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A Carbon Price Floor in the Reformed EU ETS: Design Matters![☆]

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Abstract

Despite the reform of the European Emissions Trading System (EU ETS), discussions about complementing it with a carbon price floor (CPF) are ongoing. This paper analyzes the effect of a European CPF in the reformed EU ETS using a Hotelling model of the EU ETS, amended by the market stability reserve (MSR), and the cancellation mechanism. Two 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 more cancellation of allowances. The top-up tax imposes a tax on emissions, which enhances the market price of allowances to the CPF level from the implementation year onwards. Firms 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 a dynamic context, such as the EU ETS.

Keywords: Intertemporal Emission Trading, Carbon Price Floor, EU ETS
JEL Classification: H23, H32, Q58.

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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.[1] 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.[2] 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.

[1] 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)).

[2] 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 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 2 gives an overview of the literature on a CPF in emissions trading systems. Section 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 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, the influence of the CPF level and its implementation year on the aggregate emission level is examined. Section 5 concludes.

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.[3]

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 (2018)). 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

[3]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.

emissions in the EU ETS is called the new green paradox (Gerlagh et al. (2019)).[4] 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.

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

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.[5] In a setting where 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. A Hotelling Model of the EU ETS and the Implementation of the CPF

In the following, Section 3.1 gives an overview of the model and the regulatory rules on the allowance supply. Section 3.2 describes the implementation of the different CPF designs. The parametrization of the model is specified in Section 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.[6] 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

[5] 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.

[6] Chevallier (2012) gives a comprehensive review of models in the aftermath of Rubin (1996).

(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 (2018), 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[7]

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

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 $t = 0, 1, \ldots, T$. 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 $e(t)$.[8] 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

[7]The index i is omitted for better readability, when only one firm is considered.

[8]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.

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.[9]

Optimality conditions for the representative firm are derived from the Karush-Kuhn-Tucker (KKT) conditions of the optimization problem (1), which are given in Appendix A. 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.,

$$c(t)(u(t) - e(t)) = p(t). \tag{2}$$

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

$$\frac{p(t+1) - p(t)}{p(t)} = r - (1+r)^{t+1} \frac{\mu_b(t)}{p(t)}, \tag{3}$$

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.

[9]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.

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

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

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.[10]

3.2. Modelling of Different CPF Designs

Throughout this paper, the implementation of the CPF is assumed across all countries in the EU ETS.[11] As discussed in Section 2, conclusions about the implementation through an auction reserve price can be drawn if the auction share in the EU ETS is increased.

[10] A formal definition of the regulatory supply rules, which are also necessary conditions for the market equilibrium, can be found in Appendix B. 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.

[11] 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.

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[12] 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.[13] 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. Consequently, 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 (2), namely

$$c(t) \cdot (u(t) - e(t)) = p(t) + \tau(t). \tag{4}$$

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

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

[13]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.

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.[14] 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. 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 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

[14]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.

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.[15] Since the choice of these three parameters affects the model results, a robustness analysis ensures that the main findings of this paper are preserved.[16]

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 1. This section analyzes and discusses the effects of the CPF in the reformed EU ETS. Section 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 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 4.3 exhibits how governmental revenue differs between the two CPF designs. Section 4.4 explains how

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

[16] Sections 4.1, 4.2 and 4.4 explicitly state how the parameter choices influence the model results. Moreover, a robustness analysis is included in Appendix C.

the CPF level and its implementation year affect overall emissions through the interactions of the CPF with the cancellation mechanism.

4.1. Base Scenario: The EU ETS Without the CPF

For the base scenario without the CPF, the market equilibrium is depicted in Figure 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). 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 2). When the price hits the backstop level in 2057, there are no emissions.

