Evaluating the performance of the EU ETS MSR

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Abstract

Will the Market Stability Reserve (MSR) of the European Union (EU) Emission Trading System (ETS) help: (i) address the current surplus of unused allowances and (ii) improve the EU ETSs resilience to shocks? While it has been stressed that cancellation is the crucial component that leads to deep cuts in emissions, here we demonstrate that delaying the auctioning of allowances can be equally, if not more significant. Following the intake of allowances by the reserve, the impact of cancellation is observed to be minimal and when all allowances are cancelled from the MSR, price impacts are only moderate. We also find that the MSR amplifies rather than moderates price volatility, contrary to regulators' expectations. We discuss how the trigger thresholds and outtake from the MSR lead to this outcome.

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1 Introduction

In response to a persistently large surplus of unused allowances in the European Union (EU) Emissions Trading System (ETS), European law makers adopted the Market Stability Reserve (MSR) as (i) a means to addressing short and long-term imbalances between supply and demand of allowances, and (ii) increasing the long-run shock resilience of the EU ETS. The MSR began operation in January 2019. It is intended to intake allowances when the total number of allowances in circulation exceeds 833 million but release 100 million whenever this total falls below 400 million. Presently, between 12% and 24% of the allowances in circulation will be withdrawn from auction when the number allowances in circulation exceed the upper threshold.[1] Moreover, from 2023 on wards, the maximum number of allowances held in the reserve will be limited to the auction volume of the previous year, thus allowing for a cancellation of allowances via the MSR. If the MSR works as hoped, it should raise allowance prices to levels that robustly incentivize investment in renewable technologies and at the same time lead to reductions in carbon emissions.

Given its multidimensionality, it is not at the moment clear which components of MSR are likely to have the greatest bearing on the allowance price and thereby be of most importance for limiting carbon emissions. Is it the higher linear reduction factor that actually cuts allowances outside of the stability reserve? Or is it the intake rate, which defines the volume of allowances that the MSR withdraws from circulation? Perhaps it is the rate at which allowances are reinjected into the market? Or could it be the speed of cancelling allowances that are accumulating in the MSR? Our contribution is to help answer these questions using a transparent numerical model of emissions trading that is carefully calibrated to the EU ETS power sector. The model accounts for capacity development in both fossil and renewable power generation, implements the rules of the MSR more or less as laid out by European law makers in "Directive (EU) 2018/410/EU," and can evaluate

[1] Until 2023, the MSR will withdraw from auctions, 24% of the total number of allowances in circulation. The 12% rate that is effective from 2024 onwards is still subject to review.

optimal policy under demand uncertainty.

Our principle insights are twofold. Firstly, that delaying the auctioning of allowances via the MSR has a substantive impact on the allowance price and emissions, than cancellation. Delaying issuance, through its effect on raising the near-term allowance price, stimulates (dampens) investments in renewable- (fossil-) based power generation. To the extent that allowances start to 'trickle' back into the market after substantial renewables capacity has been built up and carbon capacity decommissioned, there is little incentive to rebuild fossil capacity implying that cancelled inframarginal allowances have a minimal impact on raising the allowance price. This result is in contrast to prior findings (e.g., Salant, 2016; Perino and Willner, 2016, 2017) that emphasize cancellation on the account that withholding allowances from auction would have only temporary impacts on the price and emissions.

Secondly, we find that contrary to EU lawmakers' hopes that MSR will moderate imbalances between demand and supply and thereby, taper gyrations in the allowance price; the MSR may actually increase rather rather than reduce allowance price volatility. The primary reasons are threefold. The MSR: (i) shortens the allowance banking regime which inhibits firms' ability to reduce and smooth their compliance costs through banking activity, (ii) it is triggered with a lag and therefore fails respond to immediate imbalances between demand and supply of allowances, and (iii) it has an inflexible outtake rate that is only partially responsive to the demand for allowances following the realization of a shock. Combined, these induce the allowance price to react more explosively to demand/supply imbalances. Albeit, a higher (expected) volatility also incentivizes firms to invest even more in renewable-based energy generation as they try to mitigate escalations in their private abatement costs.

Prior findings in the literature are in some respects comparable to ours. Like us, Fell (2016) finds that the MSR can redress the overallocation of allowances[2], and he observes

[2]For a sufficiently low discount he finds that the MSR becomes ineffective at managing overallocation

that it does so with a higher volatility than with alternative instruments such as a price collar. Richstein et al. (2015) also find that the MSR increases rather than reduces allowance price volatility, attributing this to the failure of the MSR to immediately and flexibly respond to demand/supply imbalances.[3] Perino and Willner (2016, 2017) stress that the MSR does little to incentivize abatement if it is allowance preserving. Chaton et al. (2018), on the other hand, point out that the MSR by substituting for private banking efforts, can lead to a collapse in present-day allowance prices. Despite its purported shortcomings, Neuhoff et al. (2015) argue that MSR improves the performance of the EU ETS. This is corroborated by Kollenberg and Taschini (2016), who additionally suggest ways to make the MSR fully flexible and responsive to shocks. The key methodological difference of our analysis with these prior studies is that they disregard sunk costs and technological path dependency in abatement technology.[4] Accounting for both features can reverse some earlier findings on the efficacy of the MSR.

The rest of this paper is organized as follows. Section 2 presents the model developed for the analysis and 3 discusses the analytical properties of its equilibrium. Model calibration is discussed in Section 4. Sections 5 and 6 respectively discuss the numerical findings under deterministic and stochastic environments, while Section 7 concludes.

2 The model

Rubin (1996), Kling and Rubin (1997), and Cronshaw and Kruse (1996) introduced models of intertemporal emissions abatement under a cap and trade system, that have now been widely applied in the literature (see. e.g., Fell, 2016; Fell et al., 2012; Hasegawa and Salant, 2014; Holland and Moore, 2013; Holland and Yates, 2015; Leard, 2013; Perino and Willner,

allowances. In our findings, the discount factors little in influencing the MSRs efficacy.

[3] Their model features path dependency like ours but it does not accommodate for rationally optimizing actors. Moreover, uncertainty is evaluated through a Monte Carlo analysis rather than an explicit and more realistic decision making under uncertainty framework.

[4] In addition, there are subtle differences in the way that the MSR is represented, with our representation most closely reflecting the MSR as specified in “Directive (EU) 2018/410/EU.”

2016). These models feature firms that minimize the discounted costs of emissions abatement plus allowance purchases, or maximize discounted revenues from the provision of an emission-intensive good net of production and allowance costs. Allowance banking in these models aids firms lower abatement costs, but besides this provision, (marginal) abatement costs are otherwise fixed.[5]

Here we introduce a model of fossil and renewables capacity-driven power supply under bankable cap and trade. Capacity introduces two dimensions: path dependency and inertia, that have so far received minimal attention in the cap and trade literature. Moreover, through renewables (rather than fossil) capacity development, firms have an additional lever, besides allowance banking, that helps lower their compliance costs. In such a specification, the transitional stringency of a cap-and-trade program may, therefore, be as important as its cumulative stringency in helping cut back on carbon emissions.

In Section 2.1, we describe the (representative) firm's power supply program under bankable cap and trade. Section 2.2 describes market clearing for allowances, 2.3 presents the specification of the MSR and 2.4 discusses the representation of uncertainty in the model.

2.1 The representative firm

The objective of the firm is to maximize its discounted net profit defined as discounted revenues from power sales less discounted costs of (i) using the fossil fuel input, (ii) developing fossil and renewables capacity, and (iii) purchasing allowances. We assume that the two sole purposes for the firm to purchase allowances is to meet it compliance requirements and for hedging in the presence of uncertainty[6].

[5]With regard to the United States Acid Rain Program for instance, firms installed scrubbers in order to lower their abatement costs. This allowed them to lower their private cost of compliance to the program in a distinct way than through allowance banking.

[6]We abstract from holding allowances for trading purposes.

Formally, the (representative) firm's optimization program is given by:

$$\max_{I_{F,t},I_{G,t},F_t,Z_t} J_k = \int_{t\geq k}^{T} \left\{P_t E_t - P_{F,t} F_t - H\left(I_{F,t}\right) - X\left(I_{R,t}\right) - \tau_t Z_t\right\} e^{\delta(k-t)} dt \tag{1}$$

s.t.

$$\dot{A}_t = Z_t - F_t \tag{2}$$

$$\dot{K}_{F,t} = I_{F,t} - \Delta_F K_{F,t},\ \dot{K}_{R,t} = I_{R,t} - \Delta_R K_{R,t} \tag{3}$$

$$E_t^{\sigma} = \left(E_{F,t}^{\sigma} + E_{R,t}^{\sigma}\right),\ E_{F,t}^{\epsilon} = \left(K_{F,t}^{\epsilon} + F_t^{\epsilon}\right),\ E_{R,t} = K_{R,t} \tag{4}$$

$$E_t \geq E_t^d, K_{R,t},\ K_{F,t},\ F_t,\ E_{F,t},\ E_{R,t},\ E_t,\ A_t,\ I_{F,t},\ I_{R,t},\ Z_t \geq 0 \tag{5}$$

where t is the time index, k is the planning period, and T is the final period. The parameter δ is the market discount rate, Δ_F the depreciation rate for fossil capacity, Δ_R is the depreciation rate for renewable capacity, $\epsilon\ (< 0)$ is the elasticity of complementarity between the carbon input and the fossil capacity, and $\sigma\ (> 0)$ is the elasticity of substitution between fossil and renewable energy. Given the characteristics of the fossil fuel industry, we specialize the model by assuming perfect complementarity between the carbon input and fossil fuel capacity, i.e., $\epsilon \to -\infty$, and perfect substitutability between fossil and renewable energy, i.e., $\sigma = 1$.

