The Reformed EU ETS - Intertemporal Emission Trading with Restricted Banking ☆

Johanna Bocklet[a], Martin Hintermayer[a], Lukas Schmidt[a], Theresa Wildgrube[a]

[a]*Department of Economics and Institute of Energy Economics, University of Cologne,*
Contact details: Martin Hintermayer, Department of Economics and Institute of Energy Economics,
University of Cologne, Vogelsanger Strasse 321a, 50827 Cologne, Germany,
Phone: +49 221 27729 303 / Fax: +49 221 27729 400 / Email: martin.hintermayer@ewi.uni-koeln.de

---

Abstract

With the increase of the linear reduction factor (LRF), the implementation of the market stability reserve (MSR) and the introduction of the cancellation mechanism (CM), the EU ETS changed fundamentally. We develop a discrete time model of the intertemporal allowance market that accurately depicts these reforms assuming that prices develop with the Hotelling rule as long as the aggregated bank is non-empty. A sensitivity analysis ensures the robustness of the model results regarding its input parameters. The accurate modelling of the EU ETS allows for a decomposition of the effects of the individual amendments and the evaluation of the dynamic efficiency. The MSR shifts emissions to the future but is allowance preserving. The CM reduces the overall emission cap, increasing allowance prices in the long run, but does not significantly impact the emission and price path in the short run. The increased LRF leads with 9 billion cancelled allowances to a stronger reduction than the CM and is therefore the main price driver of the reform.

Keywords: Market Stability Reserve, Dynamic Optimization, Cap and Trade, EU ETS, Cancellation Mechanism, Intertemporal Trading
JEL classification: C61, D25, H23, H41, L52, P14, Q48, Q54, Q58

---

1. Introduction

In 2005, the European Union Emissions Trading System (EU ETS) was introduced as a cornerstone of the EU climate policy (European Parliament and the Council of the European

☆The authors want to thank Prof. Bettzüge and the participants of the 12th RGS Doctoral Conference in Economics for their helpful comments. The contents of this paper reflect the opinions of its authors only and not those of EWI.

Union, 2003). While many regions (e.g. California, Australia, Japan) have established other functioning carbon markets since, the EU ETS remains the largest one yet. It covers emissions from energy-intensive industries, the electricity sector and inner-European aviation in 31 countries and accounts for 45% of the total EU greenhouse gas (GHG) emissions.

An emission allowance market coordinates abatement among firms cost-efficiently, allocating abatement to firms with low and allowances to firms with high abatement costs (i.a. Tietenberg (1985) and Salant (2016)). The environment's capacity to absorb emissions without harm can be thought of as a finite and hence exhaustible resource. This is depicted in current emission trading schemes by the finite number of emission allowances issued to the market. The well known economic theory on exhaustible resources (e.g. oil exploration) is the model developed by Hotelling (1931). Thereby, the market price of emission allowances develops with the interest rate if unrestricted banking and borrowing of allowances, i.e. saving unused allowances for the future and shifting future emissions to the present respectively, is allowed. This enables emission markets to reach dynamic efficiency.

The Hotelling model was first used in the context of emission trading systems by Rubin (1996). In his seminal paper, Rubin (1996) sets up a dynamic optimization model, where heterogeneous firms minimize their abatement costs given predefined market rules. An intertemporal market equilibrium exists and is cost-efficient when firms minimize their costs intertemporally through banking or borrowing. However, as early emissions cause greater environmental damage than delayed emissions (pollution damage is assumed to be convex), unrestricted borrowing increases environmental damage. Thus, nation states are implicitly required by international climate agreements such as the Kyoto Protocol to refrain from allowing borrowing in the design of emission trading systems (UNFCCC, 2000). This restriction may create short-run scarcity in the market, leading to a deviation from the original Hotelling price path. Chevallier (2012) applies the theoretical model developed by Rubin (1996) to the EU ETS and discusses the impact of those restrictions on banking and borrowing given the prevailing EU regulation at that time.

The regulatory framework of the EU ETS has been subject to multiple changes since then. The latest major amendments have been the increase of the linear reduction factor (LRF), the introduction of the market stability reserve (MSR) and the option to cancel allowances from the MSR, referred to as cancellation mechanism (CM).

In October 2014, EU leaders adopted the 2030 climate and energy framework for the European Union. This framework comprises i.a. the target of at least 40% GHG reduction in 2030 compared to 1990 levels. To meet this target, the annual reduction of issued allowances in the EU ETS was increased from a LRF of 1.74% in the third trading period (2013-2020) (European Parliament and the Council of the European Union, 2003) to a LRF of 2.2% from 2021 onwards (European Parliament and the Council of the European Union, 2018).

In January 2019, the MSR came into force. Its intended effect is the strengthening of short-run carbon prices in the EU ETS. These were considered to not sufficiently spur investment in low-carbon technologies due to the perceived allowance surplus in phase 3 (European Parliament and the Council of the European Union, 2015). The MSR is a public deposit fed with allowances from the auction volume, whenever the number of allowances in circulation exceeds a certain threshold (European Parliament and the Council of the European Union, 2015). From 2023 onwards, the volume of the MSR is limited to the previous year's auction volume. Allowances in the MSR exceeding this upper limit are invalidated by the CM (European Parliament and the Council of the European Union, 2018).[1]

Recent contributions by Richstein et al. (2015), Perino and Willner (2016) and Beck and Kruse-Andersen (2018) evaluate the impact of the MSR on price and emission pathways. Perino and Willner (2016) and Richstein et al. (2015) find that the MSR itself impacts the market price only temporarily and increases price volatility, contrary to its intended purpose. Because the aggregated emission cap is not altered, the MSR is considered allowance preserving. In Perino and Willner (2017) the impact of an exogenous, one-time cancellation of 800 million allowances is discussed. However, the newly introduced CM decreases the overall emission cap endogenously, i.e. the cancellation depends on the number of allowances in the MSR and thus on the banking decision of the firms.

The original version of the Hotelling model uses a continuous representation of time due to the continuity of fossil fuel extraction. Continuous time models were also used in e.g. Perino and Willner (2016) and Perino and Willner (2017). This continuous representation of time, however, is not an accurate representation of the EU ETS with the MSR and CM. Clearing of allowances, intake and reinjection of the MSR and the cancellation volume are determined on a yearly basis. Consequently, this paper proposes a discrete time structure to accurately represent current EU regulation.

A discrete time model has also been used by Beck and Kruse-Andersen (2018) who evaluate the impact of (overlapping) national policies on the EU ETS in the light of the new CM. They use an iterative approach to calibrate a discrete time model to historic market outcomes and

[1]This paper refrains from the fact that the European Commission and member states hold an audit regarding the final cancellation of allowances. This introduces uncertainty whether allowances will be cancelled at all (European Parliament and the Council of the European Union, 2018).

show that the reform of the EU ETS increases allowance prices and decreases emissions in the short and long run. However, long-run effects are found to be substantially higher than in the short run. Further, they find that the effect of national policies on EU ETS emissions strongly depends on the timing of its implementation. If national abatement measures take place before 2023, they potentially increase the cancellation volume and thus reduce total EU ETS emissions.[2] However, their overall evaluation of the EU ETS amendments is ambivalent: While under the new regulation national policies potentially have an impact on abatement within the EU ETS, the complexity of the regulation may hinder the implementation of cost-efficient national policies.

The contribution of the paper at hand is threefold: Firstly, we develop a model which incorporates the current EU ETS regulation accurately, namely the change in the LRF and the introduction of the MSR and the CM. Thereby, the volumes of the MSR and the CM are endogenously determined and an exact replication of the current regulation. In particular, the decision algorithm of the EU ETS operates on an annual basis. Therefore it is depicted in a discrete time model. Secondly, the decomposition of the recent amendments into its single components facilitates a better understanding of the underlying economics. This allows us to identify the main price drivers in the market. The sensitivity analysis validates the robustness of the model results and determines which economic effects can be expected under various regulatory scenarios and parameter assumptions. Thirdly, the dynamic efficiency of the current EU ETS regulation is compared with theoretical first-best scenarios based on the unaltered Hotelling model. Thereby, we can draw conclusions on the economic implications of the different regulatory instruments by discussing their individual impact on the market efficiency in comparison to an efficient frontier.

The remainder of this paper is organized as follows: Section 2 develops the model, including the dynamic optimization problem of the firm and the equilibrium conditions in a competitive market given current EU ETS regulation. In section 3, the functioning of the model is explained and validated by sensitivity analyses. Further, the underlying economic effects are decomposed. Section 4 discusses the implications of the three amendments individually and assesses the dynamic efficiency of the new regulation. Section 5 concludes.

