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Hedging and temporal permit issuances in cap-and-trade programs: the Market Stability Reserve under risk aversion

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Abstract

Cap-and-trade programs such as the European Union's Emissions Trading System (EU ETS) expose firms to considerable risks, to which the firms can respond with hedging. We develop an intertemporal stochastic equilibrium model to analyze the implications of hedging by risk-averse firms. We show that the resulting time-varying risk premium depends on the size of the permit bank. Applying the model to the EU ETS, we find that hedging can lead to a U-shaped price path, because prices initially fall due to negative risk premiums and then rise as the hedging demand declines. The Market Stability Reserve (MSR) reduces the permit bank and thus, increases the hedging value of the permits. This offers an explanation for the recent price hike, but also implies that prices may decline in the future due to more negative risk premiums. In addition, we find higher permit cancellations through the MSR than previous analyses, which do not account for hedging.

Keywords: cap-and-trade, risk aversion, hedging, EU ETS, Market Stability Reserve
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1. Introduction

The European Union's Emission Trading System (EU ETS) is the flagship policy for the EU's aspiration to reach climate neutrality by 2050 (European Council 2019). However, observers are puzzled by the ETS permit[1] price development and question whether the EU ETS works efficiently (Ellerman et al. 2016; Friedrich et al. 2020). In particular, the permit price declined from 30 EUR/t in 2008 to well below 10 EUR/t in 2012 where the price stayed until early 2018.[2] One explanation for the price drop is lower-than-expected emissions because of, among others, the financial crisis in 2007–2009 and corresponding lower economic growth rates (Hintermann et al. 2016). According to the European Parliament and Council of the European Union (2015), the resulting "supply-demand imbalance" has destabilized the market. In response, the EU implemented the Market Stability Reserve (MSR), which has two main mechanisms: First, the issuance of permits is postponed, and they are placed in a reserve instead. Second, permits are ultimately canceled when the reserve becomes too large (European Parliament and Council of the European Union 2018). Since this mechanism was announced at the end of 2017, the price has increased to about 25 EUR/t.

However, it remains controversial whether the MSR fixes the EU ETS's problems (Flachsland et al. 2020; Gerlagh et al. 2020). For one, the EU ETS might be plagued by fundamental failures such as myopia, regulatory uncertainty and excessive discounting – all of which distort the intertemporal permit price development (Fuss et al. 2018). In this article, we also consider an intertemporal price distortion, which is affected by the temporal permit issuance: That is, the time schedule when the regulator supplies the permits to the regulated firms. In idealized cap-and-trade programs, the temporal permit issuance is irrelevant as long as permits can be freely banked between periods so that permit holders can decide when to use their permits (Salant 2016). As firms exploit intertemporal arbitrage, free banking implies that the (expected) permit price rises at

[1] In cap-and-trade programs, tradable permits allow firms to release emissions. In the EU ETS, permits are called European Union Allowances (EUAs) where one EUA permits emission of one ton of carbon dioxide equivalent.

[2] Data are publicly available, for example, at https://www.quandl.com.

the discount rate over time (Cronshaw and Kruse 1996; Rubin 1996).[3] Although banking is free in most emission trading programs, such as the EU ETS (ICAP 2020),[4] we show in this paper that the growth rate of the permit price nevertheless can be distorted by the temporal issuance of permits.

The underlying market failure in our approach is a distortion of the permit price due to hedging by risk-averse firms when the markets for risk are incomplete. Specifically, firms reduce their risk exposure (i.e., hedging) by banking permits, as the value of the banked permits (negatively) covaries with the firm profits such that the overall profits are stabilized. However, a limited number of permits are available, and as a result, hedging opportunities are constrained implying a risk premium as part of the permit price. As an alternative to hedging via permits, firms may also trade derivatives of permits (futures contracts) with financial traders (speculators), which, however, only reduces and does not eliminate the risk premium. Our analysis comprises two steps: First, we analyze theoretically how hedging affects prices in intertemporal cap-and-trade programs, such as the EU ETS, and show that the size of the permit bank becomes an important price driver. Second, we apply this theory to assess the price effects of the MSR. Analyzing the MSR is a relevant application, because it shifts permits to the future and thus, reduces the number of permits available for hedging.

Our theoretical approach regarding hedging is based on long-standing literature in financial economics that focuses on the interaction of producers and speculators in commodity (permits, in this case) futures markets (Keynes 1930; Hicks 1939; Anderson and Danthine 1979; 1981; Bessembinder and Lemmon 2002; Goldstein et al. 2014; Ekeland et al. 2019). In this hedging pressure theory, risk-averse producers reduce their profit risk exposure by trading futures contracts with speculators. The demand for futures by the producers raises the price by the risk premium, which indicates the costs of hedging for producers. Hirshleifer (1990) shows that risk premiums arise only from hedging demand

[3]This price path is known as the Hotelling price path (Hotelling 1931).

[4]In the EU ETS and many other ETS programs, banking is free, but borrowing from future periods is not allowed. However, as, for instance, in the EU ETS the actual bank levels are highly positive (European Commission 2019), the borrowing constraint does not play a large role.

in general equilibrium if there is market friction, as otherwise, speculators eliminate the risk premium through diversification. Although several frictions may cause such "limits to arbitrage" (Shleifer and Vishny 1997), we follow Acharya et al. (2013) in assuming that liquidity constraints limit speculators' risk-taking capacity. Therefore, speculators cannot fully satisfy producers' hedging demand implying a non-zero risk premium in the permit price.[5]

Several papers find empirical evidence for such risk premiums in different commodity markets (e.g., Acharya et al. 2013; Hamilton and Wu 2014; Kang et al. 2020), and in particular in the EU ETS (Pinho and Madaleno 2011; Chevallier 2013; Trück and Weron 2016). Furthermore, a survey among market participants of the EU ETS indicates that hedging is the most important motive for trading (KfW and ZEW 2016). Interviews conducted by Schopp and Neuhoff (2013) reveal that electricity producers follow risk management procedures and hold permits for hedging profits several years ahead.

Against that background, we develop a stochastic intertemporal model that comprises dirty (coal) and relatively clean (gas) firms that generate electricity and are regulated by a cap-and-trade program. Firms build up capacity stocks, which constrain electricity generation and amplify the impact of hedging. The risk premium that affects the level and growth rate of the permit price is a function of the firms' hedging demand for permits, the permit price variability and the size of the permit bank. This gives rise to a distinct intertemporal permit price profile. Initially, the dominant hedging demand of dirty coal firms creates a negative risk premium, and thus, they apply a lower discount rate compared to a risk-neutral reference firm. Over time, the market becomes cleaner, implying declining hedging demand by dirty firms. In addition, firms build up a permit bank which allows them to hedge. Thus, the risk premium becomes less negative and

[5]In addition to the hedging pressure theory, our work contains elements of the theory of storage (Kaldor 1939; Working 1949; Brennan 1958; Deaton and Laroque 1992), similar to Acharya et al. (2013) and Ekeland et al. (2019) who also combine both perspectives. The theory of storage explains the relationship between commodity spot and futures prices by the non-negative constraint for commodity inventories and storage costs (e.g., Deaton and Laroque 1992), where permit markets are a special case with negligible storage costs. Moreover, in our model, there is also a non-negative constraint for banking, but it is not our focus. However, the possibility of banking links permit prices over time, and therefore, (expected) risk premiums in the future affect current spot prices.

may turn positive. However, the price path strongly depends on the permits available for hedging purposes, which, in turn, depend on the regulator's time plan (schedule) for issuing permits.

In our stylized simulation of the EU ETS, we find a declining price until 2025–2030 and then a rising price in the counterfactual case without the MSR. Accordingly, hedging results in a U-shaped price path. The MSR amplifies the U-shape as prices are higher in early years than without the MSR, but also decline at a higher rate because the MSR reduces the permit bank level leading to a more negative risk premium. Therefore, the recently observed price hike in the EU ETS presumably due to the MSR may imply that prices in the future will rise only very slowly or even decline.

These findings stand in contrast to previous work on the originally proposed MSR without cancellation of permits (European Parliament and Council of the European Union 2015). An important result of these studies is that the temporal issuance is irrelevant as long as the overall cap remains unchanged, and banking and borrowing constraints do not bind (Salant 2016). Perino and Willner (2016) accordingly find that a cap-neutral MSR lifts the (short-term) permit price only if the borrowing constraint binds earlier due to the MSR. As long-term prices are lower, the authors also conclude that low-carbon investments with long lifetimes may decline (see also Perino and Willner 2019). We find that investments in relatively clean gas capacities are hardly affected, and investments in coal capacity significantly decline in the short-term and are slightly higher in the long-term even when the MSR is cap-neutral. This result can be traced back to worse hedging conditions for dirty firm capacity in the early years and price-level effects related to the risk premium.

Kollenberg and Taschini (2019) go a step further and relate price variability positively to the risk premium for banking permits. Because the MSR raises price variability, the MSR may even lead to lower prices in the short-term, as firms want to use more permits early due to the higher discount rate. Our approach differs from this work by deriving an endogenous (time-dependent) risk premium rather than assuming a positive relationship between price variability and the risk premium. In doing so, we find the differing result that even the cap-neutral MSR raises short-term prices substantially because the hedging value of the permits increases. This is because the risk premium becomes smaller (or more negative) reflecting that firms require a lower return for holding permits due to the hedging value. Hedging in the context of the EU ETS and the MSR is also analyzed by Schopp and Neuhoff (2013) and Schopp et al. (2015). Their approach does not explicitly account for risk and implies inconsistent price jumps (cf. Salant 2016). We overcome these drawbacks by explicitly including a risk factor (permit supply risk) and risk aversion.[6]

Furthermore, several papers[7] analyze the cancellation mechanism of the new MSR. However, these papers assume given discount rates and ignore uncertainty. An exception is provided by Quemin and Trotignon (2019) who analyze the impact of firms' limited planning horizons and limited responsiveness to the MSR. They find a relatively high number of permanent permit withdrawals (5 to 10 Gt) compared to the literature (1.7 to 6.0 Gt) especially if the firms have a limited horizon. We also find a relatively high number of MSR cancellations (8.6 Gt) due to the negative risk premiums, which reduce the applied discount rates in the early years. Therefore, the permit bank is larger, which, in turn, leads to a larger influx in the MSR and thus, more cancellations.

The remainder of this paper is structured as follows: After presenting the general model setup in Section 2.1, we derive formal results in a simplified two-period version of the model in Section 2.2. In Section 3, we apply the model numerically to the EU ETS for multiple periods to assess the MSR regarding its price and investment effects. Finally, we discuss the results and conclude in Section 4.

2. The model

In our model, we consider firms competing in an electricity market. Emissions are a byproduct of electricity generation, and firms are heterogeneous in how clean or dirty their generation is. Emissions are limited by a cap-and-trade program, but the number of

[6] Several other papers consider risk aversion (Baldursson and von der Fehr 2004; 2012; Colla et al. 2012; Haita-Falah 2016) and ambiguity aversion (Quemin 2017) in permit markets. However, all of them have a different focus than we do.

[7] Beck and Kruse-Andersen (2018), Bocklet et al. 2019, Bruninx et al. (2018), Carlén et al. (2019), Gerlagh et al. 2019, Quemin and Trotignon (2019) and Perino and Willner (2017).

permits issued in the future is uncertain, and so are firms' profits. This creates a demand for hedging profits when firms are risk averse. Electricity generators hedge by banking permits and by trading permit futures contracts. In the futures market, we also model a speculator who serves as trading counterparty to the generators. In the following, we describe the model in detail.

2.1. General model setup

We consider N competitive firms, indexed by i, that produce a homogeneous and non-storable good (electricity) x_{it} at T periods, indexed by t. Demand is given by $D(w_t)$ with $D^{'} < 0$ and price w_t. The equilibrium condition,

$$\sum\nolimits_i^N x_{it} = D(w_t), \tag{2.1}$$

is always fulfilled. Firms use production technologies that differ in emission intensity and in how costly they are to install and operate (capacity and production costs), for example, coal and gas plants. We model production costs as a function $C_{Xi}(x_{it})$ with $C^{'}_{Xi} > 0$. To produce x_{it} units, firms also need at least k_{it} units of capacity, for which the capacity costs are given by $C_{Ki}(k_{it})$ with $C^{'}_{Ki} > 0$. We assume that the production and capacity costs are separable, which is a standard assumption in electricity market modeling (Stoft 2002). Defining $\zeta_{it} \equiv \frac{x_{it}}{k_{it}}$ as the capacity utilization rate, production is constrained by

$$1 \geq \zeta_{it} \geq 0. \tag{2.2}$$

Although the utilization rates can be immediately adjusted within a period, investments in (plant) capacity, $I_{Kit} \geq 0$, are added to the existing capacity stock with a lag of one period,

$$k_{it} = (1 - \delta)\, k_{it-1} + I_{Kit-1}, \tag{2.3}$$

where δ is the rate of depreciation.

The firm-specific emission intensity is captured by a time-invariant emission factor ϕ_i;

i.e., the production of each unit of x_{it} causes ϕ_i units of emissions.[8] The heterogeneity in emission factors ϕ_i is important for our analysis, because permit supply uncertainty affects dirty coal firms (high ϕ_i) differently from relatively clean gas firms (low ϕ_i). Overall emissions are capped, because emissions are regulated by a cap-and-trade program. To comply with the regulations, firms need at least as many permits as emissions $x_{it}\phi_i$ at the end of each period t. At the beginning of each period, S_t permits are auctioned[9] by the regulator at price p_t that clears the permit market, that is,

$$S_t = \sum\nolimits_i^N y_{it}, \tag{2.4}$$

where y_{it} is the number of purchased permits. Uncertainty enters the model through permit supply risk in the following way: Initially, the regulator announces a permit auction schedule for the entire lifetime of the cap-and-trade program beginning in the first period and ending in the last period $t = T$. However, in each period the regulator may deviate from her previous announcement and in addition, may announce a new permit supply schedule for future periods τ, $S_\tau \; \forall \, \tau > t$. Thus, uncertainty about the permit supply in period t is resolved at the beginning of t, but the supply in future periods τ remains uncertain. Therefore, in firm expectation the overall supply, or cap, in any period t is

$$E_t\left[\bar{S}\right] = S_t + \sum\nolimits_{\tau>t}^T E\left[S_\tau\right]. \tag{2.5}$$

Furthermore, a reserve mechanism similar to the MSR in the EU ETS affects the permit supply as well. We explain and implement the MSR in detail in the numerical simulation

[8] Constant and time-invariant emission factors are standard assumptions for electricity plants because each unit of fossil fuel (coal, gas) leads to the same amount of emissions and electricity. We ignore technological progress which could improve the conversion efficiency from fossil fuel to electricity. Given the maturity of fossil fuel plants, this is a mild assumption.