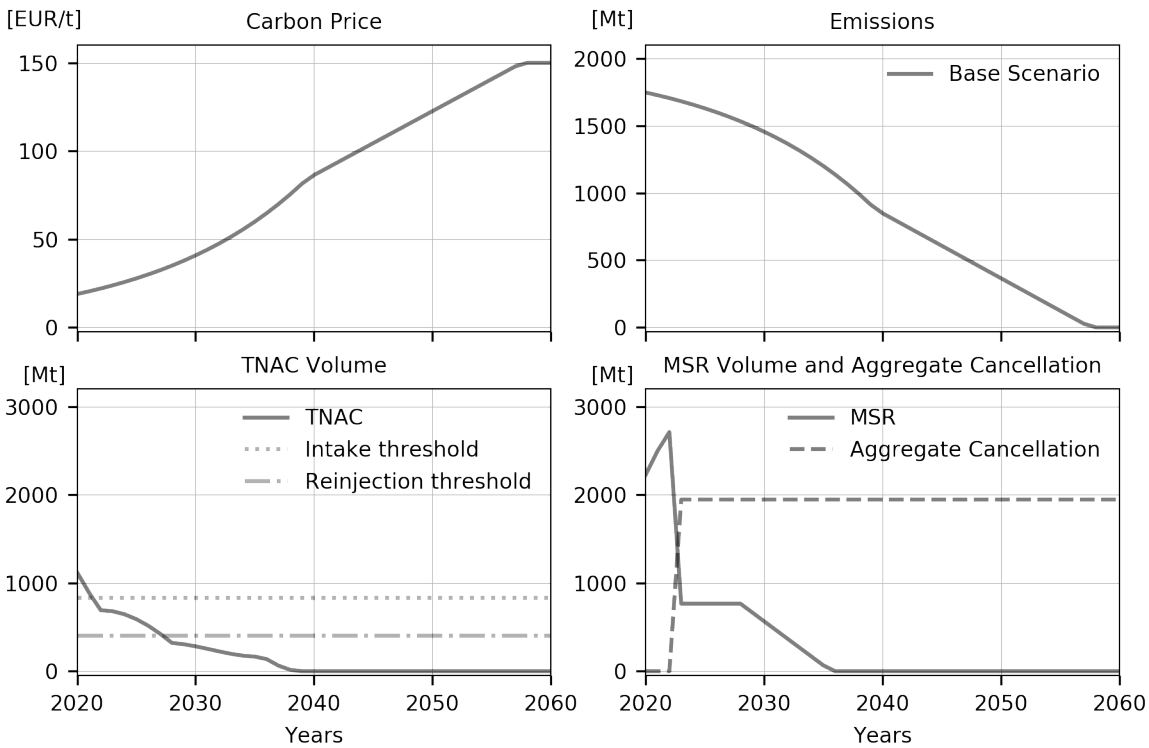

Figure 1: Carbon price, emissions, TNAC, MSR and aggregate cancellation in the base scenario

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.

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 2). A CPF level of 40 EUR/t is assumed to be implemented in 2025 and announced in 2020.[17] 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 2 for a discussion of Friesen et al. (2020) and Salant et al. (2020)). The TNAC will be empty by

[17]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%.

2040 in all cases, and thus, the results of both CPF designs coincide with the base scenario after 2040.