2. Discrete dynamic optimization model

We model the decision making of N polluting firms within the intertemporal market for emission allowances, namely the EU ETS, which is assumed to be perfectly competitive. In

[2]This effect is also found and discussed in Carlen et al. (2018).

the following section, we describe our model which covers the individual decision making on the firm level. In section 2.2 the market clearing and equilibrium conditions are derived from the individual optimality conditions. The MSR and the CM are modelled in section 2.3 as an exact replication of the current EU regulation. The parameters used for the numeric illustration are presented in section 2.4.

2.1. Decision making of a representative firm

We assume a rational firm with perfect foresight which aims to minimize the present value of its total expenditure

$$PV = \sum_{t=0}^{T} \frac{1}{(1+r)^t} [C(e(t)) + p(t)x(t)]. \tag{1}$$

In each discrete time period $t = 0, 1, \ldots, T$ the expenditure consists of two parts: the abatement costs $C(e(t))$ and the costs of acquiring of allowances $p(t)x(t)$. The firm can decide on the variables $e(t)$ for yearly emissions and $x(t)$ for yearly acquisition or sales of allowances. In line with Rubin (1996), we assume that the abatement costs follow a quadratic and convex function of the form $C(e(t)) = \frac{c}{2}(u - e(t))^2$. The counterfactual emission level u and the cost parameter c are exogenously given. Due to the assumption of a perfectly competitive market for allowances, the allowance price $p(t)$ is not influenced by the individual decision of the firm. The yearly costs are discounted at an annual interest rate of r. Let T be the first point in time when no further allowances are issued and all issued allowances are depleted. Hence, for all $t \geq T$ an emission cap of zero is established which makes allowance trading redundant.

As discussed in the previous chapter, the EU ETS enables firms to bank allowances for later use. This linking between time periods is modelled with the decision variable $b(t)$, which is the volume of acquired allowances in the private bank of the individual firm in period t. As intertemporal borrowing is prohibited, we require $b(t) \geq 0$. Additionally, in each time period the change in the bank $b(t) - b(t-1)$ has to be equal to the difference of net acquisition of allowances $x(t)$ and emissions $e(t)$.

Combining the expenditure minimization with the intertemporal banking constraint yields the optimization problem for the individual firm

$$
\begin{aligned}
\min \quad & \sum_{t=0}^{T} \frac{1}{(1+r)^t}[\frac{c}{2}(u-e(t))^2 + p(t)x(t)] \\
& s.t.\; b(t) - b(t-1) = x(t) - e(t) \quad \text{for all} \quad t = 1, 2, \ldots, T \\
& \qquad\qquad b(t) \geq 0 \\
& \qquad x(t),\, e(t) \gtreqless 0.
\end{aligned} \tag{2}
$$

We assign the Lagrange multipliers $\lambda(t)$ and $\mu_b(t)$ to the flow constraint and the positivity constraint, respectively. As the optimization problem is convex and fulfills the Slater condition, the KKT conditions are necessary and sufficient for optimality.[3] These imply that $\mu_b(t)$ is 0 if $b(t)$ is positive.

From the optimality conditions we get

$$
c(u - e(t)) = p(t). \tag{3}
$$

This states that the firm will set emissions $e(t)$ such that the marginal abatement costs equal the price $p(t)$. Economically speaking, the firm expands emissions $e(t)$ and acquires allowances $x(t)$ whenever the allowance price is below the marginal abatement cost. Contrary, the firm abates more emissions if the allowance price exceeds the marginal abatement costs.

2.2. Market equilibrium

While the firm's demand for allowances solely depends on the optimization problem stated above, the price is determined by the market. Supply, i.e. issuance of allowances, and demand, i.e. the firms acquisition of allowances, have to be balanced by the price, such that the market clears.

We define the supply $S(t)$ as the path of issued allowances in period t, which is regulated to be decreasing from an initial value $S(0)$ at a linear rate $a(t)$, hence $S(t) = S(t-1) - a(t)S_0$.[4] The issued allowances are partially auctioned ($S_{auct}(t)$) and partially distributed for free.[5]

[3] See Appendix A for details on the Lagrange function and the exact KKT conditions including complementary conditions.

[4] S_0 represents the number of allowances in 2010. $a(t)$ is the LRF.

[5] Following EU Directive 2018/410 the share of auctioned allowances is 57%, i.e. $S_{auct}(t) = 0.57\, S(t)$.

The price path $p(t)$ is determined in the market such that aggregated emissions over time are smaller than aggregated issued allowances. This is

$$\sum_{\tilde{t}=0}^{t} e(\tilde{t}) \leq \sum_{\tilde{t}=0}^{t} S(\tilde{t}) \text{ for all } t = 0, 1, \dots, T.$$

We assume that firms are homogeneous. From the individual optimality conditions stated in the previous section, we derive the rule for the development of market prices

$$\frac{p(t+1) - p(t)}{p(t)} = r - (1+r)^{t+1} \frac{\mu_b(t)}{p(t)}. \quad (4)$$

Economically speaking, whenever the private bank $b(t) > 0$, the corresponding shadow costs are $\mu_b(t) = 0$ and hence the price rises with interest rate r. This is in line with the continuous model in Hotelling (1931), where the efficient emission path of the economy can be reached if banking and borrowing is possible. If at some point in time $\tau_{b=0}$ the bank becomes 0, firms would implicitly like to borrow allowances from the future, which is forbidden by EU regulation.[6] Therefore, firms have to abate more than in the efficient emission abatement path before $\tau_{b=0}$. This in turn means that the firm abates less than the efficient abatement path after $\tau_{b=0}$. Consequently, the price will increase at a lower rate than r after $\tau_{b=0}$.[7]

2.3. Introduction of the MSR and the CM

With the introduction of the MSR and the CM the supply of allowances is no longer exogenously determined by the regulator. The amount of auctioned allowances $S_{auct}(t)$ additionally depends on the banking decisions of individual firms.

To depict the development of the allowance supply correctly, we define the total number of allowances in circulation $TNAC(t) = \sum_{i=1}^{N} b_i(t)$, where b_i represents the individual banking decision of firm i.

The MSR mechanism works as follows: If at some time t the $TNAC(t)$ exceeds an upper limit ℓ_{up}, the number of auctioned allowances will be reduced by a share $\gamma(t)$ of the TNAC of the previous year. This reduction of auctioned allowances is inserted into the MSR. If $TNAC(t)$ drops below a lower limit ℓ_{low}, R allowances from the MSR are auctioned additionally.[8]

[6]We disregard the unlikely case that it could be possible that the path of issued allowances coincides with the optimal emission path. Hence, the bank would be 0 for all t.

[7]If at a later point in time a second banking phase occurs, the Hotelling rule becomes valid again.

[8]This regulation started in 2019 with an upper limit ℓ_{up} of 833 million and a lower limit ℓ_{low} of 400 million allowances. The intake rate $\gamma(t)$ into the MSR is 24% of the TNAC until 2024 and 12% afterwards. The reinjection takes place at tranches R of 100 million allowances (European Parliament and the Council of the European Union, 2015).

