On the Theory of Emissions Trading

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Applications to the EU ETS

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1. Introduction

The climate is a common good,
belonging to all and meant for all.

Francis (2015)
Encyclical Letter Laudato si'

1.1. Background and Motivation

The climate on our planet is a common good. No one can be excluded from it, but if everyone emits without limits, the climate will change. To mitigate climate change, the emissions of greenhouse gases must be reduced. From the perspective of economists, this global challenge requires to answer two fundamental questions: How can we achieve international cooperation to solve the problem of the common good? How can we incentivize the internalization of negative externalities of greenhouse gas emissions?

The costs for emission abatement accrue on an individual level, but the benefits of abatement efforts are perceived globally. Thus, rational individuals have an incentive to emit and free-ride on the abatement efforts of others. As a result, the collectively desirable amount of emissions is exceeded, and the climate system is overused. To solve this "Tragedy of the Commons", collective action is necessary (Cramton et al., 2017). International negotiations, such as the United Nations Climate Change Conferences, aim to solve this cooperation problem.

While those negotiations have so far only resulted in pledges but not in collective action, some countries have already implemented policy measures to internalize the negative externalities of emissions. For this purpose, economic theory suggests price- or quantity-based instruments, e.g., carbon taxes or emissions trading systems.

A price on emissions increases the costs for the emitters. If this price is set equal to the social costs of carbon, the externalities of emissions are fully internalized, and the socially optimal emission level can be achieved (Pigou, 1920). However, policymakers face the problem of determining the correct value for the social costs of carbon, which itself is prone to significant uncertainties (Tol, 2005). Instead of fixing the price, policymakers can also set a quantity target for emissions. Thereby, the policymaker can guarantee to achieve the envisaged emission level. Nevertheless, the problem remains of determining the correct quantity to mitigate climate change. Following the bargaining solution proposed in Coase (1960), property rights are established by issuing emission allowances according to the predefined target. The price and allocation of emission allowances are determined by trading. Such emissions trading systems have the advantage of allocating allowances efficiently both over time and across emitters.

The world's largest emissions trading system is the European Union emissions trading system (EU ETS). It was established in 2005 to reduce emissions in the power sector and energy-intensive industries (European Parliament and the Council of the European Union (2003)). Since then, the scope has been extended on a geographical level, e.g., Iceland, Liechtenstein, and Norway joined in 2008, as well as on a sectoral level, e.g., emissions from inner-European aviation were included in 2012. Overall, the EU ETS currently covers around 40 % of the European emissions. The annual supply of allowances declines over time, but allowances can be transferred from one year to another (so-called banking of allowances). Since the start of the third trading period in 2013, the EU ETS has been reformed multiple times: At the beginning of the third trading period, the number of allowances in circulation has piled up, mainly due to the recession caused by the financial crisis. Thus, the backloading reform in 2014 shifted the allowance supply to the future by a one-time measure. The reform in 2015 introduced the market stability reserve (MSR), which absorbs allowances from the initial supply based on the number of allowances in circulation. Thereby, it automatically delays the allowance supply from 2019 onwards. In 2018, the overall allowance supply was reduced, and furthermore, a cancellation mechanism is introduced from 2023 onwards, which renders allowances invalid if the MSR volume exceeds the predefined threshold.

The reforms in the third trading period have changed the EU ETS substantially. By making the allowance supply an endogenous function of firms' banking, the reformed EU ETS has become a complex system, which has gained much attention in recent academic research. The individual chapters of this thesis cover different aspects of emissions trading systems and, in particular, the EU ETS. Chapter 2 decomposes the different amendments of the EU ETS reform and evaluates the cost effectiveness of the single amendments. Chapter 3 analyzes the effects of a carbon price floor (CPF) in the reformed EU ETS and compares two different designs of a CPF. Chapter 4 includes behavioral aspects such as myopia and risk aversion to explain the observed market outcomes between 2013 and 2019. Finally, Chapter 5 challenges a common assumption on the shape of marginal abatement cost (MAC) curves and discusses the implications for the EU ETS. Each chapter is based on an article to which all authors contributed equally:

Chapter 2: The Reformed EU ETS - Intertemporal Emission Trading with Restricted Banking (with Johanna Bocklet, Lukas Schmidt, and Theresa Wildgrube).
Published in *Energy Economics*, Vol. 84, 2019 (Bocklet et al. (2019)).

Chapter 3: A Carbon Price Floor in the Reformed EU ETS: Design Matters!
Published in *Energy Policy*, Vol. 147, 2020 (Hintermayer (2020)).

Chapter 4: How Does the EU ETS Reform Impact Allowance prices? The Role of Myopia, Hedging Requirements and the Hotelling Rule (with Johanna Bocklet).
EWI Working Paper Series, No. 01/2020 (Bocklet and Hintermayer (2020)). Revised and resubmitted to the *Journal of Environmental Economics and Management*.

Chapter 5: On the Time-Dependency of MAC Curves and its Implications for the EU ETS (with Lukas Schmidt and Jonas Zinke).
EWI Working Paper Series, No. 08/2020 (Hintermayer et al. (2020)).

The remainder of this introduction is structured as follows: Section 1.2 comprises a summary of each chapter. Further, Section 1.3 gives an overview of the used methods, discusses the underlying assumptions, and points out opportunities for future research.

1.2. Outline of the Thesis

1.2.1. The Reformed EU ETS - Intertemporal Emission Trading with Restricted Banking

The EU ETS has changed fundamentally with the implementation of the market stability reserve (MSR), the increase of the linear reduction factor, and the introduction of the cancellation mechanism. Chapter 2 develops a discrete-time model of the EU ETS as an intertemporal allowance market. According to the Hotelling rule, prices of a scarce, non-renewable resource rise with the interest rate as long as the aggregated bank of allowances is non-empty. The recent reforms of the EU ETS are accurately depicted within the model, which allows for a decomposition of the effects of the individual amendments and the evaluation of their cost effectiveness.

The MSR delays the allowance supply and shifts emissions to the future, but the total number of allowances remains unaffected. The cancellation mechanism causes a one-time cancellation of around two billion allowances, which reduces the overall emission cap. Consequently, long-run allowance prices increase, but the short-run impact on the emission and price path is negligible. However, the increased linear reduction factor reduces the allowance supply by nine billion allowances. Thus, its impact on the EU ETS is stronger than the cancellation mechanism.

1.2.2. A Carbon Price Floor in the Reformed EU ETS: Design Matters!

Despite the EU ETS reform, the introduction of a carbon price floor (CPF) is widely discussed among scholars and policymakers. Chapter 3 analyzes the effect of a European CPF in the reformed EU ETS. Due to the cancellation mechanism, a CPF can reduce overall emissions in the reformed EU ETS. The Hotelling model of the EU ETS with the MSR and the cancellation mechanism (introduced in Chapter 2) is amended by a European CPF. Two different CPF designs are compared: (1) a buyback program and (2) a top-up tax.

The buyback program sets a minimum price for the allowances from the implementation year onwards. After the announcement, firms anticipate the CPF, which immediately increases the carbon price to the discounted CPF level. Therefore, firms emit less and bank more allowances, leading to more intake into the MSR and higher cancellation volumes.

The top-up tax imposes a tax on emissions, enhancing the market price of allowances to the CPF level from the implementation year onwards. Hence, the top-up tax decreases the value of allowances in earlier periods, causing firms to increase their short-run emissions in anticipation of the upcoming tax. Only after the implementation year firms start to lower their emissions. Thus, the effect on aggregate cancellation is ambiguous. Despite being equivalent in a static setting, the design choice for the CPF matters in the dynamic context of the EU ETS.

When further comparing the governmental revenue within the EU ETS, it is recognized that the total revenue rises due to the European CPF, which opens up possibilities for compensations.

1.2.3. How Does the EU ETS Reform Impact Allowance Prices? The Role of Myopia, Hedging Requirements and the Hotelling Rule

Allowance prices in the EU ETS have more than quadrupled between 2013 and 2019. Prevalent literature (e.g., Chapter 2) cannot explain this sharp price increase through the recent reforms. However, firms in the EU ETS are likely not perfectly rational but they are prone to myopia and have to comply with hedging requirements. Chapter 4 includes those two forms of bounded rationality in the Hotelling model of the reformed EU ETS, thereby explaining the market behavior after 2013.

Due to bounded rationality, the Hotelling price path is no longer visible ex-post even though the Hotelling price rule holds ex-ante in the decision making of the firms. The reforms help to overcome the market distortions caused by myopia because they decrease the short-run availability of allowances. Hedging requirements have little impact in the pre-reform market but strongly drive market outcomes after the reform and may even cause a physical shortage of allowances. Neither form of bounded rationality can fully explain the market outcomes in the EU ETS on its own. However, if myopia and hedging requirements are considered simultaneously, the price increase and the development of the private bank in the EU ETS can be explained by the reforms.

1.2.4. On the Time-Dependency of MAC Curves and its Implications for the EU ETS

The understanding of marginal abatement cost (MAC) curves is necessary for analyses of the EU ETS. Literature commonly assumes simplified shapes of MAC curves, as also done in the previous chapters. However, the shape of MAC curves strongly drives the numerical results and is thus subject to research in Chapter 5.

The article conducts a case study for the European power sector and uses a partial equilibrium model to derive two essential properties of MAC curves: First, the shape of MAC curves is convex and depends on economic developments, e.g., fuel prices and interest rates. Second, MAC curves flatten over time. In the short term, fuel-switching is the only abatement option, and thus, the MAC curve is relatively steep. With longer investment horizons, the degree of freedom for investment grows, which flattens the MAC curve.

With convex MAC curves, marginal abatement costs in the EU ETS increase over time, which triggers higher banking of firms compared to linear MAC curves. In the reformed EU ETS, this comes together with higher cancellation volumes. On the contrary, flattening MAC curves over time leads to lower incentives for banking. Considering steeper MAC curves in the short term leads to a higher price path and an earlier depletion of the private bank.

1.3. Methodological Approaches and Future Research

The chapters of this thesis address different research questions regarding emissions trading, particularly the EU ETS. To answer the respective research questions, fundamental models of the EU ETS (Chapter 2, 3 and 4) and of European power markets (Chapter 5) are developed and applied.

The model of the EU ETS treats emissions as a scarce and non-renewable resource. Thus, Hotelling's model of oil exploration can be applied to emissions trading (Hotelling (1931)). The model assumes homogeneous firms, which face costs for the abatement of emissions. Firms optimize themselves by banking allowances over time to smooth the abatement path over time. The market equilibrium is solved by implementing the Karush-Kuhn-Tucker (KKT) conditions of the representative firm together with the rules of allowance supply in the EU ETS. In this way, the problem formulation follows the approach of a mixed complementary problem (MCP). In particular, the regulatory rule that borrowing of allowances from the future is not allowed translates into a complementarity condition. This condition implies the extended Hotelling rule, i.e., allowance prices rise with the interest rate unless the aggregate private bank of firms is empty. Further, the endogenous supply rules of the reformed EU ETS with the MSR regulation and the cancellation mechanism constitute non-linear conditions, which are linearized using binary variables. Overall, the model is formulated as a mixed-integer problem (MIP), implemented in GAMS, and solved with CPLEX.

Chapter 2 uses the model to analyze the cost effectiveness of the different amendments of the EU ETS reform. This is possible as all regulatory supply rules can be included separately in the model. Chapter 3 adds two different CPF designs to the model of the reformed EU ETS. For the buyback design, the CPF requires that the market price is greater or equal to the CPF level, and the Hotelling rule does not need to hold if the market price is equal to the CPF level. For the top-up tax design, the tax is defined as the positive part of the difference between the CPF level and the market price. Both designs are implemented using binary decision variables. Chapter 4 supplements the model with the possibility of including firms' hedging requirements by requiring that the private bank covers a certain share of future emissions. Further, the planning of firms is implemented with a rolling horizon approach to account for myopic firms.

The Hotelling model assumes perfect and complete markets. As the EU ETS is a market with European emitters and speculators, the assumption of perfect competition seems reasonable. Also, transaction costs are relatively low because firms can trade on a stock market. However, the tradeability and liquidity for long-term positions of allowances are questionable. Exchange-traded futures contracts mostly have a time to maturity of less than five years. Further, the interest rate is an important driver of results. As discussed and quantified in sensitivity analyses in Chapters 2 and 3, a lower interest rate leads to higher short-run prices and more cancellation. Furthermore, assumptions on the abatement cost function are necessary. Most contributions in the literature assume quadratic abatement costs, which results in a linear MAC curve. While this assumption simplifies the problem, it alters results in a non-realistic manner, as shown and discussed in Chapter 5. Thus, future research should apply the stylized facts on MAC curves to models of the EU ETS.

Moreover, Chapters 2 and 3 assume risk-neutral firms with perfect foresight. By doing so, real market outcomes cannot be fully explained. In contrast, Chapter 4 accounts for myopic firms which follow hedging strategies for risk mitigation. In this case, the real market outcomes can be replicated better. Thus, it should be promising to revisit the research from Chapters 2 and 3 and replace the assumption of perfectly rational firms with perfect foresight by myopic firms with hedging requirements.

The model of the EU ETS might be useful to answer further research questions. As currently discussed in politics, the EU ETS might be amended by other sectors, such as the mobility, residential, or agricultural sector. Future research could address how the market outcome and distributional aspects are affected by new sectors. Further, models of the EU ETS could relax the assumption of homogeneous firms. The depiction of different firms, e.g., in the power and the industry sector, should make results more realistic. However, the derivation of MAC curves for the industry sector seems challenging.

The last Chapter 5 uses a partial equilibrium model of the European power markets to derive stylized facts on the shape of MAC curves. To do so, the markets are assumed to be perfectly competitive, and firms in the market decide under perfect foresight. While the assumption of perfect competition seems reasonable for the day ahead market, the assumption of perfect foresight is critical. The profitability of investments in new power plants depends on the economic developments of other sectors and countries. In particular, the fuel prices are determined on a global level and are far from perfectly foreseeable.

Besides the overview of the methodological approaches in this section, each chapter contains a detailed description and discussion of the used methodology.

2. The Reformed EU ETS - Intertemporal Emission Trading with Restricted Banking

2.1. 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 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, allocating abatement to firms with low and allowances to firms with high abatement costs (e.g. 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 effectiveness.

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-effective when firms minimize their costs intertemporally through banking or borrowing. However, 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). The UN hereby discourages nation states to sell future allowances and then dropping out of the agreement.[1] 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).[2]

Recent contributions by Richstein et al. (2015), Perino and Willner (2016) and Beck and Kruse-Andersen (2020) evaluate the impact of the MSR on price and emission paths. 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

[1] Another reason for this restriction is the shape of global damage curves. Since most scholars (e.g., Rubin, 1996) assume that pollution damage functions are convex, early emissions cause greater environmental damage than delayed emissions, thereby requiring a limitation on borrowing.

[2] This paper refrains from the fact that the European Commission and member states will review the final cancellation of allowances (European Parliament and the Council of the European Union, 2018) which introduces uncertainty about whether allowances will be cancelled at all. The first review is scheduled for 2022, further reviews of the MSR and the CM will take place in five-year intervals afterwards (European Parliament and the Council of the European Union, 2015).

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 are 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 ETS regulation.

A discrete-time model has also been used by Beck and Kruse-Andersen (2020) who evaluate the impact of national policies in light of the reformed EU ETS with MSR and CM and calibrate their discrete-time models to historic market outcomes. The authors solve iteratively a firm's profit maximization problem assuming quadratic abatement costs and technological progress of renewable energies. Hereby, they 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 their implementation. If national abatement measures take place before 2023, they potentially increase the cancellation volume and thus reduce total EU ETS emissions.[3] 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. Silbye and Sørensen (2019) take a similar approach assessing the effect of national emissions reduction in light of the latest reforms. They find that if national emission reduction policies take place early, unused allowances will be transferred to the MSR and partially cancelled through the CM. If national reduction policies are implemented at a later point in time, they do not trigger an additional MSR intake and will therefore have no lasting effects on emissions.

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. The volumes of the MSR and the CM are endogenously determined within a closed-form solution. 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

[3]This effect is also found and discussed in Carlén et al. (2019).

under various regulatory scenarios and parameter assumptions. Thirdly, the cost effectiveness 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 economic performance.

The remainder of this paper is organized as follows: Section 2.2 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 2.3, the functioning of the model is explained and validated by sensitivity analyses. Further, the underlying economic effects are decomposed. Section 2.4 discusses the implications of the three amendments individually and assesses the cost effectiveness of the new regulation. Section 2.5 concludes.

2.2. 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 the following section, we describe our model which covers the individual decision making on the firm level. In section 2.2.2 the market clearing and equilibrium conditions are derived from the individual optimality conditions. The MSR and the CM are modelled in section 2.2.3 as an exact replication of the current EU regulation. The parameters used for the numeric illustration are presented in section 2.2.4.

2.2.1. 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

$$PV = \sum_{t=0}^{T} \frac{1}{(1+r)^t} [C(e(t)) + p(t)x(t)]. \tag{2.1}$$

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 section, 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 $e(t)$.[4]

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

$$\begin{aligned} \min \quad & \sum_{t=0}^{T} \frac{1}{(1+r)^t} [\frac{c}{2}(u - e(t))^2 + p(t)x(t)] \\ & s.t.\; b(t) - b(t-1) = x(t) - e(t) \quad \text{for all} \quad t = 1, 2, \ldots, T \\ & \qquad\qquad b(t) \geq 0 \\ & \qquad x(t),\, e(t) \gtreqless 0. \end{aligned} \tag{2.2}$$

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.[5] These imply that $\mu_b(t)$ is 0 if $b(t)$ is positive.

From the optimality conditions we get

$$c(u - e(t)) = p(t). \tag{2.3}$$

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.

2.2.2. 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 firm's acquisition of allowances, have to be balanced by the price, such that the market clears.

[4] We formally allow emissions to be negative. However, as borrowing is not allowed in the model, negative emissions do not occur.

[5] See Appendix A.1 for details on the Lagrange function and the exact KKT conditions including complementary conditions.

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 $S(t) = S(t-1) - a(t)S_0$.[6] The issued allowances are partially auctioned ($S_{auct}(t)$) and partially distributed for free.[7]

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

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

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

$$\frac{p(t+1) - p(t)}{p(t)} = r - (1+r)^{t+1} \frac{\mu_b(t)}{p(t)}. \tag{2.4}$$

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 optimal emission path can be achieved 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.[8] Therefore, firms have to abate more than in the optimal emission abatement path before $\tau_{b=0}$. This in turn means that the firm abates less than in the optimal abatement path after $\tau_{b=0}$. Consequently, the price will increase at a lower rate than r after $\tau_{b=0}$.[9]

2.2.3. 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

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

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

[8] 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.

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

inserted into the MSR. If $TNAC(t)$ drops below a lower limit ℓ_{low}, R allowances from the MSR are auctioned additionally.[10]

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

$$S(t) = S(t-1) - a(t)S_0 - Intake(t) + Reinjection(t). \tag{2.5}$$

The MSR is then given by

$$MSR(t) = MSR(t-1) + Intake(t) - Reinjection(t) - Cancel(t), \tag{2.6}$$

with

$$Intake(t) = \begin{cases} \gamma(t) * TNAC(t-1) & \text{if } TNAC(t-1) \geq \ell_{up}, \\ 0 & \text{else,} \end{cases} \tag{2.7}$$

$$Reinjection(t) = \begin{cases} R & \text{if } TNAC(t-1) < \ell_{low} \wedge MSR(t) \geq R, \\ MSR(t) & \text{if } TNAC(t-1) < \ell_{low} \wedge MSR(t) < R, \\ 0 & \text{else,} \end{cases} \tag{2.8}$$

and

$$Cancel(t) = \begin{cases} MSR(t) - S_{auct}(t-1) & \text{if } MSR(t) \geq S_{auct}(t-1), \\ 0 & \text{otherwise.} \end{cases} \tag{2.9}$$

2.2.4. 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

[10]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).

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.[11]

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 2.3.2 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 e.g. because of technology advancement (Beck and Kruse-Andersen, 2020), economic activity and weather conditions (Borenstein et al., 2019). For the sake of simplicity, we assume constant counterfactual emissions u of 2000 million tonnes CO_2 equivalent (CO_2e).[12]

We think of the backstop costs as the costs associated with a costly but inexhaustible abatement option, e.g. direct air carbon capture and storage. Assuming backstop costs $\overline{c}$ of 150 EUR/t[13], the cost parameter c is calculated by $c := \overline{c}/u$. By this definition we ensure that the last ton of counterfactual emissions is abated at backstop costs, i.e. for our quadratic abatement cost function $C'(0) = \bar{c}$.

2.3. 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 2.3.2.

[11] 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 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)

[12] 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 2.3.2.

[13] The backstop costs of 150 EUR/t are in line with medium-range predictions of common Carbon Capture and Storage (CCS) technologies (e.g. Saygin et al., 2012 and Kuramochi et al., 2012).

2.3.1. Results Under Current Regulation

From Equation 2.4 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 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 2.1. 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 (Equation 2.3). When all allowances are used, emissions drop to zero, and the allowance price reaches the marginal costs of the backstop technology (150 EUR/t)[14] and remains at this upper limit. This happens from 2058 onwards.

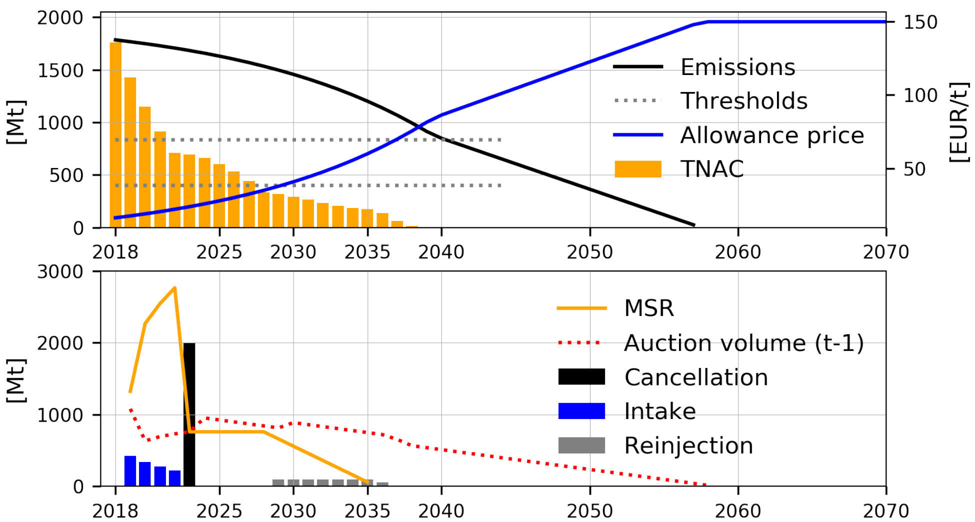

Figure 2.1.: Development of emissions, TNAC, MSR, cancellation volumes and allowance prices

After the implementation of the MSR in 2019, allowances are inserted into the MSR based on the rules described in 2.2.3 since the TNAC exceeds the limit of 833 million allowances (see Figure 2.1). 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 2.2.3. This leads to a one-time

[14]EU ETS regulation imposes a penalty of 100 EUR/t (inflation-adjusted) if firms are non-compliant. The penalty does not release firms from their obligation to surrender allowances (European Parliament and the Council of the European Union, 2003). Therefore, paying the penalty fee is never a rational outcome, independent of the backstop price level.

cancellation of 2002 million allowances in 2023.[15] 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, 760 million allowances are reinjected into the market.

2.3.2. Sensitivity Analysis

As discussed in section 2.2.4, 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, we analyze its impact in a sensitivity. Ceteris paribus (in particular for a given level of counterfactual emissions u), a change in backstop costs only shifts the price path, but does not affect the level of emissions, abatement, TNAC, MSR or cancellation. In particular, the point in time at which the TNAC is depleted does not change. This is because the initial quantities still fulfill all equilibrium and regulatory conditions from section 2.2 for a scaled version of the price path. We state and prove this finding formally in Appendix A.2.

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., 2019). 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.

If we assume higher counterfactual emissions then in the standard case from 2.3.1, the firm has higher emissions and correspondingly lower banking early on (see Figure 2.2). Since this behavior 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.

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

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.

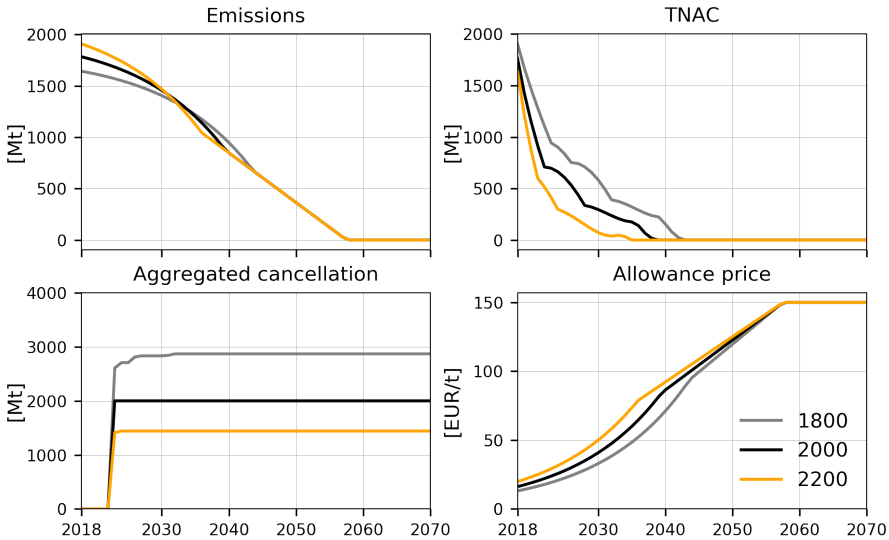

Figure 2.2.: Sensitivity analysis for counterfactual emissions

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 2.3 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.