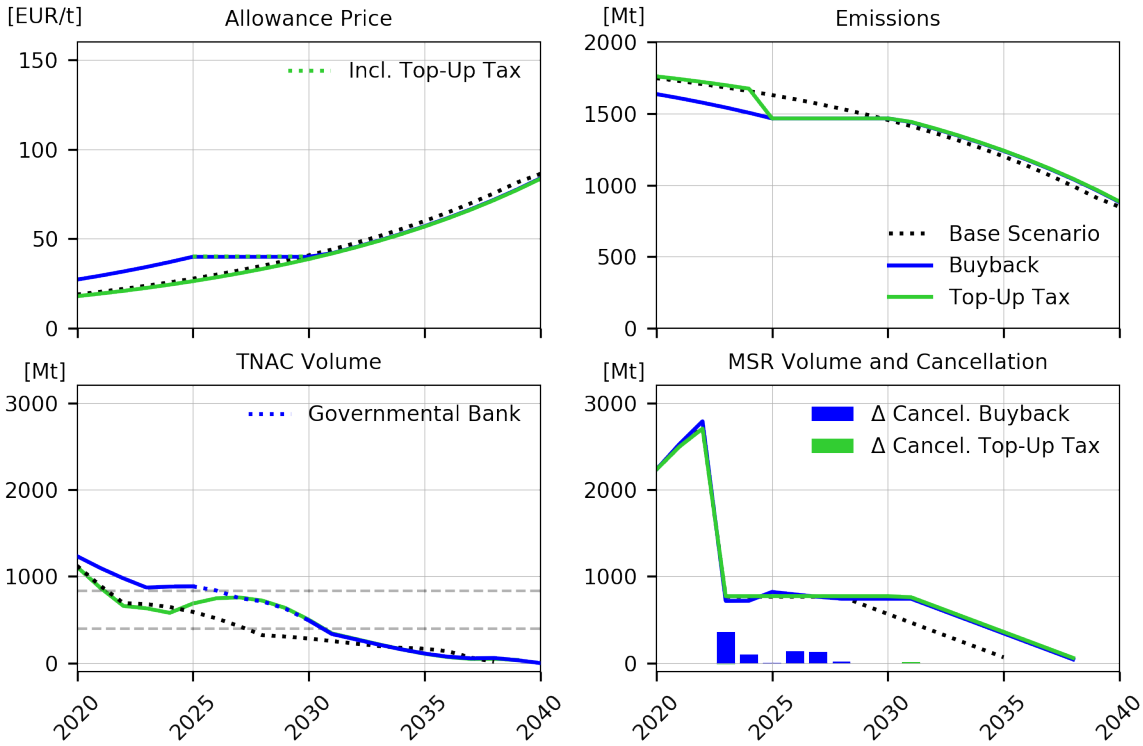

Figure 2: Allowance price, emissions, TNAC, MSR and cancellation for the base scenario, buyback or top-up tax for a CPF level of 40 EUR/t in 2025

The 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

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 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 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.[18] Because of the higher TNAC volume 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 C 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 4.4.

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.[19]

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

[18] 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.

[19] As discussed in Section 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.

CPF changes the auction revenue because it impacts the price of allowances and the auction volume via the MSR rules (compare Figure 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 2) when the price remains constant.[20] These capital costs are calculated as the product of the interest rate, the market price, and the volume of the governmental bank of allowances. The governmental revenue is calculated as

$$governmentalrevenue(t) = p(t) \cdot S_{auct}(t) + \tau(t) \cdot e(t) - r \cdot \underline{p}(t) \cdot governmentalbank(t), \quad (5)$$

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

Figure 3 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.

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.

[20] 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.