The CM states that allowances will be cancelled from the MSR, i.e. become invalid if the number of allowances in the MSR exceeds the auction volume of the previous year (European Parliament and the Council of the European Union, 2018).
These two amendments to the EU ETS are accurately expressed by

$$S(t) = S(t-1) - a(t)S_0 - \mathit{Intake}(t) + \mathit{Reinjection}(t). \tag{5}$$

The MSR is then given by

$$MSR(t) = MSR(t-1) + \mathit{Intake}(t) - \mathit{Reinjection}(t) - \mathit{Cancel}(t), \tag{6}$$

with

$$\mathit{Intake}(t) = \begin{cases} \gamma(t) * TNAC(t-1) & \text{if } TNAC(t-1) \geq \ell_{up}, \\ 0 & \text{else}, \end{cases} \tag{7}$$

$$\mathit{Reinjection}(t) = \begin{cases} R & \text{if } TNAC(t-1) < \ell_{low} \wedge MSR(t) \geq R, \\ MSR(t) & \text{if } TNAC(t-1) < \ell_{low} \wedge MSR(t) < R, \\ 0 & \text{else}, \end{cases} \tag{8}$$

and

$$\mathit{Cancel}(t) = \begin{cases} MSR(t) - S_{auct}(t-1) & \text{if } MSR(t) \geq S_{auct}(t-1), \\ 0 & \text{otherwise}. \end{cases} \tag{9}$$

2.4. Model implementation and parametrization

The regulatory decision rules and complementary conditions stated are non-linear. For the implementation and solution of the model with GAMS and CPLEX, they are equivalently reformulated as linear constraints using binary variables and the big-M method. This allows to combine the exact regulatory rules of the EU ETS with the market equilibrium model derived by the optimality conditions of the firms in an mixed integer linear program.
In 2019, the MSR is initially endowed with 900 million allowances which were backloaded between 2014 and 2016 (European Parliament and the Council of the European Union, 2015). Further, allowances that will remain unallocated at the end of phase 3 of the EU ETS are transferred into the MSR in 2020. These are estimated to amount to 600 million allowances (European Commission, 2015). As initial value for the TNAC in 2017 we use

1645 million allowances as published by the European Commission (2018). The number of issued allowances is calculated based on the 2199 million allowances issued in 2010 (European Environmental Agency, 2018) and reduced on a yearly basis by the corresponding LRF.[9] Apart from the above mentioned regulatory parameters, the model is fed with further exogenous parameters, namely the interest rate, the counterfactual emissions and the backstop costs. In section 3.2 we discuss how the choice of these parameter values impacts the results. If not stated otherwise, the following values are used in the model: We apply a private interest rate r of 8%, representing the approximated weighted average cost of capital (WACC) of fossil power plants (Kost et al., 2018) and energy-intensive industries (KPMG, 2017). We acknowledge that there is high uncertainty about the counterfactual emission level in the absence of a cap-and-trade system i.a. because of technology advancement (Beck and Kruse-Andersen, 2018), economic activity and weather conditions (Borenstein et al., 2018). For the sake of simplicity, we assume constant counterfactual emissions u of 2000 million tonnes CO_2 equivalent (CO_2e).[10] The cost parameter c is calculated assuming a backstop technology for CO_2e abatement with costs of 150 EUR/t.[11]

3. Results and sensitivity analysis

With the parametrized model set up above, we are able to assess the development of emissions, prices and MSR movements under the current regulation. Robustness of our results in terms of the parametrization is guaranteed by an extensive sensitivity analysis in section 3.2.

3.1. Results under current regulation

From Eq.4 we know that as long as banking occurs, which is the case as long as sufficient allowances are available, the allowance price increases at the rate of interest (in accordance

[9] In our model we assume that without the reform the LRF of 1.74% would have been continuously used. However, the LRF for the time after 2020 had not been defined yet. Likewise, we assume that with the increased LRF the factor of 2.2% will be used for all future trading periods. (European Parliament and the Council of the European Union, 2018)

[10] This assumption is similar to Perino and Willner (2016) and Schopp et al. (2015) who use constant counterfactual emissions of 1900 million tonnes CO_2e and 2200 million tonnes CO_2e, respectively. The sensitivity of this assumption is calculated and further discussed in section 3.2.

[11] We define $c := \frac{\text{backstop costs}}{u}$, such that the marginal abatement costs of the last emission equals the backstop costs. The backstop costs of 150 EUR/t are in line with medium-range predictions of common Carbon Capture and Storage (CCS) technologies. See e.g. Saygin et al. (2012) and Kuramochi et al. (2012) for more information about the price development of CCS technologies for carbon-intensive industries.

with the Hotelling rule). Under the current regulation, this development of abatement, emissions and the allowance price takes place until the TNAC is depleted in 2039, as depicted in Figure 1. Thereafter, annual emissions equal the number of issued allowances, which decline with the LRF. The allowance price increases at a lower, degressive rate, because marginal abatement costs equal prices (Eq.3). When all allowances are used, emissions drop to zero, and the allowance price reaches the marginal costs of the backstop technology (150 EUR/t), and remains at this upper limit. This happens from 2058 onwards.

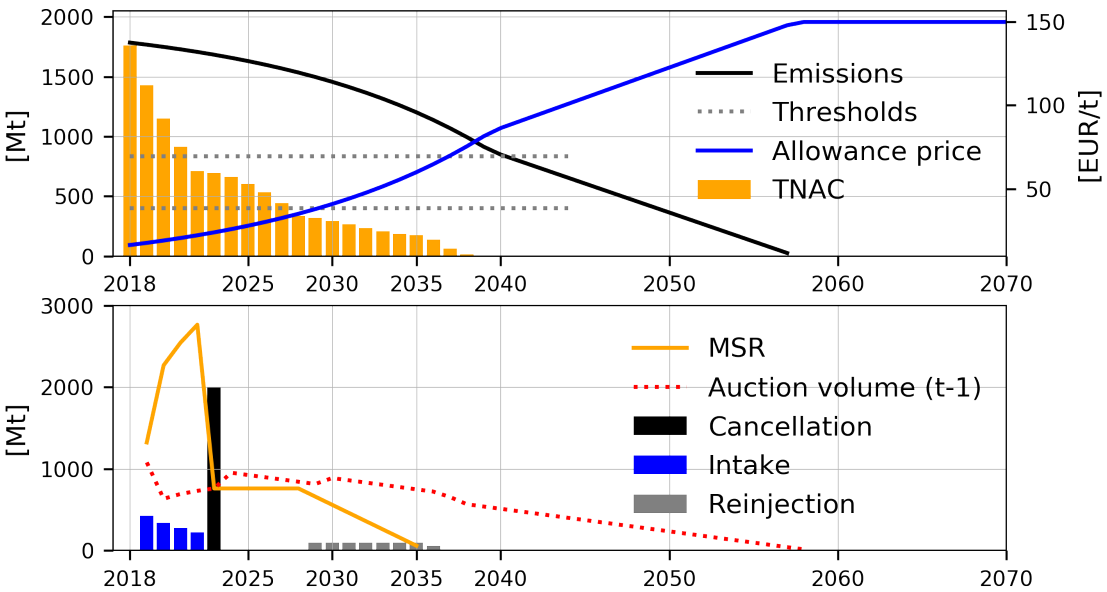

Figure 1: Development of emissions, TNAC, MSR, cancellation and allowance prices

After the implementation of the MSR in 2019, allowances are inserted into the MSR based on the rules described in 2.3 since the TNAC exceeds the limit of 833 million allowances (see Figure 1). Until 2023, the MSR accumulates 2762 million allowances. As the CM enters into force in 2023, allowances become invalid according to the rules described in 2.3. This leads to a one-time cancellation of 2002 million allowances in 2023.[12] This is equivalent to about 5% of all issued allowances from 2018 onwards. In 2028, the TNAC drops below the threshold of 400 million. Thus, from 2029 until the depletion of the MSR in 2037, allowances are reinjected into the market.

[12]In this setting cancellation only takes place once. However, this is not inevitable and depends on the parametrization. Thus, multiple cancellation phases are possible.

3.2. Sensitivity analysis

As discussed in section 2.4, the model uses three exogenous input parameters: backstop costs, counterfactual emissions and interest rate. Varying these parameters does not change the modus operandi of the model. However, the numerical results are influenced by the assumed parameter values. Therefore, in the following we carry out sensitivity analyses to carve out robust results.

Backstop costs

Due to the uncertainty when it comes to the realization of specific backstop costs in the future, the impact of the corresponding cost parameter is validated.

Lemma 3.1. *Different backstop costs do not change the level of emissions, abatement, TNAC, MSR or cancellation. Only the price path shifts up- or downwards with higher or lower backstop costs, respectively.*

Proof Let bc be some backstop costs, with corresponding optimal emissions $e(t)$, abatement $u - e(t)$, $TNAC(t)$, $MSR(t)$ and $Cancel(t)$ and the price level $p(t)$. Now let $\tilde{bc}$ be some other backstop costs. From Eq. 3 and the definition of the cost parameter c we know that $p(t) = bc(1 - \frac{e(t)}{u})$. Hence we know that for

$$\begin{aligned}\tilde{p}(t) &= \tilde{bc}(1 - \frac{e(t)}{u}) \\ &= \frac{\tilde{bc}}{bc} bc(1 - \frac{e(t)}{u}) \\ &= \frac{\tilde{bc}}{bc} p(t)\end{aligned}$$

and the above quantities for emissions, abatement, TNAC, MSR and cancellation volumes the optimality conditions are fulfilled and hence $\tilde{p}(t)$ gives the optimal price path, which is a scaled version of $p(t)$. ■

As Lemma 3.1 states, the concrete parameter of the cost function does not affect the underlying mechanisms of the EU ETS. Only the absolute price level changes with $\frac{\tilde{p}(t)}{p(t)} = \frac{\tilde{bc}}{bc}$.

