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How does the EU ETS reform impact allowance prices? The role of myopia, hedging requirements and the Hotelling rule[☆]

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Abstract

This paper uses a discrete-time partial equilibrium model of the European Emissions Trading System (EU ETS) to analyze the impact of the recent reform on allowance prices. By including bounded rationality such as myopia or hedging requirements, we find that 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. Myopia and hedging requirements have little impact in the pre-reform market but strongly drive market outcomes after the reform. In the post-reform market, hedging requirements in combination with restrictive allowance supply may even cause a physical shortage of allowances. Yet, neither form of bounded rationality can fully explain the market outcomes in the third trading period of the EU ETS. If myopia and hedging requirements are considered simultaneously, the price increase in the EU ETS can be attributed to the reform fundamentals.

Keywords: Dynamic Optimization, EU ETS, Bounded Rationality, Hotelling, Hedging, Myopia

JEL Classification: D25, D91, H32, Q58

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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 (2018) 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.[1]

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

[1] 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.

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 shortsighted. 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. (2019)) 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 modeled 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 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 behaviour, 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 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 3 we show how myopia impacts model results in the reformed EU ETS. Analogously, in Section 4 we show how hedging requirements drive model results. In Section 5, we discuss if the reform can explain the market outcomes in the third trading period of the EU ETS given bounded rationality. Section 6 concludes.

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 $t = 0, 1, \ldots, T$ under perfect foresight. Formally, the firm solves the cost minimization problem $\mathcal{M}$

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

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 A.

To derive the market equilibrium conditions, the following sections introduce the pre-reform (Section 2.1) and post-reform (Section 2.2) market rules. In Section 2.3 we explain how we model myopic firms with a rolling horizon approach. Section 2.4 exhibits how the firm's decision problem changes in light of hedging requirements. The parameterization of the model is summarized in Section 2.5.

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.[2] 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.[3] 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

$$\frac{p(t+1) - p(t)}{p(t)} = r - (1+r)^{t+1} \frac{\mu_b(t)}{p(t)}. \tag{2}$$

Hence, the market price rises with the interest rate as long as the aggregated private bank is greater than zero.[4] If the bank drops to zero, prices rise at a lower rate.

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

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

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

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.[5]

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 (c.f. 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

$$S_{auct}(t) = S_{auct}(t-1) - a(t)S^0_{auct} - Intake(t) + Reinjection(t). \tag{3}$$

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

$$Intake(t) = \begin{cases} \gamma(t) \cdot TNAC(t-1) & \text{if } TNAC(t-1) \geq \ell_{up}, \\ 0 & \text{else,} \end{cases} \tag{4}$$

and

[5] 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.

$$Reinjection(t) = \begin{cases} R & \text{if } TNAC(t-1) < \ell_{low} \wedge MSR(t) \geq R, \\ MSR(t) & \text{if } TNAC(t-1) < \ell_{low} \wedge MSR(t) < R, \\ 0 & \text{else.} \end{cases} \quad (5)$$

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

$$MSR(t) = MSR(t-1) + Intake(t) - Reinjection(t) - Cancel(t). \quad (6)$$

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

$$Cancel(t) = \begin{cases} MSR(t) - S_{auct}(t-1) & \text{if } MSR(t) \geq S_{auct}(t-1), \\ 0 & \text{otherwise.} \end{cases} \quad (7)$$

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.

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

$$\begin{aligned}
\min \quad & \sum_{t=\tau}^{\tau+H} \frac{1}{(1+r)^t}[\frac{c}{2}(u-e(t))^2 + p(t)x(t)] \\
& s.t.\ b(t) - b(t-1) = x(t) - e(t) \quad \text{for all} \quad t = \tau, \tau+1, \ldots, \tau+H \\
& \qquad b(t) \geq 0 \\
& \qquad x(t),\ e(t) \gtrless 0.
\end{aligned} \tag{8}$$

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.[6] Further, the firm is able to update 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 $\tau = 0, 1, \ldots, T$ **do**
 Solve $\mathcal{M}(\tau, H)$;
 Fix $e(\tau)$, $x(\tau)$, $b(\tau)$;
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.

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

[6]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 $t = 1, \ldots, T$.