Over time declining counterfactual emissions (as assumed by e.g. Carlén et al., 2019 and Quemin and Trotignon, 2018) require lower abatement efforts. Hence, prices are strictly lower, leading to higher emissions and a lower TNAC in the short run and less cancellation in 2023. As the TNAC and the MSR deplete later,

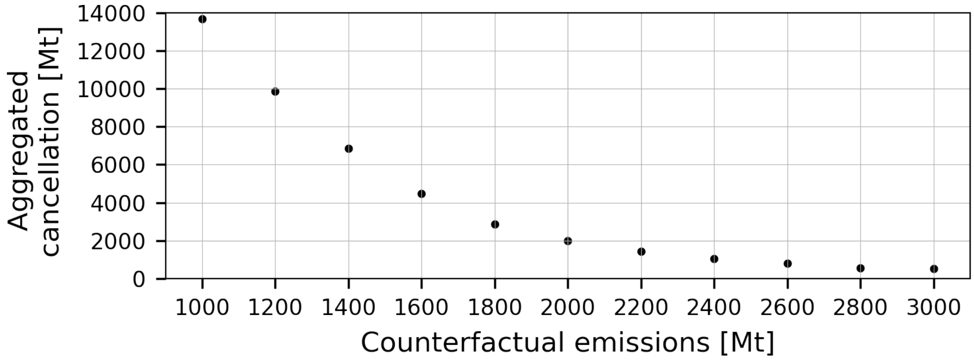

Figure 2.3.: Effect of counterfactual emissions on cancellation

emission levels in the long run are higher compared to the case with constant counterfactual emissions.

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 firm's abatement decision directly. Thereby, the emission path and banking decision is affected, finally having an impact even on the MSR and the CM.

Figure 2.4 shows the sensitivity of the model results for interest rates of 3%, 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.

In consequence, abatement has to be higher in the medium run to compensate for the initially higher emissions. In our example in Figure 2.4, 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.[16]

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. In particular, with a lower interest rate the TNAC is non-empty for a longer time period, which in turn

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

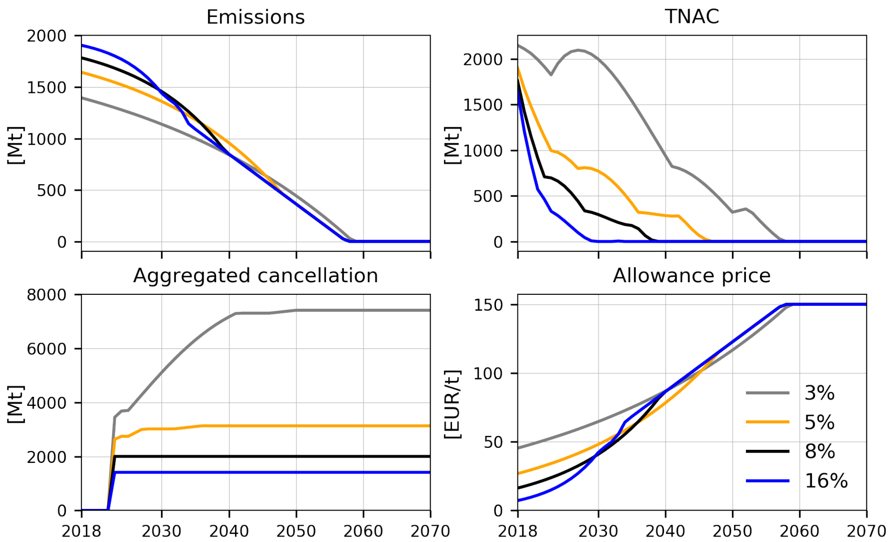

Figure 2.4.: Sensitivity analysis for the interest rate

causes the price to longer rise with the interest rate. With an interest rate of 3%, the price rises with the interest rate until 2057.

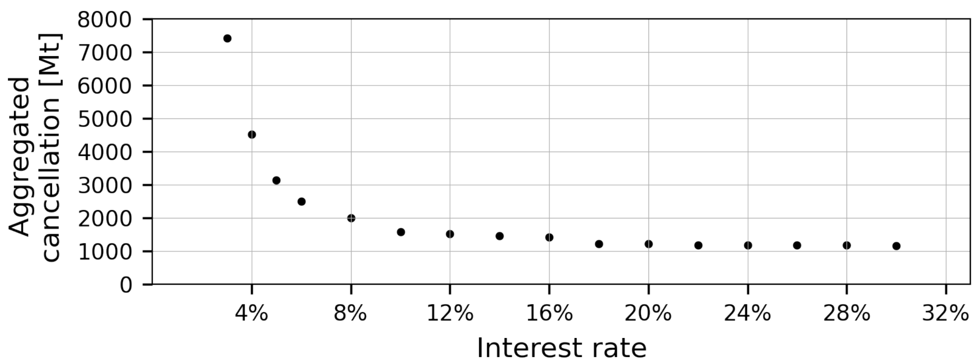

Figure 2.5.: Effect of interest rate on cancellation

Figure 2.5 assesses the impact of the interest rate on the total amount of allowances cancelled. Note that the aggregated cancellation volume and therefore the total abatement only changes significantly for low interest rates. 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.

A high interest rate of firms leads to lower cancellation volumes. Since greater uncertainty in the market is reflected by higher interest rates of market participants, we conclude that the higher the uncertainty perceived in the market, the weaker the impact of the CM.

2.3.3. Results in the Context of Previous Studies

In the following, we put the findings presented in section 2.3.1 in the context of previous studies. Silbye and Sørensen (2019) and Beck and Kruse-Andersen (2020) find that in addition to the cancellation in 2023, further allowances are cancelled during the following years, leading to cumulative cancellation volumes of 5000 million (Silbye and Sørensen, 2019) and 6000 million (Beck and Kruse-Andersen, 2020). The significantly larger cancellation volumes compared to our result can be explained by the underlying model and parameter assumptions: Both studies assume a lower initial counterfactual emission level which is moreover decreasing over time. [17] As discussed in section 2.3.2, lower counterfactual emissions cause the TNAC and the MSR to deplete later (e.g. Silbye and Sørensen (2019) find that the TNAC depletes in 2057, while our model suggests a depletion in 2039) and a larger cancellation volume. Another reason for higher cancellation volumes in Beck and Kruse-Andersen (2020) lies in their assumption of a convex marginal abatement cost curve. Compared to a linear curvature, the convexity assumption increases the TNAC and hence cancellation volumes. Further, Silbye and Sørensen (2019) calibrate their model to depict the price spike in 2018 by the assumption of a decrease in interest rate caused by the reform. They assume a demand elasticity that translates to a significantly higher backstop cost level than in our model.[18] While the backstop price itself does not influence banking behavior and cancellation volume (see section 2.3.2), it leads to a higher overall price level.

Despite the different modelling approaches, our numerical results are in line with the findings of Carlén et al. (2019) and Perino and Willner (2017). With their iterative solution approach, Carlén et al. (2019) find a one-time cancellation

[17]Their assumption of decreasing counterfactual emissions implies decreasing backstop costs given that the cost parameter is held constant.

[18]Their sensitivity parameter of allowance demand of 2.2 corresponds to an initial backstop cost level of 760 EUR/t. In other words, the initial cost parameter c implied by Silbye and Sørensen (2019) is nine times larger than the one used in Perino and Willner (2017) and six times larger than the one used in our model.

of 2400 million allowances in 2023. The TNAC is depleted in 2034 and the MSR is empty in 2035. Their slightly higher cancellation volume can be explained by their lower interest rate of 2.5% (see section 2.3.2). One of the scenarios from Perino and Willner (2017) depicts a MSR limited by the auction volume. With assumptions on counterfactual emissions and interest rate close to ours, their results are similar: Their TNAC is depleted in 2037 and their MSR remains empty from 2036 onwards. Thus, despite different modelling approaches, our numerical results (cancellation volume of 2000 million allowances, MSR depletion in 2037 and TNAC depletion in 2039) are in line with those of the two former studies.

2.4. Impact of the EU ETS Amendments on Emissions, Prices and Economic Performance

We assess the impact of the recent EU ETS amendments on abatement paths, total emissions and price paths. The results of the EU ETS reforms presented in section 2.3.1 are decomposed into the effects of single amendments, namely the increase in the LRF, the MSR and the CM (section 2.4.1). In section 2.4.2 we evaluate the economic performance of the amendments by comparing the single amendments to hypothetical first-best scenarios with the respective emission cap. Table 2.1 depicts the characteristics of the different scenarios used in this section.

	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 2.1.: Overview of examined scenarios

2.4.1. Decomposition of Effects of the Recent EU ETS Amendments on Prices and Emissions

Apart from the pre-reform scenario and the post-reform scenario that depicts the current EU ETS regulations discussed in section 2.3, 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 2.6). 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.

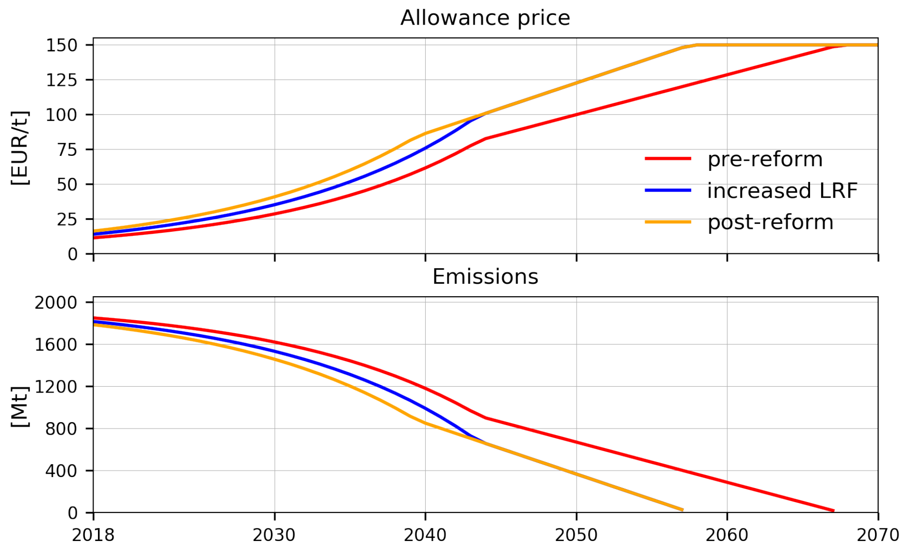

Figure 2.6.: Effect of the change in the LRF

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 today's allowance supply, 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 2.7). 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).

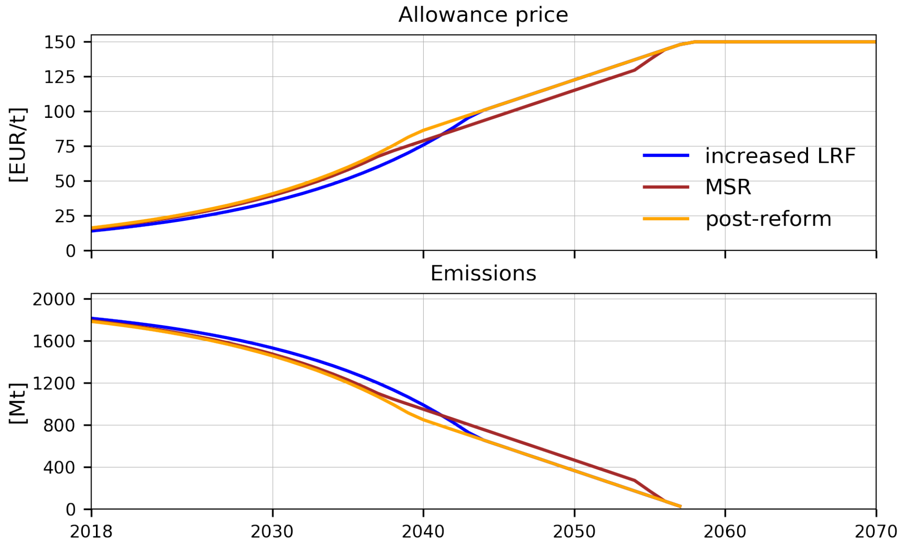

Figure 2.7.: Effect of the MSR and the CM

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 2000 million allowances are cancelled in 2023 and the remaining 760 million allowances in the MSR are reinjected into the market from 2029 onwards. The MSR is 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 $\tau_{b=0}$.[19] 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.

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

The cancellation volume of 2 billion allowances is significantly smaller than the reduction of 9 billion allowances by the increased LRF.[20] Even though the effect of an increased LRF seems to be well understood by scholars and thus has not been a focus of previous studies, it is important to stress that the increased LRF is the main price driver of the reform. [21]

2.4.2. Cost Effectiveness

In the following, we assess the impact of the reform on the intertemporal economic performance of the EU ETS. Fuss et al. (2018) differentiate between two frameworks for its assessment: Dynamic cost efficiency and dynamic cost effectiveness. Dynamically efficient policies maximize welfare by minimizing the social cost of emission abatement and damages. Those damage costs are commonly referred to as social costs of carbon (SCC). Since the SCC strongly vary with location, time preferences and other underlying factors, the estimates depicted in literature cover a broad range of potential values. Tol (2019) estimates today's global SCC to range from 14 EUR/t carbon to 55 EUR/t carbon, Cai and Lontzek (2019) argue that the SCC can raise to as much as 667 EUR/t carbon by 2100. Given the high uncertainty regarding the SCC and its importance for determining cost efficiency, we follow Fuss et al. (2018) by refraining from using this framework and instead focus on the concept of dynamic cost effectiveness. This framework assesses whether predefined quantity targets are reached by the lowest aggregated abatement costs without further consideration of external costs of emissions. The design of the EU ETS itself targets cost effectiveness. Allowance supply is predefined such that the system only minimizes the abatement costs.[22]

Figure 2.8 gives an overview of discounted abatement costs and emission levels of the different scenarios. The cost-effective frontier depicts the minimal discounted abatement costs for the respective emission level. This is achieved by a hypothetical scenario in which firms can allocate allowances in time without any intertemporal restriction. The discounted abatement costs are normalized to the discounted abatement costs of the cost-effective abatement path for the emission level where the post-reform allowance supply is fully exploited.

[20] This finding is also depicted in Appendix A.3 where we compare the effect of the CM in the post-reform scenario with a post-reform scenario with the pre-reform LRF of 1.74%.

[21] A survey conducted in 2018 revealed that there are common misconceptions about the main price driver of the reform. Experts from the field expressed their intuition about the main price driver of the allowance price. Only 21% of the respondents named the increased LRF as the main reason for the price increase, while 34 % considered the CM as the main price driver (see Wölfling and Germeshausen, 2019).

[22] A cost-efficient policy ensures that marginal abatement costs are equal to marginal social costs of carbon at each point of time (compare Fuss et al., 2018).

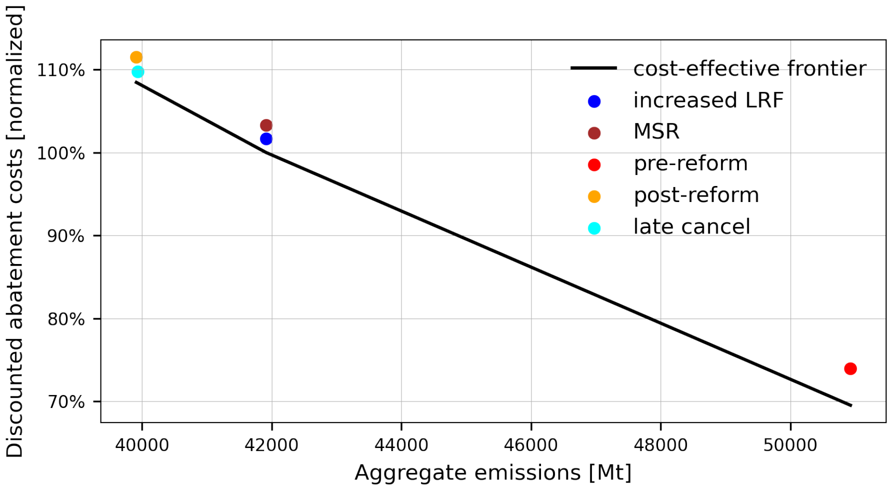

Figure 2.8.: Comparison of discounted abatement costs and emission levels in different scenarios

In general, all scenarios lie above the cost-effective frontier, i.e. firms cannot realize the cost-effective abatement path due to time-restricted availability of allowances. The time restriction on allowance availability is due to the non-borrowing constraint, the issue path of allowances and the temporal shifting of allowances through the MSR. Further, due to the underlying quadratic abatement cost function the curvature of the cost-effective 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 2.4.1. At the same time, increasing the LRF closes the gap between the cost-effective 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 cost effectiveness 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. Counterintuitively, 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 2.4.1). 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 cost-effective 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 cost effectiveness 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 unaffected, instead of instantaneously reducing the volume of the MSR in the post-reform scenario.[23] By construction, cost effectiveness in the late cancel scenario 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 cost effectiveness, 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.

Further, our theoretical evaluation of cost effectiveness neglects spillover effects. The price increase caused by the reform may trigger short-term investments into low-emission technologies which lower the costs for future abatement due to technological learning. Since firms do not internalize those spillover effects, the reform may induce benefits for cost effectiveness not accounted for in our model.

2.5. Conclusion

With the change of the linear reduction factor, the implementation of the market stability reserve and the introduction of the cancellation mechanism, 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 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 in 2057. The level of the backstop costs solely scales the

[23] The supply reduction is determined endogenously to prevent side effects on the optimization of individual firms.

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 cost effectiveness of these 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 cost effectiveness within the model. Nevertheless, the MSR increases abatement costs for firms by shifting additional abatement to earlier periods and increasing emissions later on. The initial goal of the reform was to increase today's prices and thereby a signal to invest in low-carbon technology. We find that the intended effect of the introduction of the MSR with CM does not correspond to the design chosen by policy makers which impacts prices and emissions mostly in the long run. To increase the resilience of the EU ETS towards demand shocks and to avoid additional abatement costs stemming from the MSR, a more flexible reinjection rate should be considered by policy makers. Future research should take positive externalities, e.g. learning effects of abatement technologies or other spillover effects, into account which may enhance the advantages of the MSR.

The price increase in the real EU ETS in the aftermath of the reform cannot be explained by the model presented in the paper. This might be due to the fact that the assumptions of a competitive market with perfectly rational firms that optimize themselves under perfect foresight are violated in reality. Several market imperfections might exist that could lead to a deviation from those assumptions: Hedging requirements may for example lead to higher banking volumes independent of market prices. Therefore, the price increase in the aftermath of the current reform may be underestimated by our model. Further, it is possible that firms are myopic and only optimize themselves over the next few years instead of the long run. Thus, firms do not anticipate that allowances in the MSR will become available in the future but rather see the significant short-term cut in allowance supply induced by the reform. This leads to a stronger price increase due to the reform than in the perfect foresight case. Moreover, firms might face uncertainty regarding regulatory reforms. If firms perceive the recent reforms as a signal for increasing scarcity of allowances in the future, they purchase more allowances today, amplifying the price increase of the reform. We therefore argue that the price spike in 2018 is not solely driven by the new regulation but potentially intensified by regulatory uncertainty and bounded rationality, such as myopia and hedging requirements. Thus, further research should evaluate such market imperfections.

3. A Carbon Price Floor in the Reformed EU ETS: Design Matters!

3.1. Introduction

Since its implementation in 2005, the European Emissions Trading System (EU ETS) has been the world's largest cap-and-trade system accounting for emissions in the energy sector, energy-intensive industries, and intra-European aviation. As a quantity-based instrument, it sets an allowance cap with annually declining volumes. In this way, the EU ETS defines a fixed carbon budget for all firms under its regulation. The price for allowances is determined in auctions and secondary markets. Theoretically, this mechanism ensures that the predefined abatement target is achieved cost-efficiently.

From 2012 to 2017, the market price for allowances in the EU ETS has remained below 10 EUR/t. Since this price level has been perceived as too low to spur investments in long-term abatement technologies, a European carbon price floor (CPF), which imposes a minimum price for the allowances, has been proposed. In theory, such a complementary price instrument strengthens the reliability of cap-and-trade systems and the profitability of investments in abatement technologies (Flachsland et al., 2020). In practice, the discussion over the introduction of a CPF has remained informal. Instead of implementing a CPF, the European Commission has introduced quantity-based instruments, namely the market stability reserve (MSR) in 2015 and the cancellation mechanism in 2018. If firms hold more than a predefined amount of allowances in their accounts, the supply of allowances for the following year is reduced, and the respective allowances are stored in the MSR. The cancellation mechanism invalidates allowances if the MSR volume exceeds the previous year's auction volume.

Nevertheless, the introduction of a European CPF is still under discussion and offers further improvements to the reformed EU ETS. Firstly, a European CPF stabilizes allowance prices and, therefore, decreases the price risk for investors. While allowance prices have risen to over 25 EUR/t in 2019, the stability of higher price levels remains unknown. For example, during the COVID-19 pandemic, the price of allowances has temporarily experienced a sharp decline. Moreover, Quemin (2020) indicates that the robustness of the reformed EU ETS towards demand shocks remains limited. Secondly, a European CPF strengthens the case for national policies in the EU ETS sectors. To achieve national abatement targets, many countries favor national policies such as renewable energy subsidies, coal phase-outs, and national CPFs.[24] Those unilateral policies can cause a waterbed effect, i.e., depress the carbon price in the EU ETS (e.g., Fischer et al. (2019)). A European CPF helps to diminish this waterbed effect but also causes distributional effects between member states, which impedes a unanimous agreement.[25] Thirdly, a European CPF is a valid instrument to implement tighter European emission targets, which are currently under discussion. The CPF sets an incentive to raise overall abatement efforts by increasing the costs of emissions. An opportunity to introduce a European CPF may arise after the review of the reformed EU ETS in 2023.

This article contributes to the existing literature by examining the impact of a European CPF in the reformed EU ETS. It analyzes two different designs of the CPF - a governmental buyback and a top-up tax - and their interaction with the MSR and the cancellation mechanism. For the analysis, the model in this article builds on Bocklet et al. (2019), who add the cancellation mechanism to a discretized version of the model in Perino and Willner (2016), which applies the seminal contribution of Hotelling (1931) to intertemporal allowance trading in the reformed EU ETS. The model depicts the market-clearing and equilibrium conditions and the exact replication of the current EU ETS regulations, particularly the MSR and cancellation mechanism.

The implementation of the different CPF designs yields the following findings: Once announced, the buyback design becomes effective instantaneously as firms incorporate the discounted CPF level in their decision-making. Firms immediately reduce their emissions, and overall emissions are reduced through the MSR and cancellation mechanism. On the contrary, the top-up tax decreases the value of allowances in earlier periods, causing firms to raise their emissions in anticipation of the upcoming tax. Only after the implementation year, firms start to lower their emissions. Thus, the effect of the top-up tax on aggregate cancellation is ambiguous and depends on the CPF level and the implementation year. For both CPF designs, the aggregate cancellation increases with the CPF level and decreases with its implementation year.

The remainder of the paper is structured as follows: Section 3.2 gives an overview of the literature on a CPF in emissions trading systems. Section 3.3 introduces the discrete-time Hotelling model of the reformed EU ETS. The model formulation is further extended by different designs of the CPF, namely a buyback of allowances and a top-up tax. Section 3.4 analyzes the impact of the different designs of the European CPF on market outcomes, such as allowance prices, banking, cancellation volumes, and governmental revenue. In particular,

[24] At least for the power sector, many countries and companies are in favor of a CPF (Appunn and Egenter, 2018 and Simon, 2018). Even the German government has started to support a CPF after recent discussions on the achievement of national climate targets (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit, 2019 and Edenhofer et al., 2019).

[25] For example, low-emission installations such as French nuclear power plants could benefit, whereas high-emission installations such as German coal-fired power plants could face losses (Newbery et al., 2019).

the influence of the CPF level and its implementation year on the aggregate emission level is examined. Section 3.5 concludes.

3.2. Literature on the CPF and its Design Options

The literature on cap-and-trade systems with a price instrument builds on the seminal work of Roberts and Spence (1976). They show that under uncertainty, abatement is efficiently allocated amongst firms if they are regulated by a combination of price and quantity instruments. Contributions by Burtraw et al. (2010), Wood and Jotzo (2011), Abrell and Rausch (2017), and Burtraw et al. (2018) suggest that complementing a cap-and-trade system with price regulation helps to overcome the uncertainty of marginal abatement costs. Besides, the anticipation of the price regulation plays an important role. Friesen et al. (2020) recognize that the price levels chosen by the regulator act as focal points influencing the market price for allowances. A CPF below the expected price level can also incentivize investment in abatement technology if it reduces the price risk in the market. Salant et al. (2020) further observe that a soft price floor below the expected price level is effective in a stochastic model with demand shocks ("action at a distance").

Another strand of literature analyzes the impact of price instruments in the EU ETS by applying the model of Hotelling (1931) to intertemporal allowance trading. Schopp et al. (2015) introduce quantity-based and price-based instruments in the pre-reform EU ETS and demonstrate that a complementary price regulation improves cost efficiency if the price is set appropriately. Fell (2016) confirms this finding in a stochastic model. Brink et al. (2016) compare different CPF designs and find that the CPF increases the abatement effort in the short run but decreases it in the long run because the overall amount of allowances is unaffected in the pre-reform EU ETS. Fuss et al. (2018) discuss a price collar but do not account for banking decisions and, consequently, do not analyze the effects on the MSR and the cancellation mechanism.[26]

Due to the complexity of the reformed EU ETS, the design of effective complementary policies, such as the CPF, is not straightforward. Existing literature points to the fact that understanding the timing of complementary policies is vital (e.g., Perino et al., 2019 and Gerlagh et al., 2019). A complementary policy can potentially reduce overall emissions via the cancellation mechanism (cf. Perino, 2018 and Beck and Kruse-Andersen, 2020). However, if the complementary policy is ill-timed, it can have the contrary effect and cause higher overall emissions. The phenomenon that a well-intended policy increases overall emis-

[26] Another strand of literature focuses on the impact of a (national) CPF in the power sector. Newbery et al. (2019) and Pahle et al. (2018) suggest a CPF of 25 EUR/t to decrease emissions from the power sector and to strengthen the effect of national policies (e.g., the German coal phase-out) on the EU ETS. Egli and Lecuyer (2017) analyze the effects of a potential CPF on the German electricity market and prices.

sions in the EU ETS is called the new green paradox (Gerlagh et al., 2019).[27] Quemin and Trotignon (2019) as well as Bocklet and Hintermayer (2020) find that the impact of the MSR and the cancellation mechanism depends on the planning horizon and the degree of rationality shown by the firms in the market. Bruninx et al. (2020) add that an explicit consideration of investment decisions increases the impact of the MSR and the cancellation mechanism. Most akin to the paper at hand, Quemin and Trotignon (2018) build an iterative heuristic for the reformed EU ETS and compare the MSR and a price collar, which adjusts the supply of allowances if the price is above or below predefined thresholds. Flachsland et al. (2020) point out that a CPF can improve the price stability and the performance of the reformed EU ETS in the cases where market distortions such as myopic firms and the waterbed effect persist.