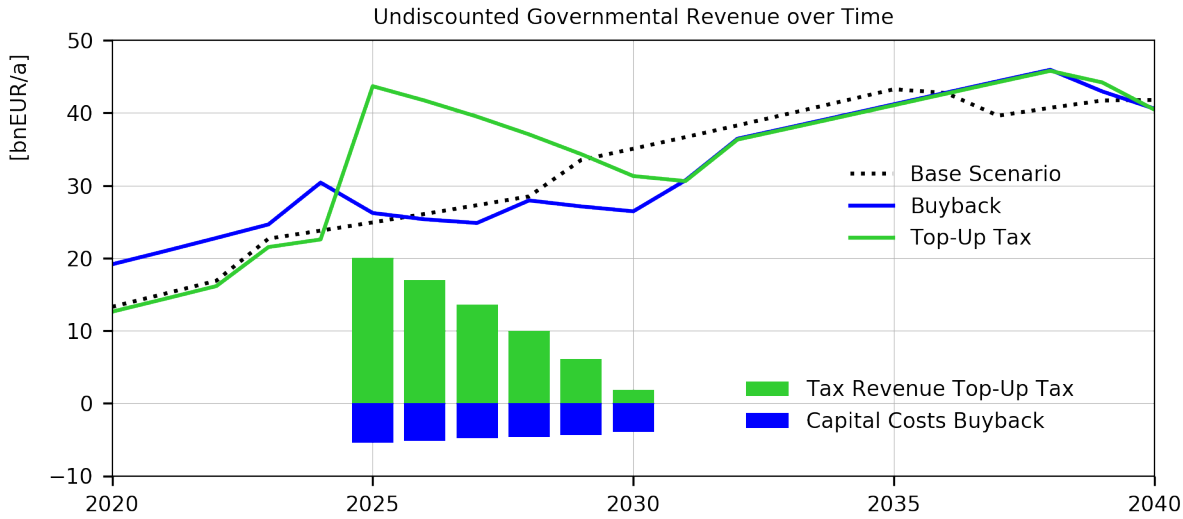

Figure 3: Undiscounted governmental revenue in the base scenario and CPF design via buyback or top-up tax, tax revenue and capital costs

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.[21] 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

[21]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.

abatement costs. The top-up tax also raises the governmental revenue but only after its implementation year in 2025.

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 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 4 and Figure 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 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.[22] In the buyback design, the aggregate cancellation increases steadily with the CPF level. As described in Section 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. 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

[22]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").

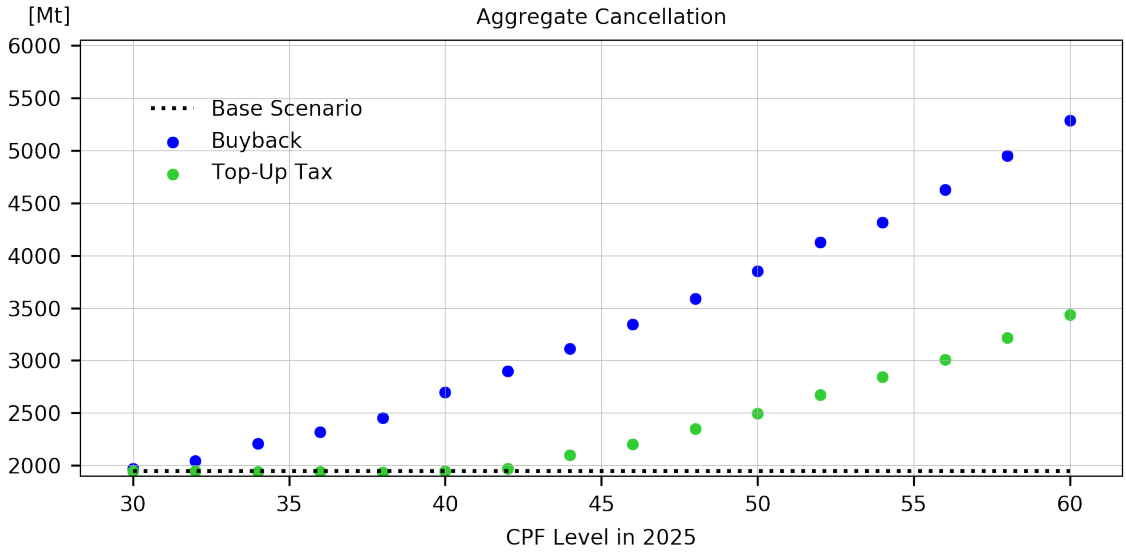

Figure 4: Aggregate cancellation for different CPF levels for an implementation in 2025

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.[23] Hence, the effect of the new green paradox, described in Section 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

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

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.