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 1) needs to be adjusted in order to take the hedging requirements into account, so that

$$b(t) \geq \sum_{\tilde{t}=t}^{T} hedgeshare(\tilde{t}-t) \cdot e(\tilde{t}), \tag{9}$$

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 A. We receive the amended Hotelling rule (Equation 2) with the dual variable $\mu_b(t)$ for the hedging constraint (Equation 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.

2.5. Parameterization

The above models are implemented as mixed integer models in GAMS and solved with CPLEX. To do so, the model is parameterized 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).[7] 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

[7] 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.

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 3 and Section 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.[8] Thus the model is ran until 2057 when the EU ETS is assumed to reach zero emissions.[9]

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 technology 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 $r = 8\%$.[10]

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 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 parameterization of the hedging share is meant to reflect a broad range of potential hedging schedules. A study by Eurelectric (2009) evaluates the hedging require-

[8] 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.

[9] 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.

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

ments 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.[11] 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 1: Exogenous hedging schedules

We depict a wide range of possible hedging requirements by scaling the above described hedging schedule proportionally.[12] The hedging shares for the different hedging schedules are given in Table 1.

3. Model Results under Myopia

As stated in Section 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 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).

[11] 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).

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

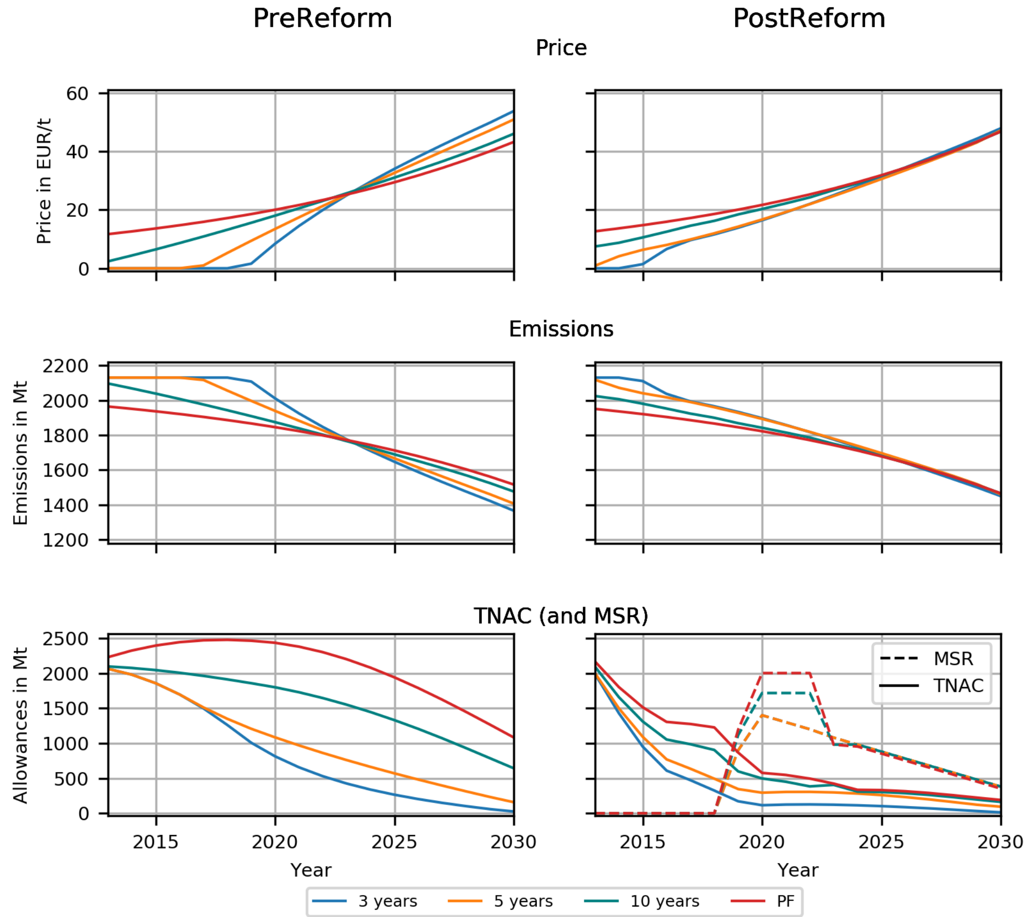

Figure 1: Allowance prices, emissions, TNAC and MSR for the pre- and post-reform scenario with different planning horizons

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 (2018).

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.[13] 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 behaviour 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 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

[13]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.

