Intertemporal Emissions Trading and Market Design: An Application to the EU-ETS*

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Abstract

We develop a model of competitive intertemporal emissions trading under uncertainty with supply-side controls. We introduce two sources of bounded rationality on the part of regulated firms: myopia and limited sophistication in understanding the interplay between their decisions in equilibrium and the control-driven supply shifts over time. We tailor the model to the EU-ETS, calibrate the market's interest rate, myopia and marginal abatement cost to match observed price and banking paths over 2008-2017, and highlight the key role of myopia in the price dynamics. We use our calibrated model to assess the recent market reform, essentially the market stability reserve (MSR). We find that the MSR always reduces the cumulated cap (even without cancellations) and raises the permit price. The MSR acts a temporary patch curbing past excess supply but displays limited responsiveness to future permit demand shocks (e.g. recession, renewable deployment). We also show how MSR performances depend greatly on the firms' types and degrees of myopia and sophistication, and compare them with those of a soft price collar.

Keywords: Intertemporal emissions trading, Supply responsiveness design, Rational expectations equilibrium, Myopia, Heuristic, EU-ETS.

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1 Introduction

The superiority of hybrid instruments over both pure price and quantity controls, first recognized by Roberts & Spence (1976) and Weitzman (1978), has been a much debated issue among scholars especially in the context of compliance markets for permits and carbon pricing – see Doda (2016) for a review. A standard hybrid control consists in introducing steps in vertical, unresponsive permit supply schedules (pure quantity controls) and typically takes the form of a price corridor, i.e. a combination of a price floor and ceiling (Grüll & Taschini, 2011; Fell et al., 2012a; Holt & Shobe, 2016; Burtraw et al., 2018). Additionally, widespread provisions for intertemporal trading, i.e. banking and to a lesser extent borrowing of permits, also imply some degree of responsiveness as regulated firms can in principle smooth out demand shocks (Schennach, 2000; Newell & Pizer, 2003; Newell et al., 2005; Fell et al., 2012b; Hasegawa & Salant, 2015; Pizer & Prest, 2016; Weitzman, 2018).

In the face of a significant, prolonged price downturn attributable to the economic recession and the demand-curbing achievements of overlapping renewable and energy efficiency policies (Bel & Joseph, 2015; Ellerman et al., 2016; Hintermann et al., 2016), as well as of attendant criticism that the market failed to display responsiveness to changing economic circumstances (de Perthuis & Trotignon, 2014; Grosjean et al., 2016), the European Union recently reformed its emissions trading system (European Commission, 2018). Main changes include a discretionary increase in the annual reduction rate of the emissions cap and, effective as from 2019, the implementation of a rule-based supply-side control, the market stability reserve.[1]

The MSR is a banking corridor and as such, unique in its kind. It annually adjusts current auction volumes downwards (resp. upwards) when the past market-wide permit bank is above (resp. below) a predetermined level. Under an emissions trading system with a declining cap trajectory it is rational for regulated firms to first cut emissions below yearly caps, accumulate a bank, and draw it down later on in a bid to minimize abatement costs over time (Rubin, 1996; Schennach, 2000). As the current bank is largely above the intake threshold, the MSR will first withdraw permits and, as the bank is being gradually exhausted, the MSR will start releasing permits so that the overall cap should in principle be left unchanged.[2] In turn, the early price increase induced by the initial supply squeeze should be counterbalanced by a price drop later on as supply is loosened (Perino & Willner, 2016). However, the final reform

[1]The reform was discussed along the lines of the long-lasting debate on rules versus discretion dating back to the seminal contribution by Kydland & Prescott (1977) and the associated trade-off between predictability and flexibility (Clò et al., 2013; de Perthuis & Trotignon, 2014; Grosjean et al., 2016).

[2]As such, the MSR constitutes an autonomous analog of the ad-hoc backloading policy implemented over 2014-2020, i.e. a postponement of scheduled auctions, see e.g. Chaton et al. (2015).

features an add-on mechanism which breaks this symmetry by placing a cap on the MSR stock above which withdrawn permits are cancelled. This implies a lower cumulated cap which is, more importantly, now dependent on past and future market outcomes (Perino & Willner, 2017; Beck & Kruse-Andersen, 2018). In other words, the cumulated cap has been endogenized, albeit in an admittedly cumbersome manner (Perino, 2018).[3]

In this context, the supply responsiveness induced by the MSR essentially depends on when it stops withdrawing permits – beyond this point, supply may no longer be adjusted downwards. With cancellations, the MSR becomes heavily tilted towards permanent supply contraction and the date at which it starts releasing permits matters much less. The MSR responsiveness and implied shift in the cumulated cap in turn depend on firms' behaviors (cost-minimization and foresight degrees, discount rate), permit demand shocks (business cycles, the magnitude and timing of emissions reductions induced by national or EU-wide overlapping policies), and MSR parameters (intake threshold, withdrawal rate).[4] So far the literature has assessed the final reform under certainty assuming rational agents with given discount rates to quantify the long-term emission effects of overlapping policies, i.e. the ability of the MSR in puncturing the associated 'waterbed effect' (Perino & Willner, 2017; Perino, 2018; Beck & Kruse-Andersen, 2018).[5] In this respect, our contributions are threefold.

First, we build a model of competitive intertemporal permit trading under uncertainty where cost-minimizing firms can deviate from perfect rationality in two respects. Indeed, empirical studies indicate that firms covered under the EU-ETS behave consistently with intertemporal cost minimization although their degrees of optimizing behaviors, levels of foresight and time horizons remain hard to elicit empirically (Fuss et al., 2018; Hintermann et al., 2016; Koch et al., 2016). Specifically, we introduce myopia on the part of firms, i.e. on top of discounting the flow of abatement costs, they further discount the flow of required abatement efforts or have an explicitly truncated planning horizon. Additionally, we allow firms to have different degrees of sophistication in understanding the interplay between the MSR-induced supply impacts and their own decisions in the competitive equilibrium over time, ranging from zero sophistication to rational expectations (Muth, 1961).

As a consequence, modelling novelties are threefold. First, we implement an iterative solving approach in the spirit of rolling procedures in Kaganovich (1985) and Grüne et al. (2015) to

[3]Note that the MSR reduces the value associated with early abatements and banking as MSR-withdrawn permits may not return to the market at an efficient rate, or do not return at all with cancellations. However, note that firms cannot leverage that channel in a competitive recursive equilibrium in which banking levels below intertemporally efficient ones are not permissible (Salant, 1983; Hasegawa & Salant, 2015).