[9] Throughout the paper, we assume that the initial allocation of permits is through auctioning; that is, there is no free allocation. Although the allocation method, in general, can affect market outcomes (e.g., Böhringer and Lange 2005), and in particular, if firms are risk averse (Baldursson and von der Fehr 2004; 2012), we omit this to streamline the analysis. In this paper, we focus on the EU ETS and on the electricity sector in the program, where, in principle, all permits are auctioned (European Parliament and Council of the European Union 2018).

in Section 3, but we consider a stylized representation in this analytical part. Recall that the MSR has two effects: First, it shifts the permit supply to the future, and second, it reduces the overall cap by the cancellation of permits. We separate these two mechanisms and model the permit shift as

$$\Delta E_t\left[\bar{S}\right] = \Delta S_t + \sum\nolimits_{\tau>1}^{T} \Delta E\left[S_\tau\right] = 0. \tag{2.6}$$

That is, any change in permit supply ΔS_t in any period is fully compensated by the (announced) supply in other periods such that the total expected cap is always the same from the perspective of period t. Thus, only the temporal permit issuance is affected which corresponds to the first mechanism of the MSR. In addition, the cancellation mechanism leads to an overall lower supply if too many permits are in the reserve. Below, we discuss how hedging affects the number of canceled permits, and we model the entire MSR explicitly in the numerical simulation.

If firms buy more permits y_{it} than they have emissions $x_{it}\phi_i = k_{it}\zeta_{it}\phi_i$, additional permits can be transferred to the next period (banking). Let b_{it} be the banked permits at the end of period t. Then, the dynamic banking constraint is

$$b_{it} = b_{it-1} + y_{it} - k_{it}\zeta_{it}\phi_i, \tag{2.7}$$

while borrowing from the future is not allowed:

$$b_{it} \geq 0. \tag{2.8}$$

Moreover, firms can also trade futures contracts on permits denoted by f_{it}. We consider only futures contracts that expire in the next period. That is, the buyer of $f_{it} > 0$ units of futures bought at price p_t^f in period t receives $f_{it}p_{t+1}$ in period $t+1$, and the seller ($f_{it} < 0$) receives $f_{it}p_t^f$ in period t and has to pay $f_{it}p_{t+1}$ in period $t+1$. For both, the expected payoff of the futures is $\left(E\left[p_{t+1}\right] - p_t^f\right) f_{it}$. As further shown below, futures are a hedging instrument for the electricity-generating firms because the futures' payoff negatively covaries with the plant profits. In addition, a representative speculator is active in the futures market who seeks to gain speculative profits given (in expectation) by the futures' payoff $\left(E\left[p_{t+1}\right]-p_t^f\right) f_{sp,t}$ where $f_{sp,t}$ is the number of futures bought $(f_{sp,t}>0)$ or sold $(f_{sp,t}<0)$ by the speculator. In the futures market equilibrium, positive and negative positions must be balanced:

$$\sum\nolimits_i^N f_{it}+f_{sp,t}=0. \tag{2.9}$$

Furthermore, firms invest in a risk-free asset stock l_{it}, providing a safe return r. This serves as an alternative investment opportunity, allowing for risk-free allocation of wealth over time. Denoting investments in the risk-free asset as I_{Lit}, the risk-free asset stock is

$$l_{it}=(1+r)\, l_{it-1}+I_{Lit}. \tag{2.10}$$

Given this setup, the profits of the electricity-generating firms in period t are

$$\pi_{it}=w_t k_{it}\zeta_{it}-C_{Xi}\left(k_{it}\zeta_{it}\right)-C_{Ki}\left(k_{it}\right)-p_t y_{it}-I_{Lit}-p_t^f f_{it}+p_t f_{it-1}, \tag{2.11}$$

where $w_t k_{it}\zeta_{it}$ describes the revenue for selling electricity, $C_{Xi}\left(k_{it}\zeta_{it}\right)$ and $C_{Ki}\left(k_{it}\right)$ are costs for producing and for plant capacities,[10] respectively. The terms $p_t y_{it}$ and I_{Lit} are costs (>0) or revenues (<0) for trading permits and the risk-free asset, respectively. The term $p_t^f f_{it}$ denotes investments in futures contracts, and the term $p_t f_{it-1}$ reflects profits from futures contracts invested in the previous period. We further assume that firms have concave preferences regarding profits described by a von Neumann–Morgenstern utility function $U_{it}\left(\pi_{it}\right)$ with $U_{it}'>0$ and $U_{it}''<0$. This implies that firms have a preference for a more stable profit, meaning they behave in a risk-averse manner which causes the desire to hedge.[11] The problem of the electricity-generating firms is

[10]Note that we assume for simplicity that there are no costs for investing in plant capacity I_{Kit}. Instead, investment costs are allocated to the capacity costs.

[11]There are several reasons why firms behave as if they are risk averse (Froot et al. 1993; Acharya

$$\max_{\zeta_{it},y_{it},I_{Kit},I_{Lit},f_{it}} \sum_{t=1}^{T} \frac{1}{(1+r)^{t-1}} E\left[U_{it}\left(\pi_{it}\right)\right] \tag{2.12}$$

subject to

$$1 \geq \zeta_{it} \geq 0 \quad I_{Kit} \geq 0 \quad b_{it} \geq 0$$

$$k_{it} = (1-\delta)\, k_{it-1} + I_{Kit-1} \tag{2.13}$$

$$b_{it} = b_{it-1} + y_{it} - k_{it}\zeta_{it}\phi_i$$

$$l_{it} = (1+r)\, l_{it-1} + I_{Lit}.$$

For the analysis below, it is convenient to rewrite the profit by using the intertemporal banking condition (2.7),

$$\pi_{it} = \pi_{it}^{plant} + p_t\left(b_{it-1} - b_{it}\right) - I_{Lit} - p_t^f f_{it} + p_t f_{it-1}, \tag{2.14}$$

with $\pi_{it}^{plant} = w_t k_{it}\zeta_{it} - C_{Xi}\left(k_{it}\zeta_{it}\right) - C_{Ki}\left(k_{it}\right) - p_t k_{it}\zeta_{it}\phi_i$.

The speculator is not active in the electricity market and trades only the risk-free asset and futures contracts. The speculator's profits are

$$\pi_{sp,t} = -I_{L,sp,t} - p_t^f f_{sp,t} + p_t f_{sp,t-1}, \tag{2.15}$$

and the speculator's maximization problem is

$$\max_{I_{L,sp,t},f_{sp,t}} \sum_{t=1}^{T} \frac{1}{(1+r)^{t-1}} E\left[U_{sp,t}\left(\pi_{sp,t}\right)\right] \tag{2.16}$$

subject to

$$l_{sp,t} = (1+r)\, l_{sp,t-1} + I_{L,sp,t}. \tag{2.17}$$

et al. 2013): for example, costs associated with financial distress or principal agent issues that result in higher utility from more stable profit.

Similar to the electricity generators, the speculator evaluates profits based on a concave function $U_{sp,t}(\pi_{sp,t})$ with $U'_{sp,t} > 0$ and $U''_{sp,t} < 0$. In doing so, we follow the financial economics literature (Acharya et al. 2013), by interpreting this as capital constraint. For instance, the constraint could be due to value-at-risk (VaR) limits, and thus, taking risky positions is constrained. Therefore, even if the speculator is risk neutral, she behaves in a risk-averse manner.

2.2. Two-period model

To derive analytical results, we solve the model for two periods, $t = 1, 2$ in this section. In addition, we make the following assumptions: The electricity demand is linear, $D(w_t) = A - aw_t$, the firms' production costs are quadratic $C_{Xi}(x_{it}) = \frac{\beta_i}{2} x_{it}^2$ and their capacity costs are linear $C_{Ki}(k_{it}) = \gamma_i k_{it}$.[12] There are only two firms, $i = c, d$, a relatively clean gas firm and a dirty coal firm with $\phi_d > \phi_c$. Moreover, to arrive at closed-form results we assume a quadratic utility function in some cases, for both electricity generators $U_{it}(\pi_{it}) = \pi_{it} - \pi_{it}^2$ and the speculator $U_{sp,t}(\pi_{sp,t}) = \pi_{sp,t} - \pi_{sp,t}^2$.[13] For the numerical application to the EU ETS in Section 3, we extend the model to multiple periods and show that the results also hold for utility exhibiting constant relative risk aversion.

2.2.1. Period 2 equilibrium

We solve the model backward and start in period 2. Note that all derivations can be found in Appendix A.

As period 2 is the final period, no further investments in plant capacity and futures contracts are made, $I_{Ki,2} = f_{i,2} = f_{sp,2} = 0$, and all available permits are used or sold

[12]These assumptions are motivated by electricity sectors: First, marginal production costs increase with production implying an upward sloping electricity supply curve as with the merit-order curve in electricity markets. Second, capacity costs typically exhibit constant marginal costs per unit of capacity (e.g., costs for coal plant capacity do not increase with the number of installed plants). However, the specific functional forms have only minor relevance for the analytical results as long as one firm type has costs which imply that the firm benefits from a higher permit price (in terms of higher profits), while another firm type has costs so that it loses from a higher price (and vice versa). We show below that this is the case given these assumptions.

[13]Assuming quadratic utility is akin to mean-variance optimization which has a long tradition in financial economics, and especially in the hedging pressure literature (Anderson and Danthine 1979; Ekeland et al. 2019).

(assuming a strictly positive permit price p_2). Similarly, the stock of the risk-free asset is depleted, implying $b_{i,2} = l_{i,2} = l_{sp,2} = 0$. As a result, the speculator has no decision to make. Uncertainty has been resolved, and the generating firms' problem, thus, is to maximize $U_{i,2}(\pi_{i,2})$ over $\zeta_{i,2}$ and $y_{i,2}$ subject to the constraints in (2.13). Taking the first-order conditions (see Appendix A.1), the utilization rate and the permit purchases can be written as

$$\zeta_{i,2} = \frac{w_2 - p_2\phi_i}{\beta_i k_{i,2}} - \frac{\mu_{i,2}}{U'_{i,2}\beta_i k_{i,2}^2}, \tag{2.18}$$

$$y_{i,2} = \phi_i \left(\frac{w_2 - p_2\phi_i}{\beta_i} - \frac{\mu_{i,2}}{U'_{i,2}\beta_i k_{i,2}} \right) - b_{i,1}, \tag{2.19}$$

where $\mu_{i,2}$ is the shadow value of the capacity constraint which is positive if the capacity is fully utilized, $\zeta_{i,2} = 1$, and zero otherwise:

$$\mu_{i,2} = \begin{cases} U'_{i,2}\left(k_{i,2}w_2 - \beta_i k_{i,2}^2 - p_2\phi_i k_{i,2}\right) & if\ \zeta_{i,2} = 1 \\ 0 & if\ 1 \geq \zeta_{i,2} \geq 0 \end{cases}. \tag{2.20}$$

The shadow value $\mu_{i,2}$ indicates the scarcity of capacity k_{it}, which cannot be increased within a period due to the time lag for investments. For (2.19), we assume that the cap is always binding, and therefore, there is always a positive permit price p_2. Note that risk aversion, reflected by the marginal utility $U'_{i,2}$, has no effect in period 2 (in (2.18), either $\mu_{i,2} = 0$ or $U'_{i,2}$ is canceled out due to (2.20)). It adjusts only the shadow value of the capacity which, however, triggers no changes in the firm behavior, because the firm cannot change its capacity level within a period.

By making use of the equilibrium condition of the electricity market, $\sum_i^N k_{i,2}\zeta_{i,2} = D_2 = A - aw_2$, the electricity price reads:

$$w_2 = \frac{1}{(\beta_d + \beta_c + \beta_c\beta_d a)} \left(A\beta_c\beta_d + p_2(\beta_d\phi_c + \beta_c\phi_d) + \beta_d \frac{\mu_{c,2}}{U'_{c,2}k_{c,2}} + \beta_c \frac{\mu_{d,2}}{U'_{d,2}k_{d,2}} \right). \tag{2.21}$$

Similarly, the permit price can be derived from using (2.19) in the permit equilibrium condition, $S_t = \sum_i^N y_{it}$. By additionally considering (2.21), we get:

$$\begin{aligned} p_2 &= \frac{A\left(\beta_d\phi_c + \beta_c\phi_d\right) - \left(\beta_d + \beta_c + \beta_c\beta_d a\right)\left(b_{c,1} + b_{d,1} + S_2\right)}{\left(\phi_c - \phi_d\right)^2 + a\left(\beta_c\phi_d^2 + \beta_d\phi_c^2\right)} \\ &+ \frac{\frac{\mu_{c,2}}{U'_{c,2}k_{c,2}}\left(\phi_d - \phi_c\left(1 + \beta_d a\right)\right) + \frac{\mu_{d,2}}{U'_{d,2}k_{d,2}}\left(\phi_c - \phi_d\left(1 + \beta_c a\right)\right)}{\left(\phi_c - \phi_d\right)^2 + a\left(\beta_c\phi_d^2 + \beta_d\phi_c^2\right)}. \end{aligned} \tag{2.22}$$

Intuitively, the electricity price is a positive function of demand, reflected by A (the intercept of the demand function), and the permit price p_2. Shocks in the permit price, therefore, are transferred to consumers via the electricity price. The only source of uncertainty (from the perspective of period 1) is the permit supply in period 2, S_2.

To examine the effect of a permit supply shock, we assume for a moment that the plant capacity constraints (reflected by the last two terms in (2.21) and (2.22)) do not bind, $\mu_{i,2} = 0$. In this case, a positive shock on S_2 (a less ambitious policy) leads to a lower permit price and vice versa, as can be seen directly from (2.22). Concerning the utilization rates, permit price shocks have the following effects.

Lemma 1. *If the capacity constraints do not bind, $\mu_{i,2} = 0$, a positive permit price shock leads to (1) higher capacity utilization by the clean firm, $\frac{d\zeta_{c,2}}{dS_2} > 0$, iff $\phi_d > \phi_c\left(1 + \beta_d a\right)$ holds, and (2) lower capacity utilization by the dirty firm, $\frac{d\zeta_{d,2}}{dS_2} < 0$. For a negative permit price shock, the opposite holds.*

While the dirty firm always produces less when the permit price increases and vice versa, for the clean firm, it depends on the parameters. Specifically, the condition $\phi_d > \phi_c\left(1 + \beta_d a\right)$ implies that if the demand reaction to price changes in the electricity market is strong enough, reflected by a high a, or the clean firm is not clean enough (i.e., ϕ_c is too large) such that the inequality is violated, the clean firm produces more if the permit price is low. However, we consider the case in which $\phi_d > \phi_c\left(1 + \beta_d a\right)$ holds, and thus, the clean firm increases production as soon as the permit price increases, which reflects the fuel switch in electricity markets. A higher permit price leads to less coal (dirty) and more gas (clean) production.[14] Note that the assumption of non-binding

[14] The fuel switch from coal to gas plants is one of the most important abatement options in the EU

capacity constraints is innocuous for this result. For one, capacity constraints would not switch the sign of the effect on the utilization rates, but instead, restrict the effect size, as the constraints limit or even prevent how firms change their production after a shock. Moreover, typically capacity constraints do not bind in expectation in electricity markets, as power plants are not always fully utilized. Demand varies on a short time scale, and plants have to be ramped up and down. In this sense, the utilization rate in the model should be interpreted as a long-term (e.g., annual) utilization rate.