Counterfactual emissions

Since it is not possible to measure counterfactual emissions, it is essential to take the uncertainty regarding this parameter into account (Borenstein et al., 2018). As the choice of its level has a significant impact on the numerical model results, a sensitivity analysis helps to assess the range of potential outcomes.

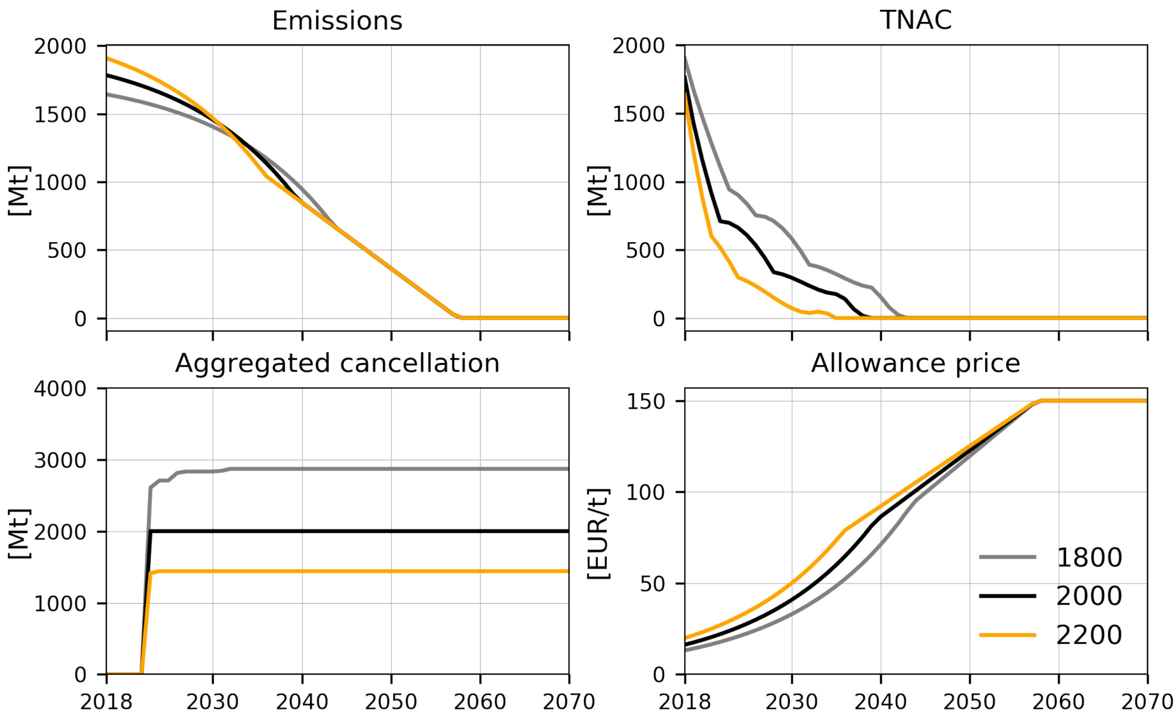

Figure 2: Sensitivity analysis for counterfactual emissions

If we assume higher counterfactual emissions then in the standard case from 3.1, the firm has higher emissions and correspondingly lower banking early on (see Figure 2). Since this behaviour drives allowance prices up, the firm increases abatement, partially compensating the effect of higher counterfactual emissions. However, the overall effect on banking remains negative. An increase of counterfactual emissions from 2000 to 2200 million tonnes CO_2e depletes the TNAC four years earlier. By regulation, the decrease of the TNAC leads to a lower intake of allowances into the MSR. Therefore, higher counterfactual emissions have a twofold negative effect on cancellation: Firstly, the lower MSR intake leads to a lower MSR volume. Secondly, it results in a larger auction volume as the MSR intake is subtracted from the allowances to be auctioned. Additionally, higher counterfactual emissions require stronger abatement to meet the same emission target. Thus, at any time t, allowance prices are above the ones in the standard case. An increase in counterfactual emissions from 2000 to 2200 million tonnes CO_2e leads to a price increase by 22% in all years in which the Hotelling rule applies.

Vice versa, lower counterfactual emissions lead to lower prices, higher TNAC levels and therefore higher intake into the MSR and larger cancellation volumes. Further, TNAC and MSR deplete at a later point in time. However, changes in the counterfactual emissions impact quantities asymmetrically. If the counterfactual emissions lie for instance at 1800 instead of 2000 million tonnes CO_2e, about 900 million allowances are cancelled additionally, whereas about 600 million allowances are cancelled additionally if the counterfactual emissions lie at 2000 instead of 2200 million tonnes CO_2e.

Figure 3 assesses the impact of counterfactual emissions on the aggregated amount of allowances cancelled. The cancellation volume increases overproportionally with a decrease of counterfactual emissions. In other words, with low counterfactual emissions, the model reaches higher levels of cancelled allowances. The higher the counterfactual emissions, the faster the private bank is depleted and thus the lower the MSR and the cancellation volume.

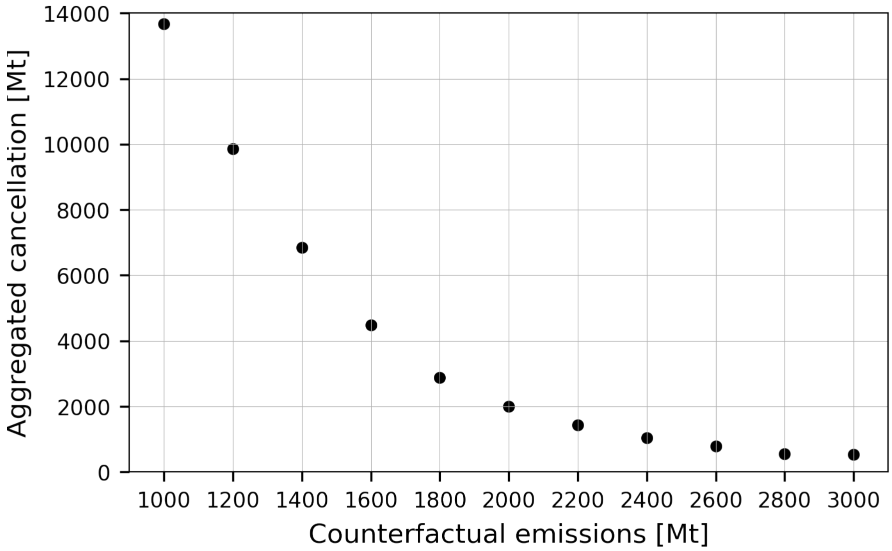

Figure 3: Effect of counterfactual emissions on cancellation

Interest rate

The interest rate of a firm reflects the opportunity costs of abatement, i.e. the profitability of alternative investments. Therefore, the interest rate impacts the firms' abatement decision directly. Thereby, the emission path and banking decision is affected, finally having an impact even on the MSR and the CM.

Figure 4 shows the sensitivity of the model results for interest rates of 5%, 8% and 16%. With a higher interest rate, the initial price level is lower but increases at a higher rate afterwards. Consequently, firms prefer to delay abatement and therefore increase emissions in the short run. With a similar rationale as in the sensitivity with higher counterfactual emissions, a higher interest rate leads to fewer MSR intake and less cancellation due to higher emissions in the short run.