[4]Fell (2016) highlights that MSR performances vary greatly with its design and assumed interest rates.

[5]Fell (2016) and Perino & Willner (2016) analyze the impacts of uncertainty for the initial reform.

account and control for myopia. Second, we develop a heuristic to obtain the rational expectations equilibrium as the fixed point of a mapping between the firms' beliefs about future MSR impacts and optimal beliefs in the spirit of Lucas & Prescott (1971). Third, we derive a first-order approximate solution for expected equilibrium paths. This approach was first suggested – but not operationalized – by Schennach (2000), and allows us to counterbalance the modelling complexities associated with myopia and sophistication.[6]

Second, the model is calibrated to the EU-ETS and features the core design elements thereof. We first parametrize permit demand using historical emissions data and assuming EU-wide renewable and energy efficiency targets are attained in the future. In line with the observed trend, the resulting baseline emissions are declining over time. We next calibrate the market's interest rate, myopia and marginal abatement costs ex post so that our simulated price and banking paths match with observed paths over 2008-2017. To the best of our knowledge, this is the first attempt to do so. The values we obtain for the interest rate and cost are in line with dedicated empirical studies and the estimated myopia constitutes a first tentative appraisal in the literature. In particular, as suggested by Fuss et al. (2018) and Ellerman et al. (2015), we show how myopia can be key in explaining observed price dynamics.

Third, we use our calibrated model to assess the role of the MSR in the EU-ETS functioning and investigate its potential to attain its two purported objectives, i.e. raising the price and improving the system resilience to demand shocks (European Commission, 2018). We find that the MSR always reduces the cumulated cap (even without cancellations) and increases the 2050 price by c.a. 30%. Cumulated cancellations are substantial, in the order of 5 to 10 $GtCO_2$ and we characterize how market outcomes depend greatly on the interplay between the firms' types and degrees of myopia and sophistication. For instance, the observed recent price surge would be consistent with rational expectations under a truncated planning horizon, irrespective of the cancellation provision. Moreover, the MSR acts as a temporary patch in that it curbs some excess supply induced by the 2008 economic downturn and past achievements of overlapping policies but displays limited responsiveness to similar demand shocks in the future. Finally, we provide a brief comparative analysis of the EU-ETS performance with an alternate control, a soft price corridor, under similar circumstances.

The remainder proceeds as follows. Section 2 sets forth the modelling framework. Section 3 describes the parametrization and calibration strategy based on market data and regulatory texts. Section 4 offers a detailed impact appraisal of the final market reform. Finally, Section 5 reviews and compares our results to the related literature, and Section 6 concludes.

[6] We describe the nature of the induced second-order bias w.r.t. the exact solution in Sections 3 and 4.

2 Model

We consider a competitive emissions trading system with full banking and limited borrowing of emission permits through time. Time is discrete and indexed by $t = 1, 2, \ldots$. The system starts at date 1 and compliance is due at each date t. The regulator sets a cap on system-wide emissions at each date t, which consists of freely allocated and auctioned permits f_t and a_t. Additionally, a fixed quantity of offset credits O may be surrendered for compliance over a given time period and o_t denotes the offsets volume used at date t. At each date t, we assume that regulated firms fully acquit their compliance obligations by remitting as many permits or offsets as to exactly cover their current emissions.[7]

It is a standard result that one can analyze the joint compliance cost minimization problem to characterize the decentralized market equilibrium indirectly (Rubin, 1996; Schennach, 2000). We thus take the perspective of the entire regulated sector (hereafter the firm) and let e_t, u_t and $q_t = u_t - e_t \geq 0$ denote its levels of realized emissions, unregulated (baseline) emissions and abatement at date t, respectively. We also let C_t denote its minimum total abatement cost function at date t, which satisfies the standard conditions that $C_t', C_t'' > 0$.[8] Moreover, we entertain the possibility that baseline emissions can be uncertain, in which case we denote them by $\tilde{u}_t$, as they depend on underlying business cycle shocks and the variable performance of complementary policies (Borenstein et al., 2016). On the supply side, we also signify that free allocation, auction and offset usage can be uncertain with the tilde notation.[9]

Compliance and banking demands for permits At date t, given the prevailing permit price p_t and realized baseline emissions u_t,[10] the firm's emission level, or demand for permits for compliance $e_t^\star(p_t, u_t)$, satisfies the usual first-order necessary condition

$$C_t'(u_t - e_t^\star(p_t, u_t)) - p_t = 0. \tag{1}$$

In addition, the firm can carry over (i.e. bank) left-over permits for future years or borrow up to next year's free allocation for present compliance.[11] As the firm minimizes costs over

[7]Penalties for permit and self-reporting violations are adequately designed (Stranlund et al., 2005).

[8]The aggregate abatement cost function is the envelope of individual abatement cost functions.

[9]For instance, both $\{f_t\}_t$ and $\{a_t\}_t$ can be affected by a regulatory change in the cap trajectory and $\{o_t\}_t$ depends on external offset market conditions and how fast the overall usage limit O is actually tapped into.

[10]We do not explicitly account for forwards and futures as the aggregate demand for such bilateral contracts is nil in equilibrium (Laffont & Tirole, 1996; Seifert et al., 2008). Thus p_t is de facto the date-t spot price. Yet note that e.g. (5) can legitimately hold as there is an active futures market for permits (Pindyck, 1993).

[11]Year-on-year borrowing is tacitly authorized in the EU-ETS as freely-allocated date-t permits are issued one month prior to date-$(t-1)$ compliance deadline. However, there will be less and less opportunities for

time, limited intertemporal trading opportunities imply a no-arbitrage condition that closely follows the rationale of competitive commodity storage with negligible storage costs and no stock depreciation over time (Wright & Williams, 1982; Deaton & Laroque, 1992, 1996).[12] Permit banking, whose level at date t we denote by b_t, thus constitutes the second determinant of permit demand and satisfies the following two conditions with complementary slackness

$$b_t + f_{t+1} \geq 0 \quad \perp \quad p_t - \beta \mathbb{E}_t\{p_{t+1}\} \geq 0, \tag{2}$$

where $\mathbb{E}_t\{\cdot\}$ denotes expectation conditional on all information available to the firm at date t and $\beta = (1+r)^{-1}$ is the firm's discount factor with r the interest rate, possibly inclusive of a permit-specific risk premium.[13] When $\beta \mathbb{E}_t\{p_{t+1}\} > p_t$, banking is profitable and increases date-t permit demand, which raises p_t and lowers $\mathbb{E}_t\{p_{t+1}\}$ until all arbitrage opportunities are exhausted and the firm breaks even, i.e. $\beta \mathbb{E}_t\{p_{t+1}\} = p_t$ and the cost-of-carry price coincides with the spot price grown at the interest rate.[14] Similarly, when $\beta \mathbb{E}_t\{p_{t+1}\} < p_t$, borrowing is profitable but only authorized up to next year's free allocation volume. As soon as this constraint is binding, the connection between current and expected future prices ceases to hold and the price rises at a rate less than the interest rate.[15] Additionally, permit demand becomes solely determined by annual compliance requirements in (1) and emissions coincide with contemporaneous total available supply. In sum, the price should rise at a rate at most as high as the interest rate in a rational expectations equilibrium.

