q + s_1^Q - q_1(p_1)) \\ &= \bar{s_2} - \delta B_1^Q + \delta s_1^Q - \delta q_1(p_1). \end{aligned}$$

Assuming that the duration is shortened from period 2 to period 1 (instead of the more general formulation of $T$and $\bar{T}$), then (27) implies that $s_2^Q, \bar{s_2}$, and s_1^Q are all equal to zero. Furthermore, by (26) then $q_1(p_1)$ is strictly positive. Therefore, for symmetry on both sides of the equal sign, B_1^Q must also be strictly positive, and hence $B_{\bar{T}}^{Q}(p^{Q}) > 0$.

Furthermore, $B_{\bar{T}}^{Q}(p^{Q}) > 0$ implies that case (ii) from Proposition 1 applies, so that $R^Q(\bar{T}, T) < S^Q(\bar{T}, T \mid p^Q)$. Moreover, since it has already been proven that $S^Q(\bar{T}, T \mid p^Q) = 0$, then $R^Q(\bar{T}, T) < 0$.

Appendix 2: Equilibrium solutions from the three-period model

Appendix 2 shows the equilibrium solutions for emissions, banking, and adjustable supply in each period. Recall that equilibrium prices are given by (22). Plug the solution from (22) into (11) to solve for emissions in respective period:

$$q_0^Q = q_0^0 - \left[\frac{q^0 - \bar{s} - \delta(2q_0^0 + q_1^0 - 2\overline{s_0} - \overline{s_1}) + \frac{1}{\beta}\big(3\alpha - \mu - \delta(3\alpha - 2\mu_0 - \mu_1)\big)}{3 - 3\delta}\right] + \frac{\alpha - \mu_0}{\beta}, (37)$$

$$q_1^Q = q_1^0 - \left[\frac{q^0 - \bar{s} - \delta(2q_0^0 + q_1^0 - 2\overline{s_0} - \overline{s_1}) + \frac{1}{\beta}\big(3\alpha - \mu - \delta(3\alpha - 2\mu_0 - \mu_1)\big)}{3 - 3\delta}\right] + \frac{\alpha - \mu_1}{\beta}, (38)$$

$$q_2^Q = q_2^0 - \left[\frac{q^0 - \bar{s} - \delta(2q_0^0 + q_1^0 - 2\overline{s_0} - \overline{s_1}) + \frac{1}{\beta}\big(3\alpha - \mu - \delta(3\alpha - 2\mu_0 - \mu_1)\big)}{3 - 3\delta}\right] + \frac{\alpha - \mu_2}{\beta}. (39)$$

From (3), define $B_1 = \overline{s_0} - q_0(p_0)$, and $B_2 = B_1 + \overline{s_1} - q_1(p_1)$. Plug the above solution for q_0^Q and q_1^Q to solve for equilibrium banking:

$$B_1^Q = \overline{s_0} - q_0^0 + \left[\frac{q^0 - \bar{s} - \delta(2q_0^0 + q_1^0 - 2\overline{s_0} - \overline{s_1}) + \frac{1}{\beta}\big(3\alpha - \mu - \delta(3\alpha - 2\mu_0 - \mu_1)\big)}{3 - 3\delta}\right] - \frac{\alpha - \mu_0}{\beta}. (40)$$

In order to simplify the proceeding solutions for banking and adjustable supply in the 2nd period, denote $\overline{s_{01}} := \overline{s_0} + \overline{s_1}$ and $q_{01}^0 \coloneqq q_0^0 + q_1^0$.

$$B_2^Q = \overline{s_{01}} - q_{01}^0 + 2\left[\frac{q^0 - \bar{s} - \delta(2q_0^0 + q_1^0 - 2\overline{s_0} - \overline{s_1}) + \frac{1}{\beta}\big(3\alpha - \mu - \delta(3\alpha - 2\mu_0 - \mu_1)\big)}{3 - 3\delta}\right] - \frac{2\alpha - \mu_0 - \mu_1}{\beta}. (41)$$