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.[14] 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.[15] 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. Model Results with Hedging Requirements

As discussed in Section 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

[14] 900 million allowances are backloaded and 600 million allowances remain unallocated. Thus, 1500 million allowances are stored in the MSR instead of being auctioned.

[15] 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.

of firms drive the model results of the EU ETS, we analyze in this section the impact of different hedging shares in the pre- and post-reform market.

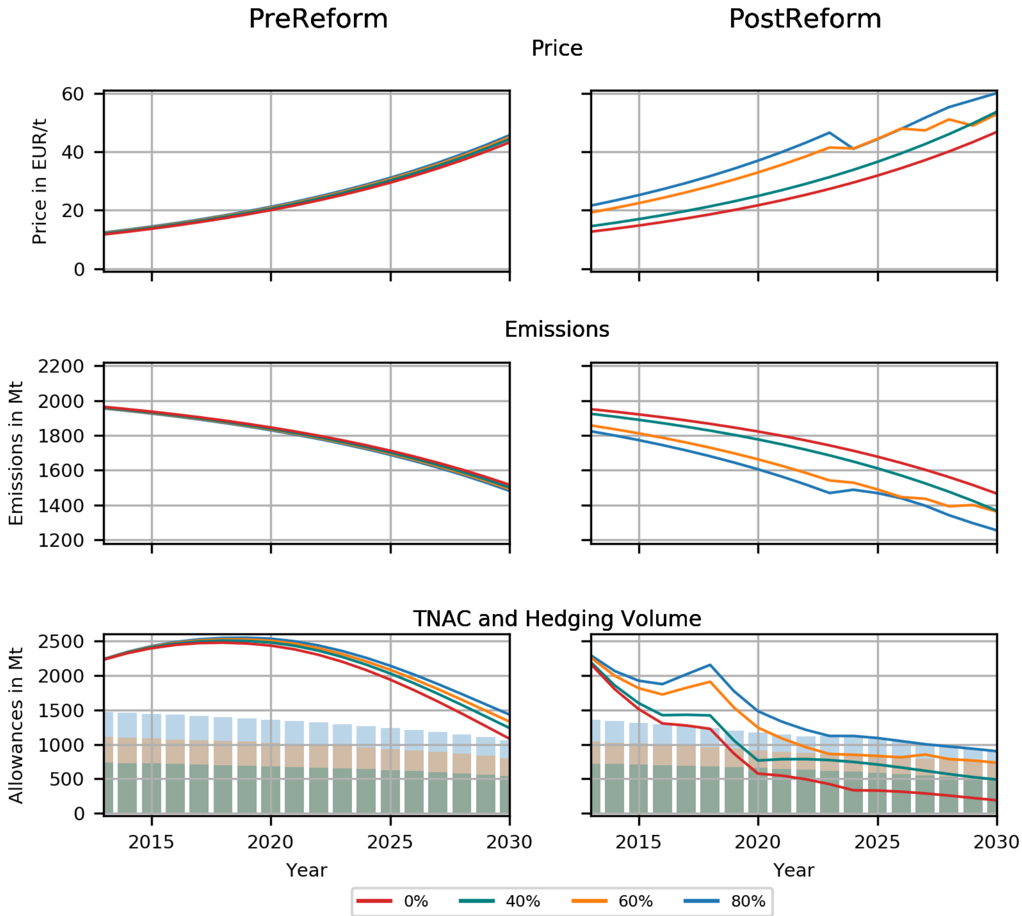

Figure 2: Allowance prices, emissions, TNAC and hedging volumes for the pre- and post-reform scenario with different hedging schedules

Figure 2 shows the model results under perfect foresight for the different hedging schedules given in Table 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 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 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.[16] 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.

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.[17] Without hedging requirements the reform increases prices only little (cf. Beck and Kruse-Andersen (2018) 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.

[16]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.

[17]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.

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.

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.[18] The private bank in the post-reform scenario is compared to the real TNAC in 2018.

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.

[18] 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.

As discussed in Section 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 3).