Note that banked (resp. borrowed) permits add to (resp. subtract from) future permit supply, i.e. total available supply at date t amounts to $f_t + a_t + o_t + b_{t-1}$. Market clearing at date t, which implies that total supply equalizes total demand, thus reads

$$f_t + a_t + o_t + b_{t-1} = e_t + b_t. \tag{3}$$

firms to borrow as auctioning is set to gradually become the dominant allocation method.

[12] Schennach (2000) first pointed out the tight connection between commodity storage and permit banking. The sole difference is that stockouts, which correspond to positive borrowing ($b_t < 0$), are not feasible.

[13] Kollenberg & Taschini (2016), Perino & Willner (2016) and Schennach (2000) introduce a risk premium on top of the risk-free rate to capture the impacts of emissions uncertainty on the firm's decisions.

[14] Specifically, (5) shows that the optimal price path follows Hotelling's rule in expectation. As long as the limited borrowing constraint is not binding, the current price reflects the present expected value of the last permit surrendered: it is the vehicle that equalizes expected long-term demand and supply. Thus, when there is long-term scarcity, the current price cannot drop to zero even if the market is currently long.

[15] Limited borrowing induces a non-linearity which implies an asymmetric demand shock dampening potential for the market. Indeed, the firm can in principle entirely smooth out the price impact of a downward demand shock (i.e. temporary glut) by stockpiling more permits while it can only be so for an upward shock of a corresponding magnitude (i.e. temporary shortage) to the extent that the bank is not too negative.

Combining the compliance, no-arbitrage, and market-clearing conditions in (1), (2) and (3) then leads to two regimes in the equilibrium price and emission dynamics

$$p_t = \max\{\beta\mathbb{E}_t\{p_{t+1}\};\ C'_t(u_t - (f_t + f_{t+1} + a_t + o_t + b_{t-1}))\}, \tag{4a}$$

$$e_t = \min\{e^\star_t(\beta\mathbb{E}_t\{p_{t+1}\}, u_t);\ f_t + f_{t+1} + a_t + o_t + b_{t-1}\}, \tag{4b}$$

$$\text{with}\ \ b_t = f_t + a_t + o_t + b_{t-1} - e_t \geq -f_{t+1}. \tag{4c}$$

The first regime corresponds to a period of intertemporal flexibility in the firm's emissions calendar satisfying Hotelling's rule and featuring a positive or slightly negative bank.[16] In the second regime emissions are pegged to the contemporaneous amount of permits on hand and the limited borrowing limit is binding. These equilibrium quantities depend on currently available supply, current baselines and, crucially, the expected future permit price.

Approximate expected solution paths By iterating (4a) over time, the expected price path at date t satisfies

$$\mathbb{E}_t\{p_{\hat{t}} - \lambda_{\hat{t}}\} = \beta^{t-\hat{t}} p_t \text{ for any } \hat{t} > t, \tag{5}$$

where $\lambda_{\hat{t}} \geq 0$ is the Lagrange multiplier associated with the limited borrowing constraint at $\hat{t}$, i.e. $b_{\hat{t}} \geq -f_{\hat{t}+1}$.[17] Because of the non-linearity induced by this constraint, the expected price path in (5) does not admit a closed-form solution and need be approximated numerically.[18] As first suggested – but not operationalized – by Schennach (2000), we thus choose to derive a certainty-equivalent approximate solution for the expected price path in (5). This induces a second-order bias relative to the exact solution, which we discuss later on.

Specifically, at any date t, u_t, f_t, f_{t+1}, a_t and o_t are given and known to the firm, which also keeps track of both the accumulated bank b_{t-1} (with $b_0 = 0$) and the history of offset usage $\{o_\tau\}_{\tau \leq t}$.[19] We dispense with a formal stochastic analysis and invoke the certainty equivalence

[16] Schennach (2000) shows that this regime is always finite in time but may not be unique under uncertainty.

[17] When there is a zero probability of a binding limited borrowing constraint in the future, i.e. $\mathbb{E}_t\{\lambda_{\hat{t}}\} = 0$ for all $\hat{t} \in [\![t_1; t_2]\!]$, the date-$t$ expected price grows at rate r over $[\![t_1; t_2]\!]$. When this probability is positive, i.e. $\mathbb{E}_t\{\lambda_{\hat{t}}\} > 0$ for some $\hat{t} \in [\![t_1; t_2]\!]$, the expected price rises at a rate less than r (which is not uniquely pinned down) with the downward offset rising over $[\![t_1; t_2]\!]$. When it is unity, the expected price is uniquely determined by $\mathbb{E}_t\{p_{\hat{t}}\} = \mathbb{E}_t\{C_{\hat{t}}(u_{\hat{t}} - (f_{\hat{t}} + f_{\hat{t}+1} + a_{\hat{t}} + o_{\hat{t}}))\}$. An *expected* price path thus exhibits this three-regime dynamics while the *actual* path only features the two regimes in (4a).

[18] For instance, Deaton & Laroque (1992) developed a fixed-point approach in a similar commodity storage problem, for which Deaton & Laroque (1992) and Cafiero et al. (2011) proved that with time-independent linear consumption demand (which is directly equivalent to time-independent linear marginal abatement cost functions in our case) there is a unique stationary rational expectations equilibrium.