As discussed by Flachsland et al. (2020) as well as Wood and Jotzo (2011), the CPF can be designed in different ways: buyback, top-up tax, or auction reserve price. These designs of the CPF are economically equivalent in a static setting, i.e., when firms face payments for their emissions, they decide on their emissions regardless of how they pay for them. In a dynamic context - such as the EU ETS - the design of the CPF is crucial because firms develop expectations of future prices.

If the CPF is implemented by buyback, a governmental institution guarantees the buyback of an unlimited number of allowances at the specified CPF level. The buyback design creates additional costs for the government to buy allowances and hold them in times when prices do not increase. Hence, the government must credibly commit to bear these costs.

If the CPF is introduced through a top-up tax, an additional tax on emissions is imposed to bridge the difference between the market price of allowances and the specified CPF level. As the top-up tax is positive, it constitutes a source of governmental revenue.

If the CPF is realized as an auction reserve price, allowances will only be auctioned if the bids are above the specified CPF level. The effect of this design hinges on the specified primary allocation of allowances. Under the current regulation in the EU ETS, 43% of the issued allowances are not auctioned but allocated freely (so-called grandfathering). In this way, the allowance market is only partly affected by an auction reserve price. Consequently, the CPF will not raise the market price to the CPF level, if the share of auctioned allowances is too low. Another difference is the treatment of non-auctioned allowances: non-auctioned allowances could either be rolled over to the next auction (implicitly banking them), placed in the MSR or cancelled immediately.[28] In a setting where

[27]The original green paradox describes a situation in which the present emissions increase due to an expected carbon tax in the future (Sinn, 2008).

[28]In Pahle et al. (2018), the auction reserve price is implemented for the power sector, and it is implicitly assumed that the non-auctioned allowances are cancelled. In this case, there is no need to explicitly account for the MSR and the cancellation mechanism.

all allowances are auctioned and the non-auctioned allowances are rolled over to the next period, the auction reserve price is equivalent to the buyback design.

3.3. A Hotelling Model of the EU ETS and the Implementation of the CPF

In the following, Section 3.3.1 gives an overview of the model and the regulatory rules on the allowance supply. Section 3.3.2 describes the implementation of the different CPF designs. The parametrization of the model is specified in Section 3.3.3.

3.3.1. General Model of the EU ETS

The general model follows the theoretical work of Rubin (1996), who applies the work of Hotelling (1931) to intertemporal emissions trading.[29] This article builds on the model from Bocklet et al. (2019), which includes the regulatory setting of the reformed EU ETS with the MSR and the cancellation mechanism. In comparison to the approach in Perino and Willner (2016), they add the cancellation mechanism and discretize the time steps to closely follow the regulatory rules on the allowance supply. In contrast to Quemin and Trotignon (2018), who apply an iterative heuristic to solve for rationally bounded firms, the model in this paper finds a solution for a market equilibrium of perfectly rational firms as a direct result of a mixed-integer optimization problem. In the following, the essential features of the general model are introduced.

In line with existing literature (e.g., Perino and Willner, 2016, Beck and Kruse-Andersen, 2020, and Bocklet et al., 2019), this paper assumes N homogeneous, perfectly rational firms with perfect foresight in a perfectly competitive allowance market. A representative firm i in the market solves its intertemporal cost minimization problem[30]

$$\begin{aligned} \min \quad & \sum_{t=0}^{T} \frac{1}{(1+r)^t}[C(e(t)) + p(t)x(t)] \\ s.t.\ b(t) - b(t-1) &= x(t) + f(t) - e(t) \quad \text{for all} \quad t = 1, 2, \ldots, T \\ b(t) &\geq 0 \\ e(t) &\geq 0 \\ x(t) &\gtreqless 0. \end{aligned} \tag{3.1}$$

The firm's objective is to minimize the discounted value of the abatement costs $C(e(t))$ and the costs for allowance trading $p(t)x(t)$ for all time periods

[29] Chevallier (2012) gives a comprehensive review of models in the aftermath of Rubin (1996).
[30] The index i is omitted for better readability, when only one firm is considered.

$t = 0, 1, \ldots, T$. In line with literature (e.g., Rubin, 1996), the abatement cost function is assumed to be quadratic, i.e., $C(e(t)) := \frac{1}{2}c(t)(u(t) - e(t))^2$, with exogenous baseline emissions $u(t)$, cost parameter $c(t)$ and the decision variable for realized emissions $e(t)$.[31] The allowance price $p(t)$ is exogenous for the firm because the firm's decision does not influence the price within a perfectly competitive allowance market. Apart from the decision on the emissions, the firm decides on the amount of traded allowances $x(t)$ and the number of banked allowances $b(t)$. The banking constraint assures that the bank in period t contains the allowances from the bank in the previous period $t-1$ together with the allowances which are purchased ($x(t)$) or received for free ($f(t)$) minus the realized emissions $e(t)$. Hereby, $f(t)$ is exogenous. Regulations prohibit firms from borrowing allowances which will be issued in the future. Hence, the banking variable should not be negative.[32]

Optimality conditions for the representative firm are derived from the Karush-Kuhn-Tucker (KKT) conditions of the optimization problem (3.1), which are given in Appendix B.1. Based on these conditions the firm optimally chooses emissions $e(t)$ so that marginal abatement costs $C'(e(t))$ equal the allowance price, i.e.,

$$c(t)(u(t) - e(t)) = p(t). \tag{3.2}$$

By using the assumption of homogeneous firms, the market equilibrium is determined by an amended Hotelling rule from the KKT conditions

$$\frac{p(t+1) - p(t)}{p(t)} = r - (1+r)^{t+1}\frac{\mu_b(t)}{p(t)}, \tag{3.3}$$

where $\mu_b(t)$ is the respective dual variable for the non-borrowing constraint. Since the KKT conditions imply a complementarity constraint, $\mu_b(t)$ is zero for a positive bank $b(t)$. The aggregate private bank held by all firms is called Total Number of Allowances in Circulation (TNAC). Thus, the condition implies that the allowance price rises with the interest rate r while the TNAC is non-empty. When the TNAC is empty, the shadow costs of the non-borrowing constraint reduce the price increase.

For the market equilibrium, the allowance purchases of the firms $N \cdot x(t)$ equals the endogenous amount of auctioned allowances $S_{auct}(t)$, specified by the regulatory rules as

$$S_{auct}(t) = \sigma \cdot S_0(t) - Intake(t) + Reinjection(t),$$

[31] The assumption of a quadratic abatement cost function makes the problem numerically tractable. Bruninx et al. (2020) explicitly model investment decisions in the power sector, making their cost function endogenous. However, they can solve the model only with an iterative algorithm.

[32] Since the free allocation of one year occurs before the previous year's compliance date, borrowing is implicitly allowed in reality for a small part of emissions. Quemin (2020) formalizes this aspect.

where σ is the share of auctioned allowances of the exogenous target path $S_0(t)$, which is corrected by the allowances inserted into the MSR ($Intake(t)$) or reinjected to the market ($Reinjection(t)$). The target path $S_0(t)$ is set to decline at the linear rate $a(t)$ from the starting value $\tilde{S}$, i.e., $S_0(t) = S_0(t-1) - a(t)\tilde{S}$. Further, the freely received allowances $N \cdot f(t)$ equals the amount of freely issued allowances $S_{free}(t) = (1-\sigma) \cdot S_0(t)$. Thus, the total allowance supply $S(t)$ is given as $S(t) = S_{auct}(t) + S_{free}(t)$.

The MSR regulation controls the allowance supply depending on the volume of the TNAC. If the TNAC is above the threshold ℓ_{up}, allowances equivalent to the share $\gamma(t)$ of the TNAC are withheld from auction and set aside in the MSR. If the TNAC falls below the threshold ℓ_{low}, allowances from the MSR are fed back to the market in yearly tranches of R until the MSR is empty. Furthermore, the cancellation mechanism enforces a permanent invalidation of allowances in the MSR if the MSR volume exceeds the previous year's auction volume.[33]

3.3.2. Modelling of Different CPF Designs

Throughout this paper, the implementation of the CPF is assumed across all countries in the EU ETS.[34] As discussed in Section 3.2, conclusions about the implementation through an auction reserve price can be drawn if the auction share in the EU ETS is increased.

For the buyback design, it is assumed that a credible governmental institution guarantees to buy back an unlimited amount of allowances at the price of the CPF level $\underline{p}(t)$ from the implementation year[35] onwards. Hence, $p(t) \geq \underline{p}(t)$ is required. If $p(t) = \underline{p}(t)$, the price path may deviate from the Hotelling rule because the governmental institution buys back allowances regardless of the expected return.[36] In the case of unallocated allowances in the primary auction, these allowances are transferred directly to the governmental institution. When the price rises again with the interest rate, the governmental institution can sell the allowances back to the firms. As long as the governmental institution holds a positive number of allowances, these are included in the TNAC volume. Con-

[33] A formal definition of the regulatory supply rules, which are also necessary conditions for the market equilibrium, can be found in Appendix B.2. The constraints are rearranged with big-M constraints and integer variables to resolve non-linearities. The problem is solved as a mixed-integer linear program.

[34] A national CPF only reduces emissions within the EU ETS if a mechanism exists (e.g., withdrawal of allowances by nation-states) that ensures that the countries without a CPF cannot use the surplus of allowances. The political discussion on the introduction of a CPF suggests that, at first, individual countries will introduce a national CPF, and other countries will follow.

[35] Implementation year means the year in which the policy becomes effective as opposed to the year in which it is announced.

[36] In this setting, all allowances are auctioned since firms will buy allowances from the primary auction for any price marginally below the CPF and sell them back to the governmental institution. In equilibrium, they buy and sell at the same price.

sequently, they are also taken into account within the regulations on the MSR and cancellation mechanism.

For the implementation of the CPF through a top-up tax, the tax $\tau(t)$ is defined as the difference between the market price and the CPF level $\underline{p}(t)$ if the market price is below $\underline{p}(t)$, i.e.,

$$\tau(t) = \begin{cases} \underline{p}(t) - p(t) & \text{, if } p(t) < \underline{p}(t) \\ 0 & \text{, else.} \end{cases}$$

The tax payment of the firms equals top-up tax times emissions. Hence, the term $\tau(t)e(t)$ is included in the objective function of the firm. Deriving the KKT conditions for the firm's optimization problem including the top-up tax results in a modified version of Equation (3.2), namely

$$c(t) \cdot (u(t) - e(t)) = p(t) + \tau(t). \tag{3.4}$$

Thus, in equilibrium, firms choose their emissions so that the marginal abatement costs equal to the market price plus top-up tax.

The existence and uniqueness of equilibria are not trivial in this setting. The model is formulated through its KKT conditions with additional constraints on the supply of allowances and the price. Thereby, the problem becomes a discrete optimization problem without an objective function, i.e., a feasibility problem. If a feasible solution to the problem is found, it is always an equilibrium. The uniqueness of the equilibrium can only be guaranteed if there is exactly one feasible solution. The regulatory rules on the MSR and the cancellation mechanism together with the implementation of the CPF require integer variables and thus make the problem discontinuous.[37] Gerlagh et al. (2019) show that this potentially leads to multiple equilibria, which differ in their price path and their overall level of emissions. The solution procedure takes this multiplicity into account: In the case of multiple equilibria, the one with the highest overall emission level is selected. This procedure implicitly assumes that firms in the EU ETS benefit from emitting more and coordinate themselves to maximize overall emissions and profits.

3.3.3. Parametrization of the Model

The model starts in the year 2020, with the respective parametrization as described below. T is chosen to cover the entire period of positive emissions within the EU ETS. With the current linear reduction factor, this will be in 2057. The rules of the endogenous allowance supply follow the current regulation (cf. European Parliament and the Council of the European Union, 2003 together with

[37]For example, if the TNAC falls slightly below the threshold of 400 million allowances, the auction volume in the next year increases discretely, i.e., it "jumps" upwards.

European Parliament and the Council of the European Union, 2015 and European Parliament and the Council of the European Union, 2018). $\tilde{S} = 2199$ million represents the issued allowances in 2010, and the linear reduction factor $a(t)$ increases from 1.74% to 2.2% in 2020. The share of auctioned allowances σ is set to 57%. The parameters of the MSR regulation are $\ell_{up} = 833$ million, $\ell_{low} = 400$ million, $R = 100$ million, and $\gamma(t) = 24\%$ until 2024 and 12% afterwards. The initial volume of the MSR in 2019 consists of 900 million allowances, which have been back-loaded between 2014 and 2016. Additionally, around 600 million unallocated allowances are transferred into the MSR in 2020 (European Commission, 2015). The initial volume of the TNAC in 2019 consists of 1385 million allowances, as published by the European Commission (2020).

In addition to the regulatory rules, the market equilibrium is driven by assumptions on the interest rate r, baseline emissions $u(t)$, and the cost parameter $c(t)$. The interest rate is set to 8%, which estimates the weighted average cost of capital of fossil power plants and energy-intensive industries (compare Kost et al., 2018 and KPMG, 2017). The baseline emissions remain constant over time at 2000 million tonnes, which is in line with the literature (e.g., Perino and Willner, 2017). Due to the quadratic abatement cost function $C(e(t))$, the last ton of carbon is abated at marginal abatement costs of $c(t) \cdot u(t)$, which can be interpreted as backstop costs. Hence, the cost parameter is defined by $c(t) := backstopcosts \cdot u(t)^{-1}$, with constant backstop costs of 150 EUR/t.[38] Since the choice of these three parameters affects the model results, a robustness analysis ensures that the main findings of this paper are preserved.[39]

3.4. The Impact of a European Carbon Price Floor on Market Outcomes

The introduction of a European CPF in the EU ETS is widely discussed, as stated in Section 3.1. This section analyzes and discusses the effects of the CPF in the reformed EU ETS. Section 3.4.1 describes the market equilibrium in a base scenario without the CPF and explains the interactions with the MSR and the cancellation mechanism. Section 3.4.2 analyzes how these results change under the different CPF designs. The CPF alters the governmental revenue of the regulator, which is an essential aspect for policymakers. Section 3.4.3 exhibits how governmental revenue differs between the two CPF designs. Section 3.4.4 explains how the CPF level and its implementation year affect overall emissions through the interactions of the CPF with the cancellation mechanism.

[38] The backstop costs rely on cost estimates for Carbon Capture and Storage (e.g., Saygin et al., 2012).

[39] Sections 3.4.1, 3.4.2 and 3.4.4 explicitly state how the parameter choices influence the model results. Moreover, a robustness analysis is included in Appendix B.3.

3.4.1. Base Scenario: The EU ETS Without the CPF

For the base scenario without the CPF, the market equilibrium is depicted in Figure 3.1. The initial allowance price of 19 EUR/t in 2020 rises with the interest rate until 2039. Thereafter, the TNAC is empty, and hence the shadow costs of the non-borrowing constraint are positive and reduce the price increase as implied by Equation (3.3). The price equals the backstop costs from 2057 onwards when there is no supply of allowances left. Together with the rising prices, emissions decrease proportionally in line with the firms' decision rule for emissions (Equation 3.2). When the price hits the backstop level in 2057, there are no emissions.

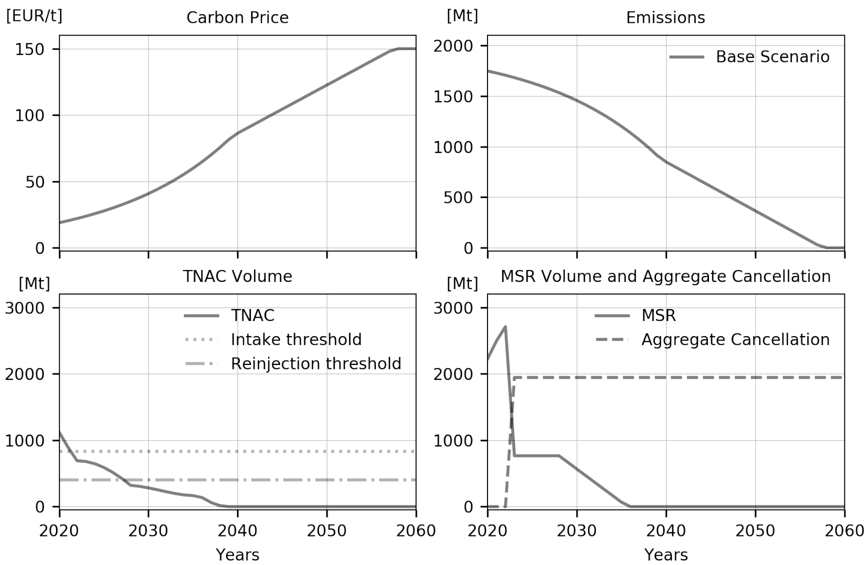

Figure 3.1.: Carbon price, emissions, TNAC, MSR and aggregate cancellation in the base scenario

Until 2021, the TNAC lies above the intake threshold, and allowances are transferred to the MSR. The volume of the MSR peaks in 2022, followed by a one-time cancellation of 2 billion allowances in 2023. The remaining allowances in the MSR are reinjected to the market starting in 2029 when the TNAC falls below 400 million allowances. Bocklet et al. (2019) comprises a more detailed description of the base scenario.

The market equilibrium changes depending on the choice of backstop costs, interest rate, and baseline emissions. As formally shown in Bocklet et al. (2019), a change in backstop costs only scales the absolute price level but does not affect the level of emissions, TNAC, and cancellation. A lower interest rate leads to a higher initial allowance price level, resulting in lower emissions, a higher TNAC, and more cancellation. Lower baseline emissions decrease the overall allowance demand and the overall price level. As a consequence, emissions are lower, the TNAC volume is higher, and more cancellation occurs.

3.4.2. Comparison of Price Effects for Different CPF Designs

In the following, the impact of different CPF designs on the development of prices, emissions, and banking behavior is analyzed in comparison to the base scenario (Figure 3.2). A CPF level of 40 EUR/t is assumed to be implemented in 2025 and announced in 2020.[40] Moreover, it is assumed that firms perfectly foresee the impact of the CPF, i.e., they anticipate in 2020 that the CPF is implemented in 2025. As discussed in prevalent literature, the anticipation of the price regulation plays an important role for the model outcome (see Section 3.2 for a discussion of Friesen et al., 2020 and Salant et al., 2020). The TNAC will be empty by 2040 in all cases, and thus, the results of both CPF designs coincide with the base scenario after 2040.

The buyback design regulates the value of allowances from the implementation year onwards. Firms anticipate the rise of the allowance price to the CPF level in the implementation year. When the CPF is announced, firms buy allowances to make arbitrage profits leading the price to rise to the discounted CPF level immediately after the announcement. During the time of a binding CPF, prices do not increase with the interest rate, and private firms have no incentive to bank allowances. Hence, the entire TNAC between 2025 and 2030 can be fully accounted for as quantities bought and held by the government (blue dotted line). Since prices are higher than in the base scenario, emissions are lower in the short run (Equation 3.2). Compared to the base scenario, private banking increases in the short run, leading to a higher MSR volume, lower auction volumes, and higher cancellation volumes until 2030.

Compared to the base scenario, the TNAC falls below the threshold of 400 million allowances later, and the MSR is fed back to the auctions later, leading to a slightly higher supply of allowances after 2030. Compared to the base scenario, the higher supply suppresses the carbon prices by 4.8% after 2030, leading to 380 Mt more emissions between 2030 and 2040. This effect is known as the temporal waterbed effect, i.e., the emission savings between 2020 and 2030 are partly caught up after 2030. The cancellation mechanism diminishes

[40] With auction reserve prices in place, the CPF level increases at a predefined rate, e.g., within the Regional Greenhouse Gas Initiative, the trigger prices increase by 7% annually (RGGI, 2017). Contrarily, this paper assumes a constant CPF level to simplify the effects. With a constant CPF level, the additional abatement due to the CPF diminishes over time because the allowance price in the base scenario rises over time. However, if the CPF level rises at a specific rate, the regulator bears the risk of choosing the "correct" rate. A low initial price increasing at a higher rate will result in additional abatement, which grows over time. A high initial price increasing at a lower rate will result in a strong abatement incentive at the beginning, diminishing over time. The level of 40 EUR/t is in line with Newbery et al. (2019) who recommend introducing a CPF of 25-30 EUR/t in 2017, which rises with an annual rate of 3-5%.

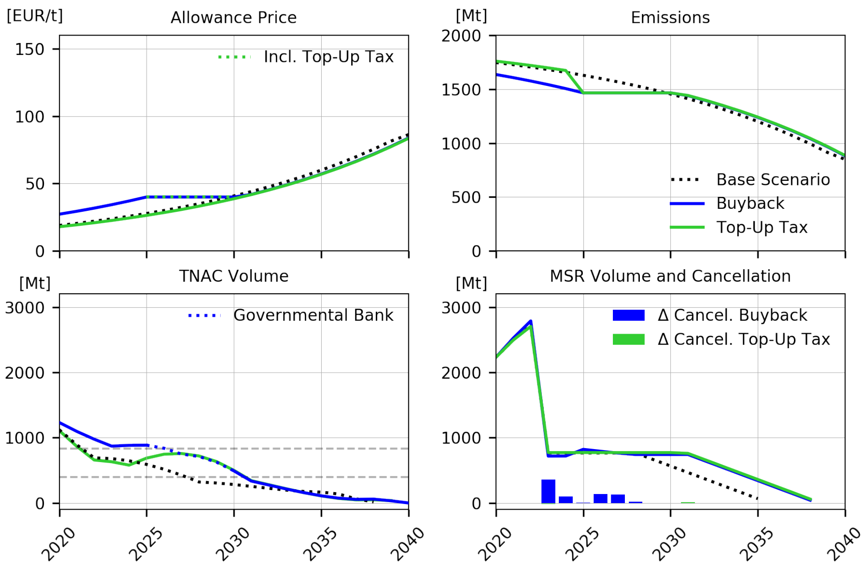

Figure 3.2.: Allowance price, emissions, TNAC, MSR and cancellation for the base scenario, buyback or top-up tax for a CPF level of 40 EUR/t in 2025

the temporal waterbed effect, and thus it is relatively small compared to the pre-reform EU ETS without cancellation.

In contrast to the buyback design, where the CPF regulates the allowance price, the top-up tax is imposed on emissions from the implementation year onwards. Consequently, the top-up tax is not transferred automatically to earlier periods. While the price of allowances increases with the interest rate, the total payment for emissions (allowance price plus the top-up tax; green dotted line) rises to the predefined level of 40 EUR/t between 2025 and 2030. If the CPF is implemented through the top-up tax design, firms foresee that payments for emissions become larger due to the tax from the implementation year onwards. Hence, the top-up tax lowers emissions in comparison to the base scenario only from its implementation year onwards to equalize marginal abatement costs and total payments for emissions (compare Equation 3.4). The announcement of the top-up tax reduces the value of allowances in the future. As firms anticipate this circumstance, they use more allowances before the top-up tax comes into effect, resulting in higher short-run emissions. Therefore, the TNAC is lower in the short run leading to a minor reduction of the MSR, which causes a decrease of cancellation volumes by 15 million allowances in 2023 (new green paradox effect). After the top-up tax is implemented, firms start to emit less and bank more so that the TNAC increases again.[41] Because of the higher TNAC volume

[41]The increasing TNAC might cause a second intake phase for the MSR. Depending on the implementation year of the top-up tax, this behavior can lead to further cancellation even after 2030.

after the CPF implementation, more allowances are available for later use. As with the buyback design, this causes a small temporal waterbed effect, i.e., prices are 5.1% lower after 2030, compared to the base scenario, and emissions are 410 Mt higher between 2030 and 2040. Again, this temporal waterbed effect is more significant in the pre-reform EU ETS without cancellation.

Like the base scenario, the equilibrium paths change with different backstop costs, interest rates, or baseline emissions. With lower (higher) backstop costs, the overall price level decreases (increases) so that the same absolute CPF level has a larger (smaller) effect, in particular on the aggregated cancellation volume. The effect of the same absolute CPF level also diminishes (grows) with a lower (higher) interest rate or higher (lower) baseline emissions. In this regard, Appendix B.3 provides more details.

To summarize, in the buyback design, the price-increasing effect of the CPF outweighs the temporal waterbed effect leading to higher aggregated cancellation than in the base scenario. With the top-up tax, the new green paradox effect reduces cancellation volumes compared to the buyback design and levels them with the base scenario. However, the overall effect on aggregate cancellation depends on the CPF level and the implementation year, discussed in Section 3.4.4.