For the analysis of hedging with permits, the relationship between plant profits and permit price is important.

Lemma 2. *If the capacity constraints do not bind, $\mu_{i,2} = 0$, a positive permit price shock leads to (1) higher plant profits for the clean firm, and thus, $Cov\left[\pi_{c,2}^{plant}, p_2\right] > 0$, if condition $\phi_d > \phi_c\,(1 + \beta_d a)$ holds, and (2) lower plant profits for the dirty firm, and thus, $Cov\left[\pi_{d,2}^{plant}, p_2\right] < 0$. For a negative shock, the opposite holds.*

If condition $\phi_d > \phi_c\,(1 + \beta_d a)$ is fulfilled, and thus, the clean firm increases its production level after a positive permit price shock, the clean firm also gains higher plant profits. The dirty firm produces less (Lemma 1) and has higher costs, and therefore, it always loses from higher ETS prices.

Although we ignore capacity constraints for Lemma 1 and Lemma 2 because they do not change the nature of the results, they have an important impact on the price sensitivity to permit supply shocks, which we consider as the measure of price variability. Specifically, it can be shown (see Appendix A.2) that if electricity generation is constrained by plant capacity, the permit price variability is higher. The intuition is that capacity partly locks in production levels. This implies that firms have less flexibility to react to shocks. For instance, after a negative permit supply shock, the production of the clean firm increases less if the capacity constraints bind. To comply with the cap, the permit price must rise to a higher level than without capacity constraints, because abate-

ETS when the permit price is above approximately 20-30 EUR/t (depending on coal and gas prices; Friedrich et al. 2020). As the permit price has been above 20 EUR/t since 2019 (with the exception of a short period due to the COVID-19 shock), modeling the fuel switch is very relevant.

ment is achieved with more expansive technologies (i.e., via lower electricity demand in the model). As a result, the higher price variability also leads to higher profit variability, and thus, it amplifies the effect of hedging which we analyze further below.

2.2.2. Period 1 equilibrium

In period 1, electricity-generating firms have to make decisions under uncertainty about the permit supply by maximizing utility in (2.12) for $T = 2$ and subject to (2.13). While the capacity utilization rate $\zeta_{i,1}$ and the permits trades $y_{i,1}$ must fulfill the same condition as in period 2, generators additionally decide about the optimal permit bank level $b_{i,1}$, capacity level for period 2 $k_{i,2}$[15] and the amount invested in the risk-free asset $l_{i,1}$ and futures contracts $f_{i,1}$. In addition, the speculator maximizes (2.16) subject to (2.17) via investments in the risk-free asset $l_{sp,1}$ and futures contracts $f_{sp,1}$ (see Appendix A.1 for all first-order conditions). First, we analyze how the generators hedge via the permit bank, and how this affects the permit price while we ignore futures markets and plant capacities. Then, we add the futures market to the analysis and show that its main effect is to reduce risk premiums. In the last two parts of this section, we examine the capacity effects and discuss the impact of the MSR.

Banking and hedging. The number of permits firms buy is equal to their period 1 emissions plus the desired bank at the end of period 1,

$$y_{i,1} = \phi_i \zeta_{i,1} k_{i,1} + b_{i,1}, \tag{2.23}$$

where the banking demand can be written as follows:

$$b_{i,1} = \frac{E\left[p_2\right] - p_1\left(1+r\right)}{\lambda_i Var\left[p_2\right]} - \frac{Cov\left[\pi_{i,2}^{plant}, p_2\right]}{Var\left[p_2\right]} - \frac{\left(1+r\right)\varphi_{i,1}}{U'_{i,1} Var\left[p_2\right]}, \tag{2.24}$$

for which we assume quadratic utility with $\lambda_i = -\frac{U''_{i,1}}{U'_{i,1}}$ as the coefficient for absolute risk aversion. The third term on the right side in (2.24) includes the shadow price of

[15]Due to the time lag for investments in capacity, we assume for simplicity that there are sufficient initial capacities $k_{i,1}$ such that the capacity constraints do not bind in period 1.

the borrowing constraint $\varphi_{i,1}$ (due to inequality (2.8)), which is positive if firms want to borrow ($b_{i,1} < 0$) but cannot, and zero otherwise. The first term reflects the intertemporal arbitrage or speculation motive. If the expected discounted price exceeds today's price $E[p_2] - p_1(1+r) > 0$, firms want to hold a positive bank for purely speculative reasons and vice versa. The second term is the hedging demand, determined by the covariance of plant profits with the period 2 permit price. It reflects the number of permits that firms want to bank to reduce their risk exposure. For this hedging demand, we have the following proposition.

Proposition 1. *For a pure hedging purpose, the dirty firm wants to hold a positive number of permits $b_{d,1} > 0$ (banking), and the clean firm holds no permits, $b_{c,1} = 0$. The clean firm holds a positive number of permits only if $E[p_2] - p_1(1+r) > \lambda_i Cov\left[\pi_{c,2}^{plant}, p_2\right]$.*

Intuitively, dirty firms want to hold a long position in the permit market (i.e., banking) because they are short with respect to the permit price in the electricity market; for clean firms, the opposite holds (see Lemma 2). This is reflected by the hedging demand, the second term in Equation (2.24), which is positive for dirty firms because $Cov\left[\pi_{d,2}^{plant}, p_2\right] < 0$ and negative for clean firms because $Cov\left[\pi_{c,2}^{plant}, p_2\right] > 0$. However, because we assume that borrowing is not allowed, clean firms cannot hedge their electricity market profits by trading permits. Only when the speculative demand exceeds the hedging demand, i.e., if $E[p_2] - p_1(1+r) > \lambda_i Cov\left[\pi_{i,2}^{plant}, p_2\right]$, clean firms bank, because the expected profit for banking compensates for the higher risk exposure due to banking.

The implications of the hedging demand for the permit price can be analyzed by decomposing the price dynamics into three parts:

$$\frac{E[p_2] - p_1}{p_1} = r + \frac{(1+r)\varphi_{i,1}}{p_1 E\left[U_{i,2}'\right]} + q_1. \tag{2.25}$$

The first term is the risk-free rate r, which reflects the opportunity to invest in the alternative asset $l_{i,1}$. The second term is present only if the borrowing constraint binds. In this case, the shadow price is positive $\varphi_{i,1} > 0$, and therefore (while ignoring q_1), the growth rate is lower than the interest rate r. This is a standard result in the deterministic or risk-neutral case (Rubin 1996; Schennach 2000; Fell 2016). The third term q_1 is the risk premium in period $t = 1$ which emerges endogenously due to the firms' hedging demand. With a general utility function, it is $q_1 = -\frac{Cov\left[U'_{i,2}, p_2\right]}{E\left[U'_{i,2}\right]p_1}$, and thus, it depends on the firms' risk preferences, reflected by the marginal utility $U'_{i,t}$ and the relationship of the firm's marginal utility to the permit price, reflected by the covariance term. Assuming quadratic utility and considering the permit market clearing in Equation (2.4), the equilibrium risk premium can be expressed as follows:

$$q_1 = \frac{\Lambda}{p_1}\left(Cov\left[\pi_{d,2}^{plant}, p_2\right] + Cov\left[\pi_{c,2}^{plant}, p_2\right] + Var\left[p_2\right]B_1\right), \tag{2.26}$$

where $B_1 = b_{d,1} + b_{c,1}$ is the total bank, and $\Lambda \geq 0$ is a parameter that reflects the risk-taking capacity of the market. The risk-taking capacity if both firms bank is $\Lambda = \left(\lambda_d^{-1} + \lambda_c^{-1}\right)^{-1}$. If only one firm banks, the risk-taking capacity is $\Lambda = \lambda_i$ (recall that λ_i is the coefficient of absolute risk aversion). A large Λ implies a low risk-taking capacity, and in the case of risk neutrality, $\Lambda = 0$, the risk-taking capacity is infinitely large, and the risk premium would disappear, $q_1 = 0$. Equation (2.26) further shows that the price variability, $Var\left[p_2\right]$, has a positive effect on the risk premium, because price variability increases the risk of permit banking, and thus, firms require a higher return for banking. Similarly, a higher overall bank, B_1, in isolation increases the volume of risky permits for which firms require a larger risk premium. In contrast, the hedging demand may have a positive or negative effect on the risk premium. The clean firm's hedging demand increases, and the dirty firm's hedging demand decreases, the risk premium, because $Cov\left[\pi_{c,2}^{plant}, p_2\right] > 0$, and $Cov\left[\pi_{d,2}^{plant}, p_2\right] < 0$ (see Lemma 2).

However, the clean firm banks only if the risk premium is positive (cf. Proposition 1), and thus, the sign of the risk premium depends only on the strength of the dirty firm's hedging demand and the risk of banking permits $\left|Cov\left[\pi_{d,2}^{plant}, p_2\right]\right| \lesseqgtr Var\left[p_2\right]b_{d,1}$. If the former exceeds the latter, the risk premium is negative. This is because banking has the additional benefit of lower risk exposure for dirty firms in this case. Therefore, they are willing to accept a lower return for banking permits (potentially even a negative one). In turn, if the permit price variability and the banked volume are too high so that $\left|Cov\left[\pi_{d,2}^{plant}, p_2\right]\right| < Var\left[p_2\right] b_{d,1}$ holds, the risk premium is positive, and the dirty firm requires a risk premium for holding permits.

Proposition 2. *The risk premium increases with the permit price variability $Var\left[p_2\right]$, and the hedging demand of the clean firm $Cov\left[\pi_{c,2}^{plant}, p_2\right]$. It is decreasing in the absolute value of the (generally negative) hedging demand of the dirty firm $\left|Cov\left[\pi_{d,2}^{plant}, p_2\right]\right|$. The sign of the risk premium is positive if $\left|Cov\left[\pi_{d,2}^{plant}, p_2\right]\right| < Var\left[p_2\right] b_{d,1}$, and vice versa.*

In the absence of capacity constraints, a positive risk premium always leads to a lower price and higher emissions in period 1, and a higher (expected) price and lower emissions in period 2. By rewriting (2.25) as $p_1 = \frac{E[p_2]}{(1+r+q_1)}$, it becomes obvious that the risk premium has the same effect as the risk-free rate. Thus, a positive risk premium increases the applied discount rate and leads to a steeper price path, and vice versa. The size of the risk premium hinges on the risk-taking capacity of the market reflected by Λ (see Equation (2.26)). Next, we show how futures markets reduce risk premiums by increasing the risk-taking capacity (lower Λ).

The effect of futures markets. In this section, we add the futures market and speculators to the model as described in Section 2.1. Assuming quadratic utility, and maximizing (2.16) via $f_{sp,1}$ subject to (2.17), yields the speculator's futures trades:

$$f_{sp,1} = \frac{E\left[p_2\right] - p_1^f\left(1+r\right)}{\lambda_{sp} Var\left[p_2\right]}. \tag{2.27}$$

The coefficient of absolute risk aversion $\lambda_{sp} \geq 0$ reflects the severity of the speculator's capital constraint (cf. Acharya et al. 2013). If $\lambda_{sp} = 0$, the constraint does not bind, and the speculator can fully exploit intertemporal arbitrage implying that she invests in the futures market until it holds $E\left[p_2\right] = p_1^f\left(1+r\right)$. If $\lambda_{sp} \to \infty$, the speculator has no liquid funds to invest in the futures market implying $f_{sp,1} = 0$. For $0 < \lambda_{sp} < \infty$, the speculator increases the funds invested in the futures market with the expected profit for this investment, $E\left[p_2\right] - p_1^f\left(1+r\right)$.

Dirty and clean firms maximize (2.12) via $f_{i,1}$ subject to (2.13), which gives the demand for futures:

$$f_{i,1} = \frac{E\left[p_2\right] - p_1^f\left(1+r\right)}{\lambda_i Var\left[p_2\right]} - \frac{Cov\left[\pi_{i,2}^{plant}, p_2\right]}{Var\left[p_2\right]} - b_{i,1}. \tag{2.28}$$

The expression shows that an increase in the permit bank $b_{i,1}$, reduces the demand for futures by the same number (all else equal). The reason is that buying a permit instead of a futures contract is a perfect substitute in terms of hedging: Buying one permit or one futures contract in $t = 1$ both yields the same random profit p_2 in $t = 2$ implying that they have the same hedging effect reflected by $Cov\left[\pi_{i,2}^{plant}, p_2\right]$. As long as there is a positive bank in equilibrium (i.e., the borrowing constraint does not bind, $\varphi_{i,1} = 0$), the permit price and the futures price must be equal, $p_1 = p_1^f$, due to arbitrage. This can be seen by using (2.28) and (2.27) in the equilibrium condition of the futures market (2.9) to derive the futures price:

$$p_1^f = \frac{E\left[p_2\right]}{(1+r)} - \frac{\Lambda^f}{(1+r)}\left(Cov\left[\pi_{d,2}^{plant}, p_2\right] + Cov\left[\pi_{c,2}^{plant}, p_2\right] + Var\left[p_2\right] B_1\right), \tag{2.29}$$

where Λ^f is the risk-taking capacity of the market if a futures market exists, as opposed to Λ without a futures market. Similarly, the permit price p_1 can be derived by using the demand for permits (2.23) in the ETS market equilibrium (2.4) (see Appendix A.3.1), which yields the same expression (if the borrowing constraint does not bind) implying $p_1 = p_1^f$. However, a difference from permits is that futures allow the clean firm to hedge as well, because short positions ($f_{it} < 0$) are possible, which is not allowed in the permit market due to the borrowing constraint ($b_{it} \geq 0$).

The main implication of the futures market is that the speculator increases the risk-taking capacity because $\Lambda^f = \left(\lambda_d^{-1} + \lambda_c^{-1} + \lambda_{sp}^{-1}\right)^{-1} < \Lambda = \left(\lambda_d^{-1} + \lambda_c^{-1}\right)^{-1}$ holds. That is, if a speculator is active in the futures market, the risk premium becomes smaller as can be shown by replacing Λ by Λ^f in the expression for the risk premium (2.26). The strength of this effect depends on the speculator's capital constraint: If the constraint does not bind ($\lambda_{sp} = 0$), the speculator eliminates the risk premium, and if the constraint is too binding ($\lambda_{sp} \to \infty$,), the risk-taking capacity becomes $\Lambda = \left(\lambda_d^{-1} + \lambda_c^{-1}\right)^{-1}$, because the speculator does not trade futures.