The variable P_t is the given energy price, E_t is energy supply, $K_{F,t}$ is installed fossil capacity, $E_{F,t}$ is fossil energy generation, and $P_{F,t}$ the unit cost for the fossil fuel input. F_t denotes carbon use in fossil fuel generation, $I_{F,t}$ is newly installed fossil capacity, and $I_{R,t}$ is newly installed renewable energy capacity. τ_t is the given allowance price, and Z_t denotes allowance purchases which in our representative agent framework can be set to the industry wide allowance allocation. A_t is the stock of banked allowances (or simply the bank), $K_{R,t}$ is installed renewable capacity, $E_{R,t}$ is renewable energy generation, and

E_t^d, defines the minimum power supply. The function $H(\bullet)$ defines the cost of investing in fossil fuel capacity and $X(\bullet)$ gives the cost of investing in renewable energy capacity.

Equation (1) gives the objective function. (2) tracks the stock of banked allowances, which accumulate from banking unused allowances, but decrease when banked allowances are used for compliance. Equation (3) tracks installed fossil and renewable energy capacity whereby investments expand capacity but it de-accumulates due to depreciation. Equation (4) gives the set of accounting equations for total energy supply, fossil energy supply, and renewable energy supply, respectively. Minimum availability and provision constraints are given in (5). Note from the Leontief production function, that fossil-based power supply can be recovered as $E_{F,t} = \min\{K_{F,t}, F_t\}$. We assume for simplicity that when the producer chooses to shut-in some fossil capacity, no extra costs are incurred[7].

2.2 The allowance auction

We introduce a platform on which allowances are auctioned. The goal of the auctioneer—who acts on behalf of the regulator—is to maximize revenues from allowance sales[8] subject to a periodical restriction on the auction volume as set by regulatory policy. Formally, we have that:

$$\max_{Q_t} \mathcal{W}_k = \int_{t \geq k}^{T} \tau_t Q_t e^{\rho(k-t)} dt \tag{6}$$

s.t.

$$Q_t \leq C_t, \quad Q_t \geq 0 \tag{7}$$

[7] Here one may of think of costs for laying off workers and decommissioning capacity.

[8] The assumption here is that achieving maximum revenues gets as close as possible to internalizing damages from carbon emissions. For a general equilibrium setting, one could think of revenues as being rebated to households, or being used to subsidize investments in renewable energy.

where the parameter ρ is the auctioneers discount rate. The variable C_t is the predetermined auction ceiling and Q_t (≥ 0) is the auction volume. Equation (6) gives the discounted revenues from allowance auctions, whereas (7) closes the auctioneer's problem with the restriction that the maximum auctioning volume is limited to that level set by legislators. We assume that this auction volume is always non-negative, meaning that the auctioneer cannot buy back allowances.

We impose market clearing in the allowance auction market such that:

$$Q_t = Z_t, \qquad \perp \tau_t \geq 0 \tag{8}$$

whereby this equation can be seen as summarizing the outcome of a uniform price auction.

2.3 The auction ceiling and market stability reserve

The auction ceiling, C_t, is set per EU ETS rules.[9] The initial Phase III (2013-2020) design set the auction ceiling passively, determining its level using a 1.74% annual (linear) reduction factor from average Phase II emissions[10]. The amendments contained in "Directive (EU) 2018/410/EU," mean that starting 2019, the auction ceiling is to be more actively determined.

Firstly, a linear reduction factor of 2.2% (rather than 1.74%) is to be used from 2021 onward. Secondly, allowances will be deducted from the current auction volume and added to the MSR at a rate of 24% between 2019 and 2023 and a rate of 12% thereafter, whenever the previous year's Total Number of Allowances in Circulation (TNAC) exceeds 0.833 billion. If the TNAC falls below 0.4 billion, allowances are to be taken out of the MSR and

[9] Further details on the MSR can be found here "https://ec.europa.eu/clima/policies/ets/revision_en", "https://www.politico.eu/wp-content/uploads/2017/11/Grand-compromise-on-ETS-reform-set-to-tighten-market-copy-2.pdf", "https://www.emissions-euets.com/carbon-market-glossary/957-market-stability-reserve"

[10] This leads to a reduction of the ceiling 38 million allowances annually.

injected into the market at a maximum annual rate of 0.1 billion allowances or whatever is left in the MSR. During its first year in operation, 2019, the MSR is to be seeded with approximately 1.6 billion allowances[11]. Moreover, from 2023 onward, allowances in the MSR in excess of the volume auctioned in the previous year are to be cancelled.

In Appendix A, we provide the equations determining C_t and those defining the state of the MSR. Considering that our modelling is focused on the power sector alone, and yet the MSR applies to the non-combustion sector as well, we make some adjustments to the initial stocks of the MSR as is later explained in Section 4.

2.4 Demand uncertainty

As well as dynamically regulating the availability of allowances, EU regulators hope that the reforms to the EU ETS will make it more resilient to major shocks. For instance, if an unexpected shortfall in economic activity were to lead to a reduced demand for allowances and thereby to a build-up of allowances in circulation, by reducing the volume of allowances that are auctioned—via absorption into the MSR—regulators would hope for a price collapse to be moderated.

To obtain insights on how firms will respond to major shocks under the MSR, we introduce demand uncertainty to our model. The firm is assumed to know present-day demand with certainty, but there is probabilistic uncertainty regarding future demand. Present-day actions must therefore hedge against an uncertain future, and once a shock is realized, the firms immediate actions are in part used to correct for perceived inefficiencies in the accumulation of renewables- and fossil- based generation capacity, as well as the volume of banked allowances. In the current paper, we focus on the risk-neutral firm and, therefore, the objective of the firm is to maximize expected net profit[12].

[11] This is the sum of 0.9 billion allowances that were backloaded during Phase II and another 0.6-0.7 billion that were unallocated.

[12] We leave to future work, exploring how demand uncertainty affects the actions of the risk averse firm.

3 Equilibrium

Our model can be solved to yield some general insights regarding the nature of the equilibrium path. First we consider the equilibrium under the deterministic setting, before exploring how uncertainty modifies the firm's solution strategy.

3.1 Deterministic setting

The firm's Lagrangian can be written down as[13]:[14]

$$\begin{aligned}\mathcal{L}^{\text{firm}} = P_t E\left(K_{F,t}, F_t, K_{R,t}\right) - P_{F,t} F_t - H\left(I_{F,t}\right) - X\left(I_{R,t}\right) - \tau_t Z_t \\ + \varphi_t\left(Z_t - F_t\right) + \mu_{F,t}\left(I_{F,t} - \delta_F K_{F,t}\right) + \mu_{R,t}\left(I_{R,t} - \delta_R K_{R,t}\right)\end{aligned} \tag{9}$$

where $\varphi_t\ (\geq 0)$, $\mu_{F,t}\ (\geq 0)$, and $\mu_{R,t}\ (\geq 0)$ are shadow prices on the stock of banked allowances, on fossil fuel production capacity, and renewables' production capacity, respectively. $E\left(K_{F,t}, F_t, K_{R,t}\right)$ denotes the supply of energy as a function of its primary determinants, $K_{F,t}$, $K_{R,t}$, and F_t.

Taking derivatives with respect to the choice variables yields:

$$P_t E^F\left(K_{F,t}, F_t, K_{R,t}\right) - P_{F,t} - \varphi_t \leq 0 \qquad F_t \geq 0 \text{ c.s} \tag{10}$$

$$-H^{I_F}\left(I_{F,t}\right) + \mu_{F,t} \leq 0 \qquad I_{F,t} \geq 0 \text{ c.s} \tag{11}$$

$$-X^{I_R}\left(I_{R,t}\right) + \mu_{R,t} \leq 0 \qquad I_{R,t} \geq 0 \text{ c.s} \tag{12}$$

$$-\tau_t + \varphi_t \leq 0 \qquad Z_t \geq 0 \text{ c.s} \tag{13}$$

where the superscript associated with a function denotes the derivative of that function

[13] This Lagrangian assumes that the firm takes the developments on the permit market as given, including the impact of banked allowances on the allowance price. The supposition here is that firms are in general too small as to explicitly take into account strategic interactions emanating from the supply-side of the allowance market.

[14] For simplicity, we have left out the non-negativity constraints on model variables. This does not change the analysis and insights gained about the (interior) equilibrium.

with respect to the indicated variable. $E^F(K_{F,t}, F_t, K_{R,t})$ for instance represents the derivative of the production function with respect to the fossil input.