[19] To simplify, we assume that the firm does not get to decide how many offsets to surrender for compliance. That is, o_t is exogenously given at each t. This is innocuous for the purposes of our model since offsets are no

property that, up to a first-order approximation, the firm's optimal decisions at date t are congruent with its decisions under full information provided that random variables be equal to their date-t expected values.[20] Then, the firm selects its date-t abatement q_t and implied banking b_t by minimizing its expected present discounted cost of compliance. That is, the firm solves the following inter-temporal planning program with $t' = t$

$$\min_{\{q_\tau\}_{\tau \geq t'}} \mathbb{E}_t\Big\{ \sum_{\tau \geq t'} \beta^{\tau - t'} C_\tau(q_\tau) \Big\} \text{ subject to:} \tag{6a}$$

$$0 \leq q_\tau \leq M_\tau \cdot \mathbb{E}_t\{\tilde{u}_\tau\} \text{ for all}\, \tau \geq t', \tag{6b}$$

$$b_\tau = b_{\tau-1} + q_\tau + M_\tau \cdot \mathbb{E}_t\{\tilde{f}_\tau + \tilde{a}_\tau + \tilde{o}_\tau - \tilde{u}_\tau\} \geq -M_\tau \cdot \mathbb{E}_t\{\tilde{f}_{\tau+1}\} \text{ for all}\, \tau \geq t', \tag{6c}$$

$$\text{and } \sum_{\tau \geq t'} q_\tau = \mathbb{E}_t\Big\{ \sum_{\tau \geq t'} M_\tau \cdot (\tilde{u}_\tau - (\tilde{f}_\tau + \tilde{a}_\tau + \tilde{o}_\tau)) \Big\} - b_{t'-1}. \tag{6d}$$

First consider that $M_\tau = 1$. The constraints are then standard: (6b) requires non-negativity of emission and abatement levels throughout, (6c) imposes annual market clearing and limited intertemporal flexibility, and (6d) specifies the firm's assessment of the system stringency at date t', which is the sum of expected future yearly raw abatement efforts $u_\tau - (f_\tau + a_\tau + o_\tau)$, and ensures that total abatement carried out through time tallies with that expected cumulated required abatement effort. Finally, (6a) dictates how that effort is efficiently split across time, which hinges on discounting and the expected evolution of abatement costs $\{C_t\}_t$.

As a modelling novelty, we introduce myopia on the part of the firm, namely $M_\tau \leq 1$. Indeed, although regulated firms are undoubtedly forward looking, it is stronger an assumption that their planning horizons extend as far as a few decades into the future. For instance, Ellerman et al. (2015) and Fuss et al. (2018) argue that myopia could be key in understanding price formation and assessing the system's intertemporal performance, especially in the EU-ETS. We consider three types of myopia, i.e. of the exponential, hyperbolic and logistic forms

$$M_\tau = (1 + \rho_e)^{-(\tau - t')} \text{ with } \rho_e \geq 0, \tag{7a}$$

$$\text{or } M_\tau = (1 + (\tau - t')\rho_h)^{-1} \text{ with } \rho_h \geq 0, \tag{7b}$$

$$\text{or } M_\tau = (1 + \exp(-k(\Delta - (\tau - t'))))^{-1} \text{ with } k, \Delta > 0. \tag{7c}$$

Note that in each case $M_\tau \in (0; 1]$ and decreases with time τ, i.e. the firm places less and less relative weight on yearly raw abatement efforts the farther away it looks into the future. In

longer authorized in the EU-ETS as of Phase IV. Hence this does not impact our ex-ante analysis in Section 4 and we explain how we deal with offset usage ex post for the calibration in Section 3.

[20] Note that this property naturally comes about with linear marginal abatement cost functions.

other words, as far as current abatement decisions are concerned, the firm takes less and less into consideration what can be expected to be required of it in terms of abatement in the future.[21] Figure 1 depicts how myopia weights evolve over time under exponential, hyperbolic and logistic myopias. Weights decrease smoothly under exponential and hyperbolic myopias and, to obtain a qualitatively different type of myopia, we will typically set k large enough so that the logistic weights in (7c) coincide with a truncated time horizon of Δ years.

We next solve (6) with $t' = t$ assuming that the expected equilibrium paths follow the same two-regime dynamics as the actual paths in (4).[22] That is, we by construction only consider the size of the bank in expectation. Therefore, a second-order bias between our approximate and the exact expected paths arises as we do not capture the possibility that $\mathbb{E}_t\{\lambda_{\hat{t}}\}$ in (5) may become positive for some $\hat{t} > t$ although the bank is still expected to satisfy the limited borrowing condition by that time.[23] This yields an optimal abatement path $\{q_\tau\}_{\tau \geq t}$ which de facto pins down the banking and price paths $\{b_\tau\}_{\tau \geq t}$ and $\{C'_\tau(q_\tau)\}_{\tau \geq t}$.

Yet, as the firm is myopic, it underestimates the actual system stringency and the obtained paths imply less cumulated abatement than actually required. To get rid of this spinoff effect from myopia when we derive the date-t expected paths, we solve (6) for each $t' \geq t$ iteratively, assuming that (1) the firm's date-t beliefs about future supply and demand are unchanged throughout and materialize as expected; and (2) the initial bank condition $b_{t'-1}$ is set by the previous optimization round. The date-t expected paths are then sequences consisting of each of the above date-t' optimal first-year outputs.[24] This iterative approach is in the spirit of rolling planning procedures à la Kaganovich (1985) or receding horizon procedures used in nonlinear models of predictive control à la Grüne et al. (2015).

Shock structure and firm's expectations The key decision quantity that the firm has to assess at each date t is its perceived cumulated required abatement over time, which depends on its expectations for future permit supply and demand schedules. For the former, the firm simply takes the cap paths $\{f_\tau\}_{\tau \geq t}$ and $\{a_\tau\}_{\tau \geq t}$ as given in currently prevailing regulation. For the latter, we consider that future baseline emissions follow an AR(1) process. Given our

[21] A qualitatively similar interpretation is that in face of large uncertainty about future baselines (Borenstein et al., 2016) or uncertainty of a regulatory nature (Salant, 2016; Koch et al., 2016; Cretì & Joëts, 2017), the firm displays gradually less confidence in its assessment of future supply and demand schedules.

[22] Recall that expected paths actually follow a three-regime dynamics, see footnote 17.

[23] Schennach (2000) shows that the approximate expected price path is slightly biased downward in the first regime and early on in the second one, biased upward for the rest of it, and unbiased in the third regime.