Capacity effects. In this section, we look at the effect of plant capacity, which we have ignored thus far. Optimal capacity investments can be decomposed into three parts:

$$k_i = \frac{1}{\gamma_i}\left(E\left[\zeta_{i,2}\right]E\left[\mu_{i,2}^{RN}\right] + Cov\left[\zeta_{i,2}, \mu_{i,2}^{RN}\right] + \frac{1}{U_{i,1}'}Cov\left[U_{i,2}', \mu_{i,2}^{RN}\right]\right), \qquad (2.30)$$

where $\mu_{i,2}^{RN}$ is the marginal capacity value in the risk-neutral case (i.e., $\mu_{i,2}$ if $E\left[U_{i,2}'\right] = 1$; see Equation (2.20)). The first two terms on the right side in (2.30) reflect the optimal capacities when firms are risk neutral. Specifically, the effect of uncertainty in the risk-neutral case compared to the deterministic case is given by $Cov\left[\zeta_{i,2}, \mu_{i,2}^{RN}\right]$. Because $Cov\left[\zeta_{i,2}, \mu_{i,2}^{RN}\right]$ is strictly positive, uncertainty has a positive impact on capacity investments, ceteris paribus. The intuition for this is that $\mu_{i,2}^{RN}$ reflects the scarcity of capacity. Thus, $\mu_{i,2}^{RN}$ is bounded at zero but has no upper bound. Therefore, capacity constraints induce an asymmetric impact of symmetric shocks if the shocks are large enough. This leads to higher expected profits reflected by a higher capacity value implying more investments in capacity.

The third term represents the effect of risk aversion. If firms do not bank permits, then $Cov\left[U_{i,2}', \mu_{i,2}^{RN}\right] \leq 0$ holds, and thus, risk aversion has a negative impact on investments, ceteris paribus. This is intuitive, as capacity investments are risky, and firms are risk averse. However, the effect of banking permits on $Cov\left[U_{i,2}', \mu_{i,2}^{RN}\right]$ is positive for the dirty firm and negative for the clean firm, and we have the following result.

Proposition 3. *Banking has a positive effect on investments in dirty capacity and a negative effect on investments in clean capacity, ceteris paribus.*

The intuition is that banking hedges dirty plant profits, but increases the risk for clean firms, and the investment incentives change accordingly. For hedging purposes, clean plants require a futures market that allows them to take short positions akin to permit borrowing as explained in the previous section.

The impact of the MSR. Next, we consider the effect of the MSR on the permit price path and investments in plant capacities. We analyze the effect of shifting permits to the future before we discuss permit cancellations.

We model shifts of permits to the future with a cap-neutral permit reallocation in the sense of Equation (2.6). Issuing more permits in period 2, rather than in period 1, reduces the permit bank of all firms with a positive bank at the end of period 1. By using the first-order conditions, we get the following relation between permit prices, $p_1 = \frac{E\left[U'_{i,2}p_2\right]}{(1+r)U'_{i,1}}$. Taking the partial derivative with respect to the bank and exploiting the concavity of the utility function ($U'_{i,1} > 0$ and $U''_{i,2} < 0$) yields

$$\frac{\partial p_1}{\partial b_{i,1}} = \frac{E\left[U''_{i,2}p_2^2\right]U'_{i,1} + E\left[U'_{i,2}p_2\right]U''_{i,1}p_1}{U'^2_{i,1}} < 0. \tag{2.31}$$

Thus, if the bank volume decreases, p_1 increases. This is because firms require a lower return for holding fewer permits (lower risk premium, see (2.26)), which is achieved with a higher price in period 1. Intuitively, a higher permit price in period 1 leads to less emissions in period 1. If the total (expected) number of permits is given, this implies that the expected emissions in period 2 must increase, and in turn, the expected period 2 permit price must decline. We summarize this in the following proposition.

Proposition 4. *A temporal reallocation of permits by the regulator to period 2 in the sense of Equation* (2.6) *such that bank B_1 decreases leads to a higher permit price and lower emissions in period 1 and a lower expected permit price and higher expected emissions in period 2, and vice versa.*

Thus, the regulator's decision about the temporal issuance of permits has real production effects even if the borrowing constraint is not affected.[16] The reason is that it matters who owns the permits: If firms bank permits in private accounts, the firms bear the risk of a changing permit price. However, this also allows firms to hedge their profits

[16] In the risk-neutral case, the shift of permits to the future affects the price only via the borrowing constraint (Perino and Willner 2016). We exclude the effect of the borrowing constraint as it never binds before all permits are used up after the second period. However, we account for this effect in the numerical simulation in the next section.

by exploiting the covariance of the permit price and plant profits (see above). In contrast, if the permits are issued later and are transferred into the MSR instead, the firms cannot use the permits for hedging purposes. Thus, if not enough permits are available for hedging purpose, dirty firms are willing to pay for holding a bank (negative risk premium) to reduce their risk exposure. If instead, too many permits are available, the firms require a positive risk premium for holding permits. These hedging or risk costs are incorporated into the permit price, such that firms emit less in the first period if the number of permits available is reduced through the shifting mechanism of the MSR.

The implications for the investment incentives in dirty and clean capacity are ambiguous. On one hand, a lower expected permit price in the future increases (decreases) investments in dirty (clean) capacity. On the other, a lower permit bank level raises the costs of hedging dirty plants (see Proposition 3) implying weaker incentives to invest in them.

The second mechanism of the MSR cancels permits if too many of them are stored in the reserve. The main effect of this measure is that the overall cap is reduced such that the entire price path is lifted upward. As the number of permits in the reserve depends on the size of the bank B_1, ultimately, the number of canceled permits depends on B_1. Compared to the risk-neutral reference case, hedging may increase or decrease the bank, and thus, cancellations: If the hedging demand of dirty firms outweighs the available permits and the hedging demand of clean firms, the bank is larger due to hedging and vice versa (see above). We analyze the implications of hedging for permit cancellations in more detail in the following section.

3. Numerical application to the EU ETS

In this section, we apply the model to the EU ETS to (1) demonstrate the impact of hedging in a multi-period setting and (2) assess the effects of the explicitly implemented MSR rather than the stylized MSR version of the previous section. As a reminder, the MSR was introduced to stabilize the permit price on a higher level and spur cleaner investments. However, as the model is highly stylized, the numerical outcomes should be interpreted as qualitative results rather than numerical estimates. In the following section, we explain the model implementation and important assumptions.

3.1. Model implementation

The main sectors of the EU ETS are the electricity sector and the energy-intensive industry. However, we explicitly consider only the electricity sector for which dirty (coal) and relatively clean (gas) plants can be identified, and hedging behavior is also observed in practice (Schopp and Neuhoff 2013). That is, we solve the firms' problems given by Equations (2.12) and (2.13) for $i = c, d$, a representative gas and coal firm. In principle, the analysis carried out in this paper should also hold for firms in other sectors because the permit price affects their profits in a similar way.

We focus on the time period between 2018 and 2057, but solve the model until 2102 to set investment incentives beyond 2057. The model explicitly considers only every fifth year such that we have $T = 17$ model periods, while we write $t = 2020, 2025, ..., 2100$ for every five-year period and $y = 2018, 2019, ...2102$ for every year.

Due to the more detailed approach of modeling the MSR compared to the analytical section, we adapt the notation slightly. At the beginning of the first year, the regulator announces it will issue $\hat{S}_y$ permits each year (for $\hat{S}_t$, we take the average of the respective five years). The parameter $\hat{S}_y$ corresponds to the (announced) permits to be auctioned in the EU ETS between 2018 and 2057, with a linear reduction factor[17] of 1.74% until 2020 and then 2.2% (European Parliament and Council of the European Union 2018), which implies that the last permits are issued in 2057. In line with current regulation, we assume that permits issued to the electricity sector are auctioned, while the auction share of all issued permits is 57% (European Parliament and Council of the European Union 2018). The remaining 43% of the permits are freely allocated to the other ETS sectors. We assume that the freely allocated permits cover the emissions from these sectors such that the expected net permit demand of these other sectors is zero.

We consider an additive shock θ_t to the permit supply such that the permits available

[17]The linear reduction factor determines by how much the annually issued permits are reduced (excluding the impact of the MSR).

to the electricity sector (excluding the MSR effects) are $S_t = \hat{S}_t + \theta_t$. Regulatory supply uncertainty is one rationale for this shock. As an alternative interpretation, the shock θ_t may also include the uncertain permit demand of the other ETS sectors, such that S_t would reflect the permit supply net of the other sectors' demand. Specifically, we assume the following shock process:

$$\theta_t = \theta_{t-1} + \epsilon_t \quad \forall\, 2045 \geq t \geq 2025, \tag{3.1}$$

with $\epsilon_t \in \{-0.35\hat{S}_t, 0.35\hat{S}_t\}$ where the positive and negative shocks have the same probability.[18] Lacking real-world guidance, we assume that the shocks are a proportion (35%) of the initially announced permits ($\hat{S}_t$). This yields a price volatility that is close to the actual observed volatility,[19] but it is clearly only a rough representation of the actual shocks in the EU ETS.

We model the MSR close to its actual implementation (European Parliament and Council of the European Union 2015; 2018). If the aggregate firm bank in the previous year B_{y-1} is larger than 0.833 Gt, a share ω_y of that bank is deducted from the auctioned permits in year y (if there are enough permits to be auctioned). The share is $\omega_y = 0.24$ until $y = 2023$ and $\omega_y = 0.12$ thereafter. Permits that are not auctioned due to this mechanism are denoted by M_y^{in} and go into the reserve denoted by M_y. If the banked permits in the previous year are lower than 0.4 Gt, the number of M_y^{out} is released from the reserve and added to the auctioned permits. This number is equal to 0.1 Gt (if there are enough permits in the MSR). If the bank in the previous year lies within the corridor, $0.4 < B_{y-1} < 0.833$, the permit supply is not adjusted. Therefore, the actual permits

[18] Note that we assume that the last shock emerges in period $t = 2045$ (2043–2047) due to computational constraints.

[19] In the model, the price volatility (measured as the relative standard deviation) is about 58% (excluding the MSR) in 2025 from the perspective of 2020 (see Figure C.5 in Appendix C). The actual price volatility of the EU ETS price (2008 until the end of 2019) is 60%. Further note that to avoid a negative auction supply, we set potential negative auction values due to the shocks to zero.

issued after the impact of the MSR S_y^M reads

$$S_y^M = \begin{cases} S_y - \min\left(\omega_y B_{y-1}; S_y\right) & if\ B_{y-1} > 0.833\,Gt \\ S_y + \min\left(0.1; M_{y-1}\right) & if\ B_{y-1} < 0.400\,Gt \\ S_y & otherwise, \end{cases} \tag{3.2}$$

and the number of permits in the reserve is given by

$$M_y = M_{y-1} + M_y^{in} - M_y^{out} - \max\left(M_y - S_{y-1}^M; 0\right). \tag{3.3}$$

The last term in (3.3) reflects the cancellation of the permits. From 2023 onward, if there are more permits in the MSR than were auctioned in the previous year, these permits are invalidated, implying that the overall cap of the ETS is tightened. The MSR starts to operate in 2019 with $M_{2019} = 1.525$ Gt permits.[20] Under the current regulation, the number of permits in the MSR would only slowly decline in some scenarios, and therefore, a positive reserve could remain in the terminal model period. Because we focus on the time until 2057, but a positive reserve in the terminal model period effectively reduces the cap (and thus, affects the permit price in all periods), we assume that from 2058 onward the outtake of the MSR increases from 0.1 to 1 Gt.

Based on the European Commission (2019), we set the initial bank volume to $B_{2018} = 1.655$ Gt and assume that initially all permits are held by the dirty coal firm because the gas firm has no incentive to bank for hedging purposes (cf. Proposition 1). The risk-free rate is assumed to be $r = 3\%$. Additional details of the assumed parameters are in Appendix B. To solve the model with the MSR, we initially run the model with the auction schedule S_t without the MSR. The resulting bank volumes B_t are then used to compute the MSR adjustments according to (3.2) and (3.3). The model is solved again

[20]The MSR is initially filled with permits that were backloaded between 2014 and 2016 (0.9 Gt) and other unallocated permits that are estimated to be between 0.55 to 0.7 Gt (European Commission 2015). Taking the sum of the arithmetic mean of this estimate and of the 0.9 Gt backloaded permits yields $M_{2019} = 1.525$ Gt.

with the adjusted permit issuance S_t^M. This procedure is iterated until it converges.[21]

3.2. Results

To disentangle the two effects of the MSR (permit shifting over time and cancellation), we consider three base scenarios: a scenario without the MSR, one with the MSR but without cancellation, and a scenario with the MSR and cancellation. Each base scenario is run in two variations, with risk aversion (RA) and with risk neutrality (RN), to show the effects of hedging. Thus, we have six scenarios in total denoted by *RN*, *RA* (both without the MSR), *RN MSR*, *RA MSR* (the MSR without cancellation), *RN MSR + cancel,* and *RA MSR + cancel* (the MSR with cancellation). In scenarios without the MSR the initial MSR bank is added to the initial bank level of the coal firm. In Section 3.2.1, we focus on the price effects of hedging and on the effect of permit shifting due to the MSR, ignoring cancellation. Then in Section 3.2.2 we examine the actual MSR as implemented in the EU ETS including cancellation. We show only results until 2055, for the full time horizon, see Appendix C.[22]

3.2.1. Hedging effects and the MSR without cancellation

Figure 3.1 (a) shows the development of the expected permit price for all six scenarios. First, we focus on the differences between the scenarios without the MSR (*RA*, *RN*, black lines) which reveal the effect of hedging. Initially, the price is higher with risk aversion; then the price declines and drops below the risk-neutral case from 2035 onward. Deviations between *RA* and *RN* are driven by the firms' hedging demand, as reflected by risk premiums, shown in Figure 3.1 (b). In the early years, the risk premium at -5% is highly negative, and because the permit price grows at the sum of the risk-free rate (3%) and the risk premium, the price actually declines. The negative risk premium can be explained by the high coal production level and thus, the coal firm's high hedging demand. The available permits for banking do not suffice to cover the coal firm's high

[21]The model is implemented with the software GAMS as Extended Mathematical Programming (EMP) model with the solver JAMS. The code is available on request.

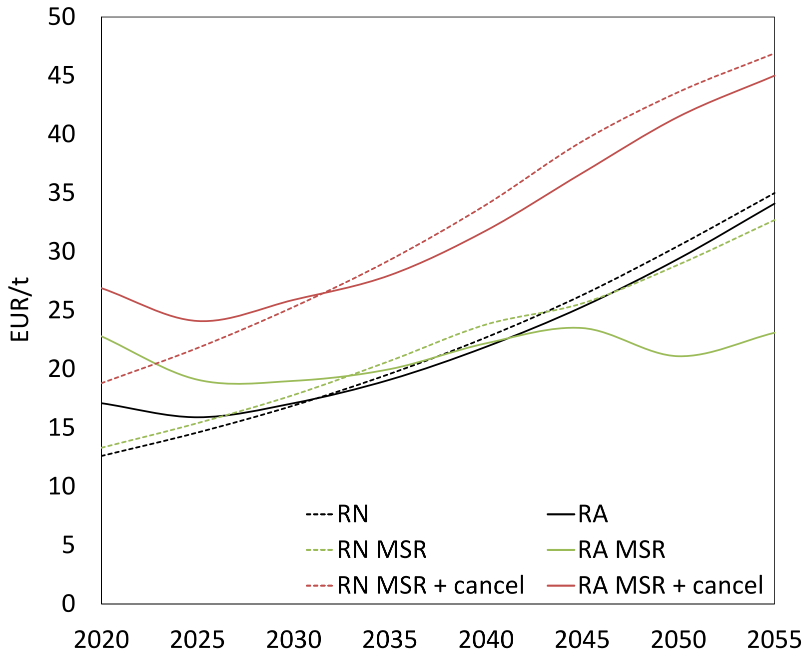
[22]Note that we concentrate on scenarios without a futures market as they do not affect the main insights (see Section 2.2.2). However, we briefly compare the results to the case with the futures market in Section 3.2.2 and show results for futures markets in Appendix C.

hedging demand. As a result, the firm accepts a reduced return for holding permits reflected by the negative risk premium. Over time, the hedging demand declines as coal production is reduced in the market, and the bank volume rises (see Figure 3.2 (a)). Consequently, the risk premium declines. Note that the lower growth rate and the price decline after 2045 are due to binding borrowing constraints.