Equation (10) says that whenever the fossil fuel input is used, the marginal revenue product of fossil-based power generation will be given by unit cost of the fossil input plus the opportunity cost of the emission allowance that is handed over to the regulator for covering any associated emissions. If, however, the marginal revenue product of the fossil fuel input is exceeded by the composite cost of deploying fossil fuels in power generation, then no fossil fuels are used. Equation (11) and (12) delineate the conditions for optimally investing in production capacity. Both require that the volume of newly installed capacity is determined such that the marginal cost of installing capacity equals the marginal profit that the marginal unit earns over its life. If this marginal profit lies below the marginal cost of installing capacity, then no new capacity is developed. Lastly, Equation (13) gives the condition for allowance purchases. The firm purchases allowances whenever the opportunity cost of an allowance is at least as great as the allowance price; otherwise, no new allowances are purchased.

The three equations tracking the development of shadow prices φ_t, $\mu_{F,t}$, and $\mu_{R,t}$ are:

$$\dot{\varphi}_t - \delta\varphi_t \leq 0 \qquad A_t \geq 0 \text{ c.s} \tag{14}$$

$$\dot{\mu}_{F,t} - \delta\mu_{F,t} + P_t E^{K_F}(K_{F,t}, F_t, K_{R,t}) - \delta_F \mu_{F,t} \leq 0 \qquad K_{F,t} \geq 0 \text{ c.s} \tag{15}$$

$$\dot{\mu}_{R,t} - \delta\mu_{R,t} + P_t E^{K_R}(K_{F,t}, F_t, K_{R,t}) - \delta_R \mu_{R,t} \leq 0 \qquad K_{R,t} \geq 0 \text{ c.s} \tag{16}$$

where in limit, the following transversality conditions apply:

$$\lim_{T\to\infty} \varphi_T A_T \exp(-\delta T) = 0, \lim_{T\to\infty} \mu_{F,T} K_{F,T} \exp(-\delta T) = 0,$$
$$\text{and} \lim_{T\to\infty} \mu_{R,T} K_{R,T} \exp(-\delta T) = 0 \tag{17}$$

Equation (14) says that whenever the firm maintains a stock of banked allowances, then the in situ value of an allowance rises over time at the firm's rate of discount. If it so happens that this value rises below the rate of discount, then the firm will not bank allowances since they can always be acquired in the future at a lower discounted cost. It follows that firms will purchase and immediately use all allowances to cover emissions if the growth rate of the allowance price falls below the rate of discount; otherwise, they purchase and bank any unused allowances[15]. This means that banking serves to reduce abatement costs only when the allowance price is rising at the rate of discount (cf. Cronshaw and Kruse, 1996; Rubin, 1996).

Equations (15) and (16) define the rate of change of the in situ value of capacity and thereby the speed at which capacity is accumulated. Since the marginal gain from installing capacity is lower at higher levels of capacity; one expects a deceleration in the investment rate after some level of capacity is accumulated. By integrating (15) and (16), then taking limits as $t \to \infty$, it becomes apparent that the marginal revenue product of installed capacity is what drives the intensity of capacity development. This has a number of implications. First, the possibility of carrying idle fossil fuel generation capacity disincentivizes fossil capacity development. Second, since fossil fuel capacity is abandoned when the carbon budget runs out, all investment in fossil capacity must cease at some future point in time. Third, since fossil and renewables capacity are perfect substitutes and yet: (i) fossil capacity can be shutdown, (ii) the fossil input is limited, and (iii) renewables capacity is always fully utilized, one can expect renewables capacity development to generally outlast fossil capacity development.

The transversality conditions in Equation (17) imply the following. The first gives the requirement that the firm's bank of allowances in the terminal period is either fully used up or all remaining allowances are of no economic benefit. The second and third require that whenever there is a positive stock of energy generation capacity of either renewables

[15]There are multiple reasons why firms may continue to purchase and bank allowances even when the growth rate of the allowance price is below the rate of discount. This includes hedging and speculative reasons, as well as trading with the strategic purpose of pre-empting one's rivals.

or fossil fuels left by the final period, then their should be no economic benefit associated with this capacity.

The auctioneer's Lagrangian is given by $\mathcal{L}^{\text{auct}} = \tau_t Q_t - \psi_t \left(C_t - Q_t\right)$ which yields the following first order necessary conditions.

$$\tau_t - \psi_t \leq 0 \qquad Q_t \geq 0 \tag{18}$$

$$\psi_t \left(C_t - Q_t\right) = 0 \qquad \psi_t \geq 0,\, C_t \geq Q_t \tag{19}$$

The first equation implies that when an auction takes place, i.e., $Q_t > 0$, the allowance price must equal the shadow price on the (regulatory) auction ceiling, ψ_t. The second equation is a complementarity condition requiring the shadow cost of the regulatory constraint to equal zero whenever the regulatory constraint implies a lower demand for allowances than mandated by the regulator.

The envelope theorem does provide some insights on how tightening the auction ceiling or the reducing the carbon budget affects the allowance price. In particular, since the total derivative of (6) with respect to C_t, is negative, we deduce that a tighter auction ceiling raises the allowance price. Via Equation (13), this in turn has implications for emissions and the banking of unused allowances. Holding constant renewable capacity, it is immediate from Equation (10) that a higher allowance price in one particular period decreases the use of the fossil fuel input. We should therefore expect to see that a tighter auction ceiling curbs cumulative investment in fossil fuel capacity and boosts cumulative investments in renewable capacity. Foremost, because allowances are physically scarcer, but also in part through price effects of a higher allowance price.

We can also evaluate the impact of withdrawing allowances in one period, and bringing back the same amount at a later point in time. If the amount is withdrawn and returned within the interval where firms are continuously banking allowances, the allowance price must increase[16]. In other words, delaying the auctioning of allowance, even without cancellation, unambiguously raises the allowance price provided firms continuously bank. If allowances are withdrawn during the banking regime and returned after banking has elapsed, it is not immediate if allowance prices rise as other factors such as where the ceiling sits at reinjection and also when allowances are reinjected in the market count.

3.2 Effect of demand uncertainty

To introduce uncertainty, we assume that due to exogenous demand shocks, the power price fluctuates from its expected growth path according to a stochastic process with independent increments. Lets assume a stochastic process γ_t that shocks industry-wide demand. This process imprints onto the power price such that $P_t = P(\gamma_t)$ can be written as,

$$dP_t = \theta P_t dt + \sigma P_t dz_t = \theta P_t dt + \sigma P_t \kappa_t \sqrt{dt} \tag{20}$$

where κ_t is a serially uncorrelated normal random variable with zero mean and unit variance (i.e. κ_t is a Wiener process). Equation (20) implies that the current price is known exactly, that uncertainty about future prices grows with the time horizon, and that fluctuations in price occur continuously over time.

Our power generation model updated with a stochastic price process can be solved, where it becomes apparent that it yields more or less the same first order necessary conditions as those in the certainty case. Moreover, by way of stochastic optimal control, it is

[16] Let ς be a small change in the ceiling such that $C_t - \varsigma$ and $C_{t+1} + \varsigma$. To substantiate the insight, we can differentiate the Lagrangian with respect to ς, and compare to the derivative prescribed by the Envelope theorem conditional on the allowance price rising at the rate of discount.

straightforward to establish that for quadratic investment costs:

$$(1/dt)E_t\left(d\tau_t\right) = \delta\tau_t \tag{21}$$

$$(1/dt)E_t\left(dI_{F,t}\right) = \frac{1}{X^{I_F I_F}\left(I_{F,t}\right)}\left(X^{I_F}\left(I_{F,t}\right)\left(\delta_F+\delta\right) - P_t E^{K_F}\left(K_{F,t}, F_t, K_{R,t}\right)\right) \tag{22}$$

$$(1/dt)E_t\left(dI_{R,t}\right) = \frac{1}{X^{I_R I_R}\left(I_{R,t}\right)}\left(X^{I_R}\left(I_{R,t}\right)\left(\delta_R+\delta\right) - P_t E^{K_R}\left(K_{F,t}, F_t, K_{R,t}\right)\right) \tag{23}$$

Whenever$A_t > 0$ the first equation holds, and when $K_{F,t}, K_{R,t} > 0$, the second and third equations apply, respectively. These equations are, in expected terms, similar to those recovered under certainty. (21) says that for a positive stock of banked allowances, firms expect the allowance price to on average rise at the rate of discount. (22) and (23), on the other hand, give the mean rate of change in capacity development with installed production capacity.

Observe from (21)-(23) that in the interior optimum, uncertainty does not introduce any unique mean rate of change impacts relative to the certainty case. Still, there can be level effects. It has been shown before in a capacity adjustment model that the representative firm increases (initial) investment in the presence of uncertainty (see e.g., Caballero, 1991). Moreover, Zhang (2007) has shown using a fuel switching model that the allowance price increases in the presence of demand price uncertainty. Zhang's model does not accommodate for capacity accumulation, however.