Adjustable supply is given by (15). Insert (31) and (32) above to solve for equilibrium supply:

$$s_1^Q = \overline{s_1} - \delta(\overline{s_0} - q_0^0) - \delta\left[\frac{q^0 - \bar{s} - \delta(2q_0^0 + q_1^0 - 2\overline{s_0} - \overline{s_1}) + \frac{1}{\beta}\big(3\alpha - \mu - \delta(3\alpha - 2\mu_0 - \mu_1)\big)}{3 - 3\delta}\right] + \delta\frac{(\alpha - \mu_0)}{\beta}, (42)$$

$$s_2^Q = \overline{s_2} - \delta(\overline{s_{01}} - q_{01}^0) - 2\delta\left[\frac{q^0 - \bar{s} - \delta(2q_0^0 + q_1^0 - \overline{2s_0} - \overline{s_1}) + \frac{1}{\beta}\big(3\alpha - \mu - \delta(3\alpha - 2\mu_0 - \mu_1)\big)}{3 - 3\delta}\right] + \delta\frac{(2\alpha - \mu_0 - \mu_1)}{\beta}. (43)$$

Appendix 3: EU ETS model details

3.1 Model description

The EU ETS model consists of time periods $t \in \{1, \dots, T\}$ that refers to years of the scheme. In the model, capital letters are used to indicate stocks at the end of a period, and lower case letters are used for flows during a time period. The size of the MSR, in terms of allowances, is given by the following mechanical rule:

$$M_t = \min(\theta s_{t-1}, M_{t-1}) + m_t - n_t, \tag{44}$$

where s_t is the number of supplied allowances in period *t*, and θ the share of the supply that is auctioned on the permit market, m_t and n_t is the annual inflow of allowances into and out of the MSR, respectively. The difference between M_{t-1} and θs_{t-1} is cut off and cancelled each year. Therefore, cancellation of allowances is given by

$$C_t = \max(0, M_t - \theta s_t)\,, \tag{45}$$

Note here that cancellation can't be negative. Moreover, m_t and n_t are given by the following rule:

$$(m_t, n_t) = \begin{cases} (0, \min(M_{t-1}, \Gamma)) & if\ B_{t-1} < B\_ \\ (0, 0) & if\ B\_ \leq B_{t-1} < \bar{B}\,, \\ (\mathrm{aB_{t-1}}, 0) & if\ \bar{B} \leq B_{t-1} \end{cases} \tag{46}$$

The model can be parameterized to resemble the EU ETS by specifying $\theta = 0.57, \Gamma = 100, \mathrm{B\_} = 400, \bar{B} = 833, \mathrm{a} = 0.24$. Equilibrium banking in period *t* is characterized by banking in the previous year, *plus* the amount of (adjustable) supply given to firms in *t*, *minus* the (demanded) amount that firms decide to emit in *t*. Hence,

$$B_t - B_{t-1} = s_t - m_t + n_t - d_t(p_t), \tag{47}$$

Recall from (23) that the demand of allowances, d_t, decreases in the allowance price, p_t. Since the price increases annually because of Hotelling's rule in (24), this implies an upper bound on demand. Eventually, the price rises until it is equal to the choke price, which is when emitting is no longer profitable, and therefore when allowances are no longer demanded. At this stage the EU ETS ends *endogenously* (i.e., through its own mechanisms), given that firms also have successfully offloaded their banked allowances and that the MSR is emptied. As mentioned in section 5.1, the endogenous final year of the EU ETS is 2054.

3.2 Parameter specifications

Table 1. Parameter specifications

Parameter	Description	Value		Source
B^{-}	Threshold for inflow into MSR	833 Mt		*
$B\_$	Threshold for ouflow from MSR	400 Mt		*
a	Withdrawal rate (percentage flow into MSR)	0.24	(2020-2023)	**
		0.12	(After 2024)	**
Γ	Outflow from MSR	100 Mt		*
θ	Threshold factor for cancelling allowances	0.57		*
s**_2020**	Supply of allowances in 2020	1859 Mt		****
	Linear reduction factor	-0.022	(2021-2023)	**
		-0.043	(2024-2027)	***
		-0.044	(After 2027)	***
B**_2020**	Banking at the end of 2020	1579 Mt		*****
M**_2020**	Size of MSR at the end of 2020	1924 Mt		*****
	First year of cancellation	2023		*
r	Interest rate	0.05		
α	Maximum demand in first year	1772.204 Mt		
β	Demand function slope in first year	8.492 Mt/€		

* Perino (2018).
** https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/market-stability-reserve_en
*** European Council (2022).
**** https://climate.ec.europa.eu/system/files/2021-10/com_2021_962_en.pdf
***** https://climate.ec.europa.eu/system/files/2021-05/c_2021_3266_en.pdf

Table 1 shows the parameter specifications , as well as the sources from where the parameter values were obtained. The parameters are either specified through the *mechanical rules of the MSR policy* ($\overline{B}, B\_$, a, Γ), *historical observations* (supply, banking, and MSR size at the end of 2020), or through *calibration* (α, β).