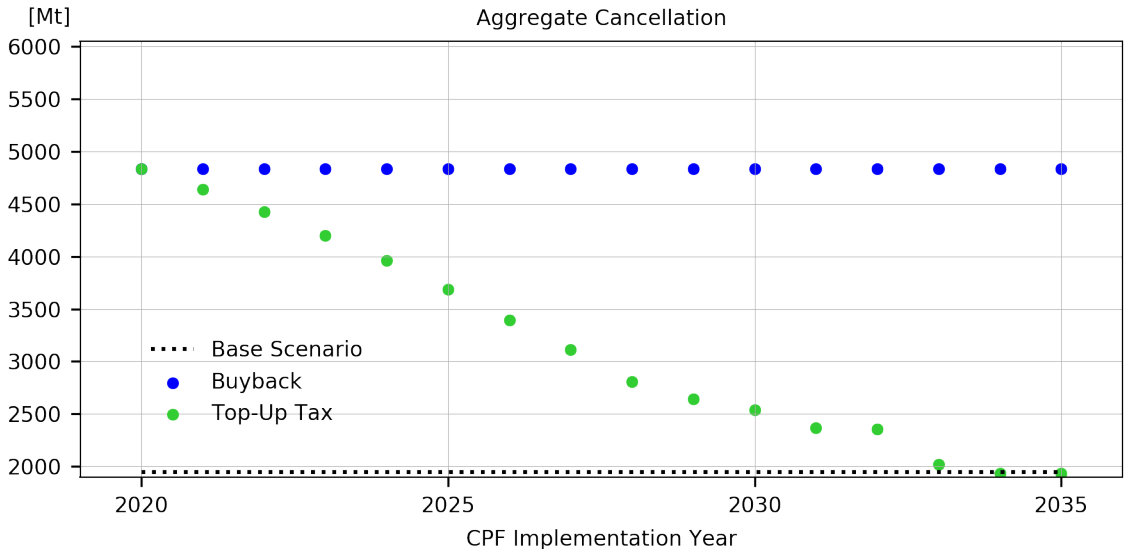

Figure 5: Aggregate cancellation for different implementation years of a rising CPF level (27.22 EUR/t in 2020 to 86.37 EUR/t in 2035)

With the buyback design, the CPF immediately becomes effective with its discounted level, because firms perfectly anticipate the CPF.[24] Consequently, the implementation year does not impact aggregate cancellation (compare Figure 5). This finding hinges both on the anticipation of the CPF and the rising CPF level.

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.

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

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.

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 C 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.

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.

Appendix A. KKT Conditions for the Firm's Optimization Problem

From the optimization problem of the firm (Equation 1), the Lagrangian is derived by assigning multipliers $\lambda(t)$ and $\mu_b(t)$ to the banking flow and positivity constraints, respectively:

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

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:

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

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

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

Primal feasibility:

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

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

Dual feasibility and complementarity:

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

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

Appendix B. 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

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

Appendix C. 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 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 4 so that different CPF levels represent different backstop cost levels.

Since the level of baseline emissions is uncertain (compare Borenstein et al. (2018)), the following robustness analysis ensures that the results from Section 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 C.6 (left) and C.7 (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.