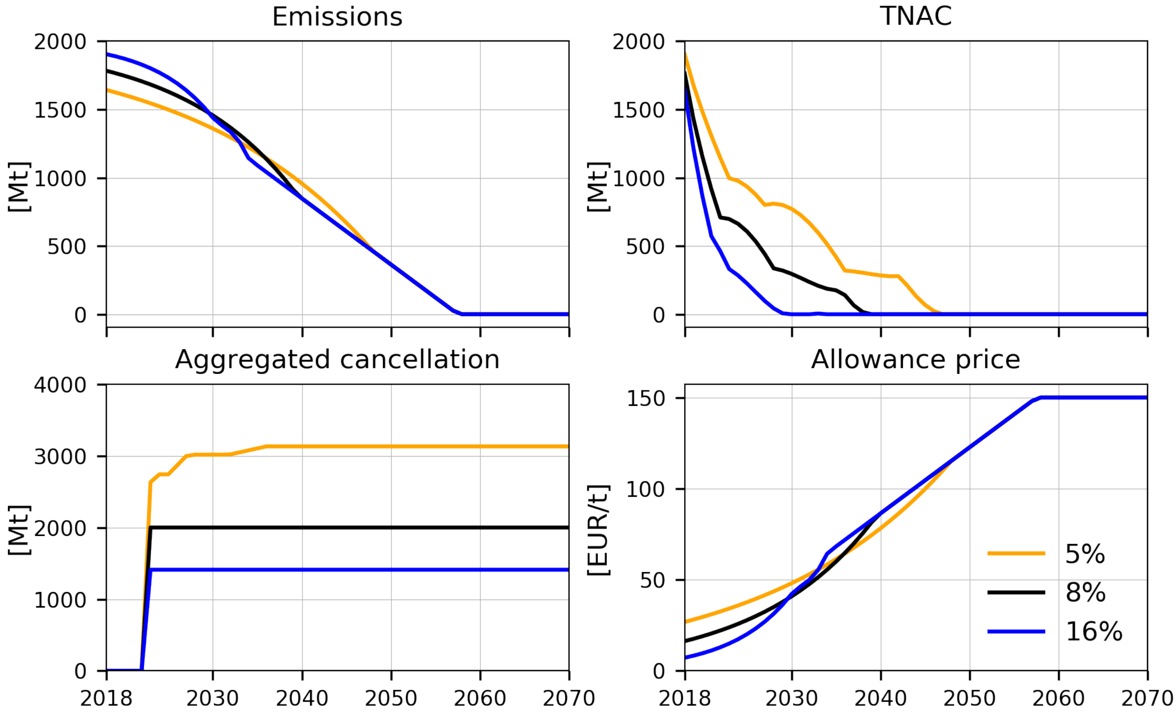

Figure 4: Sensitivity analysis for the interest rate

While the price path is strongly impacted by the assumed interest rate, the total abatement does not significantly change with this assumption.[13] In consequence, abatement has to be higher in the medium run to compensate for the initially higher emissions. In our example in Figure 4, starting with the depletion of the TNAC in 2030, the emissions in the sensitivity with 16% interest rate are lower than in the standard case with 8%. In the long run after 2040, emissions equal the exogenous supply of allowances in both cases. Hence, the price development is independent of the interest rate.[14]

[13]Except for the small effect caused by a change in the volume of allowances cancelled.

[14]In both cases the reinjection of allowances from the MSR ends before 2040.

With a lower interest rate, we can observe the opposite effects. Prices start at a higher level but increase at a lower rate. Emissions decrease in the short run and increase in later periods. A higher TNAC leads to more intake into the MSR and a higher volume of aggregate cancellation.

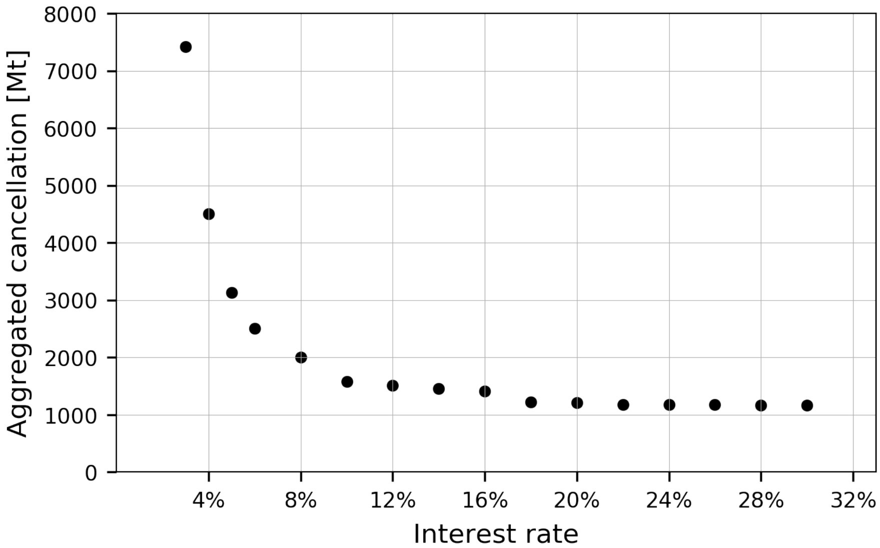

Figure 5: Effect of interest rate on cancellation

Figure 5 assesses the impact of the interest rate on the total amount of allowances cancelled. Note that the total number of cancelled allowances cannot fall below a certain level, because the emission level is bounded by the counterfactual emissions. In other words, the quantity of allowances needed in the short run is limited and therefore some amount of cancellation takes place independent of the interest rate.

Two effects determine the relationship between interest rate and cancellation volume: First, a high interest rate leads to higher emissions and less MSR intake in the short run. Therefore, the cancellation volume in 2023 decreases with the interest rate. Second, as total abatement does not change significantly, a high interest rate leads to higher abatement and a higher TNAC in the medium run, potentially causing more cancellation after 2023. The second effect partially offsets the first effect in terms of the total volume of allowances cancelled.

Because a high interest rate of firms leads to a low number of allowances cancelled, we conclude that the higher the risk perceived in the market, the weaker the impact of the CM.

4. Impact of the EU ETS amendments on emissions, prices and dynamic efficiency

We assess the impact of the recent EU ETS amendments on abatement paths, total emissions and price paths. The results of the ETS reforms presented in 3.1 are decomposed into the effects of single amendments, namely the increase in the LRF, the MSR and the CM (section 4.1). In section 4.2 we evaluate the dynamic efficiency of those amendments by comparing the single amendments to hypothetical first-best scenarios with the respective emission cap. Table 1 depicts the characteristics of the different scenarios used in this chapter.

	LRF after 2020	**MSR**	**CM**
pre-reform	1.74%	no	no
increased LRF	2.20%	no	no
MSR	2.20%	yes	no
post-reform	2.20%	yes	yes
late cancel	2.20%	yes	cancellation from the long end

Table 1: Overview of examined scenarios

4.1. Decomposition of effects of the recent EU ETS amendments on prices and emissions

Next to the pre-reform scenario and the post-reform scenario that depicts the current EU ETS regulations discussed in section 3, we set up the increased LRF scenario (high LRF from 2021 onwards, but no MSR and CM) to isolate the impact of the increased LRF from the aggregated reform results (see Figure 6). The results show that the effect of the lower cap on issued allowances is significant: with the higher LRF of 2.2% the total emission cap is reduced by over 9 billion allowances which equals a 21% reduction of the allowance volume issued after 2020. The last allowances will be issued in 2057 and thus 10 years earlier than with the lower LRF.

This additional scarcity also shows in the price difference between the pre-reform scenario and the increased LRF scenario. The higher LRF increases prices at any point in time but the difference is most noticeable in the long run. The change in the LRF does not impact the banking decision of the firm, and thus at which time $\tau_{b=0}$ the TNAC becomes zero and prices develop at a degressive rate. As the price level at time $\tau_{b=0}$ is higher in the increased LRF scenario, the degressive price path after this point develops from a higher level and at a higher rate. Thus, the price increase resulting from the change in the LRF is most significant in the long run.