[24] That is, at each date t', although entire paths are computed, only the optimal decisions for date t' are implemented, and starting from this attained state, we proceed similarly for date $t' + 1$, and so forth.

certainty-equivalent approach, only the deterministic part of it matters, that is

$$\mathbb{E}_t\{\tilde{u}_{t+1}\} = \varphi(1+\gamma_t)u_t + (1-\varphi)\bar{u}_{t+1}, \tag{8}$$

where $\varphi \in [0;1]$ captures some persistence in the shocks and γ_t is the expected annual growth rate at date t for future years. Importantly, we allow the trend $\bar{u}$ to vary over time. Indeed, it can for instance be thought of as declining due to some irreversible investment in abatement technologies induced by the permit price (Slechten, 2013) or achievements of complementary policies outside the system's perimeter (Borenstein et al., 2016).

In principle, demand shocks occur at each date as realized baseline emissions differ from their expected values. In turn, the firm must reassess its cumulated required abatement effort and adjust its intertemporal decision-making accordingly.[25] Note that supply shocks also occur when the regulator announces a regulatory change that can affect the system directly (e.g. a shift in the cap) or indirectly (e.g. a climate and energy policy package update).

Supply controls The regulator can embed some responsiveness in its system with various supply controls, e.g. corridors on the price or bank. These mechanisms require the creation of a reserve of set-aside permits whose stock at date t we denote by $s_t \geq 0$. A banking corridor automatically adjusts current auctions a_t based on banking history $\{b_\tau\}_{\tau<t}$ according to

$$a_t \longleftarrow a_t - \min\Big\{a_t; R\cdot\sum_{\tau<t}\mathbb{1}\{b_\tau > \bar{b}\}x_\tau b_\tau\Big\} + \min\{I; s_{t-1}\}\cdot\sum_{\tau<t}\mathbb{1}\{b_\tau < \underline{b}\}x_\tau, \tag{9}$$

where $\mathbb{1}\{\cdot\}$ is the indicator function, $\underline{b} > 0$ and $\bar{b} > \underline{b}$ lower and upper bank thresholds, $I > 0$ an injection quantity, $R \in [0;1]$ an absorption rate and historical weights $\{x_\tau\}_{\tau<t}$ are such that $x_\tau \in [0;1]$ for all $\tau < t$ and $\sum_{\tau<t} x_\tau = 1$. In parallel, the evolution of the stock of permits stored in the reserve follows the complementary dynamics

$$s_t = s_{t-1} + \min\Big\{a_t; R\cdot\sum_{\tau<t}\mathbb{1}\{b_\tau > \bar{b}\}x_\tau b_\tau\Big\} - \min\{I; s_{t-1}\}\cdot\sum_{\tau<t}\mathbb{1}\{b_\tau < \underline{b}\}x_\tau. \tag{10}$$

In words, when $b_{\tau<t}$ is above $\bar{b}$, a predefined share $x_\tau R$ thereof is withheld from auctions at date t and placed in the reserve. Symmetrically, when $b_{\tau<t}$ is below $\underline{b}$ and the current stock of the reserve allows, a fixed quantity of stored permits $x_\tau I$ is added to auctions at date t. Otherwise, the banking corridor is inactive. Crucially, because the shift in auctions is

[25] A change in the firm's expectation about its required abatement effort affects the abatement and banking profiles (and in particular the expected length of the intertemporal flexibility regime).

determined by the banking history it is fixed once and for all at the beginning of each date. This typically is not the case for a price corridor whereby auctions are continuously adjusted until the contemporaneous auction price falls within the predefined zone.[26] That is, auctions and the reserve stock are adjusted until the process below has converged

$$\begin{cases} a_t \longleftarrow \max\{0; a_t + \mathbb{1}\{p_t > \bar{p}\}\mathbb{1}\{s_t > 0\} - \mathbb{1}\{p_t < \underline{p}\}\} \\ s_t \longleftarrow \max\{0; s_t + \mathbb{1}\{p_t < \underline{p}\}\mathbb{1}\{a_t > 0\} - \mathbb{1}\{p_t > \bar{p}\}\} \end{cases} \tag{11}$$

where $\underline{p} > 0$ and $\bar{p} > \underline{p}$ are the price floor and ceiling, respectively. For comparability between banking and price corridors, we assume the latter to be a soft collar. That is, the mechanism has a number of permits to inject to defend the ceiling limited by the reserve and can only withdraw permits to support the floor up to the annual auction volume.[27] The price may thus conceivably fall below or reach above the price bounds. Note that both price and banking corridors may in principle be expected to be cap neutral in the long run, i.e. the cumulated cap is preserved, as they essentially operate a reshuffle of the auction schedule.

Additionally, to align with the add-on cancellation mechanism as per the final reform rules, we consider that for both types of corridors any permits stored in the reserve in excess of the number of auctioned permits in the previous year can be invalidated (i.e. cancelled). In this case, we allow for the reserve stock to be further adjusted such that

$$s_t \longleftarrow s_t - \max\{0; s_t - a_{t-1}\}. \tag{12}$$

Equipped with this add-on provision, both corridors have potential to reduce the cumulated volume of emissions allowed under the system.[28]

Interplay between controls and competitive equilibrium Expected required cumulated abatement efforts depend in part on expected future supply control driven reshuffling of yearly auction volumes, if not net shift in the overall cap. We consider two polar degrees of sophistication on the part of the firm in anticipating these adjustments, i.e. no anticipation and rational expectations (Muth, 1961). In the former, the firm does not account for control

[26] In our model, prices on the primary and secondary markets are identical. Indeed, because shocks are observed at the beginning of each date, there is no reason for them to differ (Kling & Rubin, 1997).

[27] Under a hard price corridor, the regulator would stand to limitlessly inject permits to defend the ceiling or purchase permits at the floor price so that the price bounds would not be breached (Fell et al., 2012a).

[28] This depends on the initial conditions. In the current context, because the MSR is initially seeded with more than a billion permits and is further set to take in a substantial amount of permits in its first years of operations, it is de facto non cap neutral. See Section 4 for details.

impacts on future supply when appraising its required abatement effort. It is as though the firm was, each year, discovering and factoring in annual control impacts on auction volumes, while remaining completely insensitive to what the future impacts will be.[29] In the latter, the firm fully comprehends the interplay between its decisions in the recursive competitive equilibrium and the associated control impacts over time. Expected required abatement efforts thus depend on the control design and actions, which are correctly perceived by the firm and can prompt it to adjust its intertemporal decision-making accordingly.