3.4.3. The Impact of a European CPF on Governmental Revenue

The European CPF affects the governmental revenue within the EU ETS. When deciding on the introduction of the CPF, policymakers need to be aware of its impact on governmental revenue, analyzed in this section.[42]

In the EU ETS without the CPF, the only source for governmental revenue is the auction revenue, which equals the product of the allowance price and the auction volume. The CPF changes the auction revenue because it impacts the price of allowances and the auction volume via the MSR rules (compare Figure 3.2). In the case of the top-up tax, tax revenue (top-up tax times emissions) is another source of governmental revenue. In the case of the buyback design, the government guarantees to buy allowances to reach the CPF level when the CPF is implemented. The governmental bank sells those allowances back to the market at the CPF level if firms are willing to buy them. Hence, the government is buying and selling the allowances at the CPF level and, therefore, bears the cost of holding the allowances (blue dotted line in Figure 3.2) when the price remains constant.[43] These capital costs are calculated as the product of the

[42] As discussed in Section 3.1, a CPF affects the distribution of revenue across member states. This paper refrains from analyzing distributional effects between member states but considers the aggregate revenue of the regulator.

[43] By assumption firms only hold allowances in the private bank (TNAC) if the market price rises with the interest rate. Thus, when the market price remains constant, only the governmental bank holds allowances.

interest rate, the market price, and the volume of the governmental bank of allowances. The governmental revenue is calculated as

$$governmentalrevenue(t) = \\ = p(t) \cdot S_{auct}(t) + \tau(t) \cdot e(t) - r \cdot \underline{p}(t) \cdot governmentalbank(t), \tag{3.5}$$

where $\tau(t)$ and $governmentalbank(t)$ are only positive if the CPF is implemented as a top-up tax and buyback, respectively.

Figure 3.3 displays the time structure of the undiscounted governmental revenue, which comprises auction revenue, tax revenue, and capital costs. For better comprehension, the tax revenue and capital costs are also plotted separately.

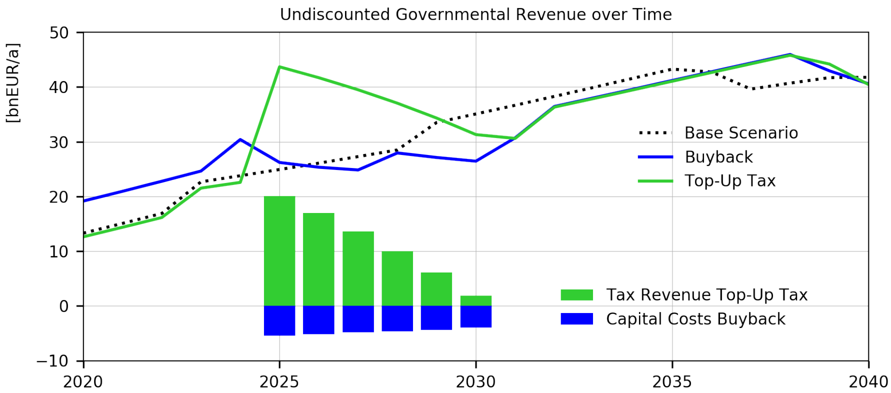

Figure 3.3.: Undiscounted governmental revenue in the base scenario and CPF design via buyback or top-up tax, tax revenue and capital costs

In the base scenario, the governmental revenue rises until 2039, when the TNAC is depleted, because allowance prices increase exponentially and auction volumes fall linearly (apart from the withheld and reinjected auction volumes from the MSR). After 2040, the decrease in auction volume overcompensates the increasing carbon prices so that the governmental revenue shrinks.

With the buyback design, the governmental revenue exceeds the one in the base scenario until 2025, because the increase in market prices outweighs the reduction in auction volumes. Between 2025 and 2030, the total governmental revenue roughly remains on the same level, as the capital costs for the holdings of the governmental bank diminish the increased auction revenues after 2025. The auction revenue between the base scenario and the buyback case falls apart after 2030, because of the different timing for the MSR reinjection.

For the top-up tax, the governmental revenues between 2020 and 2024, are slightly below the base scenario because of the slightly lower allowance price. Between 2025 and 2030, the top-up tax, on the one hand, generates additional tax revenues, but on the other hand, reduces the auction revenue (as lower emissions reduce the auction volumes through the MSR rules). After 2030 the governmental revenue coincides with the buyback design.

Summing up, the CPF increases overall governmental revenue independent of its design.[44] The buyback program reduces emissions immediately in 2020, and, at the same time, generates additional auction revenue, which can be partly used to compensate firms for higher abatement costs. The top-up tax also raises the governmental revenue but only after its implementation year in 2025.

3.4.4. The Impact of the CPF Level and Implementation Year on Aggregate Cancellation

The CPF reduces overall emissions within the EU ETS if it increases aggregate cancellation, as described in Section 3.4.2. The general performance of the CPF is not affected by its level and implementation year. Nevertheless, the choice of these regulatory parameters has a significant impact on the quantitative results. This section evaluates the impact of the CPF level and implementation year on aggregate cancellation. All scenarios below assume that the policy is anticipated in 2020. Note that in Figure 3.4 and Figure 3.5 the CPF level and the implementation year vary on the x-axis, i.e., each dot represents the aggregate cancellation for an entire scenario.

Figure 3.4 shows aggregate cancellation volumes for different CPF levels implemented in 2025. The CPF is effective only above 28 EUR/t in 2025 because the carbon price rises to that level already in the base scenario.[45] In the buyback design, the aggregate cancellation increases steadily with the CPF level. As described in Section 3.4.2, the CPF immediately raises the market price to the discounted CPF level. Reduced emissions increase the TNAC volume, resulting in higher MSR intake and lower auction volumes, hence increasing aggregate cancellation. These relations persist with a higher CPF level, and the magnitude increases.

[44] The total discounted governmental revenue is higher for the top-up tax if the same interest rate applies to the government as to firms. For higher interest rates the buyback design generates a higher discounted revenue.

[45] If one accounts for price risk, even a CPF below the expected price level incentivizes investment in abatement technology due to reduced price risk. Salant et al. (2020) find that even a soft price floor below the expected price level is effective in a stochastic model with demand shocks ("action at a distance").

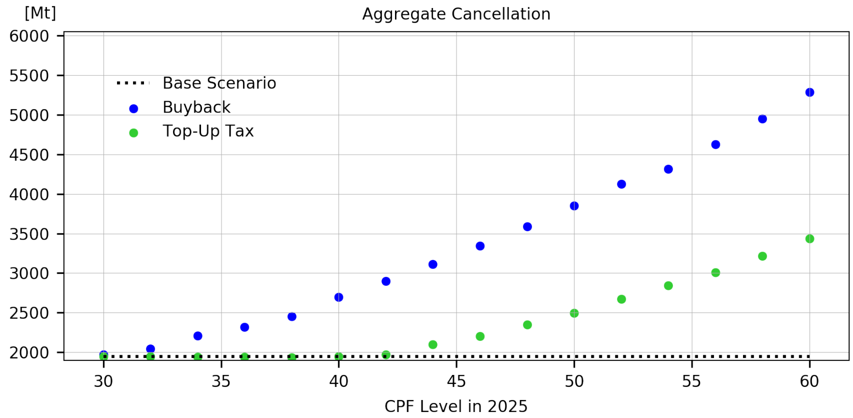

Figure 3.4.: Aggregate cancellation for different CPF levels for an implementation in 2025

Overall, the top-up tax leads to similar results: the higher the CPF level, the higher the aggregate cancellation. However, additional cancellation only occurs for CPF levels above 40 EUR/t, and the amount is smaller compared to the buyback design. The top-up tax entails two opposing effects: on the one hand, the top-up tax increases costs for emissions after its implementation and therefore reduces emissions. Analogously to the buyback design, this increases cancellation, particularly after the implementation year. This effect grows with a higher CPF level. On the other hand, firms anticipate the top-up tax and emit more before the implementation year compared to the base scenario, which reduces the first cancellation in 2023 and, consequently, the aggregate cancellation. Again, this effect grows with the CPF level. The numerical results show that both effects more or less cancel each other out at CPF levels below 40 EUR/t.[46] Hence, the effect of the new green paradox, described in Section 3.4.2, is rather small. Compared to the buyback design, aggregate cancellation increases more slowly with the top-up tax design even for CPF levels above 40 EUR/t. Since the MSR injection factor drops from 24% to 12% after 2023, the increase in the TNAC after 2025 leads to a lower MSR and lower cancellation volumes.

In order to compare different implementation years of the CPF, a CPF level of 27.22 EUR/t in 2020 is assumed, increasing to 86.36 EUR/t in 2035 with the interest rate of 8%. When the CPF is implemented later, it immediately starts on a higher CPF level. This assumption is necessary because the effect of the CPF diminishes when the price in the base scenario rises above the CPF level before the implementation year. A rising CPF level ensures that the CPF is binding even with a late implementation year. Again, firms anticipate the CPF level and the implementation year.

[46]In fact, at CPF levels between 30 and 40 EUR/t, aggregate cancellation decreases slightly by up to 15 Mt.

With the buyback design, the CPF immediately becomes effective with its discounted level, because firms perfectly anticipate the CPF.[47] Consequently, the implementation year does not impact aggregate cancellation (compare Figure 3.5). This finding hinges both on the anticipation of the CPF and the rising CPF level.

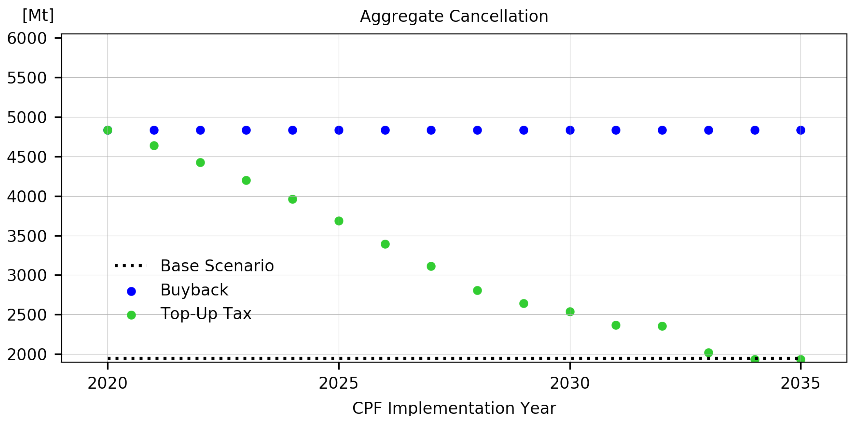

Figure 3.5.: Aggregate cancellation for different implementation years of a rising CPF level (27.22 EUR/t in 2020 to 86.37 EUR/t in 2035)

With the top-up tax design, aggregate cancellation is decreasing with a later implementation year. Since the top-up tax is not automatically transferred to other periods, unlike the buyback design, a later implementation year leads to fewer years with a CPF policy in place. However, the exact effects of the CPF on cancellation are more ambiguous due to counterbalancing effects over time and the asymmetric regulation of the MSR and cancellation mechanism. When implemented in 2020, top-up tax and buyback are equivalent. However, if the top-up tax comes into effect later, firms emit more before the implementation year because they thereby can reduce their abatement costs. The difference in emissions compared to the base scenario becomes larger with an earlier implementation because firms have fewer years to counteract the top-up tax with higher emissions. Thus, the first cancellation volume in 2023 exceeds the one in the base scenario for implementation before 2021. For later implementation years, firms manage to increase short-run emissions to reduce the cancellation volume in 2023 to around 1500 Mt. With a later implementation year, additional cancellation might occur later. In response to the top-up tax, firms cut emissions, and the TNAC rises above the threshold of 833 million after the implementation year. The increased TNAC causes a higher MSR volume, lower auction volumes, and higher cancellation volumes in later years. The later the tax is implemented, the less cancellation is caused by this secondary effect as the TNAC already lies at a lower level. Overall, the aggregate cancellation declines with the implementation year.

[47] If banking of allowances is permitted, firms do not differentiate between a discounted CPF today and a CPF tomorrow.

In general, a higher CPF level and an earlier implementation year magnify the impact of the CPF and lead to higher aggregate cancellation. A higher CPF level has a more pronounced effect for the buyback design as it immediately raises allowance prices to the discounted CPF level. When the CPF level increases with the interest rate, the market outcomes, and, in particular, the aggregate cancellation are independent of the implementation year in the buyback design. This result follows by construction and the assumption of perfectly anticipating firms. For the top-up tax, aggregate cancellation is higher the earlier the tax is implemented.

The market equilibrium depends on the assumed baseline emissions and interest rate. However, the general effects described above are robust towards other parameter choices. Appendix B.3 gives an overview of aggregate cancellation with respect to baseline emissions and interest rates. Lower (higher) baseline emissions imply a lower (higher) price level in the base scenario. Thus, the effect of the CPF is enlarged (diminished) for both CPF designs. A lower interest rate implies a higher initial price level and higher cancellation in the base scenario, which diminishes the effect of the CPF on aggregate cancellation.

To conclude, the introduction of a sufficiently high European CPF decreases overall emissions. Depending on the design of the CPF, however, emissions decrease or increase in the short run since private firms face different emissions and banking rationales. The buyback design enables to automatically transfer the CPF level to earlier periods so that emissions are reduced immediately. Contrarily, the top-up tax incentivizes firms to increase emissions before the implementation year.

3.5. Conclusion and Policy Implications

The introduction of a CPF in the EU ETS has been suggested in scientific and political discussions both before and after the recent reforms. A European CPF is proposed to set reliable incentives for low-carbon investments and to increase abatement efforts. This article uses a discrete-time model of the reformed EU ETS to analyze the impact of the CPF on market outcomes such as allowance prices, banking, and emissions. Due to the cancellation mechanism in the reformed EU ETS, the CPF can, in principle, reduce overall emissions. Therefore, if the CPF increases aggregate cancellation, it becomes an effective instrument for emission reduction. Consequently, this work particularly considers aggregate cancellation. Furthermore, the effect of the CPF on governmental revenue is examined because the fiscal budget plays a significant role for policymakers.

The impact of the CPF depends on its design: this paper compares the design of a governmental buyback program of allowances with the design of a top-up tax on emissions. The buyback design sets a boundary on the value of allowances from the implementation year onwards. Immediately after the announcement of the buyback program, firms anticipate that the price of allowances rises to the CPF level. They start to buy allowances to make arbitrage profits, directly causing the price to rise to the discounted CPF level. Thus, as soon as the CPF is announced, firms choose a lower emission level based on the discounted CPF level. Lower emissions lead to higher banking volumes, and, as a result, to more intake into the MSR and more cancellation of allowances.

The top-up tax imposes a tax on emissions, which tops the market price of allowances up to the CPF level from the implementation year onwards. Hence, the top-up tax decreases the value of allowances in earlier periods, causing firms to raise their emissions in anticipation of the upcoming tax. Only after the implementation year, firms start to lower their emissions. Consequently, the effect on aggregate cancellation is ambiguous. If the CPF level is low or the CPF is implemented late, aggregate cancellation is slightly below the base scenario. Thus, if the design or timing of the CPF is ill-chosen, such a policy intervention can be counter-effective (new green paradox). Despite being equivalent in a static setting, the design choice for the CPF matters in a dynamic context, such as the EU ETS.

For both designs, the introduction of the CPF increases governmental revenue. In the buyback design, the increased auction revenues before implementation outweigh the capital costs for holding allowances at the constant CPF level. On the contrary, the tax revenue of the top-up tax is generated only after implementation, and the auction revenues before the implementation even decrease compared to the base scenario. For both designs, the impact of the CPF grows with its level and falls with a later implementation year. In the buyback design, the effect of the CPF on prices, emissions, and aggregate cancellation directly increases with its level. If one assumes a CPF level, which rises with the interest rate, the implementation year of the CPF does not affect the buyback CPF. For the top-up tax, the impact is ambiguous: On the one hand, the tax lowers emissions by increasing their prices. On the other hand, it incentivizes short-run emissions because firms anticipate the tax. Hence, a higher CPF increases the aggregate cancellation volume less than in the buyback design. Moreover, aggregate cancellation decreases with a later implementation year, as the anticipation effect grows over time.

For policymakers willing to introduce a CPF to decrease overall emissions, the buyback design is preferable to the top-up tax in the following aspects: Firstly, the buyback design reduces emissions immediately after the policy's announcement. Secondly, the buyback design reduces overall emissions more vigorously than the top-up tax. Thirdly, the buyback design does not cause counter-productive announcement effects. If the top-up tax is selected for other reasons, the policymaker should make sure to keep the announcement effect as small as possible, i.e., announce the top-up tax shortly before its implementation.

This article analyzes different CPF designs in a stylized setting of the EU ETS, e.g., by assuming perfect markets and perfect foresight. Regulatory uncertainty plays an essential role in the EU ETS, itself, and for the CPF. Further research may evaluate how the expectations on policy adjustments drive the decision making of the firms. Moreover, it could be examined how regulators can credibly announce the CPF and commit to it. Another topic for future research should be the impact of a national CPF in the reformed EU ETS, as a national CPF seems politically easier to realize.

4. How Does the EU ETS Reform Impact Allowance prices? The Role of Myopia, Hedging Requirements and the Hotelling Rule

4.1. Introduction

Since 2005, the European Union Emissions Trading System (EU ETS) builds the foundation of European environmental policy. Aggregate emissions within the EU ETS are limited by the number of allowances supplied to the market. The cap is determined on a yearly basis and set to decline annually. Firms in the EU ETS can optimize themselves intertemporally by banking allowances for future use.

Due to low allowance prices in the market and hence a weak investment signal for low-carbon technology, policy makers reformed the EU ETS substantially between 2014 and 2018, including the backloading of allowances, the Market Stability Reserve (MSR) and a cancellation mechanism. As the aggregate private bank held by firms in the market determines the size of the MSR and the cancellation volumes, the allowance supply is partially endogenous in the reformed EU ETS.

In the aftermath of the reforms, prices in the EU ETS rose from 5 EUR/t in 2017 to over 24 EUR/t in 2019, while the aggregate private bank remained almost constant at around 1650 million allowances. Practitioners from the energy sector state that the reform fundamentals, namely the introduction of the MSR and the announcement of the cancellation mechanism, caused prices to spike (Wölfling and Germeshausen, 2019).

Theoretical models accurately depicting the new EU ETS regulation yet fail to attribute the large price increase in 2018 to the underlying reform fundamentals. Perino and Willner (2016) find that the MSR shifts allowances from the present to the future but is allowance preserving, i.e. the overall emission cap is not altered. They conclude that the MSR only affects prices if allowances become temporarily scarce. In this case, prices slightly increase in the short run but drop below their baseline level in the long run.

Bocklet et al. (2019) and Beck and Kruse-Andersen (2020) amend the work of Perino and Willner (2016) by including the cancellation mechanism into their models. Both papers find that the cancellation of allowances stored in the MSR increases the overall price level at all times but that the price increase is rather negligible in the short run.[48]

All three papers build on the seminal works of Rubin (1996) and Chevallier (2012) who established a model for intertemporal allowance trading. The right to emit is treated as a scarce, non-renewable resource. Prices of such a resource develop according to the Hotelling rule (Hotelling, 1931), given complete and perfectly competitive markets and rational firms that have perfect information and fully anticipate market and regulatory developments until the end of time. The Hotelling rule states that prices are determined by the discounted value of the expected backstop costs. The shortening of allowances caused by the reform shifts the price path upwards. Due to discounting, short-run prices only increase little while the main price effect of the reform plays out in the long run. Thus, those theoretical models fail to explain the price increase through the reform fundamentals.

Krautkraemer (1998) challenges the assumptions of Hotelling models stating that governments intervene, firms have market power, are risk averse or short-sighted. Thus, theoretical Hotelling price paths are rarely visible in reality. Instead, the market depletion path can tilt towards the present or the future, prices may be volatile around a trend or even fully deviate from the Hotelling price path (Krautkraemer, 1998).

While there is no indication that the EU ETS lacks competition, literature and industry experts likewise stress the importance of myopia (e.g., Flachsland et al., 2020) and hedging (e.g. Gallier et al., 2015, Cludius and Betz, 2016 and Kollenberg and Taschini, 2019) - as a result of risk aversion - on market outcomes.

The role of either myopia or hedging requirements within the EU ETS has been previously researched by Willner (2018), Schopp and Neuhoff (2013), Tietjen et al. (2019) and Quemin and Trotignon (2019). Willner (2018) analyzes the impact of limited foresight in a two-period partial equilibrium model of the EU ETS. He finds that limited foresight leads to an underestimation of long-term scarcity. Consequently, prices are lower in period one and higher in period two than in the perfect foresight scenario and overall abatement costs increase. Given limited foresight, the introduction of the MSR leads to higher short-run prices and lower long-run prices than in the case with perfect foresight. A similar two-period partial equilibrium model is also set up in Schopp and Neuhoff (2013) where the allowance demand for hedging requirements is modelled in response to changes in expectation of fuel and power prices. They argue that if firms flexibly adjust their hedging needs, they can stabilize prices. Tietjen et al. (2019) understand hedging as a firm's response to uncertainty. Using a stochastic optimization model, they find that hedging leads to a U-shaped price curve in the EU ETS. They further evaluate how the introduction of the MSR changes the hedging decision of a firm. Quemin and Trotignon (2019) use a rolling-horizon

[48] Bocklet et al. (2019) further show that the main price effect stems from the increase of the linear reduction factor rather than the MSR and the cancellation mechanism.

model where firms are short-sighted and exhibit cognitive limitations in responding to governmental interventions. The model is calibrated to historic outcomes, choosing a planning horizon and interest rate that minimizes the difference between simulated results and historical data ex-post. They find that applying a low interest rate of only 3% and a planning horizon of 13 years historic data can be mimicked best.

This paper differs from the aforementioned approaches and assumptions in several aspects:

Myopia is incorporated through a rolling-horizon approach into a closed-form dynamic optimization model set up in Bocklet et al. (2019). Within the model, we depict the market and the recent reforms on a yearly resolution instead of deducing market results from a simplified two period model.

We evaluate the impact of the EU ETS reform on market outcomes by modelling an exogenous hedging share. Since firms hedge their future power sales, they may have limited potential to shift their portfolio to low-carbon production in the short run. It is therefore likely that their exogenous hedging requirement is substantially larger than an endogenously derived optimal bank.

As a further extension to previous work, we use stylized facts to determine the underlying fundamentals driving the market outcomes in the third trading period of the EU ETS. In particular, we compare pre- and post-reform model results with the observed market data. By analyzing model outcomes under myopia, hedging requirements and a combination of both, we shed light on the underlying fundamentals of the price increase caused by the reform.

The paper at hands adds three main contributions to the literature:

1. Implementing myopia into a discrete-time partial equilibrium model of the EU ETS where cancellation volumes are determined in a closed-form solution, we find that myopic firms emit more in the short run than under the cost-minimal abatement path. This market friction can be partly mitigated through the introduction of the MSR. At the same time, myopia leads to lower banking volumes and hence lower cancellation volumes. Thus, dropping the assumption of perfect foresight alters market outcomes in the dynamic setting of the reformed EU ETS.
2. By including firms with exogenous hedging requirements into the dynamic optimization model of the EU ETS, we show that hedging requirements drive cancellation volumes. Thus, prevalent theoretical models neglecting hedging requirements may underestimate the overall effect of the reform. Further, the restrictive allowance supply in the EU ETS along with the hedging requirements of firms may cause physical shortages in today's allowance market.
3. By comparing the model results with stylized facts of the EU ETS, we shed light on the underlying fundamentals driving market outcomes in the third

trading period. Neither myopia nor hedging requirements on their own are able to fully depict the market outcomes. Only the combination of myopic behavior, hedging requirements and the introduction of the reform is able to simultaneously explain low initial price levels, a steep price increase in the midst of the third trading period and a large private bank after the reform.

The remainder of this paper is organized as follows: In Section 4.2 we set up a partial equilibrium model of the EU ETS. Myopia and hedging requirements are integrated into the pre- and post-reform model. In Section 4.3 we show how myopia impacts model results in the reformed EU ETS. Analogously, in Section 4.4 we show how hedging requirements drive model results. In Section 4.5, we discuss if the reform can explain the market outcomes in the third trading period of the EU ETS given bounded rationality. Section 4.6 concludes.

4.2. A Hotelling Model of the EU ETS

Our partial equilibrium model of the EU ETS builds on the model from Bocklet et al. (2019) who use a discrete-time version of the model set up by Rubin (1996). In the following we briefly outline the decision making of a representative firm in a perfectly competitive allowance market. Since the market consist of homogeneous firms, the market demand is derived by the aggregated choice of firms.

The base model assumes a representative firm which is deciding on emissions $e(t)$, banking $b(t)$ and net allowance sales $x(t)$ for all time periods $t = 0, 1, \dots, T$ under perfect foresight. Formally, the firm solves the cost minimization problem $\mathcal{M}$

$$\begin{aligned} \min \quad & \sum_{t=0}^{T} \frac{1}{(1+r)^t}[\frac{c}{2}(u-e(t))^2 + p(t)x(t)] \\ \text{s.t.} \quad & b(t) - b(t-1) = x(t) - e(t) \quad \text{for all} \quad t = 1, 2, \dots, T \\ & b(t) \geq 0 \\ & x(t),\, e(t) \gtrless 0. \end{aligned} \tag{4.1}$$

The objective function consists of the discounted (interest rate r) costs for abatement and allowance trading. Following Perino and Willner (2016) and Bocklet et al. (2019), we assume a quadratic and convex abatement cost function with cost parameter c and baseline emissions u. The allowance price $p(t)$ is determined by the market and is hence exogenous in the firm's optimization problem. If allowance purchases exceed emissions, the constraint ensures that the excess allowances are stored in the private bank of the firm. According to regulation, borrowing is not allowed in the EU ETS. Thus, we require a positive bank. The optimality conditions for the firm are given by the Karush-Kuhn-Tucker (KKT) conditions, which are stated in Appendix C.1.

To derive the market equilibrium conditions, the following sections introduce the pre-reform (Section 4.2.1) and post-reform (Section 4.2.2) market rules. In Section 4.2.3 we explain how we model myopic firms with a rolling horizon approach. Section 4.2.4 exhibits how the firm's decision problem changes in light of hedging requirements. The parametrization of the model is summarized in Section 4.2.5.