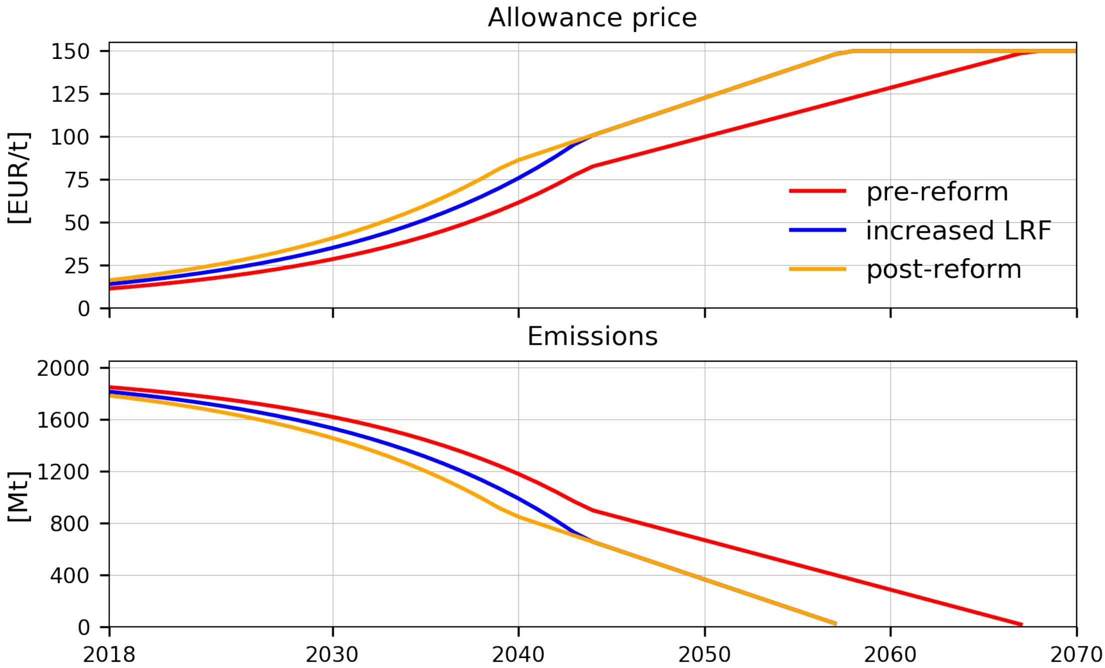

Figure 6: Effect of the change in the LRF

Now, we isolate the effect of the MSR from the change in the LRF, by comparing the introduction of the MSR with the increased LRF scenario. By regulation, the MSR only shifts emissions from the present to the future and thus can be considered an intertemporal smoothing of abatement. This results from storing allowances in the MSR and limiting the market reinjection, reinforcing abatement in the near future and decreasing abatement later on.

While the intake of allowances in the MSR leads to higher prices in the short run, the reinjection phase reverses this effect in the long run by increasing the auction volume in tranches of 100 million allowances annually compared to the increased LRF scenario. (Figure 7). Thus, the MSR remains allowance preserving and does not alter the emission cap itself. This is in line with the findings of e.g. Perino and Willner (2016) and Richstein et al. (2015).

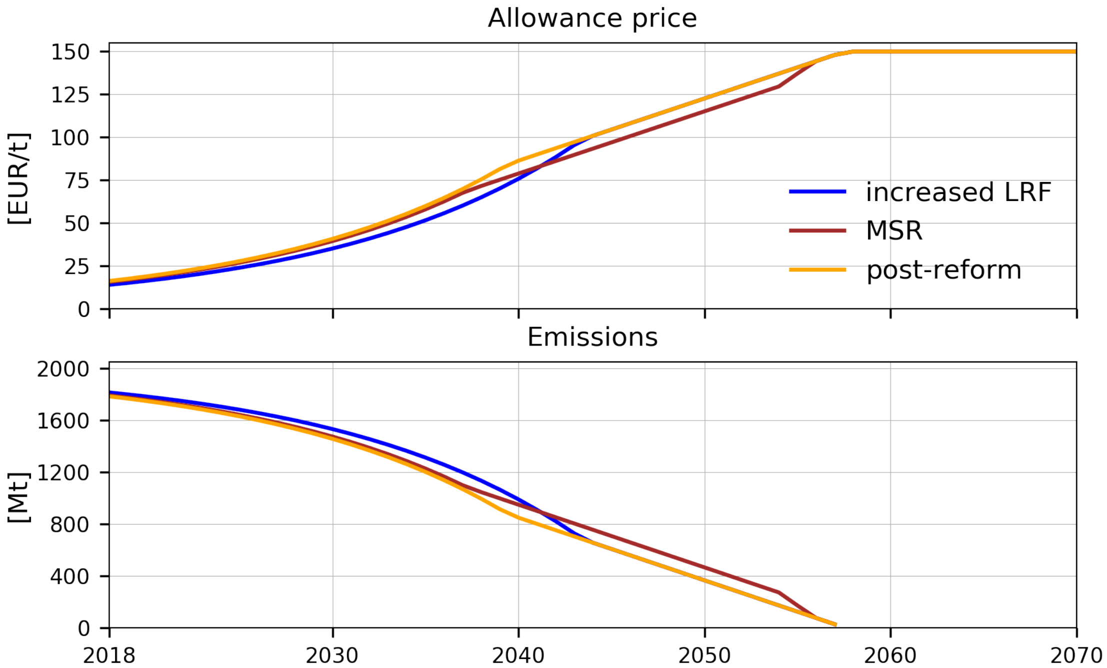

Figure 7: Effect of the MSR and the CM

In contrast, the CM alters the overall emission cap. Thus, fewer allowances are available in the post-reform scenario (including the CM) than in the MSR and increased LRF scenarios. The firms take this into account and choose an emissions path that is slightly lower in the post-reform scenario. Therefore, the overall intake into the MSR is slightly higher than in the MSR scenario. About 2 billion allowances are cancelled in 2023 and the remaining allowances reinjected into the market after 2029. The MSR is thus fully depleted in 2037, i.e. 19 years earlier than in the scenario without the CM. Compared to this MSR scenario, the model reveals only minor price effects of the cancellation in the short term (e.g. 3% price difference in 2030). However, the price difference becomes larger once the MSR is fully depleted in the post-reform scenario and the cancellation causes additional scarcity in the market (e.g. 8.5% price difference in 2040). This finding indicates that while the cancellation takes place at an early time, prices are more affected in the long run.
Conversely, the difference in prices between the increased LRF scenario and the post-reform scenario can only be observed in the short and medium run. Due to the reduced cap and

thus additional scarcity in the market, the TNAC depletes at an earlier time $\tau_{b=0}$.[15] Because the MSR is depleted once the TNAC falls below the limit ℓ_{low}, the change in the LRF is the only determining factor causing the higher price path compared to the pre-reform scenario in the long run.

The volume of 2 billion allowances that will be cancelled through the CM is significantly lower than the 9 billion allowances reduced by the increase of the LRF. While the effect of a reduced emission cap through the introduction of the CM has been widely discussed (e.g. Carlen et al. (2018) and Beck and Kruse-Andersen (2018)) the main price driver is the increase in the LRF. [16]

4.2. Dynamic efficiency

As discussed in section 1, the EU ETS was established to minimize the social costs of abating CO_2e emissions, allowing intertemporal trade of allowances to enhance cost efficiency. The latest reforms of the EU ETS change the framework for intertemporal trading. Hence, the three amendments discussed are impacting the dynamic efficiency. Dynamically efficient allowance markets are designed such that the cost-minimal abatement path is achieved by profit-maximizing firms.

The cost-minimal abatement path is derived in a scenario with unrestricted banking and borrowing, which yields that firms set their abatement according to the Hotelling rule so that the allowance price increases with their private discount rate for the entire time horizon. This first-best scenario will serve as reference point to evaluate dynamic efficiency.[17]

Figure 8 gives an overview of discounted abatement costs and emission levels of the different scenarios. The first-best scenario is depicted as efficient frontier, showing that discounted abatement costs decrease with the emission level. The emissions as well as discounted abatement costs are normalized to the first-best case of the MSR scenario. This setting is equivalent to a post-reform scenario without cancellation and hence with maximal emissions.

[15] In the increased LRF scenario $\tau_{b=0} = 2042$. This is 4 years later than in the post-reform scenario.

[16] This finding is also depicted in Appendix B where we compare the effect of the CM in the post-reform scenario with a post-reform scenario with the pre-reform intake rate of 1.74%.

[17] In literature, the first-best scenario is sometimes derived from an unrestricted banking and borrowing scenario using the social discount rate instead of the firm discount rate (compare e.g. Neuhoff et al. (2012)).