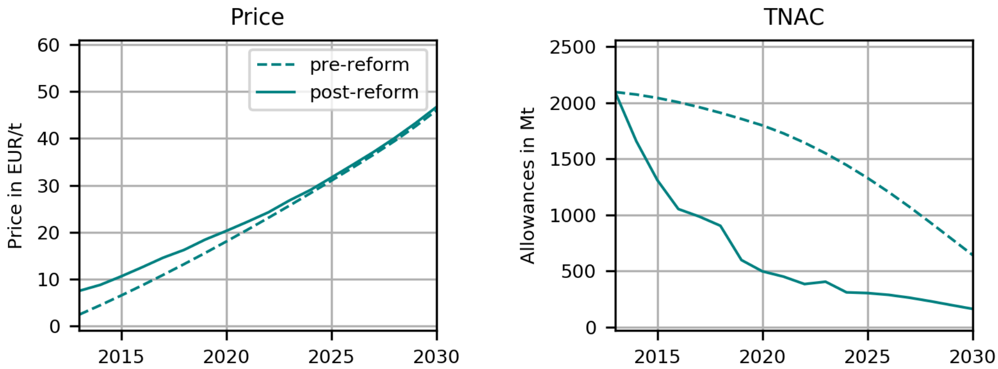

Figure 3: Impact of the reform on market outcomes with a planning horizon of 10 years

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.

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, 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).

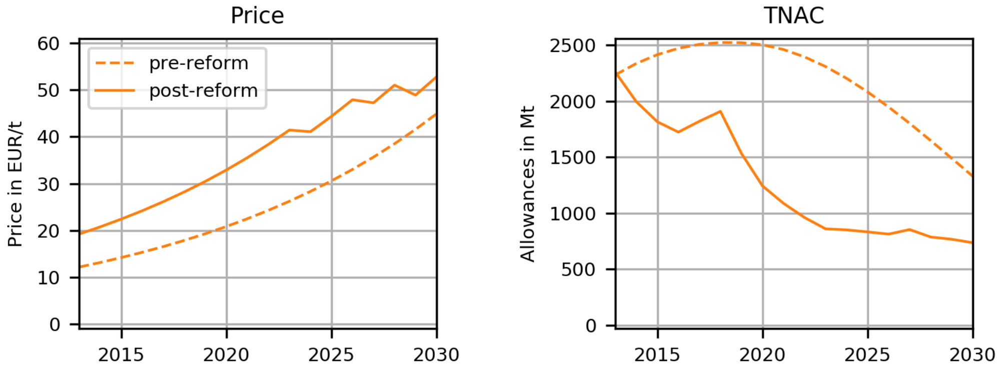

Figure 4: Impact of the reform on market outcomes with a hedging schedule of 60%

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 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.

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.[19]

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 5):

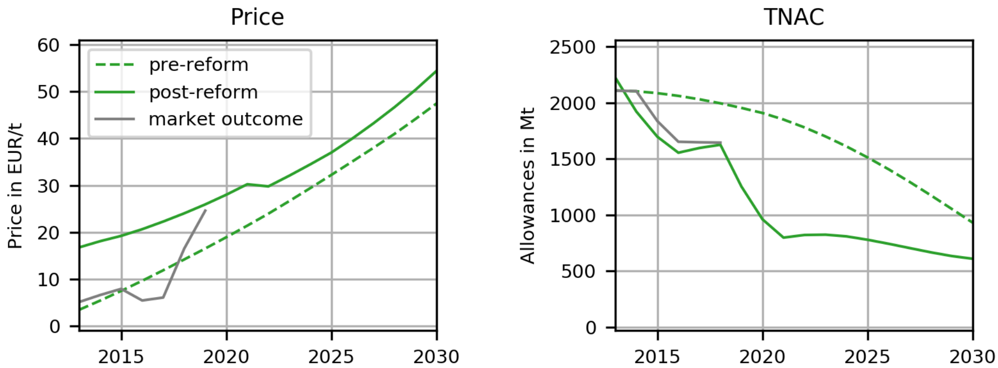

Figure 5: Impact of the reform on market outcomes with a planning horizon of 10 years and a hedging schedule of 50%

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 modeled in the pre-reform scenario and closely resembles the post-reform private bank of around 1630 million allowances in 2018.

[19]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.

The simple comparison of the model results with the stylized facts in Figure 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.

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.

Appendix A. Lagrangian with Hedging Requirements

For the optimization problem $\mathcal{M}$ (Equation 1) with the hedging constraint depicted in Equation 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[20], respectively:

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

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

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

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

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

Primal feasibility:

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

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

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

Dual feasibility and complementarity:

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

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

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