4.2.1. Pre-Reform Market

The pre-reform market is assumed to be the EU ETS at the beginning of the third trading period in 2013, i.e. the reforms on backloading, the MSR and the cancellation mechanism are not included in the model yet.[49] In the following, the variables introduced above are used for aggregate levels, i.e. e and b are overall emissions and banking. Policy makers refer to the aggregated private bank b also as Total Number of Allowances in Circulation (TNAC).

In the pre-reform case with unrestricted banking, the supply of allowances is exogenously determined by the regulator.[50] The market equilibrium is determined by a price path such that the firm's optimality conditions hold and aggregated emissions over time do not exceed aggregated allowance supply, i.e. $\sum_{\tilde{t}=0}^{t} e(\tilde{t}) \leq \sum_{\tilde{t}=0}^{t} S(\tilde{t})$ for all $t = 0, 1, \ldots, T$.

From the market equilibrium conditions and the KKT conditions we can derive an amended Hotelling price rule

$$\frac{p(t+1) - p(t)}{p(t)} = r - (1+r)^{t+1} \frac{\mu_b(t)}{p(t)}. \tag{4.2}$$

Hence, the market price rises with the interest rate as long as the aggregated private bank is greater than zero.[51] If the bank drops to zero, prices rise at a lower rate.

[49] Since the EU ETS has been reformed in 2015 and 2018, the pre-reform case serves as a counterfactual after the reform is introduced.

[50] We amend the allowance supply by the expected number of unallocated allowances equally distributed over the years 2013-2020.

[51] We assign the dual multiplier $\mu_b(t)$ to the banking flow constraint in the firm's optimization problem.

4.2.2. Post-Reform Market

In the post-reform market the reforms on backloading of allowances, the MSR and the cancellation mechanism are included in the model.[52]

Backloading refers to the decision made by policy makers in 2014 to postpone the auctioning of 900 million allowances. It is implemented in the post-reform model as a reduction of the auction volumes in 2014, 2015 and 2016. In line with regulation (cf. European Parliament and the Council of the European Union, 2015), the backloaded allowances are inserted into the MSR in 2019 and 2020 together with allowances that remain unallocated in the third trading period.

The MSR was established by the European Commission in 2015, became operational in 2019 and serves as a public bank of allowances that shifts the allowance supply partly to the future while keeping the total number of allowances constant (European Parliament and the Council of the European Union, 2015). In 2018, the EU introduced a cancellation mechanism that will become operational in 2023. If the cancellation mechanism is activated, it renders a share of allowances stored in the MSR invalid (European Parliament and the Council of the European Union, 2018).

With the introduction of the MSR and the cancellation mechanism, the allowance supply is no longer exogenously determined. If the TNAC exceeds a certain threshold ℓ_{up}, a share ($\gamma(t)$) of allowances is withhold from the auction and put into the MSR. If the TNAC falls below the threshold ℓ_{low}, R allowances are reinjected from the MSR into the auction. With $a(t)$ being the exogenous linear reduction factor, the partly endogenous allowance supply is given by

$$S_{auct}(t) = S_{auct}(t-1) - a(t)S^0_{auct} - Intake(t) + Reinjection(t). \tag{4.3}$$

The intake to the MSR and the reinjection from the MSR to the market are defined as

$$Intake(t) = \begin{cases} \gamma(t) \cdot TNAC(t-1) & \text{if } TNAC(t-1) \geq \ell_{up}, \\ 0 & \text{else,} \end{cases} \tag{4.4}$$

and

$$Reinjection(t) = \begin{cases} R & \text{if } TNAC(t-1) < \ell_{low} \wedge MSR(t) \geq R, \\ MSR(t) & \text{if } TNAC(t-1) < \ell_{low} \wedge MSR(t) < R, \\ 0 & \text{else.} \end{cases} \tag{4.5}$$

[52] In order to show the effect of the reform, we model the post-reform scenario from 2013 onwards. The post-reform scenario before the reforms thereby serves as a counterfactual which postulates that the market participants are already aware of the upcoming policy changes in 2013.

Hence, the volume of allowances in the MSR is given as

$$MSR(t) = MSR(t-1) + Intake(t) - Reinjection(t) - Cancel(t). \tag{4.6}$$

If the MSR exceeds the auction volume of the previous year, allowances in the MSR are invalidated for future use, such that

$$Cancel(t) = \begin{cases} MSR(t) - S_{auct}(t-1) & \text{if } MSR(t) \geq S_{auct}(t-1), \\ 0 & \text{otherwise.} \end{cases} \tag{4.7}$$

The accurate modelling of the MSR and cancellation mechanism within our partial equilibrium model allows for a closed-form solution of MSR and cancellation volumes.

4.2.3. The Model Under Myopia

In economic theory, perfect foresight postulates the assumption that the decision maker is fully informed about the exogenous environment for every point in time. Thereby, firms optimize themselves until the end of time, markets clear at all states and prices follow expectations (Bray, 2018). In reality, however, firms are either incapable or unwilling to consider the long-term future (Edenhofer et al., 2017) or regulatory uncertainty regarding the long-term future forces firms to neglect it. Thus, it is likely that firms are myopic, i.e. decide under a limited planning horizon. As time goes by, firms update their decisions in a rolling horizon model.

In this section we therefore deviate from the assumption of perfect foresight and assume that firms are prone to myopia. For a planning horizon of H years the decision problem $\mathcal{M}(\tau, H)$ of the myopic firm with start year τ can be formulated as

$$\begin{aligned} \min \quad & \sum_{t=\tau}^{\tau+H} \frac{1}{(1+r)^t}[\frac{c}{2}(u-e(t))^2 + p(t)x(t)] \\ & s.t.\ b(t) - b(t-1) = x(t) - e(t) \quad \text{for all} \quad t = \tau, \tau+1, \dots, \tau+H \\ & \qquad b(t) \geq 0 \\ & \qquad x(t),\, e(t) \gtrless 0. \end{aligned} \tag{4.8}$$

In the start year τ the myopic firm decides on emissions, banking and allowance trade only for the next H years. The firm disregards any information about the future after this planning horizon.[53] Further, the firm is able to update

[53] In the extreme case that firms only have a planning horizon of one year, the dynamic optimization problem becomes static and $b(t) = 0$ for all $t = 1, \dots, T$.

its decisions as time passes and future unveils. We implement this updating procedure with a rolling horizon approach:

Algorithm: Rolling horizon of the myopic firm

```
for τ = 0, 1, ..., T do
    Solve M(τ, H);
    Fix e(τ), x(τ), b(τ);
end
```

Accordingly, the firm optimizes itself from the current year τ until $\tau + H$ and implements the decision for the current year. In the next year, the firms planning horizon is extended and the firm is able to plan for the next period, taking into account the implemented decisions from previous periods. During this next planning phase, all future decisions can be revised in order to process new information. Hence, the Hotelling price rule holds in the planning process but may not be visible ex-post.

4.2.4. The Model with Hedging Requirements

In this section, we deviate from the assumption of perfectly rational firms and assume that firms are risk averse. Power producers, and thereby the largest group of emitters in the EU ETS, hedge against allowance price risk based on the quantity of power sold forward (Doege et al., 2009 and Cludius and Betz, 2016). The precise hedging strategy strongly depends on the flexibility of the portfolio and thus differs among companies and industries (Schopp and Neuhoff, 2013). We assume that the homogeneous firms in the model have the same hedging requirements and hedge themselves through a buy-and-bank strategy, i.e. by holding allowances in their private bank to cover a certain share of their planned emissions for the upcoming years.

The non-negativity constraint for banking from the cost minimization problem $\mathcal{M}$ (Equation 4.1) needs to be adjusted in order to take the hedging requirements into account, so that

$$b(t) \geq \sum_{\tilde{t}=t}^{T} hedgeshare(\tilde{t}-t) \cdot e(\tilde{t}), \tag{4.9}$$

where $hedgeshare(\tilde{t}-t)$ is an exogenous parameter defined by the firm that expresses how many allowances need to be banked in period t for emissions in the future period $\tilde{t}$. This adjustment of the constraint changes the corresponding Lagrangian and equilibrium conditions which are stated in Appendix C.1. We receive the amended Hotelling rule (Equation 4.2) with the dual variable $\mu_b(t)$ for the hedging constraint (Equation 4.9). Accordingly, the price increases with the interest rate if the firms bank more than their hedging requirements. If the hedging requirement becomes binding, prices are allowed to deviate from the Hotelling price rule.

4.2.5. Parametrization

The above models are implemented as mixed-integer models in GAMS and solved with CPLEX. To do so, the model is parametrized to depict the actual regulatory setting of the EU ETS.

The regulatory parameters of the exogenous and endogenous supply rules are taken from EU regulation. The initial supply in 2010 is 2199 million allowances and set to decline with a linear reduction factor of 1.74% until 2020 and 2.2% afterwards (European Parliament and the Council of the European Union, 2018).[54] The auction share remains constant over time at 57%. The TNAC at the beginning of the third trading period is set to 2109 million allowances (European Commission, 2019). For the post-reform model, the upper and lower thresholds of the MSR are set to $\ell_{up} = 833$ and $\ell_{low} = 400$, respectively. Further, $\gamma(t)$, the share of the TNAC which is inserted into the MSR is 24% until 2023 and 12% afterwards. If the TNAC falls below the lower threshold, tranches of $R = 100$ million allowances are reinjected to the market (European Parliament and the Council of the European Union, 2015). The MSR is initially endowed with 900 million backloaded allowances. We further assume that a total of 600 million unallocated allowances are inserted into the MSR in 2020 (European Commission, 2015).

Since EU ETS regulation beyond 2030 is not decided on yet, the results depicted in Section 4.3 and Section 4.4 focus on the third and fourth trading period, showing results from 2013 until 2030. However, it is indisputable that the EU ETS will continue beyond the fourth trading period.[55] Thus the model is ran until 2057 when the EU ETS is assumed to reach zero emissions.[56]

In addition to the regulatory parameter values described, further parameter assumptions are needed: The level of baseline emissions is assumed to be exogenously given at $u = 2130$ million tonnes CO_2 equivalent (CO_2e) and held constant over time as e.g. in Perino and Willner (2016). We follow Bocklet et al. (2019) and determine the cost parameter c through the price of a backstop tech-

[54] In order to decouple the effect of the MSR and the cancellation mechanism from the effect of the increased linear reduction factor, we also adjust the linear reduction factor in the pre-reform scenario.

[55] In light of the 'European Green Deal' recently announced by the European Commission, it seems likely that the number of issued allowances will decline even faster. In that case, the last allowance would be issued earlier and the backstop costs would be hit earlier.

[56] In the Hotelling model the point in time where the model reaches zero emissions falls together with the point in time where marginal abatement costs equal the backstop costs.

nology with backstop costs $BC = 150$ EUR/t CO_2e such that $c = \frac{BC}{u}$. Further, all costs are discounted at a yearly interest rate of $r = 8\%$.[57]

Since there is no consensus on the level of myopia and the hedging requirements of firms, we depict various scenario results covering a wide range of parameter assumptions. The planning horizon of firms widely differs among industries, size and ownership structure. In Section 4.3, we show the results for planning horizons H of 3, 5 and 10 years and compare them to the results under perfect foresight. The wide range of planning horizons depicts the discrepancy found in the literature: Stonehouse and Pemberton (2002) find that two thirds of the small and medium sized manufacturing firms have a planing horizon of 1-3 years. Edenhofer et al. (2017) suggest that power producers have planning horizons of 5-6 years. Souder et al. (2016) research publicly traded manufacturing firms and find an average planning horizon of 12 years.

Comparably, the parametrization of the hedging share is meant to reflect a broad range of potential hedging schedules. A study by Eurelectric (2009) evaluates the hedging requirements of forward power sales from large power producers in Europe. It suggests that at least 60% of power sales are hedged one year ahead, 30% two years ahead and 10% three years ahead.[58] While power generators tend to buy derivatives to hedge the inputs for their power sales, non-regulated entities such as financial investors buy the respective physical allowances on the spot market (Cludius and Betz, 2016). They hereby act as counterparties for the power generators so that the allowance futures of the forward power sales are fully hedged through a buy-and-bank strategy. We assume that firms are not able to deviate from their exogenous hedging schedules.

	$t+1$	$t+2$	$t+3$
0%	0%	0%	0%
40%	40%	20%	6.67%
60%	60%	30%	10%
80%	80%	40%	13.33%

Table 4.1.: Exogenous hedging schedules

We depict a wide range of possible hedging requirements by scaling the above described hedging schedule proportionally.[59] The hedging shares for the different hedging schedules are given in Table 4.1.

[57] An extensive sensitivity analysis of those parameter assumptions can be found in Bocklet et al. (2019).

[58] This is in accordance with the publication of one of Europe's biggest power producer who stated in 2019 that at least 60% of their power sales were hedged until 2022 (RWE AG, 2019).

[59] We only implement hedging requirements on the share of auctioned allowances and thereby assume that free allowance allocation serves as an implicit hedge.

4.3. Model Results Under Myopia

As stated in Section 4.1, it is often assumed that firms have a limited planning horizon. Therefore, the aim of this section is to understand how myopia changes the model results of the EU ETS in the pre- and post-reform scenario.

Myopic firms have a limited planning horizon H. Hence, they neglect all information (e.g. allowance demand and regulatory rules) beyond this planning horizon $t + H$. As time goes by, the future unfolds and firms update their decisions based on the revelations.

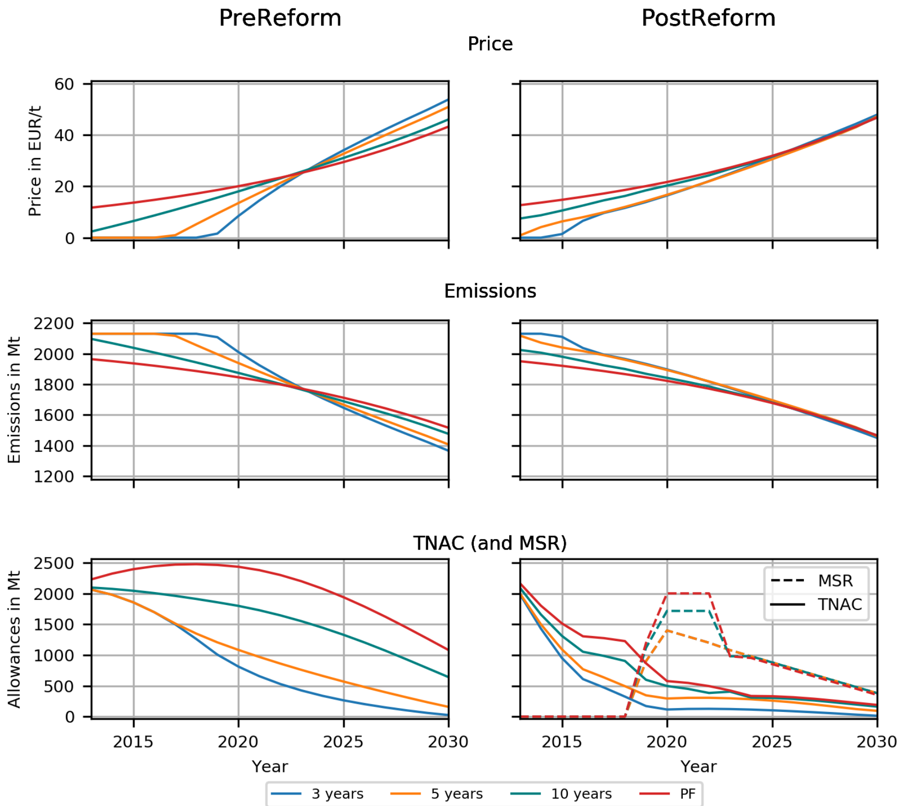

Figure 4.1.: Allowance prices, emissions, TNAC and MSR for the pre- and post-reform scenario with different planning horizons

Figure 4.1 compares the results (prices, emissions, TNAC and MSR) of the pre- and post-reform model for different degrees of myopia (planning horizon of 3, 5 and 10 years as well as perfect foresight).

Under perfect foresight, emission levels in the short and medium run are strictly smaller in the post-reform case. In accordance to the firm's equilibrium constraint (allowance price equals marginal abatement cost), price levels are strictly larger in the post-reform case. However, the overall price effect of the reform is small, in particular in the short run, since the cancellation of allowances stored in the MSR leads to a supply reduction from the long end. This finding is in line with the findings of Bocklet et al. (2019) and Beck and Kruse-Andersen (2020).

Once the assumption of perfect foresight is dropped, the divergence between pre- and post-reform model results becomes more noticeable. In the pre-reform case, myopia leads to considerably lower short-run prices than under perfect foresight. The shorter the planning horizon H of a firm, the lower short-run prices. Consequently, emissions of myopic firms are high and abatement efforts are low in the short run.[60] Due to the large "surplus" of allowances early on, short planning horizons even lead to prices of zero. This implies no abatement efforts since baseline emissions can be completely covered by the initial TNAC and the respective yearly supply.

These large emission levels early on as well as the small TNAC kept by myopic firms induce long-run scarcity. Thereby, emission levels in the long run lie below those of firms with perfect foresight. Correspondingly, by 2030 prices under myopia are higher than prices under perfect foresight. Since myopic firms update their decisions as soon as future scarcity unveils, the shorter the planning horizon of firms, the steeper the corresponding price increase.

While myopia changes the banking behavior of firms, the banking decision determines the size of the MSR and thereby the overall allowance cap. Thus, given that firms are myopic, the EU ETS reform considerably alters the market outcome, as shown in the post-reform scenario.

Under myopia the initial allowance price level is below the price level in the case of perfect foresight. As in the pre-reform scenario, this is due to the fact that myopic firms disregard the future scarcity of allowances and hence emit more in the short run, resulting in a smaller TNAC. Comparable to the pre-reform scenario, the smaller the planning horizon H, the lower the prices in the short run. However, since the allowance supply is eventually delayed through the MSR intake, prices are expected to increase. While this supply reduction is priced-in under perfect foresight, myopic firms do not foresee the resulting price increase caused by this supply reduction, and thus prices increase at a rate above the interest once firms update their decisions. This price increase in light of the MSR intake is thus steeper than under perfect foresight. In order to account for this short-term supply shortage, myopic firms correct their banking decision upwards as the future unfolds.

As firms hold an overall smaller TNAC in the short run, long-run scarcity increases for shorter planning horizons. This causes the firms to update their decisions more strongly to match the decreasing allowance supply. Hence, firms correct their emission levels downwards and their banking levels upwards, overall causing prices to deviate upwards from the original Hotelling path. Due to the

[60] Following the common assumption that environmental pollution exhibits convex damage curves, i.e. early emissions cause more damage than later ones (Rubin, 1996), myopia increases environmental damage cost.

rolling horizon model and the updating of firms' decisions, the Hotelling price rule does not hold ex-post, despite its relevance in the planning process of the firm ex-ante. Since prices increase steeper than predicted by the Hotelling price rule, the price level in 2030 is higher under myopia than under perfect foresight.

In order to evaluate the effect of the reform, we compare the results of the pre- and the post-reform model under myopia. Two main aspects are worthwhile to notice:

First, initial prices in the post-reform model exceed those in the pre-reform model. Because of backloaded and unallocated allowances, the overall allowance supply in early years is significantly smaller in the post-reform than in the pre-reform scenario.[61] This finding also holds for perfect foresight, but the effect gets stronger under myopia.

Second, in the long run the divergence between prices under myopia and perfect foresight is substantially smaller in the post-reform than in the pre-reform setting. Thus, the reform mitigates the market frictions created by myopia.[62] The reason for this lies in the intertemporal shift of the allowance supply induced by the MSR. If firms are myopic, e.g. $H = 5$, they do not account for the higher price level caused by the MSR intake. Hereby, firms overestimate the availability of allowances in future markets and underestimate market prices. The smaller the planning horizon, the smaller the TNAC. This is also found by Quemin and Trotignon (2019). A small TNAC leads to low MSR intake and (if any) low cancellation volume. Thus, under myopia, the reform reduces the overall allowances supply only little. Contrary, if firms have long planning horizons or even perfect foresight, they bank in order to follow their optimal abatement path. Hence the MSR intake is larger and more allowances are cancelled, reducing the overall allowance supply.

Against first intuition, the overall supply reduction induced by the reform is substantially higher under perfect foresight than under myopia. If firms are extremely myopic, the MSR mechanism will not be triggered and no allowances will be cancelled at all. Yet, despite larger cancellation volumes under perfect foresight, the total discounted abatement costs are always smaller.

4.4. Model Results with Hedging Requirements

As discussed in Section 4.2.4, firms may be risk averse and hence follow hedging schedules to mitigate their allowance price risk. In order to understand how hedging requirements of firms drive the model results of the EU ETS, we analyze

[61] 900 million allowances are backloaded and 600 million allowances remain unallocated. Thus, 1500 million allowances are stored in the MSR instead of being auctioned.

[62] Despite the difference in the modelling approach, our findings thereby support the intuition shown in Willner (2018) who argues that the MSR decreases the additional costs imposed by myopia and moves the market closer to the minimum cost outcome under perfect foresight.

in this section the impact of different hedging shares in the pre- and post-reform market.

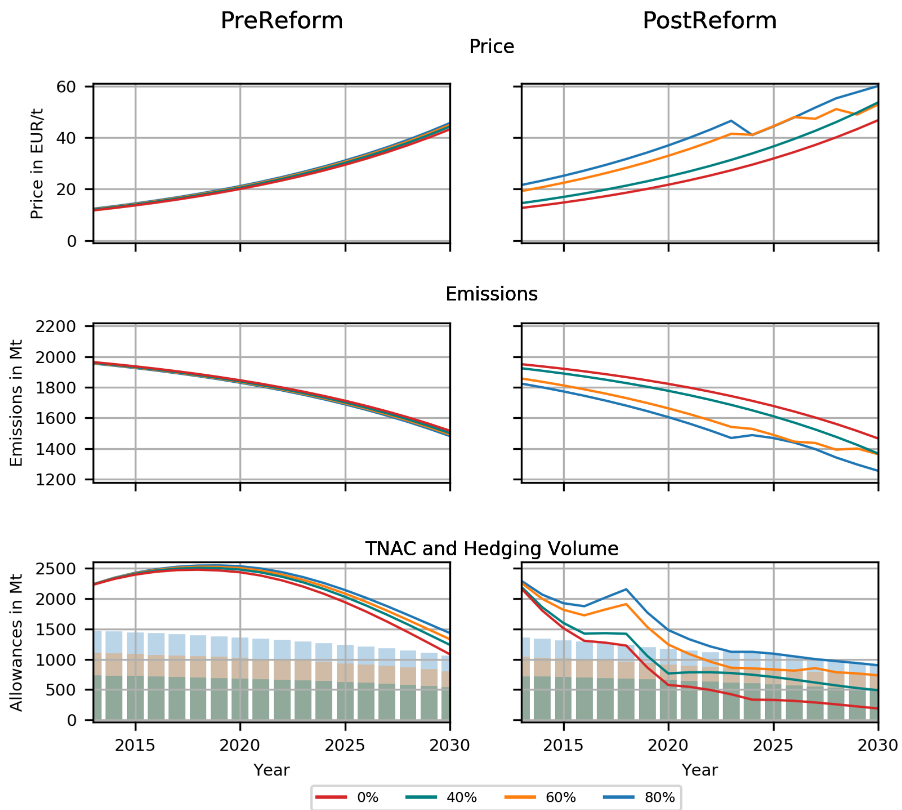

Figure 4.2.: Allowance prices, emissions, TNAC and hedging volumes for the pre- and post-reform scenario with different hedging schedules

Figure 4.2 shows the model results under perfect foresight for the different hedging schedules given in Table 4.1. In the pre-reform case, the impact of hedging requirements is rather small. For all considered hedging schedules, prices follow the Hotelling rule throughout the time span considered. Because the short-run supply of allowances is rather high in the pre-reform case, firms hold a relatively large TNAC even without hedging requirements, e.g. the TNAC falls below 1500 Mt of allowances only after 2027, whereas the hedging volume starts to decline from 1500 Mt in 2013 even in the high 80% case. Thus, in the pre-reform case, even for large hedging shares the hedging constraints are not binding during the considered time period but only bind after 2035. As hedging constraints become binding earlier for high hedging requirements, the price level increases slightly with the hedging share, leading to slightly lower emissions and a higher TNAC. The price level of the 80% case in 2030, for example, is only 6% above the scenario without hedging requirements, leading to fewer aggregated emissions of 350 Mt until 2030. Given this hedging schedule, the corresponding TNAC is about 350 million allowances larger than without hedging requirements.

In contrast, in the post-reform case hedging requirements have a major impact on the price development. Without hedging requirements and with hedging shares below 40% the Hotelling price path is still feasible throughout the time span considered. However, with larger hedging shares (e.g. in the 60% and 80% case), the Hotelling price path is only feasible for certain periods of time (e.g. until 2023). The price path is corrected downwards when the hedging constraint binds (e.g. between 2023 and 2024 by 1% and by 12%, respectively).

As the short-run supply of allowances is smaller in the post-reform case (due to backloading and the MSR), the TNAC decreases sharply without hedging requirements, enabling relatively high emissions and low prices. As hedging requirements are introduced, the TNAC is obliged to lie above the required hedging volume (which is increasing with the hedging share and decreasing with future emissions). Emissions therefore have to be reduced in the short term in order to bank the "excess" allowances for hedging requirements for future emissions. This drives down emissions while simultaneously driving up prices as they have to be equal to marginal abatement costs.

Additionally, hedging requirements lead to a supply shortage of allowances in the short run. As allowances are needed not only for compliance but also for hedging, this scarcity of allowances drives prices up. The price dumps shown in Figure 4.2 (e.g. from 2023 to 2024 under the 60% hedging schedule) depict the point in time when hedging requirements become binding but the aggregated supply up to this point does not suffice for a higher emission level when simultaneously fulfilling the hedging requirements. One can conclude that a supply shortage occurs in the short run which is resolved once the annual allowance supply increases due to the reduced intake rate of the MSR.