Regarding historical levels for the parameters, 1859 million allowances were supplied in 2020. This amount of supplied allowances reduces annually (according to the linear reduction factor) by 2.2 percent until 2023. Thereafter, the annual

reduction in supply is 4.3 percent until 2027, and after 2027 it reduces by 4.4 percent annually. Furthermore, the number of banking was 1579 million allowances at the end of 2020, and the size of the MSR amounted to 1924 million allowances.
As previously mentioned, the calibrated demand parameters α and β are uncertain but important for the analysis. These two parameters determine how price responsive the demand is, and it is hard to predict how demand might change over time. As specified in the model, demand is decreasing over time because of the increasing allowance price. Such a decrease in demand over time could realistically be explained by factors such as energy efficiency, technological progress, and substitution from fossil fuels to renewables. On the other hand, other factors such as economic growth could instead predict an increase in demand over time (Gerlagh et al., 2021).

Appendix 4: Model simulations for additional final years of the EU ETS

Here the simulated market outcome and the stocks of allowances are displayed for different end years of the EU ETS. The figures shown here are similar to figures 3 and 4, except that now the final year $\bar{T}$ of the scheme varies.

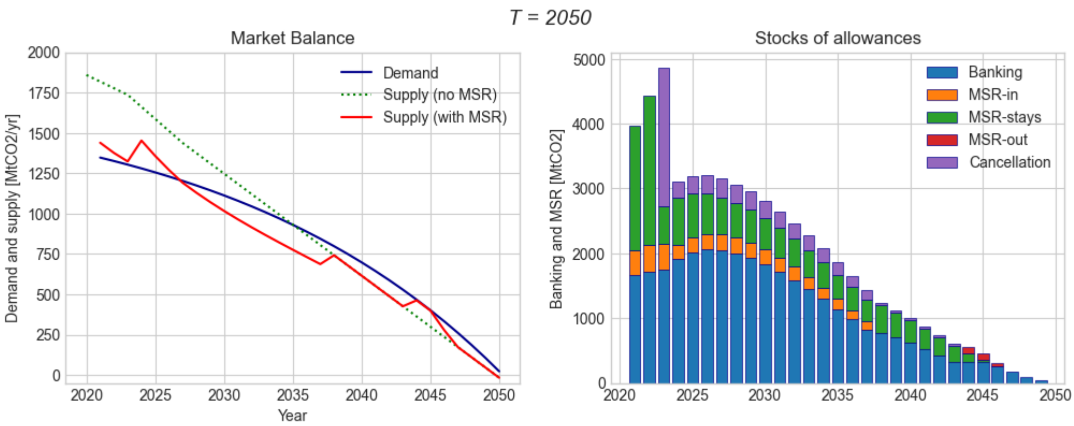

Figure 9. The EU ETS ends in 2050.

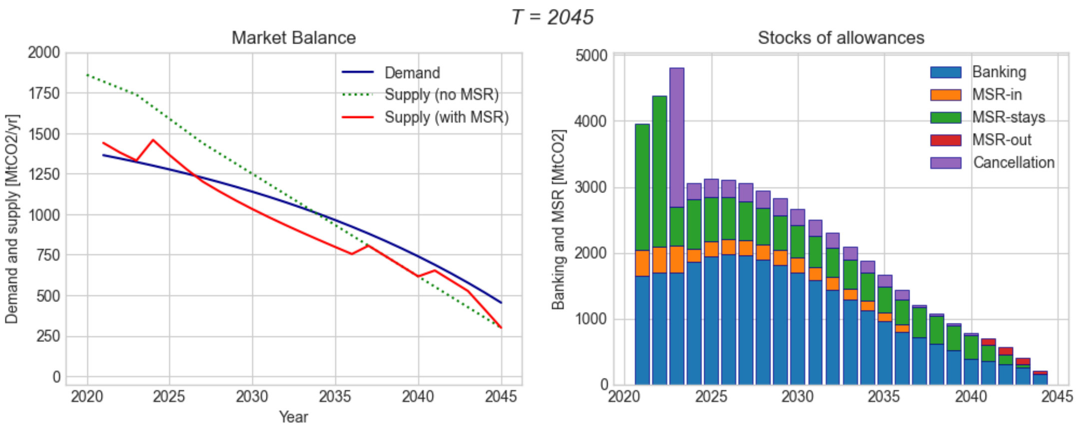

Figure 10. The EU ETS ends in 2045.