Our indirect approach to solving for the recursive competitive equilibrium as the outcome of a planning problem by a representative firm is viable under laissez-faire (Samuelson, 1971). However, Salant (1983) showed in the wider commodity storage context that such an approach may mischaracterize the rational expectations equilibrium in presence of supply-side controls aimed at stabilizing prices.[30] Indeed, forward-looking rational agents can take advantage of the control rules which the regulator adheres to, which may trigger speculative attacks on the scheme and result in a policy failure. Under a banking corridor for instance, firms would collectively like the policy handle (the bank) to fall below the intake threshold for the control to induce a minimal, if any, contraction in overall supply.[31] Individually, however, they have a negligible impact on the bank and cannot coordinate their banking decisions to 'game the system'. In a competitive equilibrium, therefore, supply controls cannot alter intertemporal efficiency (i.e. the equalization of discounted expected marginal abatement costs across firms and periods) although they do affect annual market clearing conditions.

Given our indirect planning approach, the representative firm must be able to understand the interplay between the recursive competitive equilibrium and the associated control actions over time. To this end, we develop a heuristic iterative procedure to solve for the rational expectations equilibrium as the fixed point of a mapping between the firm's beliefs about the control impact profile and optimal beliefs.[32] That is, the equilibrium obtains when a given such belief coincides with the actual law of motion for the control actions generated by intertemporally efficient choices induced by this belief. At each step of this procedure, the firm has a forecast for both the control action and annual supply profiles to evaluate its

[29] This may for instance be interpreted as an extreme form of bounded rationality for it may conceivably be challenging to tease out the supply-side implications of a price or banking corridor over time.

[30] See Hasegawa & Salant (2015) for a transposition of Salant (1983) to intertemporal emissions trading.

[31] That is, banking levels below intertemporally efficient ones could yield a smaller supply squeeze and thus lower compliance costs, but would not conform to a competitive equilibrium.

[32] Such a fixed-point approach is hardly new. Lucas & Prescott (1971) were the first to use it to determine a rational expectations equilibrium in a 'Bellmanized' indirect planning optimization program.

expected required abatement effort and then cost minimizes over time as per (6).[33]

Specifically, at each date t, starting from the zero sophistication case, the firm computes expected equilibrium paths simply by recursively solving (6), where the control further affects annual auctions according to (9) or (11) although future control impacts remain unforeseen. This yields a path for annual permit inflows into the reserve. We then reiterate the above where the firm's belief about the future supply profile is adjusted for the reserve inflow path just obtained. If this is not neutral vis-à-vis the previously optimal abatement and banking paths, the firm will revise them. This changes the annual control impact profile, which in turn again affects the firm's intertemporal decisions, and so forth. In this adjustment process the firm holds beliefs about future control impacts, behaves rationally with respect to these beliefs, and updates them after each iteration. This process generally attains a fixed point after some finite number of iterations and yields the rational expectations equilibrium.[34]

3 Calibration

In this section, we first describe how we use historical data and regulatory texts to construct the permit demand and supply schedules, and the expectations about those that the firm can form and update over time. We next calibrate the firm's discounting, myopia and abatement costs based on 2008-2017 market data. We finally parametrize the supply controls.

Permit demand Our first aim is to reconstruct a counterfactual scenario for CO_2 emissions of the EU-ETS perimeter as they would have been absent the ETS, but with all other energy and climate policies in place and industrial production growth as observed over 2008-2017. To that end we use a simple decomposition of baseline CO_2 emissions into three 'Kaya' indexes

$$CO_2\,emissions = \underbrace{Production}_{economic\,activity} \times \underbrace{\frac{Energy}{Production}}_{energy\,intensity} \times \underbrace{\frac{CO_2\,emissions}{Energy}}_{carbon\,intensity}. \tag{13}$$

Figure 2a depicts the reconstructed and projected trajectories of these three indexes between 1990 and 2050. We assume that the permit price has negligible impacts on both production

[33]The associated first-order conditions thus coincide with those obtained in the competitive equilibrium.

[34]Specifically, because with the MSR the absorption rate R is much less than unity, only a few iterations suffice for the heuristic procedure to converge while convergence is generally less rapid with a price corridor.

and energy intensity.[35] Specifically, we compute the production index ex post from Eurostat sector-level production data and consider a 1% p.a. production growth from 2018 on.[36] Next, we compute the energy intensity index ex post from total final energy consumption time series for a proxy of EU-ETS sectors (i.e. electricity, heat, industry, and energy industry own use and losses) obtained from the 1990-2015 balance sheets of the International Energy Agency.[37] From 2016 on we use a linear interpolation so that the EU energy efficiency targets for 2020 and 2030 are met and we assume this linear trend to be valid afterwards.

Next, we compute the carbon intensity index ex post by reconstructing EU-ETS CO_2 emissions over 1990-2007 based on IEA primary energy consumption data and standard EU-level emission factors.[38] From 2008 on, we need to calculate emissions as they would have been absent the ETS. We assume that the permit price may have driven some fuel switching (thus impacting the carbon content of energy) but not the development of renewable energy.[39] To isolate and account for renewable deployment while neutralizing fuel switching in the baseline emissions, we fit a linear relationship between renewable deployment and the carbon content of energy prior to Phase II. We extrapolate this first-pass relationship for later years using observed renewable deployment for 2008-2015 and then assuming that EU renewable targets set for 2020 and 2030 (and their continuation afterwards) are attained linearly. Computing the ratio of CO_2 emissions to energy consumed finally yields the carbon intensity index.

Thus, baseline emissions at any point in time are by construction independent of the history of permit prices.[40] Graphically, the black line in Figure 2b depicts the realized and projected baselines, which we obtain by plugging the evolution of the three Kaya indexes in (13). The resulting baseline path is downward sloping, which is in line with the steady decline in ETS perimeter emissions observed prior to the launch of the ETS. In Section 4, this constitutes our reference case as opposed to two types of demand shocks.

[35] Regarding production, this seems like a reasonable assumption ex post as there is no evidence of carbon leakage in the EU-ETS (Naegele & Zaklan, 2017; Joltreau & Sommerfeld, 2018). Regarding energy intensity, Figure 2a shows that it declines less over 2005-2015 with the ETS in place than over 1990-2005 without the ETS, which provides some a posteriori support to our assumption.

[36] Link to Eurostat data (`http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=sts_inpr_a`).

[37] Link to IEA data (`https://www.iea.org/statistics/?country=EU28`).

[38] Link to IEA data. Emission factors are 4.2, 3.1 and 2.4 tCO_2/toe for coal, oil and gas, respectively.