The model allows for such downward corrections of prices as the Hotelling price rule (Equation 4.2) is only applied if the TNAC is strictly greater than the required hedging volume. A smoothing of the price path to follow the Hotelling rule is not possible because of two effects: on the one hand, it is not feasible for equilibrium prices to be on a lower level before the price dump, as this would require more emissions and hence a larger hedging volume and a higher allowance demand, which is not met by the allowance supply in that time.[63] On the other hand, it is not feasible for the equilibrium price path to move to a higher level after the price dump. This would require more abatement efforts and hence lead to unused allowances. Consequently, neither a lower equilibrium price level before the price dump nor a higher equilibrium price level after the price dump would lead to an efficient abatement path. Hence, given the restrictive allowance supply, a price dump is inevitable for larger hedging requirements.

[63] This shortage is due to the short-run supply shortage induced by the reform and the restrictive allowances supply. If the regulator would issue all allowances at the start of the EU ETS instead of issuing allowances on a yearly basis, firms could follow their optimal abatement path, leading to a cost-efficient market outcome as depicted by the original Hotelling model.

The higher the hedging requirement, the earlier the supply shortage happens, resulting in more abatement efforts before and less abatement efforts after the supply bottleneck. Before the price dump in 2024 for example, the price level in the 80% hedging scenario is 71% higher than in the scenario without hedging requirements. This price difference reduces to 28% in 2030. Until 2030, a hedging share of 80% leads to 3600 Mt C02e fewer emissions than without hedging requirements. The correspondingly larger TNAC triggers an additional cancellation of 2600 million allowances.

To understand the effect of the EU ETS reform under hedging requirements, we compare the pre- and post-reform model results. The EU ETS reform increases overall prices in the third and fourth trading period.[64] Without hedging requirements the reform increases prices only little (cf. Beck and Kruse-Andersen, 2020 and Bocklet et al., 2019). However, the larger the hedging share, the larger the price effect of the reform. While hedging requirements call for a TNAC of a certain size, the MSR reduces the number of allowances available for banking. Thus, the hedging constraint becomes binding earlier in the post-reform setting, increasing prices. Additionally, the MSR and cancellation volumes also increase with the hedging shares as the hedging requirements increase the TNAC. This leads to a shortage of allowances in the post-reform case with large hedging requirements, amplifying the price effect of the reform. This is in line with Tietjen et al. (2019) who suggest that neglecting hedging requirements may have led to a underestimation of cancellation volumes.

Since the Hotelling price rule only holds as long as the TNAC is larger than the respective hedging requirements, the physical shortage of allowances in the short-run leads to an elevated price level followed by a downward correction of the Hotelling price path.

4.5. Explaining the Market Outcomes of the Third Trading Period

So far, theoretical models fail to give fundamental explanations of the market outcomes in the third trading period and in particular the allowance price increase in the aftermath of the EU ETS reform. As shown in Bocklet et al. (2019), the MSR and cancellation mechanism cause a price increase mainly in the long run. Hence, in models under perfect foresight the price increase in the short run is only small since prices are discounted based on the Hotelling rule.

In reality, allowance prices in the EU ETS remained at a low level at the beginning of the third trading period and rose significantly in the aftermath of the reform. Despite this price spike, the TNAC remained roughly at the same level.

[64] A long term price effect of hedging requirements or the reform does not exist, as finally backstop costs have to be met in every Hotelling model.

In this section, we replicate those stylized facts of the third trading period in order to unravel the underlying drivers of the EU ETS market outcomes. Using our theoretical Hotelling model with myopia and hedging requirements, we replicate in particular the following market outcomes of the EU ETS (European Commission, 2019):

- At the beginning of the third trading period and before the reform, prices remained at a low average price level of 5 EUR/t in 2013.
- Annual allowance prices rose to over 24 EUR/t in 2019.
- The TNAC fell from around 2100 million allowances in 2013 to around 1650 million allowances in 2016, where it roughly remained since.

In order to compare the model results with the real market outcomes, the prices of the pre-reform model in 2013 serve as benchmark for the initial price level. The difference between the pre-reform price in 2013 and the post-reform price in 2019 is compared to the price increase observed in the third trading period.[65] The private bank in the post-reform scenario is compared to the real TNAC in 2018.

4.5.1. Explaining Market Outcomes Through Myopia

We first evaluate if the market outcomes can be explained through the reform fundamentals given that firms are myopic.

As discussed in Section 4.3, the more myopic a firm is, the lower the initial price level in the market. We find that a planning horizon of 10 years is able to replicate the observed price level in the beginning of the third trading period best (compare Figure 4.3).

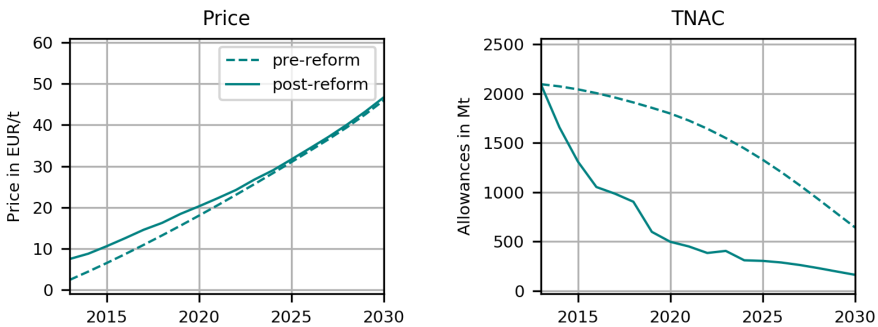

Figure 4.3.: Impact of the reform on market outcomes with a planning horizon of 10 years

[65]The market outcomes in the EU ETS are driven by firms' expectations. Since it is not clear at what point of time firms acknowledge the new regulatory setting, we refrain from depicting a precise transition path from the pre- to the post-reform scenario. The post-reform scenario before firms adapt to the reform and the pre-reform scenario after the reform has been acknowledged serve as counterfactuals, respectively.

The respective scenario results show a price increase of around 16 EUR/t and thus a similar size than the absolute price increase of 19 EUR/t observed in the market. A shorter planning horizon captures the price increase even better, but at the same time decreases the initial price level below the price level observed in the beginning of the trading period. Note that given myopia, the reform itself impacts prices only little but the main part of the price increase is caused by the updating of the rolling horizon approach. Thus, prices would have increased in almost similar magnitude even without the reform.

A planning horizon of 10 years further leads to a private bank of only 900 million allowances in the post-reform scenario in 2018, only half the size of the real TNAC. Longer planning horizons - or even perfect foresight - replicate the real TNAC better. However, a large private bank comes at the expense of higher initial prices and a smaller price increase.

Since myopia reduces the initial price level and the private bank while increasing the price effect induced by the reform, the stylized facts can not be met simultaneously through a variation of the planning horizon.

We conclude that if firms are myopic, the price increase observed in the market has not been caused by the reform fundamentals but mainly by the updating of firm's decision in order to meet the reduced allowance supply. Since myopia lacks explanatory power when it comes to the large bank held by firms in the market, we reason that myopia was arguably not the only fundamental driver of market outcomes in the third trading period.

4.5.2. Explaining Market Outcomes Through Hedging Requirements

We now turn to the alternative explanation, namely that given hedging requirements, the EU ETS reform leads to a price increase and a TNAC of a considerable size. As analyzed in Section 4.4, the larger the hedging requirements, the larger the price effects induced by the reform. However, large hedging schedules also imply large initial prices levels and thus constitute a mismatch to the market outcomes observed in the EU ETS.

Nonetheless, we find that if firms apply a hedging schedule of 60% the stylised facts observed in the market can be replicated best (compare Figure 4.4).

If firms follow this exogenous hedging schedule, prices increase by over 18 EUR/t between 2013 and 2019. The difference between the pre-reform price path and the post-reform price path grows over time. Hence, the later firms acknowledge the reform, the steeper the price increase visible in the market.

Besides the absolute price increase, the 60% hedging schedule also replicates the banking behavior of firms in the market well. In order to account for the supply shortage induced by the MSR intake, firms keep an average private bank

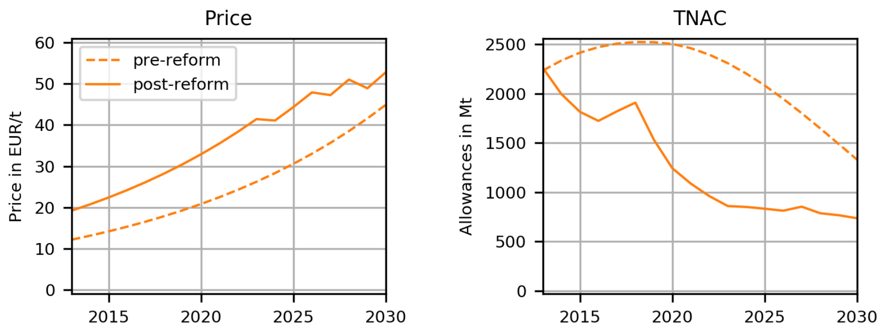

Figure 4.4.: Impact of the reform on market outcomes with a hedging schedule of 60%

of around 1700 million allowances between 2017 and 2019, comparable to the magnitude of the TNAC observed in the market.

Thus, two stylized facts, the absolute price increase and the level of the TNAC, can be replicated by incorporating hedging into the model. Still, none of the hedging schedules are able to depict the absolute price level in particular in the beginning of the third trading period since perfect foresight causes firms to abate already in the short run.

We conclude that given hedging requirements, the model performs well in attributing the price increase to the EU ETS reform. While hedging requirements are also able to explain the large private bank held by firms in the market, they lack explanatory power when it comes to replicating the absolute price level in the beginning of the third trading period. Thus, hedging requirements on their own cannot fully explain the impact of the reform on market outcomes in the EU ETS.

4.5.3. Explaining Market Outcomes Through a Combination of Myopia and Hedging Requirements

In the previous sections, we find that neither myopia nor hedging requirements are able to fully explain the impact of the reform on stylized EU ETS market outcomes. Thus, we examine whether a combination of both forms of bounded rationality is able to capture the market outcomes of the EU ETS.[66]

When applying a planning horizon of 10 years along with a hedging schedules of 50%, i.e. if firms hedge 50% of their allowances one year ahead, 25% two years ahead and 8% three years ahead, the model results match the stylized facts (compare Figure 4.5):

[66]While hedging requirements and myopia might seem conflicting concepts at first, it is likely that even though firms have a limited planning horizon, they mitigate price risk within the respective planning horizon. Thus, myopia and hedging requirements can be combined as long as the planning horizon exceeds the time span of the hedging schedule.

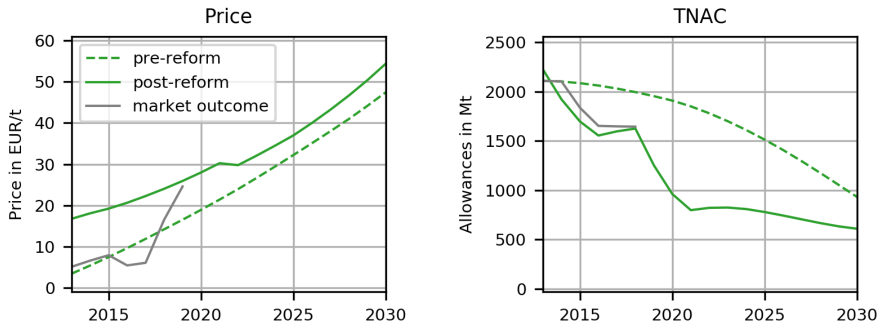

Figure 4.5.: Impact of the reform on market outcomes with a planning horizon of 10 years and a hedging schedule of 50%

The initial price level in the pre-reform scenario lies at 4 EUR/t and therefore only slightly below the price level in the beginning of the third trading period. Due to the reform, prices rise to 26 EUR/t in 2019 in the post-reform scenario, closely resembling the price increase visible in the market. The real world TNAC until 2014 matches the private bank modelled in the pre-reform scenario and closely resembles the post-reform private bank of around 1630 million allowances in 2018.

The simple comparison of the model results with the stylized facts in Figure 4.5 suggests that firms in the market started taking notice of the policy changes already before the last reform took place in 2018 by adjusting their decisions in expectation of the post-reform regulation. The price increase observed in the midst of third trading period thereby reflects the transition from the pre-reform to the post-reform market.

In conclusion, we find that a theoretical model of the EU ETS is indeed able to attribute the price increase to the reform fundamentals if myopia and hedging requirements are both taken into account.

4.6. Conclusion

In the paper at hand, we use a discrete-time partial equilibrium model to analyze the impact of the EU ETS reform on allowance prices. We contribute to the existing literature by finding that theoretical models of the EU ETS need to take bounded rationality into account when they aim to explain the sudden price increase of the recent reforms in the midst of the third trading period. We show that even though the Hotelling price rule is ex-ante applied in a firm's planning phase, it is not necessarily visible ex-post in a setup that considers myopia or hedging requirements. In line with the suggestions of Krautkraemer (1998), we show that prices deviate ex-post from the Hotelling price path if regulatory interventions and bounded rationality, such as myopia and hedging, are considered.

While myopia and hedging requirements do not have a major impact on the pre-reform model results, they strongly drive results once the EU ETS reform (i.e. backloading, the MSR and the cancellation mechanism) is introduced:

First, if firms are myopic, they neglect future scarcity of allowances by emitting more in the short run than under the cost-minimal abatement path. This friction is mitigated by the introduction of the MSR which counteracts the firm's time preferences. The effect of the cancellation mechanism diminishes under myopia, as a short planning horizon implies a small private bank and thus low cancellation volumes.

Second, hedging requirements reinforce the impact of the reform on model results. In particular, cancellation volumes increase with hedging requirements. Thus, if hedging requirements are considered, the overall effect of the reform is larger than depicted by the prevalent theoretical models. Further, the restrictive allowance supply in the EU ETS along with binding hedging requirements of firms lead to physical shortages in the market. Thereby prices might even decrease when the binding hedging constraint suspends the Hotelling price rule.

Further, we find that under myopia as well as hedging requirements prices in the EU ETS increase in the short run. While myopic behavior on its own fails to explain the large private bank held by firms in the market, hedging requirements by themselves cannot explain the low price level in the beginning of the third trading period. If both forms of bounded rationality are combined, the initial price level, the price increase and the large TNAC can be simultaneously replicated within a theoretical Hotelling model. We deduce that a combination of myopia and hedging requirements provoked the reform to fundamentally increase prices and might thus be the missing piece to the puzzle.

In the paper at hand, we model market frictions caused by myopia and hedging requirements. Thereby other forms of bounded rationality and other market frictions, such as asymmetric information or incomplete markets, are not considered within our model. Further, the model is simplified by assuming that risk averse firms stick to exogenous hedging schedules. We thus neglect that the allowance demand of a firm for hedging requirements might be endogenously determined in response to changing expectations on input prices as suggested in Schopp and Neuhoff (2013).

Further, Tietjen et al. (2019), point out that risk averse firms might apply a lower interest rate in times when their private bank is sufficiently large, i.e. when the TNAC exceeds the hedging requirements. Policy interventions such as the recent EU ETS reform increase uncertainty and might further impact the interest rate applied by firms in the market (Salant, 2016). Thus, in order to understand the economic impacts of the EU ETS reform even better, the interplay between interest rate, hedging requirements and governmental regulations should be the subject of further research.

5. On the Time-Dependency of MAC Curves and its Implications for the EU ETS

5.1. Introduction

The mitigation of greenhouse gas emissions requires a fundamental overhaul of the capital stock, i.e., investments in low-carbon technologies. The efficient coordination of investment capital is essential to minimize overall abatement costs. Economists agree that the pricing of emissions is a suitable instrument for allocating capital efficiently (e.g., Coase, 1960 and Borenstein, 2012). By introducing the European emissions trading system (EU ETS), the EU has implemented a quantity control system with an endogenous price on emissions. The EU ETS requires that firms in the power sector, energy-intensive industries, and inner-European aviation submit allowances to cover their emissions. Overall, the EU ETS regulates about 40 % of total European emissions.

The latest reform of the EU ETS has introduced the Market Stability Reserve (MSR) and the Cancellation Mechanism (CM), which have fundamentally changed the EU ETS to a system with restricted banking and responsive allowance supply (cf. Bocklet et al., 2019). A comprehensive literature strand evaluates the reforms' impact via partial equilibrium models of the EU ETS (e.g., Perino and Willner, 2016 and Bocklet et al., 2019). Most of these articles do not model allowance demand endogenously.[67] They assume allowance demand exogenously based on marginal abatement cost (MAC) curves. MAC curves match emission mitigation with abatement costs and have been crucial tools to evaluate environmental policies for decades (e.g., Jackson, 1991 or Aaheim et al., 2006).

In the EU ETS related literature, the assumptions on MAC curves are heterogeneous. While some articles assume linear MAC curves (e.g., Perino and Willner, 2016 or Bocklet et al., 2019), others use convex MAC curves (e.g., Beck and Kruse-Andersen, 2020 or Schmidt, 2020). Without evidence from the literature, papers usually presume a time-independent shape of MAC curves. Nevertheless, both the shape as well as its development over time drives results. In particular, these assumptions affect total emissions in the EU ETS due to the responsive allowance supply of the EU ETS.

[67] To the best of our knowledge, Bruninx et al. (2020) present the only approach that combines power market modelling with a depiction of the EU ETS regulation.

This paper assesses the fundamental properties of MAC curves and their implications for the EU ETS. To this end, we carry out a case study to derive stylized MAC curves for the European power sector. Multiple runs of a partial equilibrium model map carbon price paths onto emission abatement. We find that MAC curves are convex. The curvature is subject to economic developments, such as fuel prices and interest rates. Further, MAC curves are time-dependent. In the short term, they are steep since coal-to-gas fuel switching is the only abatement measure. With enlarging investment opportunities and technological learning, MAC curves flatten over time.

Assuming convex instead of linear MAC curves increases banking since future abatement becomes relatively more expensive. On the contrary, flattening lowers incentives for banking. Under idealized assumptions, steep short-term MAC curves shift the equilibrium price path upward while also reducing short-term banking. This effect could cause strong price reactions in the short term when market frictions such as myopia are considered. For a numerical evaluation of these effects, we propose methodological approaches to account for the time-dependency of MAC curves.

The remainder of the paper is organized as follows: Section 5.2 reviews the prevailing literature on MAC curves. Section 5.3 derives stylized MAC curves for the European power sector. Section 5.4 discusses the implications of the identified properties of MAC curves for the EU ETS. Section 5.5 concludes.

5.2. Prevailing Literature on MAC Curves

This section sheds light on the properties of MAC curves discovered in the existing literature. We consider quantitative evaluations as well as qualitative discussions of MAC curves.

The prevailing literature uses four methodological approaches to quantitatively evaluate MAC (compare Huang et al., 2016): (1) Estimations based on distance functions, (2) expert-based evaluations, (3) top-down models, and (4) bottom-up models.

MAC evaluation via distance functions estimates past and present marginal abatement costs based on historical data (Ma et al., 2019). For example, Du et al. (2015) find that the marginal abatement costs in the Chinese energy system increase over time in a convex shape. However, these historical observations do not allow statements about future MAC or the construction of MAC curves.[68]

Expert-based evaluations, e.g., performed by McKinsey & Company (2013), derive MAC curves by gathering expert knowledge on abatement costs and po-

[68] In particular, observed marginal abatement costs reflect rather the part of the MAC curve with low mitigation efforts, which likely do not represent MAC for extensive emission mitigation. For a comprehensive and critical review of MAC evaluation by distance functions, the reader is referred to Ma et al. (2019).

tentials. While revealing abatement potential even at negative abatement costs, the derived MAC curve for 2030 is convex-shaped in its positive part.

The use of top-down models, mostly integrated assessment models, covers economy-wide activities, their interactions, and the consequences on the natural environment at a global level.[69] For the EU ETS sectors, Landis (2015) finds that MAC curves are convex in abatement.

In contrast to top-down models, bottom-up partial equilibrium models abstract from global interactions between the different economic sectors but allow for more technical details. Kesicki (2013) finds that the MAC curve of the UK energy system in 2030 is convex-shaped and robust to changes in fossil fuel prices, but depends strongly on the underlying interest rate. Delarue et al. (2010) find that short-run abatement in the European power markets depends on the carbon price as well as on the price margin between coal and gas. Van den Bergh and Delarue (2015) compare two abatement options, namely fuel-switching from coal to gas and wind investments, with a model of the central-western European power sector. They point out that MAC of the different abatement options are not additive but impact each other.

Summing up, articles with different methodological approaches consent that MAC curves are convex. However, Kesicki and Ekins (2012) generally calls for caution when interpreting MAC curves. MAC curves depend on uncertain assumptions, which are often not transparent. Further, the concept of MAC curves takes the perspective of a perfectly informed central planner who decides cost-efficiently on abatement under perfect foresight. In reality, the decisions on abatement measures depend on individual preferences. If individuals decide solely based on abatement costs and their actions are coordinated in perfect markets, the cost-efficient MAC curve of the central planner coincides with the aggregation of individual decisions on abatement measures. However, individual decision-making is subject to non-financial costs and behavioral aspects. Consequently, MAC curves of a central planner often identify abatement measures with negative abatement costs, which are not realized yet. Moreover, MAC curves are always a static snapshot in time and do not reveal what abatement measures are taken before and after the reference year. Historic abatement and expectations about future abatement drive the shape of MAC curves.[70]

[69] Most integrated assessment models use a computable general equilibrium framework to depict economic interrelations via substitution elasticities. Kuik et al. (2009) provides a comprehensive meta-analysis on the derivation of MAC curves with integrated assessment models.

[70] At the same time, today's decisions on abatement also impact future's abatement costs, e.g., due to technological learning effects.

5.3. Case Study: MAC Curves of the European Power Sector

To illustrate the different properties of MAC curves, this section carries out a case study for the European power sector.

5.3.1. Methodological Approach

Power Market Model DIMENSION

We derive MAC curves with the partial equilibrium European power market model DIMENSION.[71] By assuming inelastic electricity demand in the short term and perfectly competitive markets without transaction costs, the decision making of individual, profit-maximizing firms under perfect foresight is equivalent to a central planner's cost minimization problem. The central planner minimizes the total discounted costs of investments in power plants and their dispatch to satisfy electricity demand. Appendix D.1 presents the most relevant equations of DIMENSION.

Approach for Deriving MAC Curves

To obtain MAC curves for the European power sector, we feed different carbon price paths $\boldsymbol{\tau}$ into the model and derive the corresponding level of emissions $emissions(y)_{|\boldsymbol{\tau}}$ for each considered year y. The emissions of the baseline scenario (baseline emissions) $u(y) := emissions(y)_{|\boldsymbol{\tau}=0}$ are used to define the abatement level of a carbon price path $\boldsymbol{\tau}$ as $abatement(y, \tau) = u(y) - emissions(y)_{|\boldsymbol{\tau}}$. Figure 5.1 sketches the methodology to derive MAC curves using the power market model DIMENSION.

We assume that carbon prices develop according to the Hotelling rule (cf. Hotelling, 1931), i.e., they rise with the interest rate.[72] The model derives MAC curves in time period t anticipating this price development for a time horizon H of 15 years.

[71] The model DIMENSION has been developed by Richter (2011) and has been used in many analyses, e.g., Bertsch et al. (2016), Peter and Wagner (2018) and Helgeson and Peter (2020).

[72] Emission allowances are a scarce resource. Rational firms with perfect foresight use allowances so that the corresponding carbon price increases with their private interest rate. Otherwise, arbitrageurs could take advantage of inter-temporal price differences. Ex-post, prices develop differently due to external shocks or new information on future costs or demand (cf. Bocklet and Hintermayer, 2020).

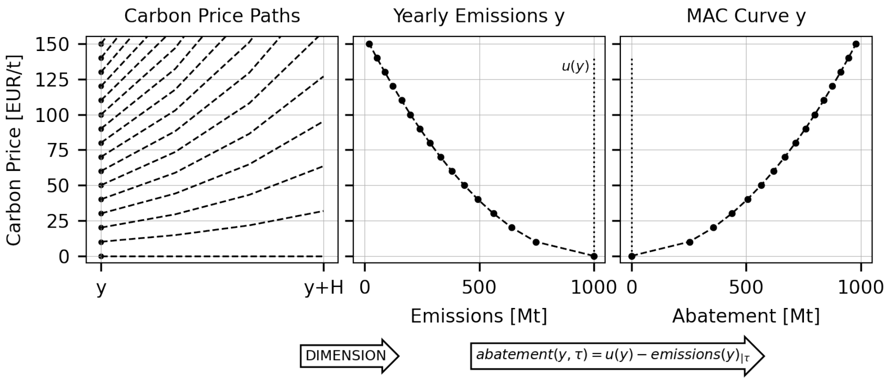

Figure 5.1.: Schematic illustration of the approach for deriving MAC curves

Parametrization

This case study derives stylized facts on MAC curves, using the European power sector as an example. To isolate the impact of single restrictions or input parameter changes, we keep the parametrization as plain as possible. We fix the status quo of European power plants, i.e., we abstract from decommissioning due to technical restraints or political goals. We assume the existing fleet of power plants in 2019 according to the database developed at the Institute of Energy Economics at the University of Cologne, which is continuously updated based on Platts (2016), Bundesnetzagentur (2020) and ENTSO-E (2020). Net transfer capacities develop according to the ENTSO-E Ten-Year Network Development Plan 2018 (ENTSO-E, 2018). Fuel prices, investment costs, net trade capacities, and electricity demand are as of 2019. By default, we use an interest rate of 8%. Time-series rely on the historical weather year 2014. For keeping the model tractable, 16 representative days approximate the development for one year. Appendix D.2 gives an overview of the considered technologies and their techno-economic parameters.