The following lemma characterizes our model's interior optimum under demand uncertainty

Lemma 1. *In the interior optimum, increasing demand uncertainty leaves the mean rate of change of the allowance price and investment in capacity development unchanged but, increases the initial allowance price as well as initial fossil and renewables capacity development.*

The intuition for why initial investment and allowance price increase is as follows. Since an increase in demand increases counterfactual emissions and yet the carbon budget is fixed, total required emissions reduction must increase. Considering that capacity development costs are convex, marginal costs of developing capacity rise with an increase in required emissions reductions. As such, when demand increases, marginal capacity developments increase faster than they decrease when demand falls[17]. This means that the potential gain from banking the marginal allowance is higher when demand increases than the potential loss when demand falls. In the presence of extreme demand gyrations, firms thus have a higher incentive to bank more permits and also hold more capacity.

4 Model calibration and solution strategy

This section describes the calibration of our proposed model to the EU ETS power industry. It also describes the solution strategy used to identify the optimal solution path.

4.1 Model calibration

While there is no consensus on the appropriate discount rate, we settle for 10% in our baseline simulations. This value is, however, in the upper range of probable discount rates actually used by firms (Kost et al., 2018; Oxera, 2011). In our counterfactual analysis we, therefore, also evaluate the impacts from a lower (4%) and a higher (16%) discount rate.

For the rate of capacity depreciation, we take the inverse of the average lifetime of a representative technology. Coal power plants are typically operational for up to 40 years. Gas power plants, on the other hand, have a shorter lifetime, typically of 25-30 years. For the fossil technology, we consider a lifetime of 40 years in the baseline specification but also report on the consequences of a shorter lifetime of 30 years. This corresponds to capacity depreciation rates of 2.5% and 3.3%, respectively.

For renewable energy, on the other hand, wind turbines typically remain operational

[17]This argument follows from a direct application of Jensen's inequality.

for 20-30 years. Solar panels, by contrast, have a much longer operational life of up to 50 years. Since we treat nuclear—with a lifetime of up to 70 years—as a renewable (or at least carbon-free) energy resource; and because hydro, another leading source for renewable energy, has typical lifetimes of more than 50 years, we select 40 years for the representative lifetime of renewables. In the counterfactual analysis we, nevertheless, report on the impact of a shorter lifetime of 30 years.

In the main simulations, we set the price of the carbon input to €13/MWhe. Fuel prices exhibit substantial variability over time and by technology, however. Empirical data shows that the gas price per MWh can lie just above the per MWh coal price in some periods but can be up to five times greater in other periods. Over extended durations, the coal price appears to revert to about €13/MWhe and the gas price to €20/MWhe. We regard these prices to be representative of longrun future prices. In our baseline simulations we assume that all fossil-based power is generated from coal, at an input cost of €13/MWhe price[18]. In a counterfactual evaluation, we assume that gas is the sole fuel input at a cost of €20/MWhe.[19]

For the period 2018 onward, we assume a linear demand growth rate of 1%. This amounts approximately to a 20% increase in fuel consumption by 2050, consistent with the predictions of the EU PRIMES model[20]. Moreover, we adopt a linear demand specification and calibrate its intercept using the load in 2018, a -0.5 price elasticity of demand, and €50/MWh electricity price.

We specify a quadratic cost function for the cost of developing capacity. This function is calibrated to fit the reported data on investment costs. For fossil generation, Kost et al. (2018) report capital expenditures between €800 and €2200 per KW. For renewables, this range is between €800 and €6000 per KW. We use the lower bounds of these ranges as

[18]We focus on a single fossil generation technology at a time, as opposed to multiple technologies, in order to make the numerical computation of the stochastic equilibrium more tractable.

[19]For emission-allowance accounting, we apply emission intensities of 0.956 tCO2/MWhe for coal and 0.593 tCO2/MWhe for gas.

[20]See "https://ec.europa.eu/clima/policies/strategies/analysis/models_en" for more information on the PRIMES model.

intercepts for the marginal investment cost function. We then assume that at 4% of 2018 installed fossil and renewables capacities, marginal investment costs per technology hit their higher value. We settle for 4% because given our depreciation rate of 2.5%, and our assumed demand growth of 1%, simulated annual investment turns out to be more or less in line with historical investments expenditures.

We initialize the model's generation capacity as follows. In 2018, total energy supply amounted to 3244 TWh. This quantity sets initial capacity in our model. To obtain initial capacity by technology, divide initial capacity between fossil and renewable energy using their 2018 shares. This implies an initial fossil generation capacity of 1440 TWh, and an initial renewables generation capacity of 1804 TWh.

Since our simulations focus on the power sector alone and yet the EU ETS applies to the industrial sector as well, we adjust quantities relating to: (i) banked allowances, (ii) allowances seeded to the MSR in 2019, (iii) the MSR trigger thresholds, and the (iv) the auction ceiling. The goal is to evaluate the power sector with the industrial sector held fixed.[21] We fix the percentage share of the industrial sector in the EU ETS based on 2017 emissions data. This amounts to adjusting the outlined EU ETS quantities by about 72%.

Banked allowances: In 2017, banked allowances in the EU ETS summed up to about one year worth of emissions. We set the volume of allowances banked by the power sector to a years worth of emissions. Since about 1.68 billion allowances where banked by both the power and industry sectors as of 2017, we set the quantity banked by the power sector alone to 1.23 billion allowances[22].

Allowances in the MSR: The MSR in 2019 is seeded with about 1.6 billion allowances.[23] We

[21] Due to international competitiveness concerns, the industrial sector has traditionally received its allocation of allowances free of charge. And while regulators currently plan on phasing out this 'grandfathering,' they still intend to allocate about 40% of allowances in the remaining EU ETS carbon budget free. What is clear for now is that very few of these free allowances will go to the power generating sector. In a way, this justifies our holding of industrial sectors actions fixed since if they use up all allowances that are issued to them, then this should have no material impact on the emission choices of power generators, and how much they are willing to pay for the marginal allowance.

[22] Data on the banking of allowances by sector are available from the European Union Transaction Log with a lag of five years. At the time of writing 2017/2018 data are not yet available.

[23] 0.9 billion allowances that were backloaded during the 2014-2016 period and another 0.55-0.7 billion

adjust this figure by 72% such that the MSR in our calibration is seeded with approximately 1.17 billion allowances.

Trigger thresholds: The MSR will intake (outtake) allowances if the number of banked allowances exceeds 0.833 (falls below 0.4) billion. We also adjust these quantities by 72% such that the MSR in our model intakes (outtakes) when banked allowances exceed 0.599 (fall below 0.288) billion. Moreover, we adjust the outtake rate from 0.1 billion to 0.72 billion allowances.

Primary auction ceiling: Current EU ETS legislation specifies that the gross auction ceiling is to be calculated using a linear reduction factor of 1.74% between 2018 and 2021, and a linear reduction of 2.2% from 2021 onward, using average Phase II (2008-2012) emissions as the basis. We adjust this basis by 72%, to 1.42tCO2 (and hence billion allowances), as opposed to 1.96 billion tCO2.

Table A.1 summarizes the calibrated parameters as well initialized variables that are used under our baseline specification.

4.2 Solution strategy

We solve the model as a standard optimization problem using the KNITRO solver via the General Algebraic Modelling System[24]. The model is solved at an annual timescale, with 2018 as the initial year and 2100 as the terminal year. The reporting period is limited to 2030. The primary reason for this is to ensure that the reported results are robust to terminal effects that are the consequence of using a finite (rather than infinite) planning horizon.

When simulating the model under uncertainty, we evaluate 8192 possible futures. In particular, we assume that in each of the periods between 2019 and 2031 inclusive, demand either remains unchanged or experiences a 2% linear growth[25]. We solve this model

allowances that remained unallocated from previous years.

[24]"https://www.gams.com/"

[25]The reference point for the linear growth rate is the year 2018.

using stochastic programming methods as detailed for instance in Shapiro et al. (2009), assuming an equal for chance for demand to either increase or remain unchanged. The calculated pathways are fully consistent with decision making under uncertainty and like in dynamic programming, the outcome in any given period is a function of state of that period (cf., Tahvonen et al., 2018).

5 Simulated impacts of the MSR under certainty

This section documents the impacts of the MSR under certainty. To isolate the contributions of the MSR's various components, we simulate policies under four auction ceiling designs. The first features the EU ETS per its initial Phase 3 design. That is, the ceiling is set using an annual linear reduction factor of 1.74%.[26] The second introduces, from 2021 onward, a higher linear reduction factor of 2.2% that was rolled out as part of the EU ETS reform.[27] The third additionally considers the intake and outtake of allowances via the MSR, but disregards their cancellation. The final specification accommodates for cancellation of allowances via the MSR from 2023 onward.[28] In respective order, we label these four specifications: "linear 1.74," "linear 1.74 & 2.2," "MSR plain," and "MSR cancel."