[39] This is supported by evidence that the EUA-price equivalent of renewable subsidies has been significantly higher than the observed EUA price (Marcantonini & Ellerman, 2015; Marcantonini & Valero, 2017).

[40] This independence assumption becomes less tenable when prices reach higher levels than those observed up to now. Note, however, that endogenous baselines are not considered in similar modelling approaches. Fell (2016) and Perino & Willner (2016, 2017) assume given baseline paths, respectively increasing and constant over time. Similarly, baselines in Beck & Kruse-Andersen (2018) are decreasing over time due to increasing renewable development, which slows down over time but nonetheless remains independent of the permit price.

Regarding expected future baselines in (8), we assume that the trend at date t for some future year $t' > t$ $\bar{u}_{t'}$ is set to be in line with the attainment of the currently prevailing climate energy package at date t. Table 1 reports these trends. Next, we set γ_t as per GDP growth forecasts by the European Commission over 2008-2017 and we consider 2% p.a. growth afterwards.[41] Finally, we follow Fell (2016) and take $\varphi = 0.9$ for the shock persistence.[42] Demand shocks thus occur each year as actual and expected baselines differ.

Permit supply The firm expects future supply to coincide with the total cap path (free allocations and auctions) as given in prevailing regulatory texts (e.g. EU Directives, Decisions or Communications). As soon as regulation is amended or upon release of actual supply data (e.g. EC Carbon Market Reports), the firm corrects its expectations. Supply shocks thus naturally come about. For instance, the firm considers a cap path from Phase IV on based on the currently effective linear reduction factor, i.e. 1.74% before and 2.2% after the reform. In 2021, 57% of the cap is auctioned off and this ratio increases over time.[43]

For offset usage in Phases II and III (viz. CERs and ERUs), the firm assumes at date t that the remaining allowed quantity of offsets that can be remitted for compliance from date $t+1$ on (i.e. $O - \sum_{\tau=2008}^{\tau=t} o_\tau$) is equally split across the remaining years of the period. Again, this introduces supply shocks as actual volumes of offsets used over 2008-2017 differ from their expected values, with notable peaks in 2011-12 (de Perthuis & Trotignon, 2014; Tvinnereim, 2014). From Phase IV on, offset usage for compliance is no longer authorized.

Graphically, the grey line in Figure 2b depicts the realized and projected total annual supply $\{f_t + a_t + o_t\}_t$. The early peak is due to a massive use of offsets totalling about 1 $GtCO_2$ over 2008-2012. The following dip is due to the backloading of 900 MtCO2 between 2014 and 2016 (Chaton et al., 2015) and to non-issued Phase-III permits over 2013-2017 totalling about 600 $MtCO_2$ (European Commission, 2015). From early Phase IV on, supply is assumed to coincide with the announced cap declining at a yearly linear reduction factor of 2.2%, implying that supply is nil from 2058 on. Figure 3b shows alternative cap paths with linear reduction factors of 1.74% (pre-reform level) and 2.75% (supply is nil from 2051 on).[44]

[41] Link to EC forecasts published in spring t for date $t+1$.

[42] In related contexts, Heutel (2012) and Lintunen & Kuusela (2018) use $\varphi = 0.95$ and $\varphi = 0.8$ respectively. Roughly speaking, the lower φ the more the firm expects future baselines to coincide with the trend. As the trends happen to be relatively close to actual baselines, a lower φ thus implies 'better foresight'. Finally note that $1 - \varphi$ could also be loosely interpreted as a probability of success of complementary policies.

[43] Specifically, we compute the number of freely allocated permits from 2021 on by extending the observed declining trend for the share of free allocation in the total cap. Auction volumes then obtain as the difference between the total cap and the computed free allocations.

[44] The amounts by which the cap decreases yearly correspond to the LRF multiplied by the 2010 emissions

Calibration We consider linear marginal abatement costs with constant technology through time, i.e. $C''_t = c$ for all t, and we let this be known to the firm in its decision making.[45] This is a conservative assumption given that we have little empirical guidance about how the slope of marginal abatement cost functions may vary over time due to innovation or low-carbon investments, see e.g. Bréchet & Jouvet (2008).[46] This notwithstanding, recall that baselines are declining over time due to decreasing energy and carbon intensities, which here translates into a lowering of the linear intercept of the marginal abatement cost curve over time.

We calibrate the firm's parameters ex post following a two-step approach. First, we calibrate the firm's interest rate and myopia parameters so as to approximate the observed aggregate banking path over 2008-2017 as finely as possible with ordinary least squares. The results are reported in the second column of Table 2 with standard deviations given within parenthesis. Without myopia, our first-pass calibration suggests that a rate of return $r \approx 7\%$ would best replicate past banking. This is in line with general returns on risky assets (Jordà et al., 2017) though in the higher range of discount rates implied from futures' yield curves since early Phase II (Bredin & Parsons, 2016; Trück & Weron, 2016).[47]

With myopia, we choose to fix the interest rate and calibrate the myopia parameters. Specifically, we arbitrarily let $r = 3\%$, which is a central value for inferred discount rates.[48] Under logistic myopia, another parameter need be fixed. We deliberately set $k = 5$ which implies that (7c) collapses to the Heaviside function with step from 1 to 0 occurring at $\tau - t' = \Delta$, i.e. an explicitly truncated time of horizon of Δ years. Our calibrated estimates $\rho_e \approx 3.5\%$, $\rho_h \approx 4.7\%$ and $\Delta \approx 12$ years have no counterparts in the empirical literature dedicated to the EU-ETS and thus constitute first-pass, tentative assessments.

Second, given calibrated interest rates and myopia parameters we next calibrate c to approximate the average annual spot price path over 2008-2017, again with ordinary least squares.[49]

of the covered perimeter in Phase III: 38.3, 48.4 and 60.5 million under a LRF of 1.74%, 2.2% and 2.75%.

[45] This can be viewed as a local Taylor approximation of more general functional forms, which implies that the compliance demand in (1) is linear in the permit price. Note also this is a standard assumption in our context (Schennach, 2000; Ellerman & Montero, 2007; Perino & Willner, 2016; Lintunen & Kuusela, 2018).

[46] The assumption of a constant c implies that the absolute price levels we simulate in Section 4 should be taken with a bit of caution. However, because c is merely a scaling parameter that translates a net demand into a price level, focusing on relative price variations eliminates the imprecision due to our assumption.