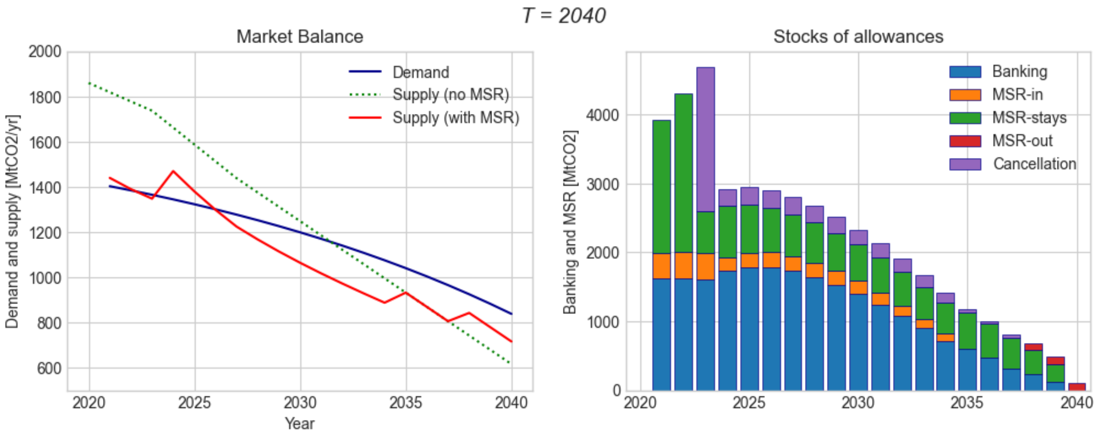

Figure 11. The EU ETS ends in 2040.

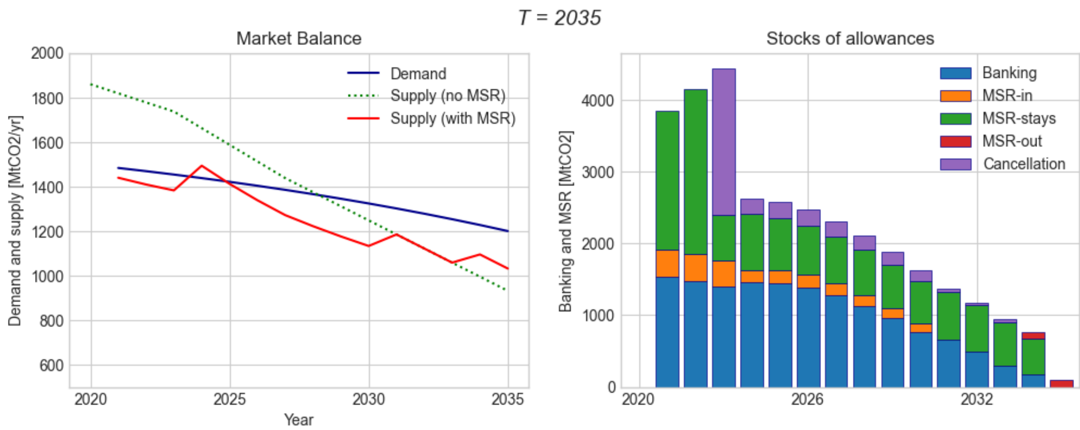

Figure 12. The EU ETS ends in 2035.