We start by showing in Section 5.1 that the withdrawal of allowances from auction and the subsequent placement into the MSR has a positive meaningful impact on the allowance price, and on boosting (limiting) investment in renewables (fossil) generation capacity. Interestingly, cancellation of allowances via the MSR, per current rules, has a minimal impact on allowance prices. Section 5.2 then shows that the predicted generation mix under the MSR is robust to alternative modelling assumptions, and 5.3 that generators have little incentive to redeploy fossil generation, even as allowances are later auctioned from the MSR.

[26]Here the auction ceiling hits zero in 2052.

[27]In this case the auction ceiling hits zero in 2045.

[28]Here allowances are cancelled by restricting their maximum accumulation to the previous year's auction ceiling.

5.1 Performance of the MSR

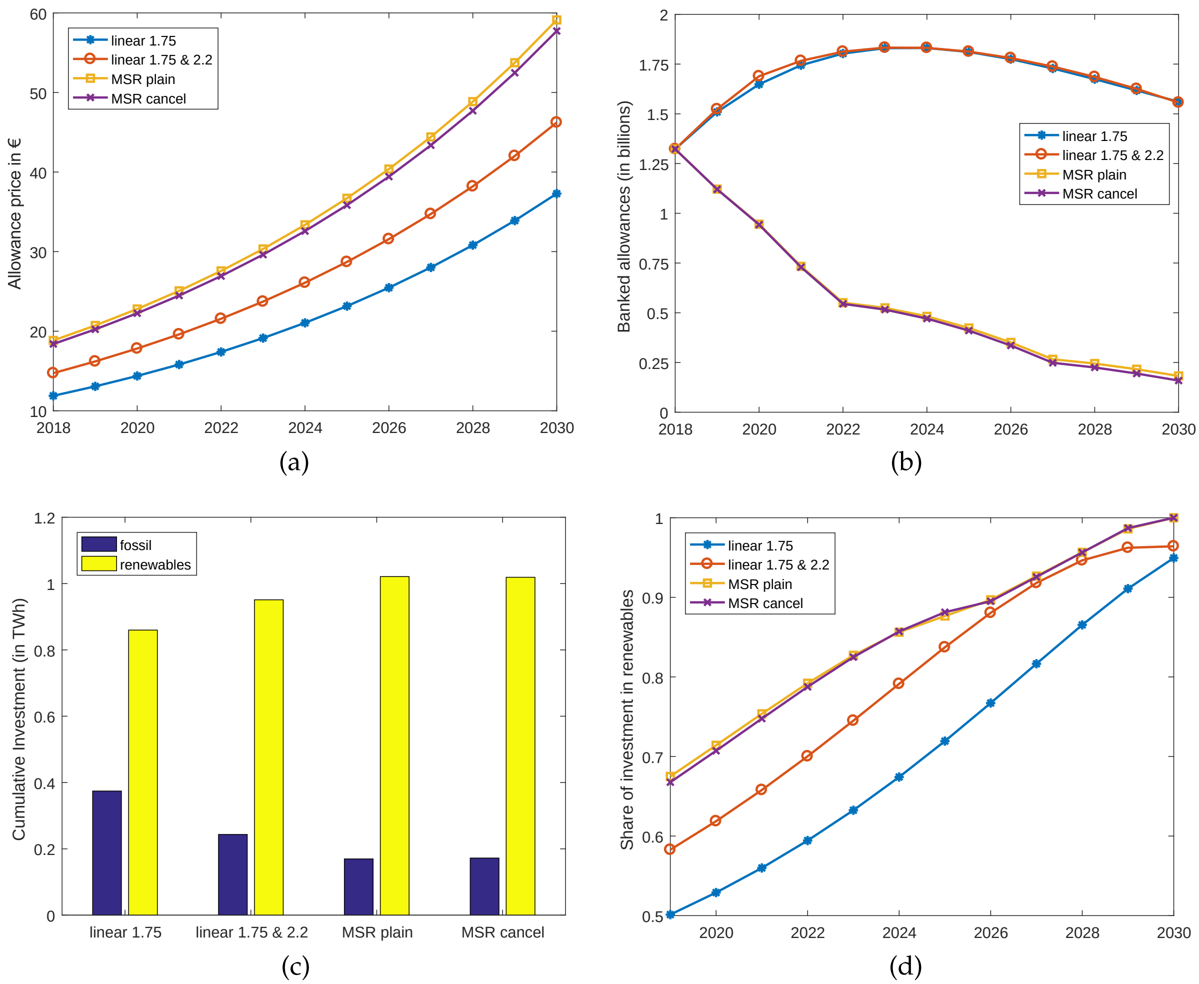


Figure 1: Allowance price, banked allowances, and investment under certainty and perfect foresight.

Figure 1 presents allowance prices (panel (a)), banked allowances (panel (b)), cumulative investments in capacity to 2030 (panel (c)), and the investment share in renewable energy (panel (d)). For specification "linear 1.74," the allowance price starts at €11.881/tCO2 in 2018 and increases exponentially at the rate of discount to €37.287/tCO2 in 2030. This kind of increase is expected when firms are banking allowances. Furthermore, because the allowance price's initial level ensures that its level at termination of the banking regime, equals the marginal cost of abatement from using all of the then auctioned allowances for immediate compliance: (i) a higher auction ceiling in the immediate aftermath of the banking regime elapsing and (ii) a longer banking duration, precipitate low allowance prices.

Compared to specification "linear 1.74," "linear 1.74 & 2.2" has a higher reduction factor after 2020. Figure 1 panel (a) shows that this leads to an increase in the initial allowance price by €2.848 to €14.729. From this level, the allowance price rises at the rate of discount, eventually reaching €46.226 in 2030. Banking here ceases in 2043, with renewable capacity generating 3020 TWh and the auction ceiling sitting at 0.420 billion tCO2 in the year 2044. This can be contrasted with specification "linear 1.74," which has a lower 2929 TWh of renewable energy generation and an auction ceiling that sits at a higher 0.580 billion tCO2, in 2047, the year after banking elapsing. By reducing the long-run availability of allowances, "linear 1.74 & 2.2" raises the allowance price, which in turn disincentivizes investments in fossil fuel capacity by nearly 35% as of 2030 (panel (c)), and also hastens and boosts renewables capacity development (panel (d)).

Although the carbon budget under "MSR plain" is not altered relative to "linear 1.27 & 2.2," because the issuance of allowances is delayed and therefore desired (fossil) production initially more constrained, allowances become more valuable to firms. This increased initial (or short-term) scarcity of allowances means that firms are willing to pay more in order to receive the marginal allowance while additional renewables capacity is still built up. Relative to "linear 1.74 & 2.2," the initial allowance price under "MSR plain" is higher by €4.106.[29] This gives an initial allowance price of €18.392 that also rises at the rate of discount, reaching €59.113 in 2030. Banking here ceases much earlier in the year 2037, with green capacity reaching 2552 TWh and the ceiling sitting at 0.680 billion tCO2 in 2038.[30] Without having to cancel any allowances but simply postponing their availability,

[29]Half of this increase is explained purely by the MSR and not due to the fact that unallocated allowances are seeded to the MSR and not released directly into the market by 2030 as is the case with "linear 1.27" and linear 1.27 & 2.2."

[30]In 2044 and 2046, the ceiling sits at 0.493 and 0.431 billion tCO2, respectively. Renewables generation, on the other hand, sits at 2952 and 3087 TWh, in the same years, respectively.

the intake/outtake mechanisms of the MSR additionally curb fossil capacity development between 2018 and 2030 by an additional 25% relative to specification "linear 1.74 & 2.2," and further boost renewables capacity development.

Cancellation of allowances as specified using "MSR cancel" produces a minimal change in the allowance price when contrasted with "MSR plain."[31] And in fact, we observe a slight decrease rather than increase in the allowance price.[32] Banking under "MSR cancel" lasts until the year 2035.[33] In the following year, renewables energy generation capacity reaches 2416 TWh and the auction ceiling sits at 0.743 billion tCO2. This contrasts with a slightly lower accumulation of 2409 TWh,[34] but an identical auction ceiling at the same point in time under "MSR plain."[35] This implies that the slightly higher accumulation of renewables for "MSR cancel" relative to "MSR plain,"[36] is what primarily drives the allowance price lower. This comes about due to both their connection to the marginal abatement cost that terminates the banking regime. The more depressed this marginal abatement costs is, the lower the initial allowance price.

Perino and Willner (2016, 2017) and Salant (2016) emphasize the need to cancel allowances, arguing that failure to do so would lead only to a temporary increase or no increase in allowance prices.[37]. Conversely, our analysis illustrates that postponing the issuance of allowances, even in the absence of cancellation, can be equally (if not more) effective

[31] About 1.222 billion allowances are cancelled in 2023, and nothing thereafter. If everything that enters the MSR is cancelled, this amounts to about 2.14 billion allowances. If one adjusts for the size of the power sector in the EU ETS as of 2017, these figures imply cancellation of 1.714 and 3.06 billion allowances.

[32] To ensure that this is indeed the case, we solved the model with four other solvers besides KNITRO. These solvers are shipped with GAMS (CONOPT, SNOPT, SCIP, and PATHNLP). We obtained the same result. We also initialized the algorithm to different starting values. It always converged to the same solution.