Next, we consider the impact of the MSR if cancellation is not active by comparing the green and black lines in Figure 3.1 (a). The figure shows that the MSR raises near-term prices but lowers long-term prices under risk neutrality and risk aversion. The effect is small for risk neutrality and can be explained by an earlier binding borrowing constraint for permits (see Perino and Willner 2016). With risk aversion, the effect of the MSR is significantly amplified: Instead of a price increase of only 0.70 EUR/t in 2020 (*RN MSR* vs. *RN*), the price increases by 5.70 EUR/t (*RA MSR* vs. *RA*) if the firms' hedging demand is considered. However, the short-term price increase in the case of risk aversion implies a lower growth rate such that the price level in *RA MSR* in 2040 is only as high as in 2020. The reason for the strong effects of the MSR even without cancellation is the firm's reduced bank level as shown in Figure 3.2 (a). Instead of firms holding permits, a large number of permits are transferred into the MSR bank (see Figure 3.2 (b)) where they cannot cover the firms' hedging demand. Note that even without the MSR there are not enough permits to cover the hedging demand reflected by the negative risk premium. Because the MSR reduces the permit availability further, it implies an even more negative risk premium (see Figure 3.1 (b)), leading to higher short-term and lower long-term prices as explained above.

Figure 3.1: Expected permit price and risk premium

(a) Price



(b) Annual risk premium

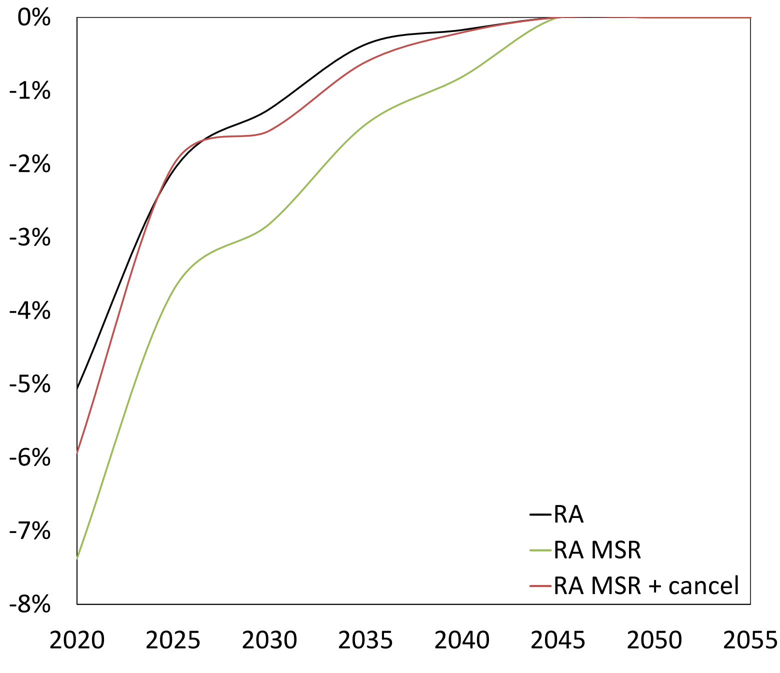
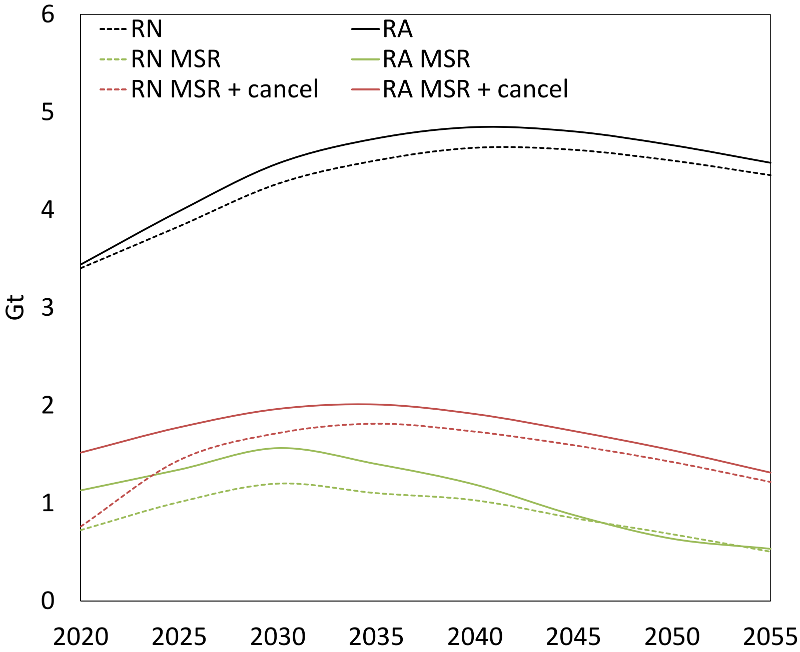
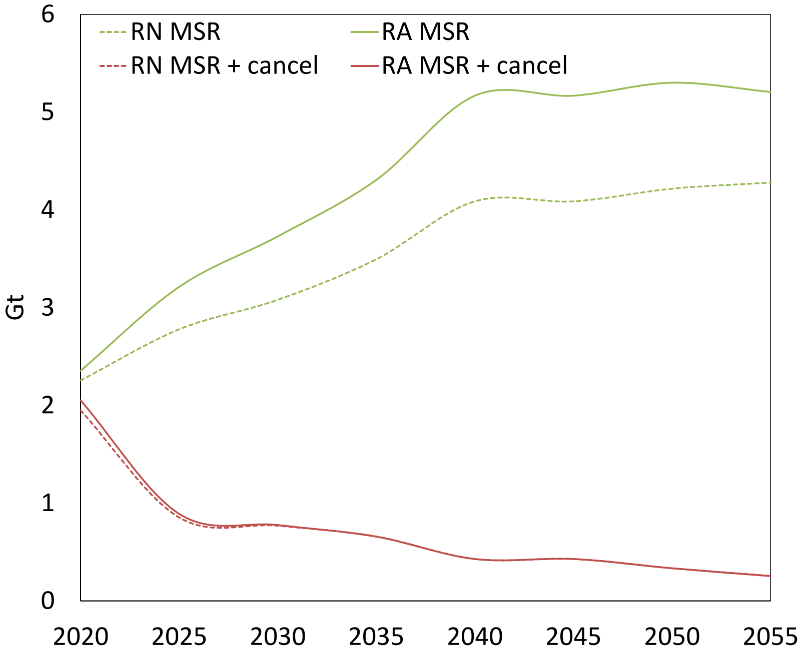


Figure 3.2: Expected firm bank and MSR level

(a) Aggregate firm bank



(b) MSR level



Note: At the beginning of the first period firm banks in *RA* and *RN*, as well as in the four MSR scenarios are the same, respectively. The figure shows bank levels at the end of each period and thus the lines in the figure do not start from the same point. The same holds for the MSR level. In line with Proposition 1 the gas firm does not bank in *RA* scenarios before 2025 or 2030, depending on the scenario.

3.2.2. MSR with cancellation

We consider how the cancellation mechanism affects the price pattern and how hedging affects the number of cancellations. Then, we briefly discuss the impact of the MSR on plant investments.

In scenarios with cancellation (red lines in Figure 3.1 (a)), a similar price pattern to scenarios without cancellation can be observed but at a higher level. Moreover, cancellation mitigates the price drop after 2020, and thus, the price level of 2020 is reached in 2035 instead of 2040 as without cancellation. This can be traced back to the higher price level induced by cancellations: First, higher prices imply less coal production, and thus, a reduced need to hedge dirty profits. Second, less coal production also implies a higher bank level (see Figure 3.2 (a)). Therefore, the mismatch between hedging demand and permit availability is lower compared to *RA MSR,* and in turn, the risk premium is less negative as well (see Figure 3.1 (b)). Overall, the price starts at a higher level and declines less. As a result, prices are strictly higher than without the MSR.

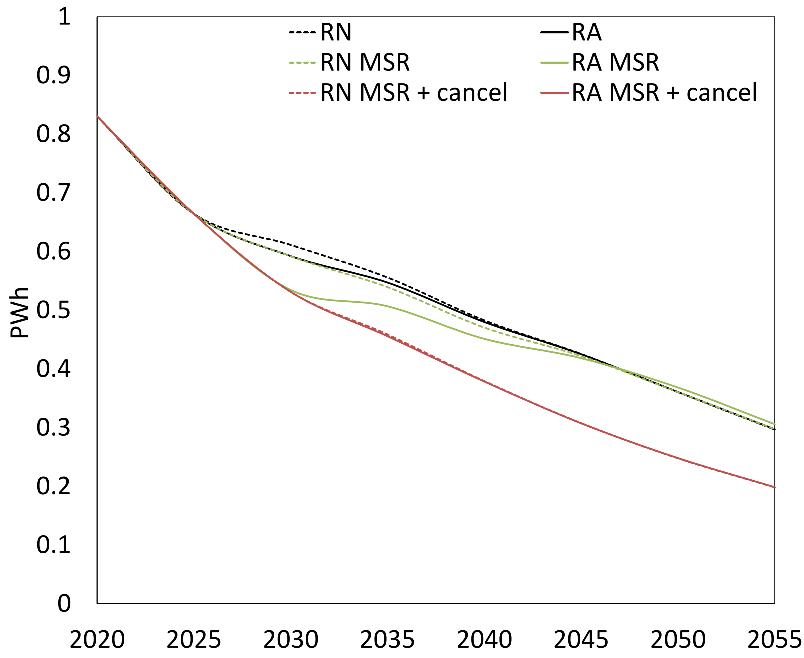
The cancellation totals to 7.60 Gt and 8.59 Gt in the case of *RN MSR + cancel* and *RA MSR + cancel*, respectively. Thus, if the hedging demand is considered, cancellation is about 1 Gt higher. This can be explained by the higher value of the permits in the early years due to firms' hedging demand. Specifically, the hedging value raises the price in 2020 significantly in *RA MSR + cancel* compared to *RN MSR + cancel* (see Figure 3.1 (a)) leading to less emissions and a larger bank (see Figure 3.2 (a)). In turn, the influx into the MSR is higher, and thus, more permits are canceled. The lower prices after 2030 (implying opposite effects) cannot outweigh this effect because the cancellations mainly take place before 2030.

Two modifications illustrate how the numerical findings are affected by the risk-free rate and the futures market. First, we run a scenario with a risk-free rate of 5% in which cancellations are lower (6.23 Gt in *RN MSR + cancel* and 6.81 Gt in *RA MSR + cancel*), which is in line with results from the literature (e.g., Bocklet et al. 2019). Second, adding futures contracts and speculators to the model reduces the risk premium, because the risk-taking capacity of the market increases (see Section 2.2.2). The cancellations are somewhat lower with the futures market (8.27 Gt in *RA MSR + cancel* compared to 8.59 Gt; note in the case of risk neutrality, futures markets have no effect), because the effect of risk aversion becomes weaker. Both modifications do not change the nature of the results because the price pattern is similar (see Appendix C).

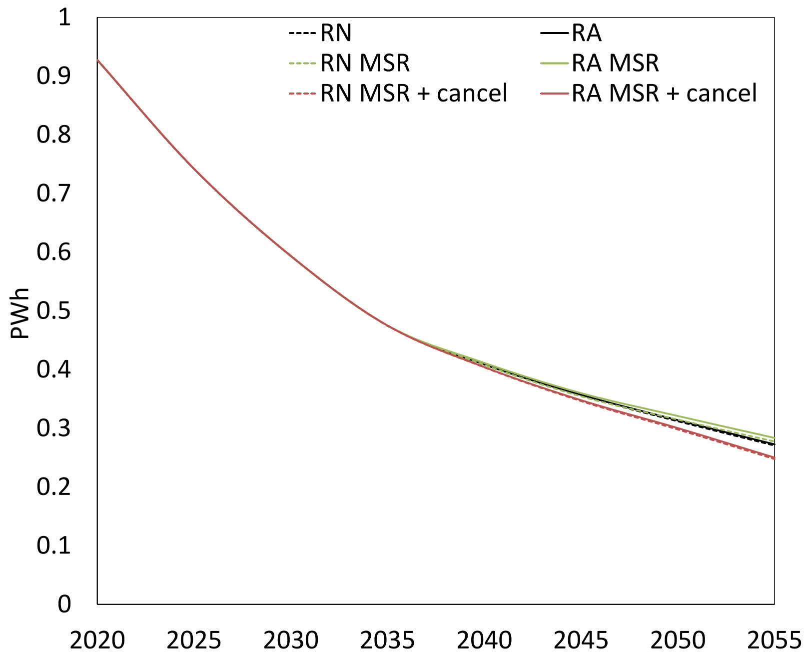
Finally, we consider the impact of the MSR on investments in capacity. Figure 3.3 shows that the higher permit price path due to the cancellation mechanism significantly reduces investments in coal capacity, while gas capacity is only slightly affected. If the cancellation mechanism is not active, the MSR also has a significant effect on coal capacities if firms are risk averse (*RA MSR*): Due to the higher permit price until about 2040 and the worse hedging opportunities (see Section 2.2.2), there is less coal capacity compared to *RA*. However, from 2045 onward there is slightly more coal capacity, because the MSR leads to lower prices in the long-term. Overall, the effect of the cancellation mechanism is significantly stronger than the effect of shifting permits to the future. However, a potential disadvantage of the cancellation mechanism that deserves more attention in future research is that it may increase the price variability (see Figure C.5 in Appendix C).

Figure 3.3: Expected capacity

(a) Coal capacity



(b) Gas capacity



4. Conclusion

We analyze the impact of hedging on the permit price path of a cap-and-trade program in an intertemporal stochastic equilibrium model. Hedging demand arises from uncertain profits due to a permit supply risk and has different implications for relative clean (gas) and dirty (coal) firms. Hedging by dirty firms via permit banking has a negative effect on the risk premium of the permit price – the sign is opposite for the clean firm's hedging via borrowing. If permit borrowing is not allowed, which is typically the case, the dirty firm's hedging demand becomes decisive for the permit price path. When the hedging demand exceeds the available permits, the resulting permit price is higher than in the risk-neutral case, but rises at a lower rate. When the dirty firm's hedging demand falls short of the permit supply, the opposite holds. As the hedging demand of dirty firms is typically high in the early years (implying price growth at a low rate) of a cap-and-trade program and low in later years (implying a higher growth rate), the expected growth rate of the permit price may has a U-shape.