5.3.2. The Change of MAC Curves over Time

This section evaluates how different lead times for investment affect MAC curves. In the short term, the power plant fleet is fixed. Switching electricity generation from power plants with higher carbon intensity (e.g., hard coal or lignite) to power plants with lower carbon intensity is the only viable abatement measure (*Fuel Switching*). The existing capacity of the power plants with lower carbon intensity limits the abatement potential of fuel switching. With longer lead times, investment into generation capacities as a reaction to higher carbon prices is possible. Yet, installation capacities or necessary approval processes restrict the speed of changing the power plant fleet via investments. In the long term, freedom to invest is unrestricted. Additionally, demand can react to rising carbon prices, e.g., via investments into energy efficiency or carbon leakage.

For determining the development of MAC curves over time, we make the following stylized assumptions. In the short term, all capacities are fixed and only the dispatch of the generation portfolio can change with the carbon price. In the medium term, the expansion of RES capacities must not be higher than five times the average expansion between 2017 and 2019, reflecting investment lead times of five years. Investments into gas power plants are restricted to about 9 GW per year within the European electricity system. In the long term, investments are not restricted. Further, we assume that the development of long-term demand depends on the carbon price development.[73] Ceteris paribus, figure 5.2 depicts the resulting MAC curves for different time horizons and disaggregates the abatement into static fuel switching, (restricted) investment into power plants, and demand adjustment.[74]

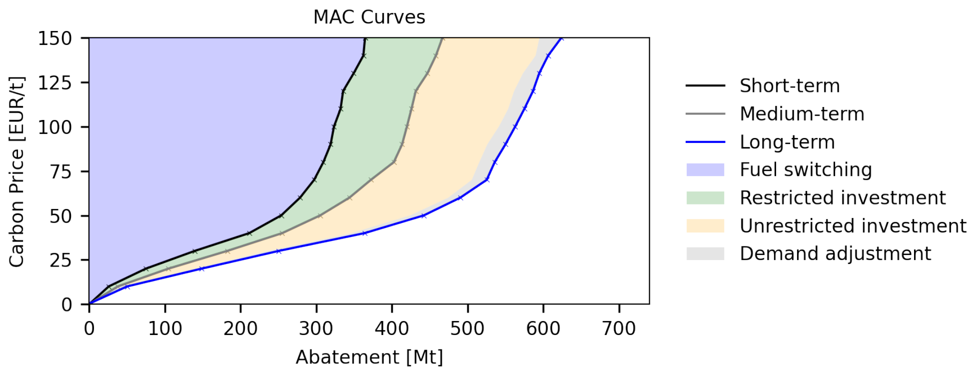

Figure 5.2.: Short-, medium- and long-term MAC curves and disaggregation of the abatement measures

In line with the literature, MAC curves are convex independent of the time horizon. They further flatten over time, primarily due to the increasing investment possibilities. In the short run, replacing coal generation with gas-fired power plants allows to reduce emissions. The short-term MAC curve is convex since modern gas power plants drive inefficient coal power plants out of the market already at low carbon prices. Later on, inefficient gas power plants replace modern coal generators at higher abatement costs.

Progressing in time, fuel switching is not the only abatement option but investments into modern gas power plants and particularly RES power plants are possible. As a result, the MAC curves flatten, i.e., the same carbon price results in higher abatement. While investment restrictions prevail in the medium term,

[73]We approximate the impact of rising carbon prices on electricity prices via the difference in marginal costs of modern Combined Cycle Gas Turbine Power Plants (CCGT) and assume a demand elasticity of 5 % with regard to the electricity price.

[74]Throughout this paper, the end of the x-axis depicts maximum abatement, i.e., zero emissions.

unrestricted investment possibilities further flatten MAC curves in the long term. Besides developments on the supply side, adjustments of the electricity demand further bend MAC curves downward.[75]

While the MAC curves above consider variations in investment freedom and demand adjustment, the following section analyzes how developments in markets beyond the power sector (i.e., fuel prices and interest rates) or technological progress affect long-term MAC curves.

5.3.3. Drivers of Long-Term MAC Curves

This section analyzes three exogenous parameters, which influence long-term MAC curves: fuel prices, interest rates, and technological learning.

Fuel Prices

With regard to fuel prices, the power sector is mainly subject to the development of gas and hard coal prices. In particular, the margin between these fuels is considered a major driver. For a stylized illustration of the impact of fuel prices on the MAC curve, we compare three different levels of gas prices (10, 20, or 30 EUR/MWh_{th}, respectively), while the coal price is not varied. The variation of gas prices with constant coal prices alters the margin between coal and gas. Figure 5.3 depicts the corresponding MAC curves.

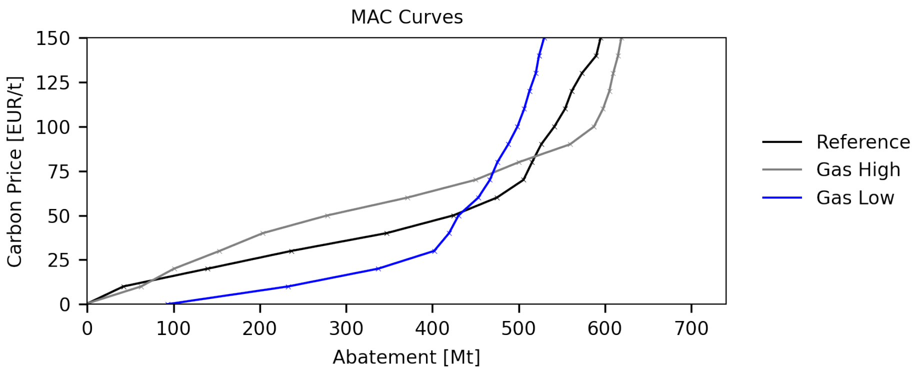

Figure 5.3.: Long-term MAC curves for different coal-gas price spreads

Lower gas prices affect MAC curves in two ways: First, gas power plants are more competitive against carbon-intensive coal generation. As a result, more abatement takes place at lower carbon prices, and the lower end of the MAC curve shifts downward. Second, investments into RES power plants are less competitive to gas power plants, since gas generation becomes cheaper. As a

[75]Based on our stylized assumptions, demand adjustment is only a minor abatement measure. Whether it is more relevant in reality depends on the assumed elasticity.

result, the MAC curve becomes steeper at the upper end. For higher gas prices, the same effects hold true vice versa.

The same reasoning holds with a variation of fuel prices in the short term. As there is no investment in the short term, the only effect is the altered margin of fuel switching (see Appendix D.3).

Interest Rates

Apart from fuel markets, the development of financial markets affects the shape of MAC curves. The interest rate reflects the general development of financial markets, i.e., the risk-free interest rate, and the risk premium accounting for sector-specific uncertainty. Figure 5.4 depicts long-term MAC curves for different interest rates on long-term MAC curves.

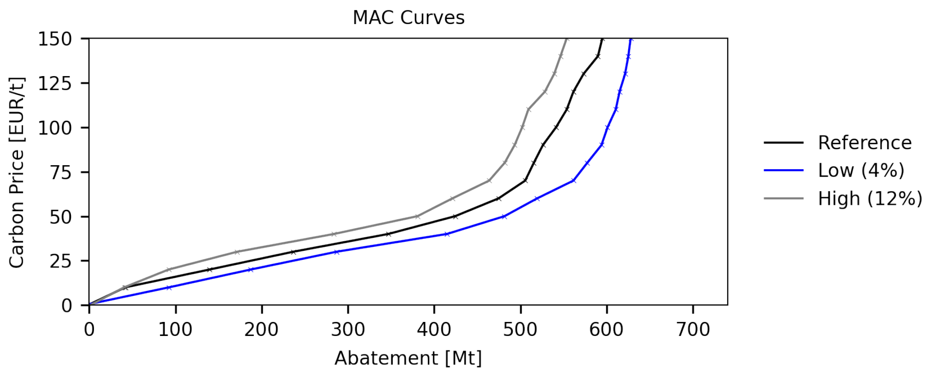

Figure 5.4.: Long-term MAC curves for different interest rates

Interest rates primarily affect the weighted costs of capital. The transformation of the power sector requires capital-intensive installations of RES power plants. With lower interest rates, RES becomes cheaper. As a result, the MAC curve is lower at all abatement levels. Since the lower part of the MAC is dominated by fuel-switching, the effect increases with abatement so that it mainly affects the end of MAC curves. A higher interest rate mirrors the effect of lower interest rates.

Technological Learning

Until now, we refrain from technological learning. However, new technologies exhibit possibilities to drive down investment costs or improve technological parameters such as efficiency. Figure 5.5 depicts the change in long-term MAC curves with projected technological learning of RES power plants. The respective cost assumptions can be found in Appendix D.2.

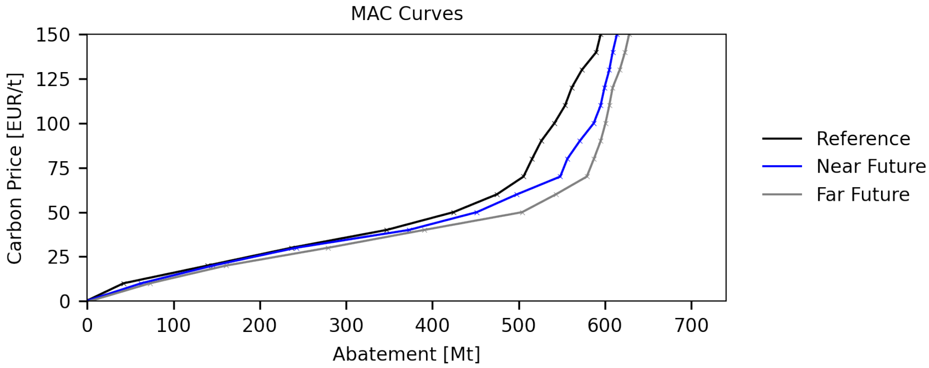

Figure 5.5.: Long-term MAC curves for different assumptions on investment costs

The impact of technological learning is clear-cut: Lower investment costs drive down costs of RES generation. Hence, uncertainty about the future development of techno-economic properties mainly affects the upper part of MAC curves, i.e., beyond the potential of fuel-switching.

Beyond improvements of existing technologies, the cost development of so-called backstop technologies underlines this finding. These technologies are able to remove an arbitrarily large amount of emissions for a fixed price, the backstop price. In light of recent plans to establish a hydrogen economy, experts consider hydrogen-fueled gas turbines as a potential carbon-free and dispatch-able backstop technology in the power sector. In this case, the backstop price level is subject to future costs of hydrogen. The prevailing literature (e.g., Brändle et al., 2020) projects costs of carbon-neutral hydrogen of roughly 1.5 to 3 EUR/kg. These prices equal about 45-90 EUR/MW_{th}, the marginal abatement costs to replace gas generation is thus approximately between 125 and 350 EUR/t compared to gas prices of 20 EUR/MW_{th}.[76]

Summing up, this case study of the European power sector reveals: first, MAC curves are convex. Their curvature depends on economic developments such as fuel prices and interest rates. Second, they flatten over time due to technological learning and investment restrictions.

5.4. Implications for the EU ETS

As pointed out in Section 5.1, model-based analyses of the EU ETS typically assume static MAC curves. On the contrary, MAC curves are dynamic. They are only a snapshot in time so that they conceal dynamic interactions. Further, MAC curves flatten over time due to restrictions on investments and technological

[76]The (direct) marginal abatement costs reflect the difference in fuel prices between natural gas and hydrogen, divided by the emission factor of natural gas of about 0.2 t_{CO2}/MWh_{th}.

advancements. This section discusses the implications of these findings for the EU ETS.

5.4.1. The Functioning of the EU ETS

The EU ETS is a cap-and-trade system, which requires firms to buy allowances to compensate for their emissions. By reducing the yearly supply of allowances to the market, the EU ETS enforces abatement. Firms are allowed to bank allowances for later use while borrowing allowances from future allocations is prohibited.

Firms choose their abatement so that they minimize abatement costs. In equilibrium, carbon prices equal MAC in a friction-less market. In line with the Hotelling rule (cf. Hotelling, 1931), the carbon price rises with the interest rate as long as firms hold a positive bank of allowances. If the aggregate private bank is empty, the price increases at a lower rate according to the yearly issued allowances (cf. Bocklet et al., 2019).

In this idealized setting, the market determines an initial price, which reflects the discounted backstop costs and fully sets up a price path that sooner (lower initial price) or later (higher initial price) leads to an empty private bank. Market equilibrium paths, which consist of a sequence of price-emission tuples, solve the trade-off between low initial prices and a late point in time where allowances are scarce so that overall (discounted) abatement costs are minimal.

The implementation of the Market Stability Reserve and the Cancellation Mechanism poses additional restrictions on the banking of allowances. First, if banking volumes exceed a pre-defined level, the MSR absorbs allowances from the market. The allowances from the MSR enter the market when the bank falls below the reinjection threshold.[77] Second, the size of the MSR is limited. If the MSR exceeds the previous year's auction volume, the CM invalidates overhanging allowances. As a result of the MSR and the CM, banking decisions affect both the timing and the total volume of allowance supply. In particular, higher banking volumes increase cancellation volumes and thus reduce total emissions within the EU ETS.

5.4.2. Implications of Time-Dependent MAC Curves in the EU ETS

Chapter 5.3 reveals two properties of MAC curves, which should be considered in models of the EU ETS: MAC curves are convex and they flatten over time.

If the MAC curve is convex instead of linear, the MAC curve becomes steeper with higher abatement, which makes future abatement relatively more costly.

[77] Allowances from the MSR enter the market in junks of 100 million allowances per year if the previous year's bank is below 400 million allowances.

Accordingly, firms bank more allowances to smooth the abatement in the steep upper part of the MAC curve. Due to the endogenous supply rules in the reformed EU ETS, a convex MAC curve causes higher banking volumes and more cancellation compared to a linear MAC. Osorio et al. (2020) provides quantitative evidence by comparing the cancellation volumes of several articles. Modelling approaches that consider convex curvatures (e.g., Bruninx et al., 2020 and Beck and Kruse-Andersen, 2020), exhibit comparatively high cancellation volumes.

Along the same lines, models of the EU ETS usually assume the shape of the MAC curves to be time-independent, neglecting that short-term MAC curves are steeper due to investment restrictions and technological learning. As a result, abatement is more expensive in the short term and becomes cheaper over time. Figure 5.6 visualizes the stylized impact of a steeper short-term MAC curve on the price path in comparison to the assumption of the long-term MAC curve for all points in time.[78]

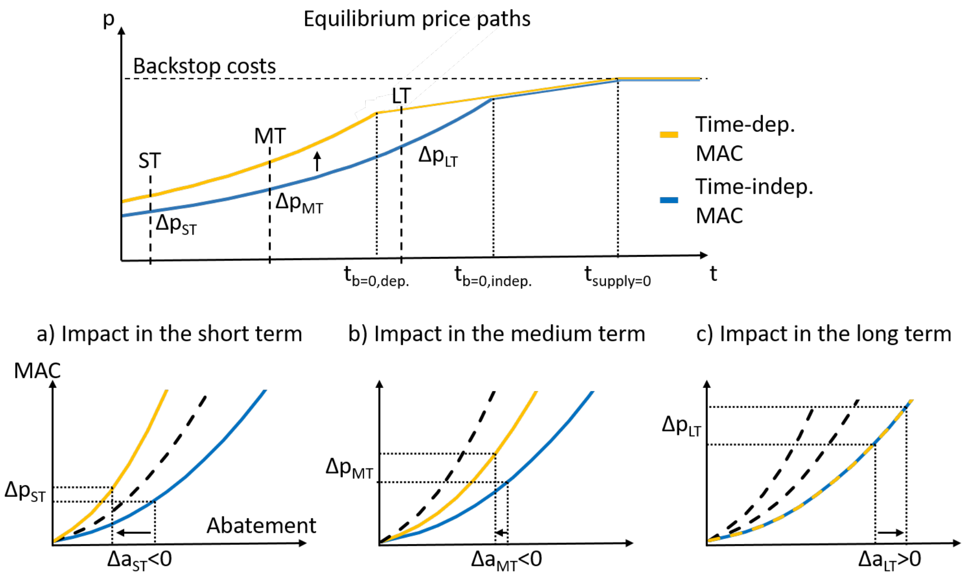

Figure 5.6.: Stylized impact of time-dependent MAC curves on the equilibrium price path and implications for abatement in the short (ST), medium (MT) and long term (LT)

Under perfect foresight, the whole price path is determined already in the first period. Backstop costs are obtained when the last allowance is issued ($t_{supply=0}$ in the upper part of Figure 5.6).[79] The quasi-linear price development after the bank is emptied ($t_{b=0,dep.}$ and $t_{b=0,indep.}$), depends on the allowance supply and

[78]This stylized analysis assumes that there is only one banking phase. If, for example, the flattening of MAC curves overcompensates the firms' interest rate, a second banking phase is economically rational.

[79]This holds true as long as backstop costs decrease slower than the firms' interest rate. In general, backstop costs only shift the price path as long as the rest of the MAC curve is kept constant (compare Bocklet et al., 2019). Abatement and banking remain unaltered.

the shape of long-term MAC curves.[80] Firms choose a sequence of price-emission tuples that suffice the two fundamental rules, namely the price development with Hotelling until the bank is empty and the equivalence of MAC and carbon prices. Due to steeper short-term MAC curves (i.e., short-term abatement becomes more expensive), firms increase their short-term emissions, and thus, decrease banking volumes. At the same time, prices increase since the short-term MAC are higher even at the lower abatement level (see Figure 5.6a). In the medium term, the time-dependent MAC curve flattens and the difference in abatement decreases but abatement is still lower (see Figure 5.6b). As a result, the bank empties earlier ($t_{b=0,dep.} < t_{b=0,indep.}$). In the long term, firms need to increase their abatement with time-dependent MAC curves due to lower banking volumes (see Figure 5.6c). Summing up, with time-dependent MAC curves, the price level rises, and banking decreases in the short-term. Since cancellation volumes increase with short-term banking (see Herweg, 2020), the described effect increases total emissions due to lower cancellation volumes.

Beyond this theoretical analysis, myopia is considered important to understand the EU ETS market (compare Bocklet and Hintermayer, 2020). In a myopic setting, steep short-term MAC curves might be an additional driver of the price increase observed after the introduction of the MSR and the CM.

All in all, banking and cancellation volumes increase with convexity while flattening has the opposite effect. Accurate numerical models of the EU ETS should consider the shape and dynamic evolution of MAC curves to quantify the overall effects.

5.4.3. Approaches for Time-Dependent MAC Curves in EU ETS Models

In general, there are two approaches to account for the time-dependency of MAC curves: using exogenous but time-dependent MAC curves in EU ETS models or coupling of models for allowance demand and the EU ETS.

Exogenous dynamic MAC curves for the power sector can be derived via modelling, e.g., as described in Section 5.3. Deriving MAC curves for the energy-intensive industries - as the other large sector within the EU ETS - is more challenging, since industry processes are more heterogeneous and data availability is limited. Further, it is important to depict interactions between the sectors to account for the non-additivity of abatement measures. For example, the electrification of industry processes saves carbon in the industry sector but interacts with the MAC curves of the power sector. Feeding the derived time-dependent MAC curves into a model of the EU ETS improves the accuracy of the results. However, this approach neglects that MAC curves are interrelated, i.e., they are

[80] After the private bank is empty, abatement decreases linearly with the allowance supply. Correspondingly, the price increases in accordance with the upper part of the MAC curve.

not a sequence of static curves but rather a family of curves, that depends on the carbon price path.

For considering interactions between the allowance demand and the EU ETS price path, it is worth to consider the coupling of an allowance demand-side model (covering the power sector and energy-intensive industries) and an EU ETS model. Via soft-coupling, the EU ETS model feeds the derived price paths to the allowance demand-side model, which then updates the MAC curves. By iterating these steps, a consistent model framework is set up if the model runs converge. Alternatively, the two models could be hard-coupled, i.e., a simultaneous equilibrium is calculated by an integrated approach. For example, the implementation as a mixed complementary problem (MCP) allows to derive a consistent solution with an endogenous depiction of allowance demand and the EU ETS market. Both variants of model-coupling open up possibilities to evaluate alternative EU ETS designs (e.g., the implementation of carbon price floors) or related environmental policies, such as electrification efforts.

5.5. Conclusion

Recent literature relies on MAC curves to analyze the design of the EU ETS as the key emission abatement instrument in Europe. While the assumptions on MAC curves drive the results, the literature on the shape of MAC curves within the scope of the EU ETS is scarce. Against this backdrop, this paper identifies implications of MAC curve properties for the EU ETS.

In a case study, we derive MAC curves for the European power sector. To this end, a partial equilibrium model is fed with carbon price paths to determine corresponding emission and abatement levels. We identify two fundamental properties of MAC curves of the European power sector: First, the shape of MAC curves is convex for all points in time. The curvature depends on economic developments, such as fuel prices and interest rates. Second, MAC curves flatten over time. In the short term, fuel-switching is the only abatement option and thus, the MAC curve is steep. With longer investment horizons, the degree of freedom for investment grows and enables the transformation of the capital stock. This additional abatement option flattens the MAC curve. Further, technological learning and demand adjustments lowers in particular the upper part of the MAC curve.

Idealized market equilibrium paths in the EU ETS consist of price-emission tuples that minimize overall abatement costs and comply with the allowance supply path. Emission decisions and thus market prices are a trade-off between emissions today and in the future. After introducing the Market Stability Reserve and the Cancellation Mechanism, the total allowance supply and thus total emissions decrease with banking volumes. With convex MAC curves, marginal abatement costs increase over time, which makes future abatement relatively more expensive compared to today's abatement. Thus, firms increase banking volumes compared to linear MAC curves. On the contrary, MAC curves flatten over time, which lowers the incentives for banking. Considering steeper MAC curves in the short term leads to a higher price path and an earlier depletion of the firms' bank. For quantifying these effects, the time-dependency of MAC curves should be depicted. A model of the allowance demand side could derive MAC curves, which are fed into a model of the EU ETS. Ideally, the allowance demand-side model is coupled with the EU ETS model to derive consistent equilibrium paths.

Beyond the power sector, MAC curves of energy-intensive industries should be analyzed to cover the whole scope of the EU ETS. Since MAC curves are only snapshots of a dynamic context, path dependencies and uncertainties are worth considering. In particular, the impact of global deep decarbonization and its implications for MAC curves are a subject of further research.

A. Supplementary Material for Chapter 2

A.1. 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

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

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:

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

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:

$$\begin{aligned}
\frac{\partial \mathcal{L}}{\partial x(t)} &= \frac{1}{(1+r)^t}p(t) - \lambda(t) &= 0 \quad \forall\, t = 1,2,\dots,T \qquad \text{(A.3)}\\
\frac{\partial \mathcal{L}}{\partial e(t)} &= (-1)\frac{1}{(1+r)^t}c(u-e(t)) + \lambda(t) &= 0 \quad \forall\, t = 1,2,\dots,T \qquad \text{(A.4)}\\
\frac{\partial \mathcal{L}}{\partial b(t)} &= \lambda(t) - \lambda(t+1) - \mu_b(t) &= 0 \quad \forall\, t = 1,2,\dots,T. \qquad \text{(A.5)}
\end{aligned}$$

Primal feasibility:

$$\begin{aligned}
b(t) - b(t-1) - x(t) + e(t) &= 0 \quad \forall\, t = 1,2,\dots,T \qquad \text{(A.6)}\\
x(t),\ e(t) &\gtrless 0 \quad \forall\, t = 1,2,\dots,T. \qquad \text{(A.7)}
\end{aligned}$$

Dual feasibility and complementarity:

$$\begin{aligned}
0 \leq b(t) \perp \mu_b(t) &\geq 0 \quad \forall\, t = 1,2,\dots,T \qquad \text{(A.8)}\\
\lambda(t) &\gtrless 0 \quad \forall\, t = 1,2,\dots,T. \qquad \text{(A.9)}
\end{aligned}$$

A.2. The Impact of Backstop Costs

Lemma *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 cost parameter $c(t)$ and optimal emissions $e(t)$, abatement $u - e(t)$, $TNAC(t)$, $MSR(t)$, $Cancel(t)$ and the price level $p(t)$. We know that these variables fulfill both the individual KKT conditions of the firm stated in A.1 and the regulatory conditions from sections 2.2.2 and 2.2.3.

Now let $\tilde{bc}$ be some other backstop costs. We now want to show that the individual KKT conditions from A.1 and the regulatory conditions are fulfilled for the same variables and a scaled version of the price path. From the definition of backstop costs, we know that $\tilde{c} = \frac{\tilde{bc}}{u} = \frac{\tilde{bc}}{bc}c$. We further define

$$\tilde{p}(t) := \frac{\tilde{bc}}{bc}p(t) \qquad \tilde{\lambda}(t) := \frac{\tilde{bc}}{bc}\lambda(t) \qquad \tilde{\mu_b}(t) := \frac{\tilde{bc}}{bc}\mu_b(t).$$

Then we can easily check that $\tilde{p}(t), \tilde{\lambda}(t)$ and $\tilde{\mu_b}(t)$ together with the unchanged quantities $e(t)$, $TNAC(t)$, $MSR(t)$ and $Cancel(t)$ satisfy all KKT conditions and regulatory market conditions. Hence they give a solution to the problem with backstop costs $\tilde{bc}$ with the same values for the quantities and a scaled price path $\tilde{p}(t)$. ■

As the lemma 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 $\frac{\tilde{p}(t)}{p(t)} = \frac{\tilde{bc}}{bc}$. The lemma also holds true for other definitions of c as long as $c \cdot u$ is not affected by the change of the backstop costs. In particular it also holds true for time dependent $u(t)$ and $c(t)$ as long as $u(t) \cdot c(t)$ is not affected.

A.3. Effect of the CM with a Reduced LRF

In Figure A.1 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.