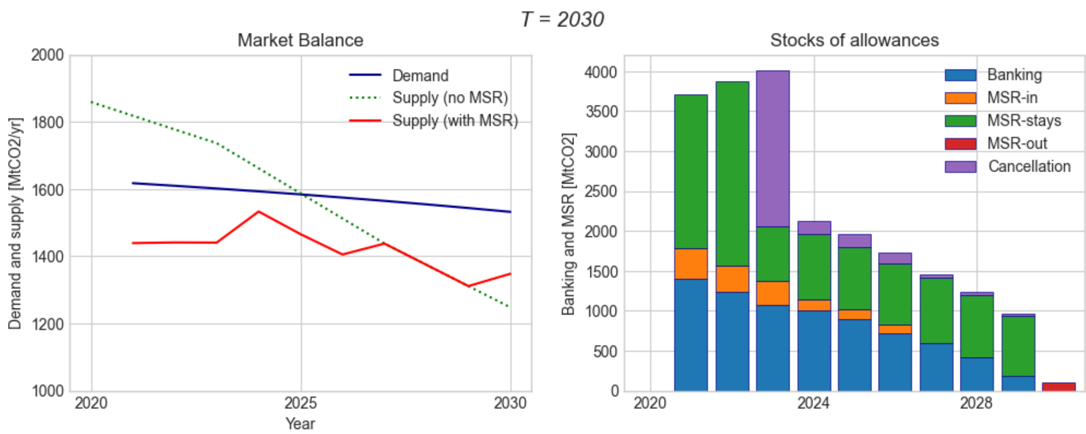

Figure 13. The EU ETS ends in 2030.

Appendix 5: Multiple equilibria

Appendix 5 extends the discussion on multiple equilibrias. More specifically, this appendix shows figures that were not included in section 6.2, and which further check the occurrence of multiple equilibria for different end years of the EU ETS. Similar to figure 7, an equilibrium is characterized by the intersection of the banking curve in blue and the horizontal line at 0. For simplicity, this is illustrated by a red circle in the figures.

Multiple equilibrium price paths have been found for seven different end years of the EU ETS: 2030, 2037, 2038, 2039, 2041, 2050, and 2053. Among these, more than two equilibria were even found for 2030, 2038, and 2053. An additional analysis was carried out to check whether any of the newly found equilibria (shown in the figures below) have an impact on the main results of this paper. As already mentioned, the outcome of this extended analysis was shown in figure 8 in section 6.2, which highlighted that the additional equilibria that were found had at most a very minor impact on the main findings. Therefore, the main results are highly robust to multiple equilibria.

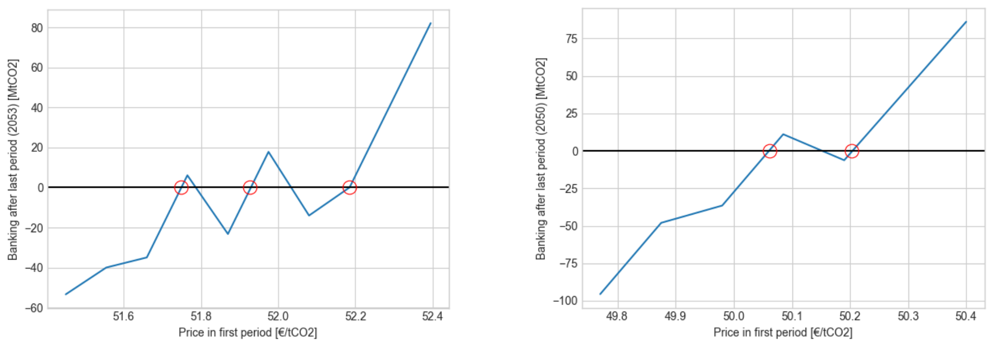

Figure 14. Multiple equilibria for 2053 and 2050.

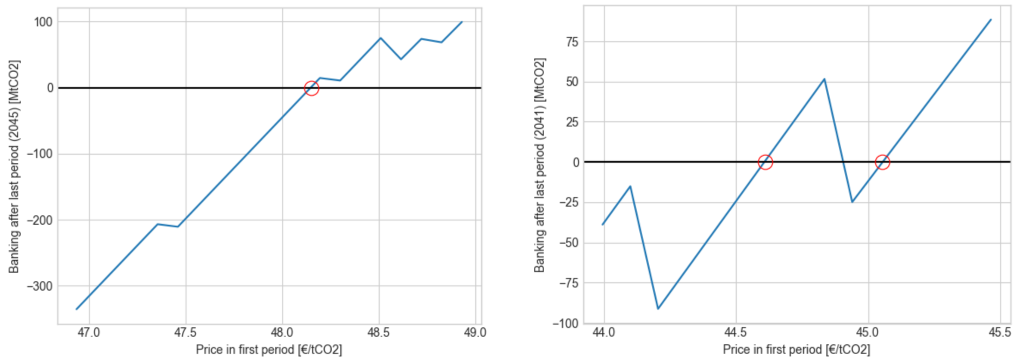

Figure 15. Multiple equilibria for 2045 and 2041.