We numerically apply the model to the EU ETS to investigate price effects of the MSR. The core mechanisms of the MSR are shifting permits to the future and canceling permits if the aggregate permit bank exceeds certain thresholds. In our stylized model, the hedging demand of the dirty coal firm always exceeds the available permits, and thus, risk premiums are always negative. The MSR induces even more negative risk premiums because it reduces the size of the permit bank. The results offer an explanation for the recent permit price hike in the EU ETS because more negative risk premiums lead to higher short-term prices. An additional consequence is that prices may grow only at a low rate or even decline in the coming years, which is also in line with analysts' forecasts for the coming decade (see Carbon Pulse 2019 for a poll).

In addition to the higher hedging value of permits due to the MSR, an important reason for the recent price increase is the cancellation of permits from 2023 onward. We find that cancellations may be higher than previous analyses suggest. The hedging demand and the associated negative risk premium imply that firms use a lower discount rate for banking permits and build up a larger bank. This, in turn, increases the MSR cancellations. We also stress the role of capacity constraints, which prevail in electricity markets. Specifically, we show that they increase the permit price variability and therefore, amplify the effects of risk aversion.

However, this study also has limitations. First, we consider a highly stylized model with only two electricity generators and one speculator. Considering more firm types would affect how risks can be allocated as, for instance, firms may pursue a plant portfolio approach by investing in clean and dirty plants to lower their overall risk exposure (Roques et al. 2008). In reality, there are also more, and essentially more complex, derivatives, such as options that allow to improve hedging opportunities. The main effect of including more derivatives and more complex firm structures is more efficient risk allocation implying lower risk premiums which could be further analyzed in future research. Similarly, we assume simple functional forms for electricity costs and demand, and ignore certain aspects of the EU ETS, such as grandfathering of permits and the explicit modeling of non-electricity sectors. In general, our model is only roughly calibrated to the EU ETS so that the numerical results should be understood only as stylized illustrations. A more detailed and calibrated modeling of financial aspects such as hedging and capital constraints in emission trading systems is an interesting avenue for future research.

Our work also raises other issues for further research. At the time of writing, actual discount rates in futures markets of the EU ETS are about 1.5%,[23] far below the typically assumed rate of 3% to 10% in the theoretical and numerical ETS literature. Given the high degree of uncertainty in this market, our analysis suggests that such a low rate can be explained by negative risk premiums. For future research, it would be interesting to empirically investigate the risk premium, ideally with a dedicated proxy for the firms' hedging demand (see Acharya et al. 2013 for a similar analysis for other commodity markets). Another promising research field would be to examine the impact of the MSR on the permit price variability, given that previous work considering uncertainty examines only the original MSR without the cancellation mechanism (Richstein et al. 2015; Fell 2016; Perino and Willner 2016; Kollenberg and Taschini 2019). In particular, our results

[23] See https://www.barchart.com/futures/quotes/CK*0/futures-prices (18-07-2019)

indicate that the permit price variability may increase due to the cancellation mechanism.

Acknowledgments

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Appendix A. Derivations

Appendix A.1. First-order conditions

The first-order conditions of the generators' problem in period 2 are

$$U'_{i,2}\left(k_{i,2}w_2 - \beta_i\zeta_{i,2}k_{i,2}^2\right) - \rho_{i,2}\phi_i k_{i,2} - \mu_{i,2} = 0 \quad (\zeta_{i,2}), \tag{A.1}$$

$$U'_{i,2}p_2 - \rho_{i,2} = 0 \quad (y_{i,2}). \tag{A.2}$$

The first-order conditions of the generators' problem in period 1 are

$$U_{i,1}^{'}\left(k_{i,1}w_1-\beta_i\zeta_{i,1}k_{i,1}^2\right)-\rho_{i,1}\phi_i k_{i,1}-\mu_{i,1}=0 \quad (\zeta_{i,1}), \tag{A.3}$$

$$U_{i,1}^{'}p_1-\rho_{i,1}=0 \quad (y_{i,1}), \tag{A.4}$$

$$\frac{E\left[U_{i,2}^{'}p_2\right]}{1+r}-\rho_{i,1}+\varphi_{i,1}=0 \quad (b_{i,1}), \tag{A.5}$$

$$E\left[U_{i,2}^{'}\left(\zeta_{i,2}w_2-\beta_i\zeta_{i,2}^2k_i-p_2\phi_i\zeta_{i,2}-\gamma_i\right)\right]=0 \quad (k_{i,2}), \tag{A.6}$$

$$U_{i,1}^{'}-E\left[U_{i,2}^{'}\right]=0 \quad (l_{i,1}), \tag{A.7}$$

$$U_{i,1}^{'}p_1^f-\frac{E\left[U_{i,2}^{'}p_2\right]}{1+r}=0 \quad (f_{i,1}). \tag{A.8}$$

The first-order conditions of the speculator's problem are

$$U_{sp,1}^{'}-E\left[U_{sp,2}^{'}\right]=0 \quad (l_{sp,1}), \tag{A.9}$$

$$U_{sp,1}^{'}p_1^f-\frac{E\left[U_{sp,2}^{'}p_2\right]}{1+r}=0 \quad (f_{sp,1}). \tag{A.10}$$

Note that for a risk-neutral firm that maximizes its expected profits the optimality conditions are the same but with constant marginal utility; i.e., $U_{i,1}^{'}=E\left[U_{i,2}^{'}\right]=1$.

Appendix A.2. Period 2 equilibrium

Lemma 1. Inserting the electricity market price (2.21) in the utilization rate (2.18), if the capacity constraints do not bind, $\mu_{c,2}=\mu_{d,2}=0$, yields

$$\zeta_{i,2}=\frac{A\beta_c\beta_d+p_2\left(\beta_d\phi_c+\beta_c\phi_d\right)}{\left(\beta_d+\beta_c+\beta_c\beta_d a\right)\beta_i k_i}-\frac{p_2\phi_i}{\beta_i k_i}. \tag{A.11}$$

Considering the case for $i=c$, and taking the derivative with respect to the permit price yields

$$\frac{d\zeta_{c,2}}{dp_2}=\frac{\phi_d-\phi_c\left(1+\beta_d a\right)}{\left(\beta_d+\beta_c+\beta_c\beta_d a\right)k_c}>0, \tag{A.12}$$

if $\phi_d-\phi_c\left(1+\beta_d a\right)>0$. Similarly, for the dirty firm we get

$$\frac{d\zeta_{c,2}}{dp_2} = \frac{\phi_c - \phi_d\left(1+\beta_c a\right)}{\left(\beta_d+\beta_c+\beta_c\beta_d a\right)k_d} < 0, \tag{A.13}$$

as, by definition, $\phi_d > \phi_c$.

Lemma 2. Using the electricity price (2.21) and the utilization rate (2.18), the plant profit can be written as

$$\pi_{i,2}^{plant} = \frac{\left(A\beta_c\beta_d + p_2\left(\beta_d\phi_c+\beta_c\phi_d\right)\right)^2}{2\beta_i\left(\beta_d+\beta_c+\beta_c\beta_d a\right)^2} - \frac{\left(A\beta_c\beta_d + p_2\left(\beta_d\phi_c+\beta_c\phi_d\right)\right)p_2\phi_i}{\beta_i\left(\beta_d+\beta_c+\beta_c\beta_d a\right)} + \frac{p_2^2\phi_i^2}{2\beta_i}, \tag{A.14}$$

for which we assume that the capacity constraints do not bind. For the clean firm, it can be shown that the profit increases with the ETS price, $\frac{d\pi_{c,2}^{plant}}{dp_2} > 0$, if

$$A\beta_d + p_2\left(\phi_d - \phi_c\left(1+\beta_d a\right)\right) > 0, \tag{A.15}$$

which is always the case if $\phi_d - \phi_c\left(1+\beta_d a\right) > 0$ holds. From $\frac{d\pi_{c,2}^{plant}}{dp_2} > 0$ directly follows that $Cov\left[\pi_{c,2}^{plant}, p_2\right] > 0$. For the dirty firm, the profit decreases with the ETS price, $\frac{d\pi_{d,2}^{plant}}{dp_2} < 0$, if

$$A\beta_c + p_2\left(\phi_c - \phi_d\left(1+\beta_c a\right)\right) > 0 \tag{A.16}$$

holds. If the price is

$$p_2 = \frac{A\beta_c}{\left(\phi_d\left(1+\beta_c a\right)-\phi_c\right)}, \tag{A.17}$$

profits are not affected; i.e., $A\beta_c + p_2\left(\phi_c - \phi_d\left(1+\beta_c a\right)\right) = 0$. If the price is larger than in (A.17), the dirty firm does not produce, and thus, profits also are not affected. This can be seen by inserting (A.17) in the utilization rate (A.11) which yields $\zeta_{d,2} = 0$. The same is true for higher prices because of Lemma 1. For lower prices than in (A.17), condition (A.16) is fulfilled, and thus, $\frac{d\pi_{d,2}^{plant}}{dp_2} < 0$ and $Cov\left[\pi_{d,2}^{plant}, p_2\right] < 0$ hold.

The effect of plant capacity constraints on permit price variability. The effect of capacity constraints on the ETS price is given by the second line in (2.22), which we replicate for convenience

$$\frac{\frac{\mu_{c,2}}{U'_{c,2}k_{c,2}}\left(\phi_d-\phi_c\left(1+\beta_d a\right)\right)+\frac{\mu_{d,2}}{U'_{d,2}k_{d,2}}\left(\phi_c-\phi_d\left(1+\beta_c a\right)\right)}{\left(\phi_c-\phi_d\right)^2+a\left(\beta_c\phi_d^2+\beta_d\phi_c^2\right)}. \tag{A.18}$$

The first line in (2.22) is the same as without capacity. There are four cases.

Case 1: Before the shock on S_2 is realized, the capacity constraint of the clean firm binds, $\mu_{c,2}>0$, and the capacity constraint of the dirty firm does not bind, $\mu_{d,2}=0$. A negative shock implies that $\mu_{d,2}=0$ still holds after the shock because of Lemma 1. For the effect on the constraint of the clean firm, we make use of (2.22) and (2.21) in (2.20) such that we get

$$\begin{aligned}\frac{\mu_{c,2}}{U'_{c,2}k_{c,2}} &= \frac{A\phi_d\left(\phi_d-\phi_c\right)-k_{c,2}\left(\left(\phi_d-\phi_c\right)^2+a\left(\beta_d\phi_c^2+\beta_c\phi_d^2\right)\right)}{\phi_d^2 a} \\ &\quad+\frac{\left(b_{c,1}+b_{d,1}+S_2\right)\left(\phi_c\left(1+\beta_d a\right)-\phi_d\right)}{\phi_d^2 a}.\end{aligned} \tag{A.19}$$

The effect of a change in the permit supply is given by

$$\frac{d\left(\frac{\mu_{c,2}}{U'_{c,2}k_{c,2}}\right)}{dS_2}=\frac{\phi_c\left(1+\beta_d a\right)-\phi_d}{\phi_d^2 a}<0, \tag{A.20}$$

because $\phi_d-\phi_c\left(1+\beta_d a\right)>0$, and thus, capacity constraints lead to a larger price increase due to a negative shock on S_2 compared to the model without capacity constraints.

Case 2: Before the shock is realized, $\mu_{c,2}=0$ and $\mu_{d,2}>0$ hold. A negative shock implies that $\mu_{c,2}$ rises or may still be zero, $\mu_{c,2}\geq 0$, and that the dirty capacity constraint no longer binds, $\mu_{d,2}=0$ (Lemma 1). To see that a declining $\mu_{d,2}$ and a rising $\mu_{c,2}$ lead to a stronger ETS price increase in (2.22), consider that $\phi_c-\phi_d\left(1+\beta_c a\right)<0$ and $\phi_d-\phi_c\left(1+\beta_d a\right)>0$ hold.

Case 3: Before the shock is realized, $\mu_{c,2}>0$ and $\mu_{d,2}>0$ hold. As in case 2, the dirty constraint cannot bind after a negative shock has emerged, which has a positive effect on the price. As in case 1, $\mu_{c,2}$ rises which also has a positive effect on the price.

Case 4: Before the shock is realized, $\mu_{c,2} = \mu_{d,2} = 0$ holds. As in case 1, a negative shock implies that $\mu_{d,2} = 0$ still holds and $\mu_{c,2} \geq 0$. Thus, if $\mu_{c,2} > 0$ after the shock, capacity constraints have a positive effect on the price and no effect if $\mu_{c,2} = 0$.

In sum, a negative shock on S_2 leads to a stronger or the same price effect than in the case without capacity constraints. A positive shock on S_2 has opposite effects and thus, leads to a stronger or equal price decline. Therefore, the price variability is amplified due to capacity constraints.

Appendix A.3. Period 1 equilibrium

Appendix A.3.1. Banking and hedging

Combining first-order conditions (A.7), (A.4) and (A.5) yields

$$\frac{E\left[p_2\right]-p_1}{p_1}=r+\frac{\left(1+r\right)\varphi_{i,1}}{p_1 E\left[U'_{i,2}\right]}-\frac{Cov\left[U'_{i,2},p_2\right]}{E\left[U'_{i,2}\right]p_1}. \tag{A.21}$$

Assuming quadratic utility, $U_t\left(\pi_{it}\right)=\pi_{it}-\pi_{it}^2$, we can write the covariance as $Cov\left[U'_{i,2},p_2\right] = -2\left(Cov\left[\pi_{i,2}^{plant},p_2\right]+Var\left[p_2\right]b_{i,1}\right)$, and inserting it in (A.21) yields

$$b_{i,1}=\frac{E\left[p_2\right]-p_1\left(1+r\right)}{\lambda_i Var\left[p_2\right]}-\frac{Cov\left[\pi_{i,2}^{plant},p_2\right]}{Var\left[p_2\right]}-\frac{\left(1+r\right)\varphi_{i,1}}{U'_{i,1}Var\left[p_2\right]}. \tag{A.22}$$

Assuming a risk premium of zero, $E\left[p_2\right]-p_1\left(1+r\right)=0$, the pure banking or borrowing demand is due only to the second term. Because of Lemma 2, we have $Cov\left[\pi_{c,2}^{plant},p_2\right]>0$ and $Cov\left[\pi_{d,2}^{plant},p_2\right]<0$. Obviously, if firms bank, the borrowing constraint does not bind, and thus, $\varphi_{i,1}=0$. It follows that dirty firms want to bank $b_{i,1}>0$ permits, and clean firms want to borrow $b_{i,1}<0$ permits for hedging reasons. However, clean firms cannot borrow by assumption. Instead, clean firms bank permits only if the expected profit is at least as high as the costs of the risks of this action, $E\left[p_2\right]-p_1\left(1+r\right)>\lambda_i Cov\left[\pi_{c,2}^{plant},p_2\right]$.