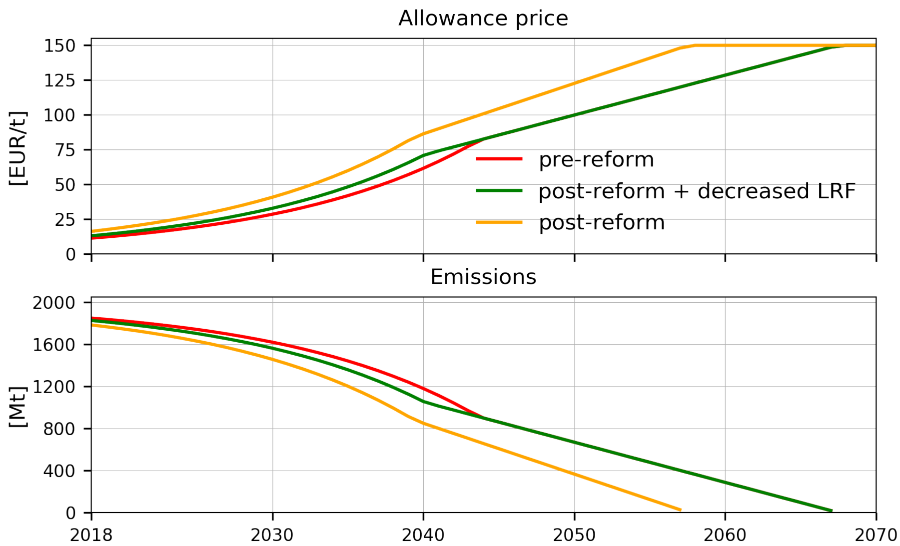

Figure A.1.: Effect of the CM

B. Supplementary Material for Chapter 3

B.1. KKT Conditions for the Firm's Optimization Problem

From the optimization problem of the firm (Equation 3.1), the Lagrangian is derived by assigning multipliers $\lambda(t)$ and $\mu_b(t)$ to the banking flow and positivity constraints, respectively:

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

As the Slater conditions are fulfilled, the KKT conditions are necessary and sufficient for optimality. Thus, for all $t = 0, 1, 2, \ldots, T$:

Stationarity conditions:

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

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

$$\frac{\partial \mathcal{L}}{\partial b(t)} = \lambda(t) - \lambda(t+1) - \mu_b(t) = 0 \quad \forall\, t = 1, 2, \ldots, T. \tag{B.4}$$

Primal feasibility:

$$b(t) - b(t-1) - x(t) - f(t) + e(t) = 0 \quad \forall\, t = 1, 2, \ldots, T \tag{B.5}$$

$$e(t) \geq 0, \quad x(t) \gtrless 0 \quad \forall\, t = 1, 2, \ldots, T. \tag{B.6}$$

Dual feasibility and complementarity:

$$0 \leq b(t) \perp \mu_b(t) \geq 0 \quad \forall\, t = 1, 2, \ldots, T \tag{B.7}$$

$$\lambda(t) \gtreqless 0 \quad \forall\, t = 1, 2, \ldots, T. \tag{B.8}$$

B.2. Supply Rules of the Reformed EU ETS

As borrowing allowances from the future is not allowed, aggregate emissions over time have to be smaller than aggregate issued allowances, i.e.,

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

In correspondence to the endogenous auction volume, the MSR volume is given by

$$MSR(t) = MSR(t-1) + Intake(t) - Reinjection(t) - Cancel(t),$$

where the regulatory rules are formalized as

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

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

Further, cancellation takes place if the volume of the MSR exceeds the previous year's auction volume, or formally

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

B.3. Robustness of the Results with Respect to Baseline Emissions and Interest Rate

Apart from the CPF regulation, the model in this paper mainly depends on three parameters: backstop costs, interest rate, and baseline emissions. The following section discusses the impact of these parameters on the market outcomes in the base scenario without a CPF. Furthermore, it is analyzed how a different choice of these parameters alters the impact of the CPF on the market outcomes, particularly the aggregate cancellation.

As discussed in Section 3.4, the backstop costs only scale the abatement costs of firms. Thus, in the base scenario, the equilibrium quantities of allowance trading do not change with the backstop costs, only the absolute price level shifts. In particular, the aggregate cancellation remains unaltered if the backstop costs change. A formalized argument on the price scaling of backstop costs is given in Bocklet et al. (2019). The impact of the CPF does not change if one accounts for the scaled price level, i.e., if the CPF level is scaled accordingly. In other words, for the same absolute CPF level, higher (lower) backstop costs decrease (increase) the effectiveness of the CPF. In that way, one can reinterpret Figure 3.4 so that different CPF levels represent different backstop cost levels.

Since the level of baseline emissions is uncertain (compare Borenstein et al., 2019), the following robustness analysis ensures that the results from Section 3.4 remain valid under different assumptions regarding the baseline emissions. In this regard, two cases are considered where the baseline emissions are 10% higher or lower. Lower baseline emissions correspond with overall lower demand for allowances, resulting in an overall lower price level. Thus, initial emissions are lower, leading to a higher TNAC volume, and thus more cancellation. This mechanism does not change when the CPF is introduced. With lower baseline emissions, the overall price level is lower. Thus, the same absolute CPF level has a bigger impact on the aggregate cancellation as depicted in Figures B.1 (left) and B.2 (left). The same reasoning holds analogously for higher baseline emissions. Overall, aggregate cancellation increases with the CPF level regardless of the chosen baseline emissions, and the increase in aggregate cancellation is faster for the buyback implementation.

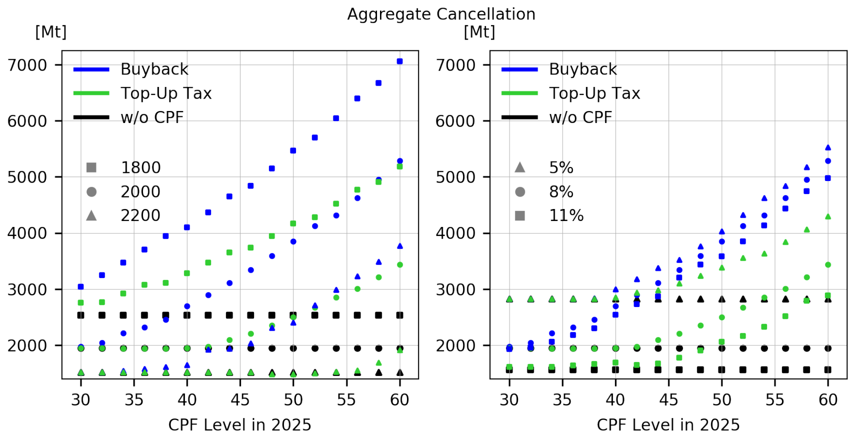

Figure B.1.: Aggregate cancellation for different CPF levels implemented in 2025 with respect to baseline emissions (left) and interest rate (right)

By construction, the impact of the CPF is not affected by the implementation year in the buyback implementation.[81] Still, the impact of the CPF is much higher with lower baseline emissions: additional 2000 Mt aggregate cancellation due to the CPF for low baseline emissions (1800 Mt) instead of the standard case (2000 Mt). For the top-up tax, the aggregate cancellation decreases for later implementation years. With low baseline emissions, the CPF is effective, even if implemented in 2035. With high baseline emissions, the CPF does not influence aggregate cancellation if implemented after 2024. Overall, the findings of Section 3.4 remain valid if the baseline emissions are altered. However, the absolute size of the effect changes.

The interest rate used represents the opportunity costs of capital for other investment options for firms. As such, also the interest rate in the market is prone to uncertainty. In this robustness analysis, a higher (11%) and a lower (5%) interest rate are exemplary depicted in Figures B.1 (right) and B.2 (right). A lower interest rate corresponds with a higher initial price level, which is increasing at a lower rate. Thus, with a lower interest rate, firms abate more in the short run leading to higher TNAC volumes, more intake into the MSR, and more cancellation. Only later, the price is below the case with the higher interest rate, as the increasing rate outweighs the initial price level. The effect on the aggregate cancellation is only minor because by then, the TNAC is below the intake thresholds. Due to the higher initial price level, the effect of the CPF is diminished for lower interest rates. Thus, for the same absolute CPF level, the impact of the CPF on aggregate emissions is smaller for lower interest rates (B.1 (right)). This line of arguments holds vice versa for a higher interest rate. In general, aggregate cancellations increase for a higher CPF level regardless of the underlying interest rate. As before, the increase is faster for the buyback design as the anticipation of the CPF enforces cancellation.

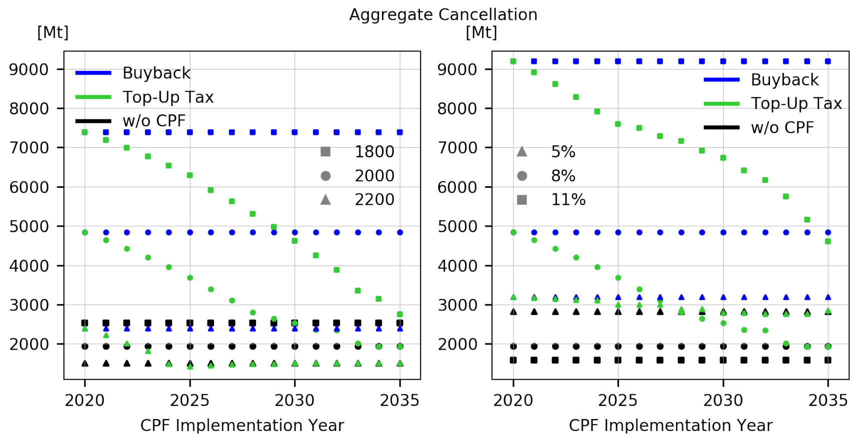

Figure B.2.: Aggregate cancellation for different implementation years with respect to baseline emissions (left) and interest rate (right)

[81]Again, it is assumed that the CPF level increases with the interest rate in this case.

When comparing different implementation years, the CPF is increasing with the respective interest rate. The CPF level is set so that it is 40 EUR/t in 2025. By construction, the impact of the buyback CPF is not affected by the implementation year. However, the impact of the CPF is much higher with a higher interest rate. With a higher interest rate, the price level is lower, but the CPF level increases at a higher rate and reaches a higher absolute level. In contrast, for the case with a lower interest rate, the effect of the CPF is rather small.

In conclusion, other choices of the main model parameters backstop costs, baseline emissions, and interest rate change the absolute effect of the CPF on aggregate cancellation. However, the relationships discussed in Section 3.4.4 are not altered and are robust towards the parameter choices: the effect of the CPF on aggregate cancellation increases with the CPF level and an earlier implementation year.

C. Supplementary Material for Chapter 4

C.1. Lagrangian with Hedging Requirements

For the optimization problem $\mathcal{M}$ (Equation 4.1) with the hedging constraint depicted in Equation 4.9 we can derive the corresponding Lagrangian by assigning multipliers $\lambda(t)$ and $\mu_b(t)$ to the banking flow constraint and the hedging constraints[82], respectively:

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

As the Slater conditions are fulfilled for the optimization problem, the KKT conditions give sufficient and necessary conditions for an optimum. From Eq. C.1, the stationary conditions are derived:

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

$$\begin{aligned}
\frac{\partial \mathcal{L}}{\partial e(t)} = &(-1)\frac{1}{(1+r)^t}c(u-e(t)) + \lambda(t) + \\
&+ \sum_{\tilde{t}=0}^{t} hedgeshare(t-\tilde{t})\mu_b(\tilde{t}) = 0 \quad \forall\, t = 1,2,\ldots,T
\end{aligned} \tag{C.3}$$

$$\frac{\partial \mathcal{L}}{\partial b(t)} = \lambda(t) - \lambda(t+1) - \mu_b(t) = 0 \quad \forall\, t = 1,2,\ldots,T. \tag{C.4}$$

[82] Note that the base model without hedging constraints is equivalent to the model with hedging constraints for $hedgeshare(\tilde{t}-t) = 0$.

Primal feasibility:

$$b(t) - b(t-1) - x(t) + e(t) = 0 \quad \forall\, t = 1, 2, \ldots, T \tag{C.5}$$

$$x(t),\;\; e(t) \gtreqless 0 \quad \forall\, t = 1, 2, \ldots, T. \tag{C.6}$$

Dual feasibility and complementarity:

$$0 \leq b(t) - \sum_{\tilde{t}=t}^{T} hedgeshare(\tilde{t} - t)e(\tilde{t}) \perp \mu_b(t) \geq 0 \quad \forall\, t = 1, 2, \ldots, T \tag{C.7}$$

$$\lambda(t) \;\; \gtreqless 0 \quad \forall\, t = 1, 2, \ldots, T. \tag{C.8}$$

D. Supplementary Material for Chapter 5

D.1. The Power Market Model DIMENSION

Table D.1 presents the notation used within this paper. Capitalized terms represent endogenous decision variables. Lower case terms denote exogenous parameters.

Table D.1.: Sets, parameters and variables

Sets		
$i \in I$		Elec. generation and storage technologies
$m, n \in M$		Countries
$y \in Y$		Years
$t \in T$		Representative time steps
Parameters		
$d(y,t,m)$	[MWh]	Elec. demand
r	[-]	Discount rate
$avail(y,t,m,i)$	[-]	Availability of elec. generation technology
$ntc(y,m,n)$	[MW]	Net transmission capacity
$\eta(i)$	[MWh/MWh_th]	Generation efficiency
$\delta(y,i)$	[EUR/MW]	Annualized investment cost
$\sigma(i)$	[EUR/MW]	Fixed operation and maintenance cost
$\gamma(y,i)$	[EUR/MWh]	Variable fuel cost
$\tau(y)$	[EUR/tCO2eq]	Carbon price
$\nu(i)$	[tCO2eq/MWh_th]	Fuel-specific emission factor
$cap_{add,min}(y,m,i)$	[MW]	Existing or under construction capacity
$cap_{sub,min}(y,m,i)$	[MW]	Decomm. due to lifetime or policy bans
$l(m,n)$	[-]	Relative transmission losses
Variables		
$CAP(y,m,i)$	[MW]	Elec. generation capacity
$GEN(y,t,m,i)$	[MWh]	Elec. generation
$EM(y,t,m,i)$	[tCO2eq]	Emissions
$CAP_{add}(y,m,i)$	[MW]	Investments in elec. generation capacity
$CAP_{sub}(y,m,i)$	[MW]	Decomm. of elec. generation capacity
$TRADE(y,t,m,n)$	[MWh]	Trade flow of elec. from m to n
TC	[EUR]	Total costs
$FC(y)$	[EUR]	Invest and fixed O&M costs
$VC(y)$	[EUR]	Variable generation costs

The central planner minimizes total discounted costs for serving the electricity demand. Consequently, she decides on the investment in capacity and the dispatch of power plants. The total discounted costs consist of fixed (FC) and variable (VC) costs, i.e.,

$$TC = \sum_{y \in Y} (1+r)^{-(y-y_0)} \cdot [FC(y) + VC(y)], \tag{D.1}$$

where the fixed costs per year comprise the annualized investment costs and the fixed operation and maintenance costs for installed capacity. The variable costs embody generation-dependent costs, namely for fuel and emission allowances.The installed capacity of electricity generators develops endogenously according to equation D.2.

For a realistic depiction of European energy markets, equations D.3 and D.4 account for existing as well as under construction capacities ($cap_{add,min}$) and decommissioning due to end-of-lifetime or technology bans ($cap_{sub,min}$). Equation D.5 formally defines the fixed costs.

$$\begin{aligned}
CAP(y,m,i) = {} & CAP(y-1,m,i) + \\
& + CAP_{add}(y,m,i) + CAP_{sub}(y,m,i) && \text{(D.2)} \\
CAP_{add}(y,m,i) \geq {} & cap_{add,min}(y,m,i) && \text{(D.3)} \\
CAP_{sub}(y,m,i) \geq {} & cap_{sub,min}(y,m,i) && \text{(D.4)} \\
FC(y) = {} & \sum_{\substack{\tilde{y}: \\ y-\tilde{y}<lifetime(i)}} CAP_{add}(\tilde{y},m,i) \cdot \delta(\tilde{y},i) + \sum_{m \in M, i \in I} CAP(y,m,i) \cdot \sigma(i) && \text{(D.5)}
\end{aligned}$$

Further, the dispatch of installed capacities is restricted by technical constraints. First, for every representative time step, electricity generation has to balance the inelastic demand adjusted by the trade flows from and to neighboring countries (Equation D.6). Second, electricity generation of each technology and in each time step is bound by the available capacity (Equation D.7). The availability factor accounts for maintenance shutdowns of conventional power plants or the infeed profile of renewable energy. The trade flows are restricted by the net transfer capacities between countries and have to be symmetric, i.e., exports from m to n are imports from n to m (Equations D.8 and D.9). Variable costs comprise fuel costs and costs for emissions (Equation D.10). The former is calculated as the product of generation per technology and the technology-specific variable fuel costs. The latter is the product of the carbon price and realized emissions which are calculated through the fuel input and the fuel-specific emission factor (Equation D.11).

$$\sum_{i \in I} GEN(y,t,m,i) = d(y,t,m) + \\ + \sum_{n \neq m} (1 - l(m,n)) \cdot [TRADE(y,t,m,n) - \\ - TRADE(y,t,n,m)] \tag{D.6}$$

$$GEN(y,t,m,i) \leq avail(y,t,i) \cdot CAP(y,m,i) \tag{D.7}$$

$$TRADE(y,t,m,n) \leq ntc(y,m,n) \tag{D.8}$$

$$TRADE(y,t,m,n) = -TRADE(y,t,n,m) \tag{D.9}$$

$$\forall y \in Y, m,n \in M,\ i \in I$$

$$VC(y) = \sum_{m \in M,\, i \in I,\, t \in T} [GEN(y,t,m,i) \cdot \gamma(y,i) + EM(y,t,m,i) \cdot \tau(y)] \tag{D.10}$$

$$EM(y,t,m,i) = GEN(y,t,m,i) \cdot \frac{\nu(i)}{\eta(i)} \tag{D.11}$$

The presented equations constitute the core functionality of DIMENSION: The objective function D.1 is minimized over the feasible region, which is defined by the constraints D.2-D.11.

Moreover, the model incorporates features such as ramping and storage constraints as well as area restrictions for RES. For a thorough introduction of DIMENSION and its characteristics, the reader is referred to Richter (2011).

D.2. Numerical Assumptions

Table D.2.: Considered technologies and their techno-economic characteristics based on Knaut et al. (2016) and Peter (2019)

Technologies	**Efficiency**	**Fixed O&M Costs** (EUR/kWa)
Nuclear	0.33	101 - 105
Lignite	0.32 - 0.46	45 - 60
Coal	0.37 - 0.46	40 - 60
Combined Cycle Gas Turbines (CCGT)	0.39 - 0.60	24 -30
Open Cycle Gas Turbines (OCGT)	0.28 - 0.40	12 - 17
Oil	0.4	7
Biomass	0.3	120
PV	1	15 - 17
Wind Onshore	1	13
Wind Offshore	1	93
Hydro	1	11.5
Pumped Storage	0.76	11.5

Table D.3.: Assumptions on fuel prices [EUR/MWh$_{th}$]

Fuel	**Price**
Uranium	3
Lignite	3
Coal	10
Natural Gas	20
Oil	33

Table D.4.: Assumed electricity demand per country [TWh], based on 2019 levels according to ENTSO-E (2020)

Country	Demand	Country	Demand
AT	67	IE	29
BE	85	IT	307
BG	32	LT	12
CH	62	LV	7
CZ	63	NL	114
DE	530	NO	128
DK	35	PL	156
EE	8	PT	49
ES	248	RO	52
FI	86	SE	132
FR	456	SI	14
GR	51	SK	28
HR	17	UK	263
HU	41		

Table D.5.: Technological learning regarding investment costs [EUR/kW], based on the World Energy Outlook 2019 (IEA, 2019)

Technology	Status quo	Near Future	Far Future
Wind Onshore	1580	1503	1430
Wind Offshore	3985	3038	2600
PV (roof)	883	688	580
PV (base)	750	585	480
OCGT	412	412	412
CCGT	900	900	900

D.3. Impact of Fuel Prices on Short-Term MAC Curves

Figure D.1 depicts the impact of different gas prices (10, 20 or 30 EUR/MWh_{th}) on short-term MAC curves, i.e., if no investments are possible.

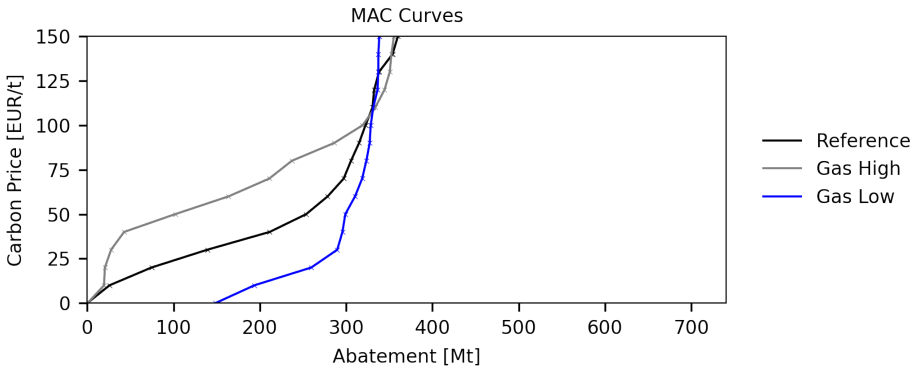

Figure D.1.: Short-term MAC curves for different coal-gas price spreads

The lower part of the MAC curve reflects the margin between coal and gas prices. Under lower gas prices, modern gas power plants replace inefficient coal generation even without a carbon price signal. Higher gas prices have the opposite effect. Only below 10 EUR/t, higher gas prices do not impact fuel switching as the margin between coal and gas is not closed by such low carbon prices. The upper part of the MAC curve is similar since the fuel-switching potential is reached independently of the gas price. Only minor shifts in the dispatch of, e.g., biomass affect the MAC curve.

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01/2012 - 06/2014	**Chair of Macroeconomics and Development at the Georg-August-Universität Göttingen Prof. Dr. Strulik** Research assistant
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LANGUAGES

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PUBLICATIONS

Articles in Peer-Reviewed Journals:

- M. Hintermayer (2020). A Carbon Price Floor in the Reformed EU ETS: Design Matters! *Energy Policy*, Vol. 147, Article 111905.
- J. Bocklet, M. Hintermayer, L. Schmidt, T. Wildgrube (2019). The Reformed EU ETS – Intertemporal Emission Trading with Restricted Banking. *Energy Economics*, Vol. 84, Article 104486.

Working Papers:

- M. Hintermayer, L. Schmidt, J. Zinke (2020). On the Time-Dependency of MAC Curves and its Implications for the EU ETS. *EWI Working Paper Series* 08/2020.
- M. Hintermayer (2020). A Carbon Price Floor in the Reformed EU ETS: Design Matters! *EWI Working Paper Series* 03/2020.
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- J. Bocklet, M. Hintermayer, L. Schmidt, T. Wildgrube (2019). The Reformed EU ETS – Intertemporal Emission Trading with Restricted Banking. *EWI Working Paper Series* 04/2019.

Further Publications:

- M. Hintermayer, A. Sitzmann, C. Tode (2018). Ökonomische Bewertung des Marktentwicklungsmodells. *EWI study on behalf of ARGE Netz.*
- M. Gierkink, H. Hecking, O. Hennes, M. Hintermayer, J. Kruse, D. Lencz, S. Lorenczik, J. Peter, T. Wildgrube (2018). dena-Leitstudie Integrierte Energiewende. *EWI study on behalf of Deutsche Energie-Agentur (dena).*
- H. Hecking, M. Hintermayer, F. Weiser. (2018). Central European Gas Market Congestion Analysis. *EWI study on behalf of Nord Stream 2.*
- H. Hecking, M. Hintermayer, D. Lencz, J. Wagner. (2017). Energiemarkt 2030 und 2050 – Der Beitrag von Gas- und Wärmeinfrastruktur zu einer effizienten CO_2-Minderung. *EWI study on behalf of Gelsenwasser, Open Grid Europe, Rheinenergie.*
- H. Hecking, M. Hintermayer, D. Lencz. (2018). Der Beitrag der Gasinfrastruktur für eine effiziente CO_2-Vermeidung. *et – Energiewirtschaftliche Tagesfragen*, Vol. 68 (3), pp. 14-16.
- H. Hecking, M. Hintermayer, D. Lencz. (2018). Gas- und Wärmeinfrastruktur ermöglichen flexible Erreichung der Klimaziele. *gwf Gas + Energie*, Vol. 159 (4), pp. 42-46.

CONFERENCE PRESENTATIONS

- How Does the EU ETS Reform Impact Allowance Prices? The Role of Myopia, Hedging Requirements and the Hotelling Rule (Nomination for the Distinguished CESifo Affiliate Award). *CESifo Area Conference on Energy and Climate Economics.* October 2020. Munich (online).
- A Carbon Price Floor Within the Reformed EU ETS. *Jahrestagung des Vereins für Socialpolitik (VfS).* September 2020. Cologne (online).
- A Carbon Price Floor Within the Reformed EU ETS. *25th EAERE International Conference.* June 2020. Berlin (online).
- A Carbon Price Floor Within the Reformed EU ETS (accepted but postponed due to COVID-19). *16th IAEE International Conference.* June 2020. Paris, France.
- A Carbon Price Floor Within the Reformed EU ETS (accepted but postponed due to COVID-19). *8th International Symposium on Environment & Energy Finance Issues.* May 2020. Paris, France.
- The Reformed EU ETS – Intertemporal Emission Trading with Restricted Banking. *16th IAEE European Conference.* August 2019. Ljubljana, Slovenia.
- Assessing Shocks and Overlapping Policies in the EU ETS – Can the Reform Live up to its Promises? *42th Bergen Economics of Energy & Environment Research Conference (BEEER).* May 2019. Bergen, Norway.
- Gebäude im integrierten Energiemarkt bis 2050 *EWI Energy Conference.* November 2017. Cologne.