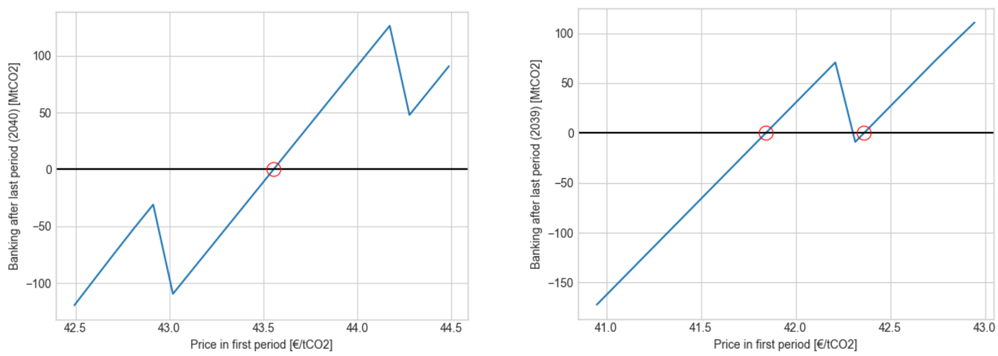

Figure 16. Multiple equilibria for 2040 and 2039.

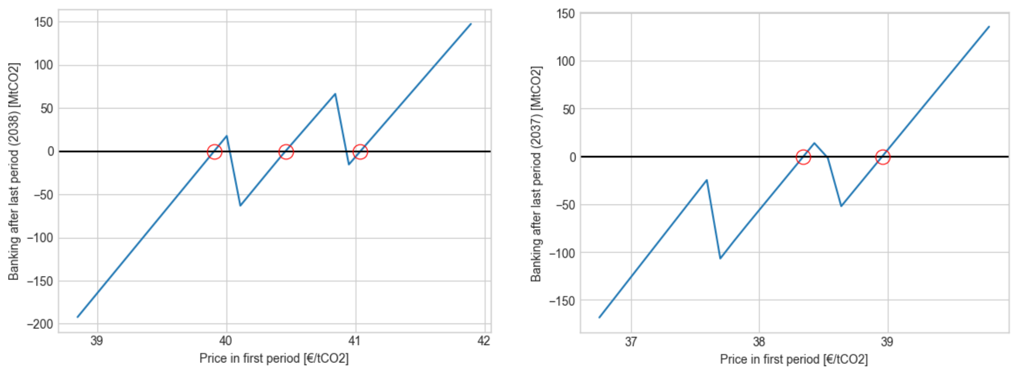

Figure 17. Multiple equilibria for 2038 and 2037.

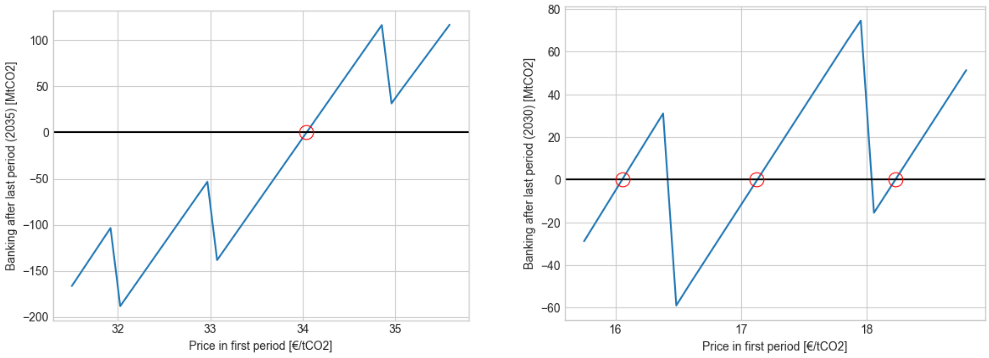

Figure 18. Multiple equilibria for 2035 and 2030.

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