Next, we turn to the price effects of hedging. Consider that the permit demand can be written as

$$
\begin{aligned}
y_{i,1} \;\; = \;\; & \frac{\phi_i A \beta_c \beta_d}{\left(\beta_d + \beta_c + \beta_c \beta_d a\right) \beta_i} + p_1 \left(\frac{\left(\beta_d \phi_c + \beta_c \phi_d\right) \phi_i}{\left(\beta_d + \beta_c + \beta_c \beta_d a\right) \beta_i} - \frac{\phi_i^2}{\beta_i} - \frac{(1+r)}{\lambda_i Var\left[p_2\right]} \right) \quad \text{(A.23)} \\
& + \frac{E\left[p_2\right]}{\lambda_i Var\left[p_2\right]} - \frac{Cov\left[\pi_{i,2}^{plant}, p_2\right]}{Var\left[p_2\right]},
\end{aligned}
$$

for which we used (2.24) and (A.11) (but for period 1) in (2.23), and we assumed non-binding capacity constraints. Inserting this permit demand for clean and dirty firms in the permit equilibrium condition (2.4) yields the permit price,

$$
p_1 = \frac{E\left[p_2\right]}{(1+r)} - \frac{\Lambda}{(1+r)} \left(Cov\left[\pi_{d,2}^{plant}, p_2\right] + Cov\left[\pi_{c,2}^{plant}, p_2\right] + Var\left[p_2\right] B_1 \right), \qquad \text{(A.24)}
$$

The whole term in brackets is the absolute risk premium, and dividing by p_1 this term becomes the relative risk premium as shown in (2.26). Repeating the steps in this section for the case with the futures market shows that Equation (A.24) is still valid, but $\Lambda = \left(\lambda_d^{-1} + \lambda_c^{-1}\right)^{-1}$ must be replaced by $\Lambda^f = \left(\lambda_d^{-1} + \lambda_c^{-1} + \lambda_{sp}^{-1}\right)^{-1}$.

Appendix A.3.2. Capacity effects

The first-order condition for $k_{i,2}$ (Equation (A.6)) can be reformulated as

$$
\begin{aligned}
& E\left[\zeta_{i,2}\right]\left(E\left[w_2\right] - E\left[\zeta_{i,2}\right]\beta_i k_i - E\left[\zeta_{i,2}\right]\phi_i\right) - \gamma_i \\
& \quad + Cov\left[\zeta_{i,2}, w_2 - \zeta_{i,2}\beta_i k_i - p_2\phi_i\right] \qquad \text{(A.25)} \\
& \quad + \frac{1}{U_{i,1}^{'}} Cov\left[U_{i,2}^{'}, \zeta_{i,2} w_2 - \zeta_{i,2}^2 \beta_i k_i - p_2 \zeta_{i,2} \phi_i\right] \;\; = \;\; 0,
\end{aligned}
$$

for which we used covariance properties and the first-order condition for the risk-free asset (A.7). By further noting that the marginal capacity value in the risk-neutral case is $\mu_{i,2}^{RN} = k_{i,2} w_2 - x_{i,2} k_{i,2} \beta_i - p_2 k_{i,2} \phi_i$ (see Equation (2.20) and consider that in the case of risk neutrality $U_{i,2}^{'} = 1$ holds), we can rewrite this further and finally get (2.30).

Effect of uncertainty if firms are risk neutral. Risk neutrality implies $U'_{i,2} = 1$, and thus, $Cov\left[U'_{i,2}, \mu^{RN}_{i,2}\right] = 0$. Therefore, only the first two terms in (2.30) matter in the risk-neutral case. Moreover, in the deterministic case $Cov\left[\zeta_{i,2}, \mu^{RN}_{i,2}\right] = 0$ holds, and investments are determined by only the first term in (2.30) (ignoring the expectation operator). Thus, given risk neutrality, the effect of uncertainty compared to the deterministic case is given by the second term, $Cov\left[\zeta_{i,2}, \mu^{RN}_{i,2}\right]$. We can rewrite this term as $Cov\left[\zeta_{i,2}, \mu^{RN}_{i,2}\right] = E\left[\mu^{RN}_{i,2}\right](1 - E[\zeta_{i,2}])$, for which we used $E\left[\mu^{RN}_{i,2}\right] = E\left[\zeta_{i,2}\mu^{RN}_{i,2}\right]$, because $\mu^{RN}_{i,2}$ is positive only if $\zeta_{i,2} = 1$ and zero otherwise. As $0 < E[\zeta_{i,2}] < 1$, and $E\left[\mu^{RN}_{i,2}\right] > 0$, $Cov\left[\zeta_{i,2}, \mu^{RN}_{i,2}\right] > 0$ holds. Thus, uncertainty has a positive effect on investments if firms are risk neutral.

Effect of risk aversion without banking. Next, we consider the effect of risk aversion given by the third term in (2.30). As $\frac{1}{U'_{i,1}} > 0$, the sign of the effect of risk aversion depends on $Cov\left[U'_{i,2}, \mu^{RN}_{i,2}\right]$. Assuming that the permit bank is zero, marginal utility $U'_{i,2}$ depends only on plant profit $\pi^{plant}_{i,2}$ and risk-free asset returns. The latter do not affect the covariance because they are nonrandom. Due to the concavity of $U_{i,2}$, it follows $\frac{dU_{i,2}}{d\pi^{plant}_{i,2}} < 0$. Thus, the sign of $Cov\left[U'_{i,2}, \mu^{RN}_{i,2}\right]$ is inversely related to $Cov\left[\pi^{plant}_{i,2}, \mu^{RN}_{i,2}\right]$ which is positive,

$$Cov\left[\pi^{plant}_{i,2}, \mu^{RN}_{i,2}\right] = Cov\left[\zeta_{i,2}\left(w_2 - \frac{\beta_i}{2}x_{i,2} - p_2\phi_i\right), \zeta_{i,2}\left(w_2 - \beta_i x_{i,2} - p_2\phi_i\right)\right]k^2_{i,2} \geq 0, \tag{A.26}$$

as firms increase only their utilization rate, if this covers at least their marginal cost (A.1). Therefore, $Cov\left[U'_{i,2}, \mu^{RN}_{i,2}\right] \leq 0$ holds.

Effect of risk aversion with banking. We again consider $Cov\left[\pi_{i,2}, \mu^{RN}_{i,2}\right]$ which becomes $Cov\left[\pi_{i,2}, \mu^{RN}_{i,2}\right] = Cov\left[\pi^{plant}_{i,2}, \mu^{RN}_{i,2}\right] + Cov\left[p_2 b_{i,1}, \mu^{RN}_{i,2}\right]$ when firms bank. Compared to the case without banking, there is an additional effect given by $Cov\left[p_2 b_{i,1}, \mu^{RN}_{i,2}\right]$. Firms invest, ceteris paribus, more if $Cov\left[p_2 b_{i,1}, \mu^{RN}_{i,2}\right] < 0$ and less if $Cov\left[p_2 b_{i,1}, \mu^{RN}_{i,2}\right] > 0$, because a lower $Cov\left[\pi_{i,2}, \mu^{RN}_{i,2}\right]$ implies a higher $Cov\left[U'_{i,2}, \mu^{RN}_{i,2}\right]$ due to the concavity of the utility function. Due to Lemma 1, dirty firms always produce less, if there is a positive permit price shock. Therefore, $Cov\left[p_2 b_{i,1}, \mu^{RN}_{i,2}\right] < 0$ holds. For clean firms, the opposite holds.

If capacity constraints are strictly binding such that firms cannot produce more in the case of positive (clean firm) or negative (dirty firm) price shocks, or stick to the full capacity utilization in the opposite case, we get $Cov\left[p_2 b_{i,1}, \mu_{i,2}^{RN}\right] = (Cov\left[p_2, w_2\right] - Var\left[p_2\right]\phi_i)\, b_{i,1} k_{i,2}$. Thus, if permit price shocks are disproportionately transferred to the electricity market price ($Cov\left[p_2, w_2\right] - Var\left[p_2\right] < 0$), firms want to invest even more given that they are dirty enough (large ϕ_i). Very clean firms, in contrast, with $\phi_i \approx 0$, always want to invest less in plant capacity if they bank.

Appendix B. Parameter assumptions for the numerical simulation

Cost function parameters are chosen in line with coal and gas power plants for the representative dirty and clean firms, respectively (for the parameters see Table B.1). For the electricity demand function, $D(w_t) = A - a_t w_t$, we assume the intercept is $A = 3,462$ TWh, which is the total electricity generation in the EU28, Iceland and Norway (the EU ETS countries except Liechtenstein) in 2017 according to Eurostat. Deviations from A due to aw_t are interpreted as production from other plant types (mostly nuclear and renewable energy), which we do not model explicitly. Therefore, a higher a_t means that other technologies gain a larger market share. This parameter leaves a degree of freedom to calibrate the model to recent EU ETS outcomes. Specifically, we calibrate the model such that the outcomes of the first period (2018–2022) of the scenario *RA MSR + cancel* (the actual EU ETS) are in line with recent EU ETS values. For this purpose, we set the initial value to $a_{2020} = 60$ and assume that it increases at a 9% rate every five years. The increase in a_t mainly reflects market entry of renewable energies (e.g., due to support programs).

These parameter assumptions lead to an ETS price of 26.9 EUR/t and 0.78 Gt emissions in the first model period of the scenario *RA MSR + cancel*. The price is in line with actual (futures) prices between 2018 and 2022 (26.15–27.44 EUR/t).[24] Our emission level is somewhat lower than the emissions due to combustion in the EU ETS in 2018,

[24]https://www.barchart.com/futures/quotes/CK*0/futures-prices (05-07-2019)

which are 1.1 Gt.[25] However, emissions are likely to fall due to recently rising ETS prices compared to 15.92 EUR/t, on average, in 2018. The production shares of gas (16.7%) and coal (17.8%) in the model are close to the actual values in 2017, with 19.2% for gas and 19.1% for coal (Eurostat), which again are likely to be lower in 2018–2022 due to the higher ETS prices and the growing renewable energy output.

Regarding risk aversion, we assume in contrast to the analytical part a more common functional form. Specifically, we assume $U_{it} = \frac{\pi_{it}^{1-\eta}-1}{1-\eta}$ with constant relative risk aversion η. In line with the empirical estimates, we set relative risk aversion to $\eta = 1.5$ (cf. Gandelman and Hernández-Murillo 2015). We further assume an initial endowment of $l_{i,2020} = 40$ billion EUR. This value roughly corresponds to the profit made with the plant and permit trades in the first period, which is between 23 and 38 billion EUR for the coal firm and 41 and 42 billion EUR for the gas firm, depending on the scenario. That is, we assume the firms made a comparable profit in the previous (not modeled) period which is at their disposal in the first model period.

[25] https://www.eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1 (05-07-2019)

Table B.1: Firm data

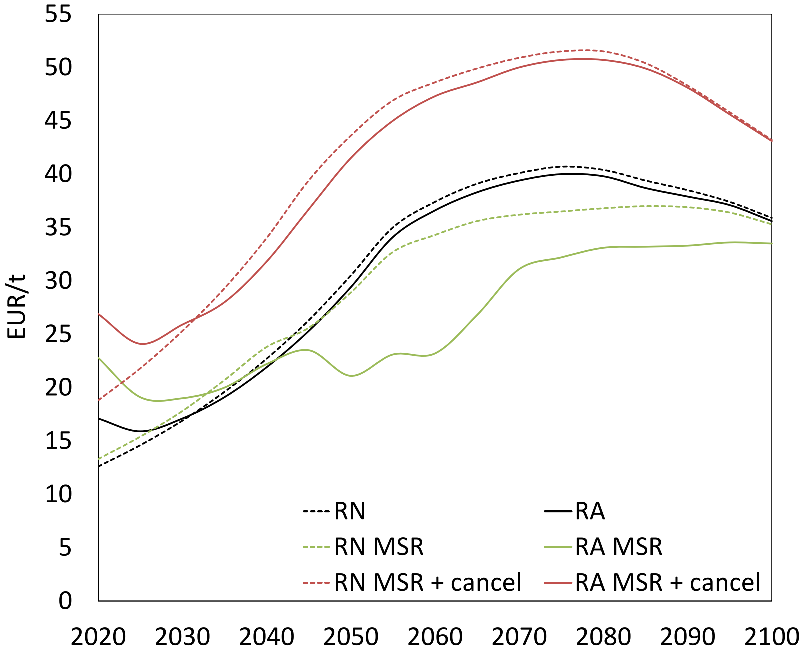
	Clean	Dirty
Production costs (EUR/GWh):β_i	0.050	0.020
Capacity costs (EUR/GWh): γ_i	0.0049	0.0084
Emission factor (t/GWh): ϕ_i	333	950
Initial capacities (TWh): $k_{i,2020}$	830.2	927.5
Capacity depreciation: δ	0.2	0.2

Note: Emission factors are based on UBA (2014) and divided by conversion efficiencies (fuel to electricity) of 60% for gas and 40% for coal. Capacity costs are based on the IEA (2016) but converted to annuities by considering plant lifetimes of 40 years and a 3% discount rate. Capacity costs are further converted from TW to TWh by assuming that plants are used 70% of the time. The production cost parameters β_i are roughly in line with gas and coal production costs (excl. emission costs). Initial capacities are from Eurostat for 2017: values for steam (coal) and gas turbine and combined cycle (gas) are converted from W to Wh by multiplying the respective value with (8760*0.7), i.e., hours per year times the assumed utilization of 70%.