[33] Between 2018 and 2022 the MSR withdraws between 0.317 billion and 0.175 billion allowances annually and starting 2028 reinjects 0.073 billion allowances annually. In "MSR plain" the reserve is exhausted in 2057 but is exhausted 27 years earlier, in 2040, under "MSR cancel."

[34] Renewables capacity under "MSR cancel" exceeds that under "MSR plain" between the years 2027 and 2060. Outside of this window capacities more or less match.

[35] In fact, the ceilings continue to remain identical until banking elapses with "MSR plain."

[36] Post-banking, allowance prices are generally higher with "MSR cancel," which gives firms more incentive to accumulate renewables during the banking regime.

[37] Perino and Willner (2016, 2017) argue that allowances placed into the MSR should be cancelled while Salant (2016) argue that allowances at the tail end of the auctioning regime should be cancelled.

at dealing with low allowance prices. Considering that the future is uncertain, cancelling can result in committent and credibility problems, as regulators may later have to uncancel allowances so as to contain price escalations. Moreover, if firms act with limited foresight, cancelling allowances in the future is bound to have little to no impact on the current allowance price.

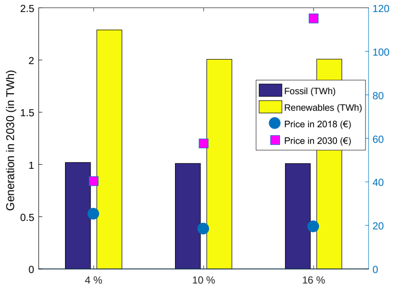
We reach a different perspective regarding the importance of cancelling allowances because the related literature disregards technological path dependency and sunk costs. These are both characteristic of the power and the industrial sectors. As such, they overestimate the consequence that the outtake of allowances from the MSR can have on allowance prices and abatement. In our model, once capacity is sunk, additional investments serve mainly to replace deprecated capacity and are therefore less costly. For this reason, by pursuing renewables capacity development early when allowances are relatively scarce, it can be cost-effective in the future as well, to maintain the dominance of renewable energy than reinvest in fossil capacity generation. Moreover, to the extent that the marginal allowance that is auctioned from the MSR is of little economic value to the firm, we can expect to observe a minimal impact on allowance prices.

5.2 Sensitivity analysis

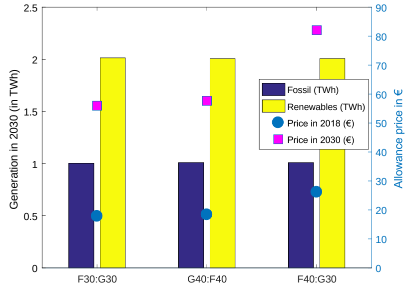
Is the finding that the MSR boosts renewable generation and curbs fossil generation robust to alternative parametric assumptions? To provide an answer, we focus on how both the power generation profile in 2030 and the allowance price between 2018 and 2030 under "MSR cancel," respond to alternate model assumptions.[38] We evaluate how the: (i) discount rate, (ii) depreciation rate, (iii) volume of allowances cancelled via the MSR, (iv) intake rate of the MSR, (v) outtake rate of the MSR, and (vi) thresholds that trigger the MSR matter for the optimal solution.

Figure 2 panel (a) shows that fossil (renewables) generation capacity is invariant (re-

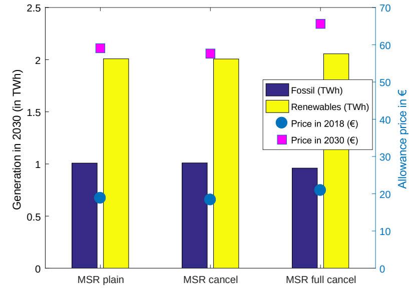
[38] The results under "MSR plain" are found to be consistent with those that we present here.



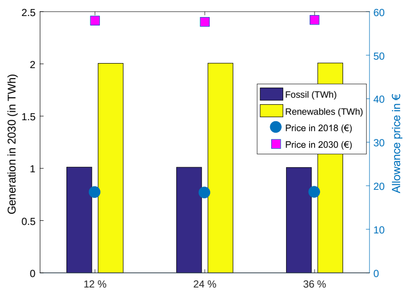
(a) Discount rate



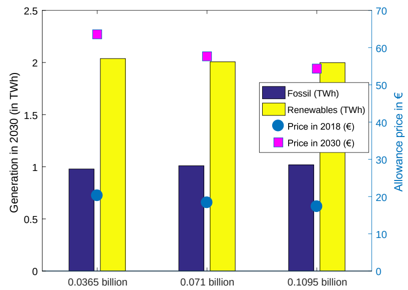
(b) Depreciation rate



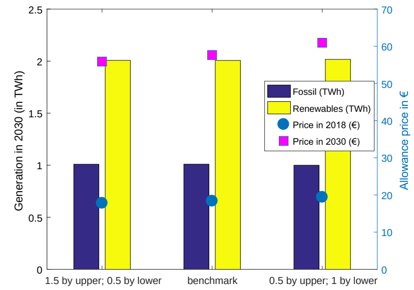
(c) Cancellation



(d) Intake



(e) Outtake



(f) Threshold

Figure 2: Power generation in 2030, and allowance prices in 2018 and 2030 for alternative parametrizations of the model.

sponsive) to changing the discount rate.[39] In pure capacity adjustment models, increasing the discount rate raises the user cost of capacity which disincentivizes capacity accumulation—i.e. a 'delay' effect. In pure resource models, on the other hand, a higher discount rate hastens depletion as producers give more preference to the present—i.e an 'impatience' effect. The 'delay' effect, due to the fixed carbon budget, and the 'impatience' effect, coming from fossil capacity accumulation, cancel each other out thusly explaining the non-response of fossil generation. For investment in renewables energy generation, through its dependence on the user cost of capital, seemingly decreases in the discount rate at an increasing rate. The allowance price responds similarly as renewables' investment to the changing discount rate. By and large, there is a minimal to moderate response by agents to changing the discount rate. The response is greatest at low discount rates.

The power generation profile in 2030 is invariant to changing the depreciation rate

[39] In 2030, fossil fuel use is stable at about 1 TWh for the various discount rates. Renewables consumption is higher at 2292.678 TWh with a 4% discount rate but lower at about 2 TWh with the 10% and 16% discount rates.

(panel b Figure 2). The explanation for this is that before 2030, investment responds with firms investing more in the technology with the higher depreciation rate. The allowance price also responds to varying the depreciation rate. A higher depreciation rate for renewables (fossil fuels) leads to a higher (slightly lower) allowance price than in the baseline "F40:G40." However, we know from theory that the user cost of capacity increases as the depreciation rate is increased, and this disincentivizes investing in the affected technology. In our model where we also have a carbon budget, the allowance price responds to the first order counterfactual shifts which leaves the energy profile in 2030 unaffected. In particular, a higher depreciation rate for renewables (fossil fuels) raises the demand for fossil fuels (renewables) which in turn increases (decreases) the allowance price. This increase (decrease) in the allowance price helps incentivize renewables (fossil fuel) investments thereby countering the first-order effects.

In the previous section, we saw that cancelling allowances from the MSR has a minimal impact on the allowance price. Panel (c) Figure 2 contrasts the effects of cancelling, none (i.e. "MSR plain"), per the MSR rules (i.e. "MSR canclel"), or everything that enters the MSR (i.e. "MSR full cancel"). Observe that full cancellation raises the initial allowance price by €2.515 to €20.907. This higher allowance price helps trigger increases (reductions), albeit small, in renewables (fossil) capacity accumulation. About 2.17 billion units are cancelled under "MSR full cancel" compared to 1.22 billion in the "MSR cancel" specification. That cancelling 77.3% more allowances yields a mere 13.7% increase in the allowance price and a minimal shift in the investment and power generation profiles underscores why cancellation of allowances—especially after they have been placed in the MSR—can be limited at driving emissions reductions.[40]

[40] About 9 billion allowances are cancelled in moving from "linear 1.74" to linear "linear 1.74 & 2.2". This amounts to cancelling about 23% of allowances. This as seen earlier results in an increase in the initial price of about 24%. Contrast this with 25% increase in the allowance price when moving from "linear 1.74 & 2.2" to "MSR plain" even when no allowances are cancelled.

We carry out an additional experiment where relative to "linear 1.74 & 2.2", 2.17 billion additional are cancelled and the stability reserve is deactivated. This yields.....Add numbers.... The key problem with cancellation is knowing how much cancellation generates an ideal price increase. Moreover, cancelling

Figure 2 panel (d) contrasts the baseline 24% with a 12% and 36% intake rate for the period 2019 to 2023. Although a higher intake should in theory lead to a higher allowance price; here we see that both the price and generation profile are minimally affected. To explore this result, we ran an additional simulation where the intake rate between 2019 and 2023 is set to 0%. In this case, the initial allowance price decreases but by only €0.3 relative to the baseline. In yet another scenario, we set the intake rate to 0% throughout, and the initial allowance price fell by €1.4 relative to the baseline. Thus, while the intake rate can raise allowance prices, its impact is only minimal to moderate. This is in part because the volume of allowances that can be withdrawn are limited by the duration that banked allowances remain above the upper trigger threshold. One key advantage of the MSR thus appears to be in delaying the allocation of allowances that are initially seeded to the MSR.