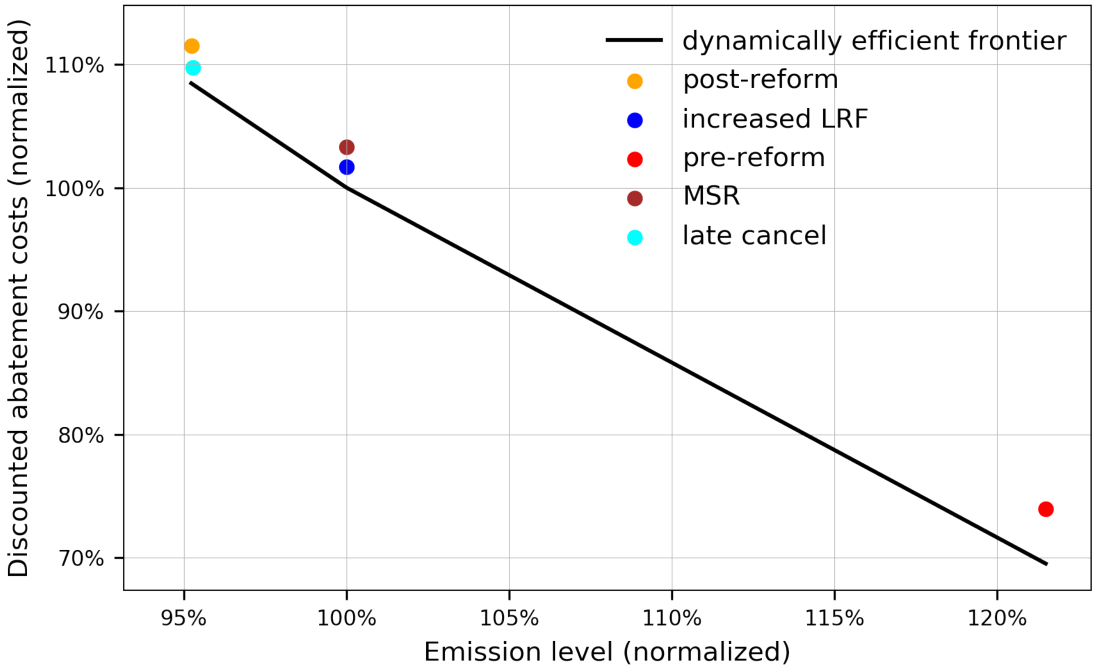

Figure 8: Comparison of discounted abatement costs and emission levels in different scenarios

As a consequence of the underlying quadratic abatement cost function, the development of the efficient frontier is convex. Higher abatement, leading to lower emissions, is disproportionately cost-intensive.

Comparing the pre-reform scenario (with unrestricted banking and no possibility to borrow) with a LRF of 1.74% and 2.2%, we see that increasing the LRF has a strong effect on the level of emissions, as also discussed in section 4.1. At the same time, increasing the LRF closes the gap between the dynamically efficient frontier and the discounted abatement costs. Increasing the LRF reduces the allowance supply - in particular in later periods - and hence diminishes the additional costs imposed by the non-borrowing constraint since fewer allowances can be borrowed from the future.

The MSR scenario adds a restriction on banking without changing the emission level (since the CM is not active in this scenario). It weakens dynamic efficiency by shifting emissions into the future, antagonistic to firms' time preferences.

The CM invalidates about 2 billion allowances in 2023, cutting allowances by approximately 5% of allowances issued after 2017. Against the first intuition, this is not an instantaneous cancellation of allowances early on, but rather a reduction of future allowance supply since it eliminates reinjection from the MSR into the market in later periods (compare 4.1). The cancellation changes little in the short-term abatement, impacting mainly the allowances available in later periods where the shadow costs of the non-borrowing constraint are rather low. Hence, the introduction of the CM slightly reduces the gap to the dynamically efficient frontier (+3.2%-points in the MSR scenario, +3%-points in the post-reform scenario). The discounted abatement costs increase due to the introduction of the CM according to the additional costs of tightening the emission budget.

To assess the dynamic efficiency of the post-reform scenario, an alternative design of the CM is considered: In the late cancel scenario the cancellation is implemented by cutting the allowance supply from the long end, leaving allowances in the MSR untouched, instead of instantaneously reducing the volume of the MSR in the post-reform scenario.[18] In the late cancel scenario, the dynamic efficiency improves compared to the post-reform scenario.

As stated before, in the post-reform scenario the allowance supply is reduced by a shortening of the reinjection phase. In contrast, in the late cancel scenario the reinjection phase lasts longer, leading to more available allowances before 2050. Instead, the allowance supply is reduced from the very end and thus the last allowance is issued earlier than in the post-reform scenario. Hence, the alternative cancellation design enables firms to use the allowances more flexibly over time and to partly harmonize their abatement path with their time preferences. Making the reinjection rate more flexible, e.g. by defining it as share of the previous years emission level or by increasing its value in early periods - could further boost dynamic efficiency, and may contribute to making the EU ETS more resilient towards demand shocks, which Perino and Willner (2016) identified as a drawback of the MSR. To evaluate this aspect, further research should be conducted.

5. Conclusion

With the change of the linear reduction factor (LRF), the implementation of the market stability reserve (MSR) and the introduction of the cancellation mechanism (CM), the EU ETS changed fundamentally. This paper developed a discrete dynamic optimization model reflecting firms' optimal choice of abatement under the new regulation.

The results for the post-reform scenario including all three amendments show that about 5% of allowances issued from 2018 onwards are invalidated through a one-time cancellation

[18]The supply reduction is determined endogenously to prevent side effects on the optimization of individual firms. The cancellation within this scenario, though, is slightly lower ($< 1\%$) than in the post-reform scenario.

in 2023. All remaining allowances in the MSR are reinjected into the market from 2029 to 2036. The assumed backstop costs of 150 EUR/t are reached after 2057. The level of the backstop costs solely scales the price path, but does not further impact the resulting quantities. Counterfactual emissions in absence of the EU ETS can only be estimated with significant uncertainty, but the assumption strongly drives model results. Higher counterfactual emissions increase emissions, abatement and prices and diminish the impact of the MSR and the CM.

Varying the interest rate has a similar effect. If firms have higher private interest rates, they choose to delay abatement and increase emissions in the short run, leading to a smaller MSR intake and cancellation volume. This extensive sensitivity analysis of the underlying parameter assumptions proved the robustness of the model results. While the choice of the parameter values influences the numeric results of the model, it does not impact the underlying modus operandi.

By decomposing the reform into its single amendments, we evaluate the economic impact and the dynamic efficiency of those amendments individually. In the increased LRF scenario, we showed that with the higher reduction factor of 2.2% the total emission cap is reduced by over 9 billion allowances, and thus increases prices in the short and long run. We identify the change in the LRF as the main driver of change in the post-reform EU ETS. The MSR itself shifts emissions from the present to the future. This does not impact the overall emission cap, but adds a restriction on banking and thus deteriorates dynamic efficiency.

The CM changes little in the short run, but mainly reduces the available number of allowances in the long run by about 2 billion. Further, we show that an alternative cancellation of allowances from the long end increases the dynamic efficiency within the model. Nevertheless, the MSR increases abatement costs for firms by shifting additional abatement to earlier periods and increasing emissions later on. We find that the intended effect of the introduction of the MSR with CM - to increase prices early on - does not correspond to the design chosen by policy makers which impacts prices and emissions mostly in the long run. The price increase in the market observed in 2018 following the amendments cannot be explained by our model.

Thus, further research could evaluate market imperfections, such as regulatory uncertainty or short-run constraints like hedging needs that may cause the observed price increase. While the reinjection rate under the current regulation is - in contrast to the intake rate - rather stiff, a more flexible reinjection could help to avoid additional abatement costs stemming from the MSR and may increase the resilience of the EU ETS towards demand shocks.

Appendix A. Optimization of the firm, Lagrange function and KKT conditions

Assuming a perfectly competitive allowance market the optimization problem of a rational firm with perfect foresight is given as

$$\begin{aligned} \min \quad & \sum_{t=0}^{T} \frac{1}{(1+r)^t}[\frac{c}{2}(u-e(t))^2+p(t)x(t)] \\ s.t. \quad & b(t)-b(t-1)-x(t)+e(t)=0 \quad \text{for all} \quad t=1,2,\ldots,T \\ & b(t) \geq 0 \\ & x(t),\, e(t) \gtrless 0. \end{aligned} \tag{A.1}$$

By assigning Lagrange multipliers $\lambda(t)$ and $\mu_b(t)$ to the banking flow constraint and the positivity constraints, respectively, we derive the following Lagrangian function:

$$\begin{aligned} &\mathcal{L}(\mathbf{x},\mathbf{e},\mathbf{b},\lambda,\mu_{\mathbf{b}}) = \\ &= \sum_{t=0}^{T} \frac{1}{(1+r)^t}[\frac{c}{2}(u-e_i(t))^2+p(t)x_i(t)] + \\ &\quad + \sum_{t=1}^{T} \lambda(t)[b(t)-b(t-1)-x(t)+e(t)] - \\ &\quad - \sum_{t=0}^{T} \mu_b(t)b(t). \end{aligned} \tag{A.2}$$