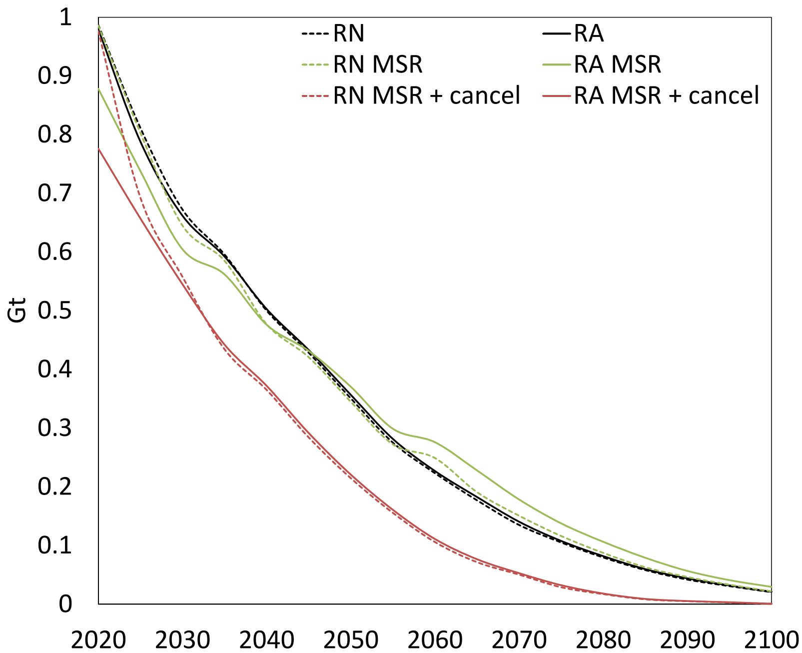
Appendix C. Additional simulation results

Figure C.1: Results for the full time horizon: price and emissions

(a) Price



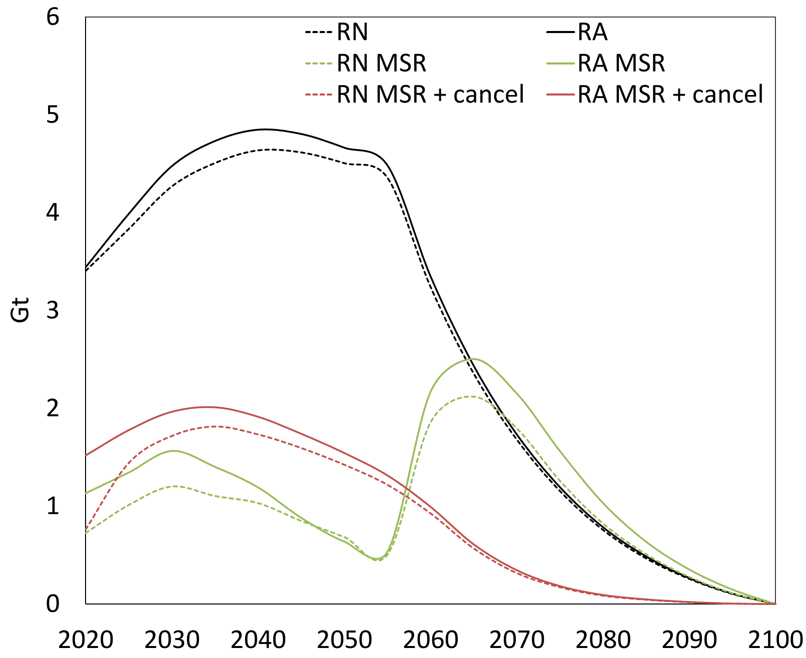
(b) Emissions



Note: The volatile permit price after 2045 in scenario *RA MSR* is due to the binding borrowing constraint (declining price) and the assumed higher output parameter for the MSR (rising price), which increases from 0.1 Gt to 1 Gt (see Section 3.1).

Figure C.2: Results for the full time horizon: firm bank and MSR level

(a) Aggregate firm bank



(b) MSR level

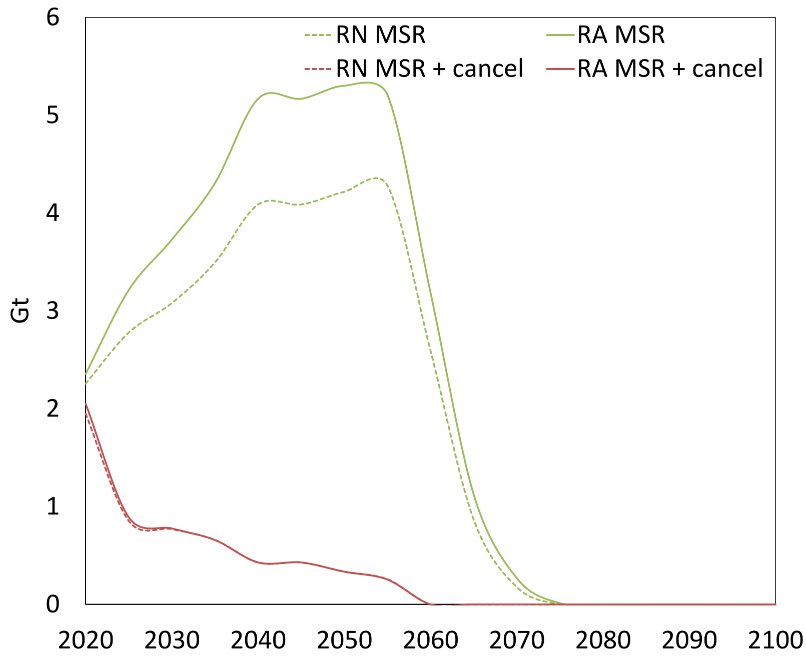
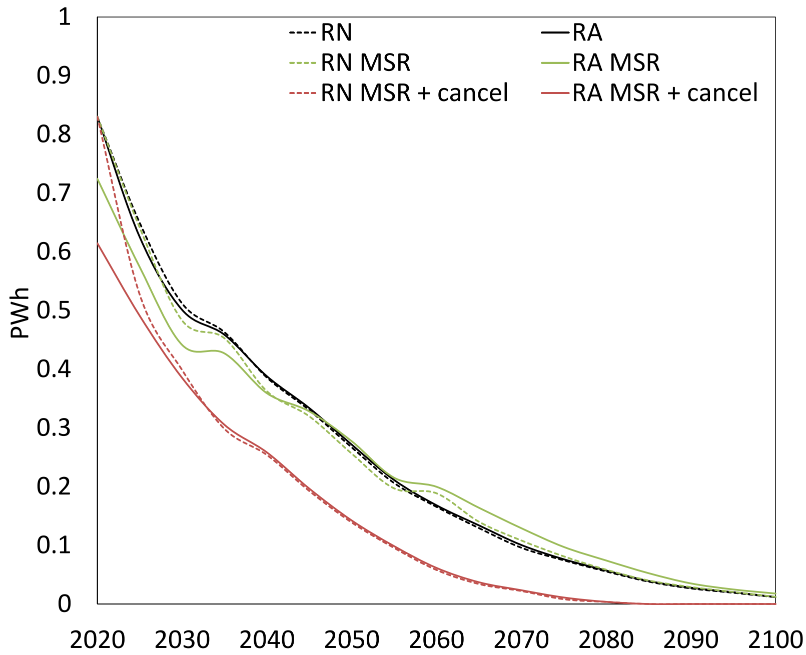


Figure C.3: Results for the full time horizon: production

(a) Coal production



(b) Gas production

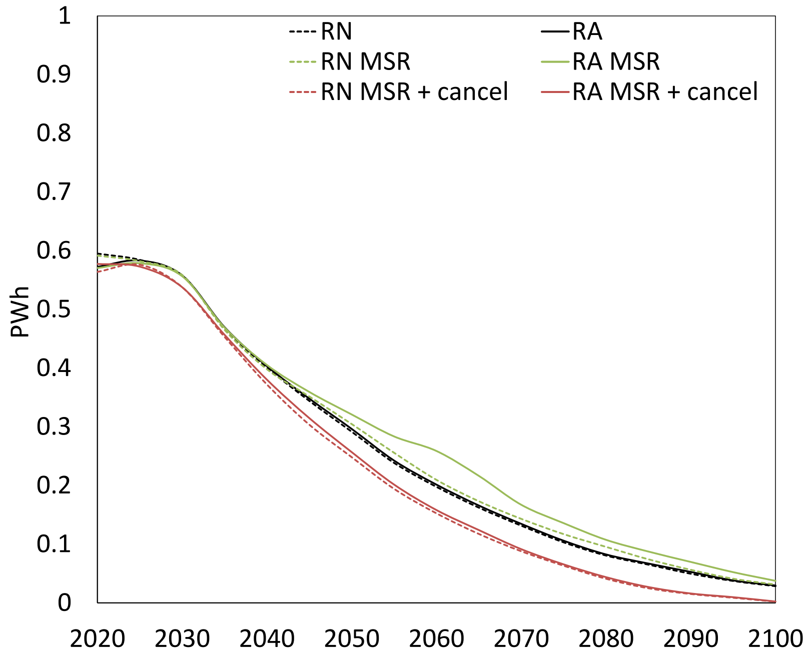
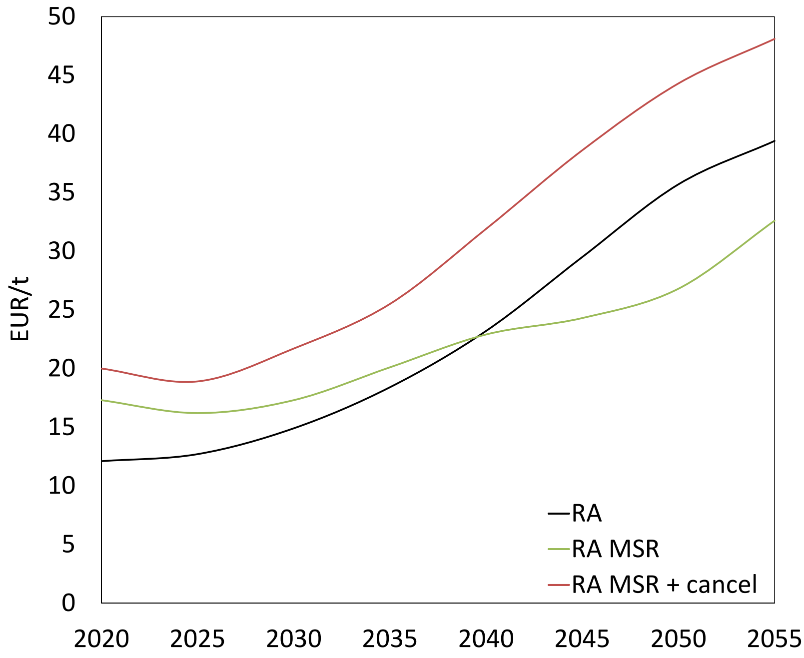
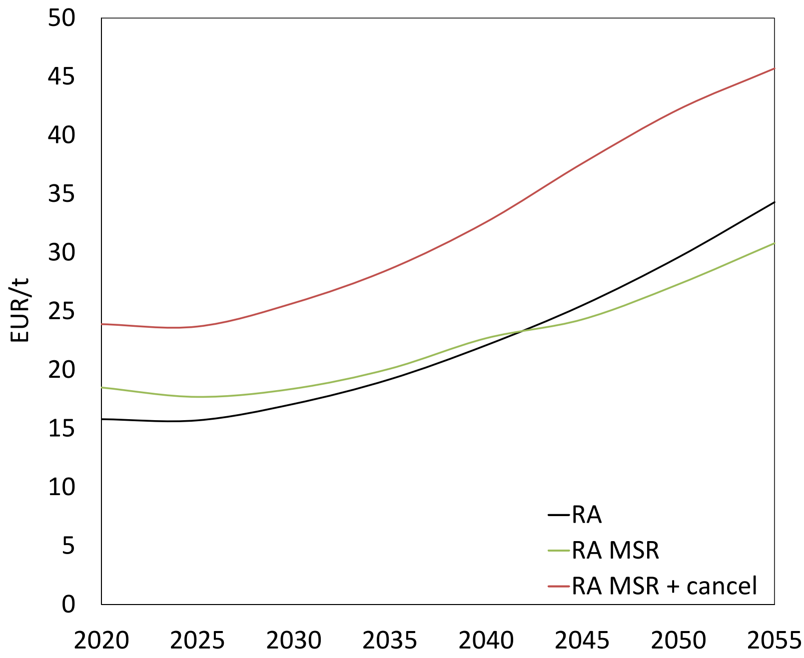


Figure C.4: Expected permit price with risk-free rate of 5% and futures market

(a) Risk-free rate of 5%



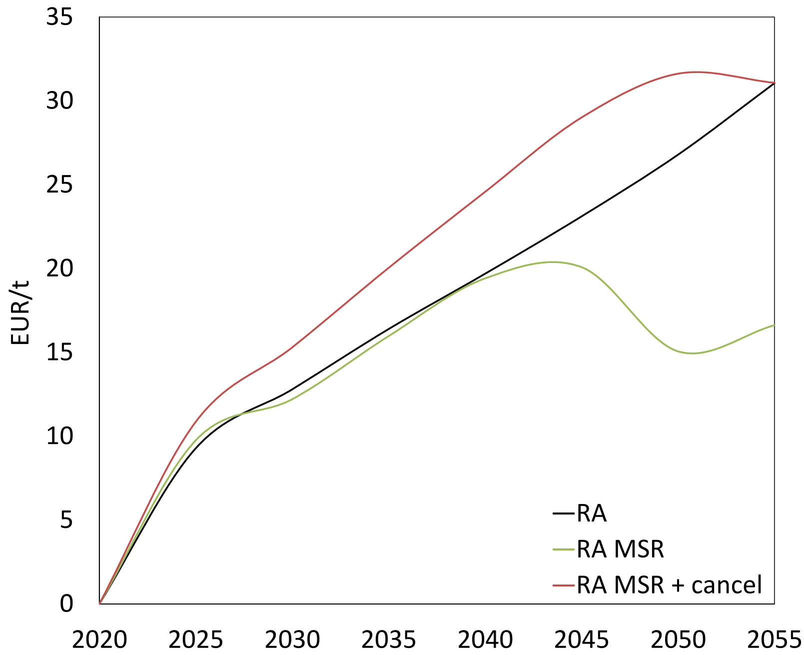
(b) Futures market



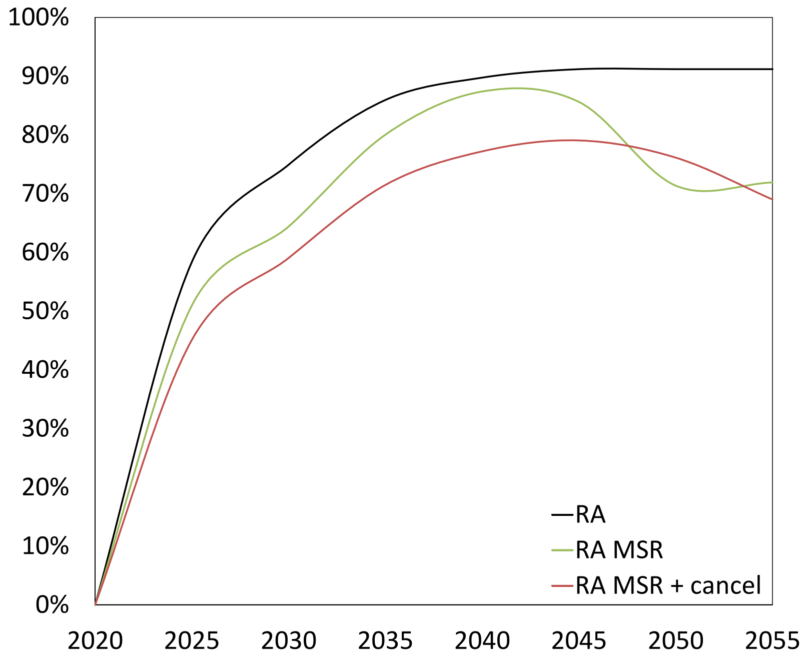
Note: For part (b), we assume a risk-free rate of 3% and that speculators have the same initial endowment and level of risk aversion as the electricity generators.

Figure C.5: Permit price variability

(a) Standard deviation



(b) Relative standard deviation



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