Figure 2 panel (e) shows that raising the outtake rate, lowers the allowance price. The impacts on generation are minimal, however. Because a lower outtake increases post-banking marginal abatement costs, this raises the allowance price that terminates the banking regime and in turn the initial allowance price. Note, however, that the allowance price only indirectly affects investment through its impact on the marginal productivity of capacity. Since allowances are generally withdrawn from the MSR after some excess capacity has built up, the future marginal productivity of capacity factors little in determining the present user cost of capital. As such, as outtake is varied, the user cost, and thereby investment and generation capacity remain mostly unresponsive, in spite of the responsiveness of price.

Finally, we clarify the impact from altering the thresholds that trigger the MSR. We consider two cases that relative to the baseline, weaken or strengthen the MSR. In the first, we widen the MSR thresholds by 50%, meaning that the MSR is inactive over a larger state space of banked allowances. In the other, we narrow the upper threshold of

at at tail end, rather than reducing the auction amount immediately could fail to raise allowance prices, especially if firms have limited foresight.

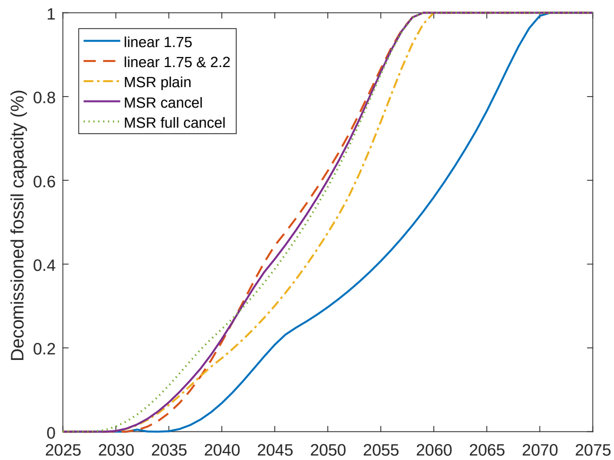


Figure 3: Decommissioned fossil-based generation capacity.

the MSR by 50% but leave the lower threshold unchanged. In this latter case, the MSR takes in more allowances over the state space of banked allowances. Figure 2 panel (f) shows that when the MSR becomes less (more) active, prices are lower (higher). The 2030 generation profile remains pretty much unaffected, however. In the less (more) active case, the MSR takes in 0.815 (1.159) billion allowances by 2023. This compares with 0.988 billion allowances in the baseline also by 2023. These results are consistent with the rest of the sensitivity analysis's findings: that while tweaking certain aspects of the MSR can have an impact on prices, the pass-through to the generation mix tends to be minimal.

5.3 Incentives for redeploying fossil-fired generation

The MSR has a meaningful impact on allowance prices and emission reductions, even when no allowances are cancelled. Yet, a key concern observers have is that if allowances are merely withdrawn and returned to auction at a later date, a temporary increase in the allowance price will lead to a resurgence in fossil fuel use. Any reforms to the EU ETS that exclude cancellation are, therefore, likely to be in vain.

Figure 3 shows that capacity is continuously decommissioned[41] across all specifica-

[41] We measure decommissioned capacity as the the amount of installed capacity that producers leave unused, rather than employ in fossil-based electricity generation.

tions but, "linear 1.74."[42] The MSR helps accelerate the decommissioning of capacity with all fossil capacity eventually being shutdown by 2060, almost a decade earlier than in specification "linear 1.74." Contrasting "linear 1.74 & 2.2" and "MSR plain," we see that decommissioning is delayed in the latter. Indeed, because MSR allowances are returned at a later date, generators have the incentive to delay decommissioning capacity. Installed generation capacity is, however, consistently lower in "MSR plain." Comparing "MSR plain" to "MSR cancel" and "MSR full cancel," wee see that cancelling (some of) the allowances held in the MSR helps maintain a moderately accelerated pace for decommissioning of capacity.

The auctioning of allowances from the MSR clearly delays decommissioning but, does not lead to a resurgence in fossil fuel use. The primary reason for this is the low outtake rate. Allowing the MSR to absorb more allowances initially is key for curbing investments in fossil generation capacity and thereby inducing an immediate shift in the generation profile. Our analysis makes the distinction between: (i) delaying decommissioning and (ii) depressing fossil-based investments. Achieving the former is much more relevant for hastening the transition to renewable energy generation.

6 Simulated impacts of the MSR under demand uncertainty

So far, we have disregarded the influence of uncertainty on the firms optimal generation and banking policy. The MSR was, however, set up in part to increase the long-run 'shock' resilience of the EU ETS. In essence, if a negative demand shock such as that induced by the Great recession reoccurs, the MSR should systematically absorb allowances thereby helping mitigate a collapse in allowance prices. In times of unexpectedly high demand, by contrast, the MSR should release allowances, helping mitigate price escalations.

Table 1 presents results for the optimal allowance price and generation mix when fu-

[42] Figure A.1 shows a similar result. In this case, all fossil-based generation uses gas as the sole fuel input.

Table 1: Allowance price, renewables-based energy generation, and fossil-based energy generation.

	Allowance prices				Renewables' generation				Fossils' generation			
	2018	**2025**	**2030**	**% change**	**2018**	**2025**	**2030**	**% change**	**2018**	**2025**	**2030**	**% change**
Deterministic path												
"linear reduction 1.7"	11.881	23.153	37.287	213.843	1.498	1.681	1.864	24.435	1.179	1.271	1.181	0.138
"linear reduction 1.7 & 2.2"	14.729	28.703	46.226	213.843	1.498	1.716	1.947	29.950	1.179	1.181	1.070	-9.253
"MSR plain"	18.835	36.704	59.113	213.843	1.498	1.749	2.009	34.093	1.179	1.121	1.008	-14.515
"MSR cancel"	18.392	35.840	57.721	213.843	1.498	1.747	2.007	33.979	1.179	1.123	1.010	-14.371
"MSR full cancel"	20.907	40.741	65.614	213.843	1.498	1.775	2.056	37.280	1.179	1.095	0.960	-18.564
Expected path												
"linear reduction 1.7"	17.149	33.418	53.820	213.843	1.498	1.772	2.051	36.926	1.179	1.301	0.986	-16.352
"linear reduction 1.7 & 2.2"	19.992	38.958	62.742	213.843	1.498	1.811	2.124	41.797	1.179	1.260	0.912	-22.647
"MSR plain"	30.552	59.536	95.884	213.843	1.498	1.892	2.242	49.647	1.179	0.984	0.795	-32.618
"MSR cancel"	30.534	59.503	95.829	213.843	1.498	1.892	2.242	49.653	1.179	0.984	0.795	-32.625
"MSR full cancel"	31.930	62.222	99.227	210.767	1.498	1.907	2.267	51.352	1.179	0.969	0.769	-34.784
Negative demand shocks												
"linear reduction 1.7"	17.149	33.395	43.931	156.175	1.498	1.771	2.034	35.774	1.179	1.298	0.653	-44.634
"linear reduction 1.7 & 2.2"	19.992	38.890	46.373	131.962	1.498	1.810	2.091	39.573	1.179	1.255	0.586	-50.271
"MSR plain"	30.552	53.021	59.864	95.946	1.498	1.884	2.194	46.438	1.179	0.793	0.484	-58.991
"MSR cancel"	30.534	52.986	59.846	95.995	1.498	1.884	2.194	46.447	1.179	0.793	0.483	-59.003
"MSR full cancel"	31.930	53.642	59.168	85.308	1.498	1.895	2.208	47.391	1.179	0.782	0.469	-60.203
Positive demand shocks												
"linear reduction 1.7"	17.149	33.435	69.859	307.372	1.498	1.772	2.070	38.206	1.179	1.303	1.325	12.365
"linear reduction 1.7 & 2.2"	19.992	39.001	104.885	424.643	1.498	1.812	2.172	44.973	1.179	1.263	1.224	3.769
"MSR plain"	30.552	67.719	767.767	2413.020	1.498	1.899	2.410	60.867	1.179	1.176	0.986	-16.421
"MSR cancel"	30.534	67.716	772.810	2430.966	1.498	1.899	2.410	60.887	1.179	1.176	0.985	-16.447
"MSR full cancel"	31.930	79.037	838.118	2524.875	1.498	1.920	2.499	66.811	1.179	1.155	0.897	-23.972

Notes: % change calculated for 2030 relative to 2018. "Expected path" is the expected sum over all paths in the scenario tree at a point in time. "Negative demand shocks" isolates the path in scenario tree that is consistently hit with a negative demand shock. By contrast "Positive demand shocks" isolates the path in scenario tree that is consistently hit with a positive demand shock.

ture demand is uncertain. As well as reducing compliance costs, banking allowances here helps firms smooth these costs. Accordingly, there is a premium placed on the marginal allowance which ultimately leads to the higher observed initial allowance price than in the deterministic environment. This higher initial allowance price tilts investments toward renewables-based generation and away from fossil-based generation. Sure enough, the expected allowance price rises at the rate of discount—as in the deterministic case—increasing by just over twofold as of 2030. The cancellation of allowances through a higher linear reduction factor also raises the initial allowance price, as does the intake of allowances which additionally raises it by one-third. The difference in the initial allowance price between "MSR plain" and "MSR cancel" is minimal under uncertainty as well, and cancelling all allowances within the MSR also lead to a marginal increase in the initial allowance price.