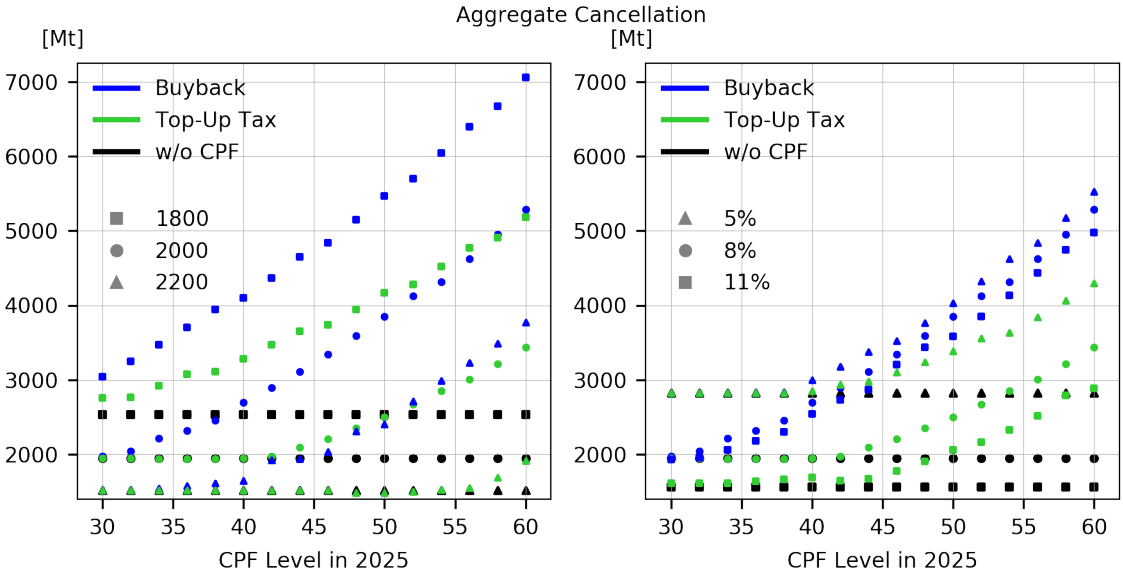

Figure C.6: Aggregate cancellation for different CPF levels implemented in 2025 with respect to baseline emissions (left) and interest rate (right)

By construction, the impact of the CPF is not affected by the implementation year in the buyback implementation.[25] 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

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

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 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 C.6 (right) and C.7 (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 (C.6 (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.

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.

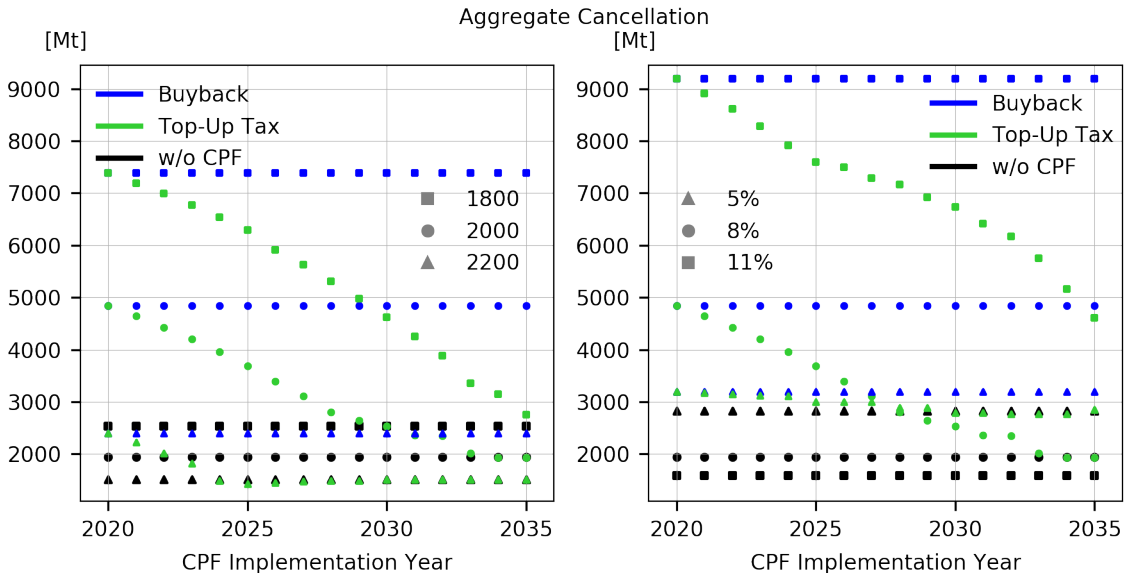

Figure C.7: Aggregate cancellation for different implementation years with respect to baseline emissions (left) and interest rate (right)

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 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.

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