As the optimization problem is convex and fulfills the Slater condition, we know that the corresponding KKT conditions are necessary and sufficient for optimality. We derive these conditions by the above Lagrangian function for all $t=0,1,2,\ldots,T$:

stationarity conditions:

$$\frac{\partial \mathcal{L}}{\partial x(t)} = \frac{1}{(1+r)^t}p(t)-\lambda(t) = 0 \quad \forall\, t=1,2,\ldots,T \tag{A.3}$$

$$\frac{\partial \mathcal{L}}{\partial e(t)} = (-1)\frac{1}{(1+r)^t}c(u-e(t))+\lambda(t) = 0 \quad \forall\, t=1,2,\ldots,T \tag{A.4}$$

$$\frac{\partial \mathcal{L}}{\partial b(t)} = \lambda(t)-\lambda(t+1)-\mu_b(t) = 0 \quad \forall\, t=1,2,\ldots,T. \tag{A.5}$$

primal feasibility:

$$b(t) - b(t-1) - x(t) + e(t) = 0 \quad \forall\, t = 1, 2, \ldots, T \tag{A.6}$$

$$x(t), \;\; e(t) \gtrless 0 \quad \forall\, t = 1, 2, \ldots, T. \tag{A.7}$$

dual feasibility and complementarity:

$$0 \leq b(t) \perp \mu_b(t) \geq 0 \quad \forall\, t = 1, 2, \ldots, T \tag{A.8}$$

$$\lambda(t) \;\; \gtrless 0 \quad \forall\, t = 1, 2, \ldots, T. \tag{A.9}$$

Appendix B. Effect of the CM with a reduced LRF

In Figure B.9 we compare the effect of a CM with the amended LRF of 2.2% to the effect of a CM given the pre-reform intake rate of 1.74%. The results indicate that the CM only slightly decreases emissions and increases prices in the short run. The change in the LRF however, is the main price driver and responsible for the long-run emission reduction.

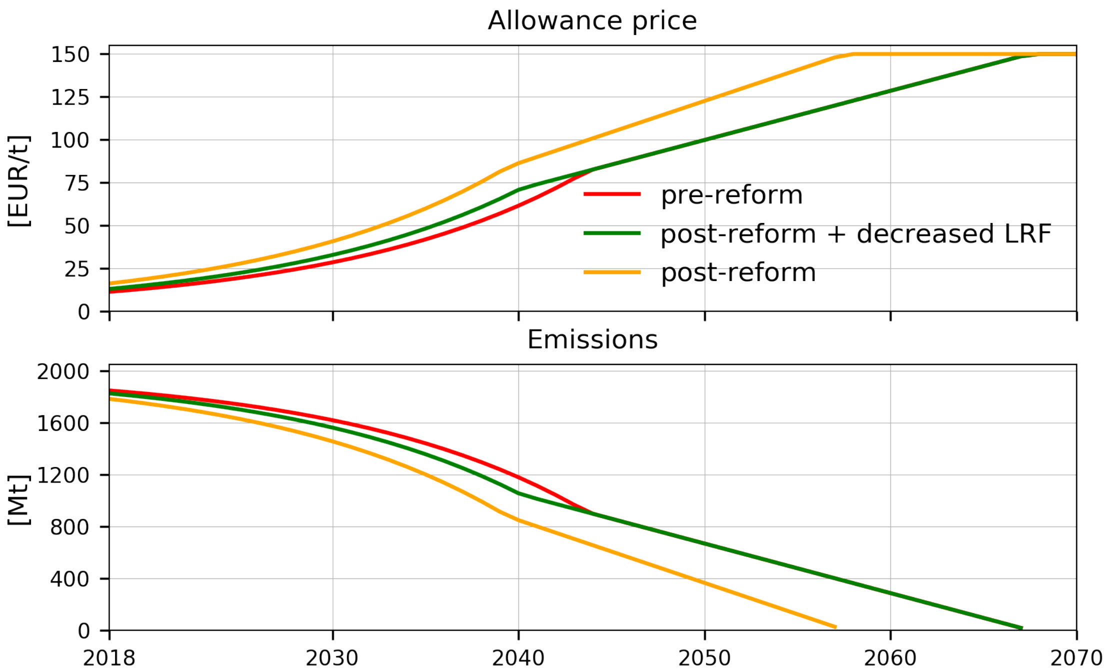

Figure B.9: Effect of the CM

References

Beck, U. R. and Kruse-Andersen, P. (2018). Endogenizing the cap in a cap-and-trade system: assessing the agreement on EU ETS phase 4. *De Okonomiske Rads Sekretariatet, Denmark*, Working Paper.

Borenstein, S., Bushnell, J., Wolak, F., and Zaragoza-Watkins, M. (2018). Expecting the Unexpected: Emissions Uncertainty and Environmental Market Design. *Energy Institute at Haas*, Working Paper 274R:1–66.

Carlen, B., Dahlqvist, A., Mandell, S., and Marklund, P. (2018). EU ETS emissions under the cancellation mechanisms: Effects of national measures. *National Institute of Economic Research*, Working Paper No 151.

Chevallier, J. (2012). Banking and Borrowing in the EU ETS: A Review of Economic Modelling, Current Provisions and Prospects for Future Design. *Journal of Economic Surveys*, 26:157–176.

European Commission (2015). Impact assessment. Accompanying the document Proposal for a Directive of the European Parliament and of the Council amending Directive 2003/87/EC to enhance cost-effective emission reductions and low carbon investments. *Commission Staff Working Document*.

European Commission (2018). Publication of the total number of allowances in circulation in 2017 for the purposes of the Market Stability Reserve under the EU Emissions Trading System established by Directive 2003/87/EC. *Communication from the European Commission*.

European Environmental Agency (2018). EU Emissions Trading System. `https://www.eea.europa.eu/`.

European Parliament and the Council of the European Union (2003). Directive 2003/87/EC of the European Parliament and of the of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC. *Official Journal of the European Union*.

European Parliament and the Council of the European Union (2015). Decision (EU) 2015/1814 of the European Parliament and of the of the Council of 6 October concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme and amending Directive 2003/87/EC. *Official Journal of the European Union.*

European Parliament and the Council of the European Union (2018). EU Directive 2018/410 of the European Parliament and of the of the Council of 14 March 2018 amending Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments, and Decision (EU) 2015/1814. *Official Journal of the European Union.*

Hotelling, H. (1931). The Economics of Exhaustible Resources. *Journal of Political Economy*, 39(2):137–175.

Kost, C., Shivenes, S., Verena, J., Nguyen, H.-T., and Schlegl, T. (2018). Stromgestehungskosten Erneuerbarer Energien. *Fraunhofer-Institut für Solare Energiesysteme ISE.*

KPMG (2017). Kapitalkostenstudie 2017. Divergierende Märkte - konvergierende Geschäftsmodelle. *KPMG.*

Kuramochi, T., Ramirez, A., Turkenburg, W., and Faaij, A. (2012). Comparative assessment of CO_2 capture technologies for carbon-intensive industrial processes. *Progress in Energy and Combustion Science*, 38:87–112.

Neuhoff, K., Schopp, A., Boyd, R., Stelmakh, K., and Vasa, A. (2012). Banking of surplus emissions allowances - does the volume matter? *DIW Discussion Papers*, 1196.

Perino, G. and Willner, M. (2016). Procrastinating Reform: The Impact of the Market Stability Reserve on the EU ETS. *Journal of Environmental Economics and Management*, 52:37–52.

Perino, G. and Willner, M. (2017). EU-ETS Phase IV: allowance prices, design choices and the market stability reserve. *Climate Policy*, 17(7):936–946.

Richstein, J., Emilie, C., and de Vries, L. (2015). The market (in-)stability reserve for EU carbon emission trading: Why it might fail and how to improve it. *Utilities Policy*, 35:1–18.

Rubin, J. D. (1996). A Model of Intertemporal Emission Trading, Banking and Borrowing. *Journal of Environmental Economics and Management*, 31:269–286.

Salant, S. (2016). What ails the european union's emission trading system. *Journal of Environmental Economics and Management*, 80:6–19.

Saygin, D., van der Broeck, M., Ramirez, A., Pate, M., and Worell, E. (2012). Modelling the future CO_2 abatement potentials of energy efficiency and CCS: The case of the Dutch industry. *International Journal of Greenhouse Gas Control*, 18:23–27.

Schopp, A., Acworth, W., Huppmann, D., and Neuhoff, K. (2015). Modelling a market stability reserve in carbon markets. *DIW Discussion Papers*, 1483.

Tietenberg, T. H. (1985). *Emissions trading. An exercise in reforming pollution policy.* Resources for the Future.

UNFCCC (2000). Report of the Subsidiary Body for Implementation on its Twelfth Session, Bonn 12-16 June 2000.