The value from modelling uncertainty explicitly lies in evaluating the impact of the

MSR when demand turns out to be lower or higher than expected. The panels "Negative demand shocks" and "Positive demand shocks" in Table 1 present results for when demand is consistently lower and higher than expected, respectively. Specifications "linear 1.7" and "linear 1.7 & 2.2" result in less divergence in the allowance price than the other three MSR specifications. And in fact, the variance of the allowance price at each point in time, computed over all scenarios in the tree, turns out to be greater with the MSR than without it. Contrary to regulators expectations, the MSR increases rather than reduces allowance price volatility.

The are three primary reasons for why the MSR increases volatility. First, the MSR cuts short the banking regime and without the flexibility for firms to reduce and smooth compliance costs, allowances prices reflect more the immediate demand for allowances and therefore react more explosively to demand imbalances. Second, the MSR is triggered with a lag meaning that it cannot immediately offset a demand or supply imbalance. Third, the MSR has fixed outtake rate. It is, therefore, incapable of fully offsetting a demand imbalance. This impracticality can lead to explosive growth in allowance prices which our model puts at up to 2400% by 2030.

7 Conclusion

We have evaluated how the MSR is likely to impact the allowance price and the power generation mix. The MSR is the most significant reform yet to the EU ETS. Our findings demonstrate that, on the one hand, the MSR by withdrawing allowances from auctions, succeeds in raising the allowance price and tilting the generation mix towards renewables and away from fossil fuels. On the other hand, the MSR increases price volatility as it: (i) shortens the banking regime, a key avenue through which firms smooth and reduce compliance costs, (ii) does not immediately respond to demand and supply imbalances since it is triggered with a lag, and (iii) has an inflexible outtake rate that does not fully respond to firms demand for allowances following the realization of a demand shock.

A caveat of our analysis is that we focus on the power generation sector alone, holding constant the contribution of the non-power sector. Future work could extend our analysis along this dimension, to accommodate the industrial and aviation sector that will become increasingly important in the EU ETS. Evaluating how robust our findings are to the assumption of forward-looking agents would be another insightful extension. While predictions on the efficacy of the MSR in regulating the availability of allowances are likely to remain, predicted EUA price paths might differ, which may in turn have impacts on speed of building up renewable energy capacity.

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A Model equations

Power generation

$$K_{F,t} = K_{F,t-1} + I_{F,t} - \delta_F K_{F,t-1}$$

$$K_{R,t} = K_{R,t-1} + I_{R,t} - \delta_R K_{R,t-1}$$

$$A_t = A_{t-1} + Z_t - F_t$$

$$E_{F,t} \leq \min\left(K_{F,t},\, F_t\right)$$

$$E_{R,t} = K_{R,t},\; E_t = E_{R,t} + E_{F,t},\; F_t \leq K_{F,t},\; E_t \geq \bar{E}_t$$

$$I_{R,t} \leq \Delta_R K_{R,t}, I_{F,t} \leq \Delta_F K_{F,t}$$

$$E_{R,t}, E_{F,t}, E_{R,t}, K_{R,t}, K_{F,t}, F_t, A_t, Z_t \geq 0$$

Allowance market clearing:

$$Z_t = Y_t$$

MSR accounting equations.

$$M_t = M_{t-1} + I_{T,t} - I_{J,t} \qquad t < 2023$$

$$M_t = \min\left\{M_{t-\Delta t} + I_{T,t} - I_{J,t},\, C_{t-\Delta t}\right\} \qquad t \geq 2023$$

$$C_t = \bar{C}_t - I_{T,t} + I_{J,t}$$

$$\bar{C}_t = C_{2010} - C_{2010} \times lr_t \times (t - 2012)$$

$$I_{T,t} = ir_t \times A_{t-\Delta t} \qquad A_{t-\Delta t} \geq 833$$

$$I_{T,t} = 0 \qquad A_{t-\Delta t} < 833$$

$$I_{J,t} = 100 \qquad A_{t-\Delta t} \leq 400$$

$$I_{J,t} = 0 \qquad A_{t-\Delta t} > 400$$

$$lr_t = 1.74\ t < 2021,\ lr_t = 2.2\ t \geq 2021$$

$$ir_t = 0.24\ t < 2024,\ ir_t = 0.12\ t \geq 2024$$

$$M_t, C_t, \bar{C}_t \geq 0$$

Planners objective:

$$\max_{I_{F,t}, I_{G,t}, F_t} J_k = \sum_{t \geq k}^{\infty} \beta_t \left\{P_t E_t - C\left(I_{F,t}\right) - C\left(I_{R,t}\right) - P_{F,t} F_t - W\left(K_{F,t}, E_{F,t}\right)\right\}$$

Firms objective functions:

$$\max_{I_{F,t}, I_{G,t}, F_t, Z_t} J_k = \sum_{t \geq k}^{\infty} \beta_t \left\{P_t E_t - C\left(I_{F,t}\right) - C\left(I_{R,t}\right) - P_{F,t} F_t - W\left(K_{F,t}, E_{F,t}\right) - \tau_t Z_t\right\}$$

Auctioneers objective:

$$\max_{Y_t} J_k = \sum_{t \geq k}^{\infty} \beta_t \left\{\tau_t Y_t\right\}$$

subject to $Y_t \leq C_t$

B Extra Tables

Table A.1: Parameters and initialized variables

Attribute	Explanation	Baseline value
	Parameters	
δ	annual discount rate	10%
Δ_F	depreciation rate for fossil energy capacity	2.5%
Δ_R	depreciation rate for fossil-free energy capacity	2.5%
P_C	unit price for coal [€/MWhe]	13
P_G	unit price for gas [€/MWhe]	21
int_C	emissions intensity factor of coal [tCO2/MWhe]	0.956
int_G	emissions intensity factor of gas [tCO2/MWhe]	0.593
c_F^{low}	lower bound of unit costs of investment in fossil energy capacity [€/MWh]	800
c_F^{up}	upper bound of unit cost of investment in fossil energy capacity [€/MWh]	2200
c_R^{low}	lower bound of investment cost in fossil-free energy capacity [€/MWh]	800
c_R^{up}	upper bound of investment cost in fossil-free energy capacity [€/MWh]	6000
ϵ_E	elasticity of energy demand	-0.5
g_{E^D}	growth rate of energy demand	0.01
P^{max}	choke price in 2018 [€/MWh]	50
adj	adjustment factor: share of allowances banked by the power sector	0.73
M_{2019}	MSR in 2019 adjusted by share of power sector [billion allowances]	1.48
A_{adj}^{up}	upper threshold of bank adjusted by share of power sector [billion allowances]	0.599
A_{adj}^{low}	lower threshold of bank adjusted by share of power sector [billion allowances]	0.288
lr_t	linear reduction factor [$t \leq 2020/\ t \geq 2021$]	0.0174 / 0.022
ir_t	intake rate of the MSR [$t \leq 2023/\ t \geq 2024$]	0.24 / 0.12
$I_{J,t}$	allowances injected by the MSR adjusted by share of power sector [billion allowances]	0.072
	Initialization of variables	
$K_{F,2018}$	generation capacity in base year for fossil energy [000 TWh]	1440
$K_{R,2018}$	generation capacity in base year for renewable energy [000 TWh]	1804
E_{2018}	total energy supply in base year [000 TWh]	3244
A_{2018}	inital stock of banked allowances adjusted by the share of the power sector [000 TWh]	1440

C Extra Figures

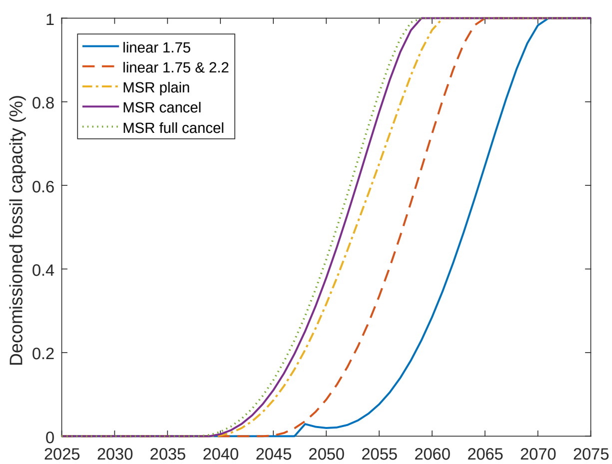

Figure A.1: Decommissioned fossil-based generation capacity with gas as the sole fuel input.