[47] As firms might bank permits for hedging purposes, required returns should be below those for standard risky assets. The market for futures can provide information about the discount rates applied by EU-ETS participants in valuing present versus future EUAs, see e.g. Ellerman et al. (2015) for a similar argument. See Ellerman & Montero (2007) for a finer parametrization of r in the context of the U.S. Acid Rain Program.

[48] Fell (2016) and Kollenberg & Taschini (2016) pick the same value while Beck & Kruse-Andersen (2018) and Perino & Willner (2016, 2017) use 5% and 10%, respectively. Roughly, note that a higher r implies that 'less myopia' is required for calibration. Specifically, as r grows, ρ decreases and Δ increases.

[49] Note that our two-step calibration approach is legitimate since a constant c over time does not influence

The results are reported in the third column of Table 2 with standard deviations given within parenthesis. Our calibration results are similar across types of myopia, in the order of 5.5 to $6 \cdot 10^{-8}$€$/(tCO_2)^2$, which is in line with dedicated CGE studies, e.g. $4.3 \cdot 10^{-8}$€$/(tCO_2)^2$ (Böhringer et al., 2009) or $5.7 \cdot 10^{-8}$€$/(tCO_2)^2$ (Landis, 2015).[50]

Our calibration results are depicted in Figure 4 where Figure 4a (resp. 4b) shows the observed and simulated aggregate banking (resp. permit price) paths over 2008-2017.[51] While all our simulated aggregate banking paths match the observed path quite satisfactorily, this is less so true in terms of price. In particular, logistic myopia better captures the annual average price dynamics than the other types of myopias for which simulated price levels are flatter. Some have argued that observed price dynamics could be partly explained if EU-ETS participants exhibited limited farsightedness (Fuss et al., 2018), or that limited farsightedness could be a key element to account for when assessing the intertemporal performance of the EU-ETS (Ellerman et al., 2015). Our calibration exercise provides some validity to these claims and suggests a limited time horizon whose length is approximately one Phase long.[52]

Recall that what our stylized partial-equilibrium model with constant marginal cost picks up and translates into a price level is the key quantity the firm has to assess annually, i.e. its perceived cumulated required abatement, and in turn how it affects its current abatement decision. While this is proving sufficient to roughly capture the annual average price dynamics, intra-annual variations are not considered here, which, as is well-established in the EU-ETS empirical literature, are feebly driven by underlying market fundamentals (Hintermann et al., 2016; Koch et al., 2016; Cretì & Joëts, 2017).

Supply control parametrization We parametrize the banking corridor to conform with the features of the Market Stability Reserve as adopted (European Commission, 2018). The MSR starts operating in 2019 and is initially seeded with backloaded permits, i.e. $s_{2018} = 900$ million. Additionally, non-issued Phase III permits up to 2017 are also placed in the reserve in 2021, the number of which we calculate to be 581 million.[53] The MSR parameters are set

banking strategies, which thus only depend on the firm's discounting and myopia.

[50]From Böhringer et al. (2009), we obtain 1 $GtCO_2$ of abatement in 2020 for 43 €$/tCO_2$, which pins down the marginal abatement cost slope, and see Table 4 for 2020 in Landis (2015).

[51]We only report simulated paths under exponential and logistic myopias as those paths under no, exponential or hyperbolic myopias are very similar. See also Section 4 and footnote 56.

[52]Relatedly, Salant (2016) argues that due to market-distorting regulatory uncertainty, EUA spot prices were depressed as from 2013 – a fact that Figure 4b here corroborates (assuming a constant c) as all our simulated annual prices (thus without distortion) are above the maximum observed annual prices.

[53]According to the European Commission (2015) the expected number of unallocated Phase III permits is between 550 and 700 million. The cumulated difference between announced annual caps and effective annual

at $\bar{b} = 833$ million, $\underline{b} = 400$ million, $I = 100$ million, and $R = 0.24$ until 2023 and $R = 0.12$ afterwards. Moreover, the weights are set such that $x_{t-2} = 2/3$ and $x_{t-1} = 1/3$ to account for the mismatch between the MSR and compliance calendars.[54]

Because we lack regulatory guidance to parametrize the soft price corridor, we select the floor and ceiling paths in a bid to minimize the difference in cumulated emissions relative to the MSR. Specifically, we set the initial floor and ceiling in 2019 at $\underline{p}$ =€15 and $\bar{p}$ =€30, and let them rise at an annual rate of 3%.[55] This reserve is seeded like the MSR.

Finally, the cancellation mechanism can be active only from 2024 on. Additionally, since the final reform was formulated in late 2017 and enacted in early 2018 (European Parliament and Council, 2018) we consider that the impacts of both controls on annual auction volumes can be anticipated and factored in by the firm only from 2018 on.

4 Analysis

In this section, we use our calibrated model to provide a quantitative assessment of different aspects of the final EU-ETS reform on the price and banking paths, cumulated MSR impacts on supply, as well as evaluate the associated market resilience in the face of typical demand shocks. We further characterize some comparative implications of implementing a soft price corridor in lieu of a banking corridor like the MSR. We present our results until 2100 as all permits are used and emissions are zero in all scenarios by that time. We focus our analysis on exponential and logistic types of myopia since these generate the most clear-cut differences across paths in the scenarios we consider.[56]

All price paths are given in current € values where we use the observed annual inflation rates between 2008 and 2017 and take 1.5% per annum afterwards. Additionally, the absolute path levels we simulate should be taken with a grain of salt for two reasons. First, our calibrated

caps mostly arises due to non-distributed permits from the New Entrants Reserve and Article 10(c), or from plant closures and production capacity changes. We are thus in the lower range of the estimate as we assume 2018-20 allocation to coincide with the announced caps, but note that the exact number of non-issued permits or date at which they enter the reserve is not crucial for our quantitative results. Over the entire Phase III, note that as much as 1.2 billion permits may not be distributed, about two thirds of one year's cap.

[54]Specifically, the bank, or 'total number of allowances in circulation', for date $t-1$ is published in May of date t, and is used for MSR operations over a twelve-month period from 1 September of date t onwards.

[55]This ensures that cumulated permanent permit withdrawals are on average similar under the MSR and the soft price corridor when the firm cannot anticipate future control-driven supply impacts.

[56]With our calibrated model, the paths obtained under no, exponential and hyperbolic myopia are similar in all scenarios. This suggests that the intertemporal behavior of a firm exhibiting exponential or hyperbolic myopia is observationally equivalent to that of a non-myopic firm with a higher interest rate (with a higher premium the more pronounced the myopia) although the two psychological traits at play are different.

model is a stylized representation of the EU-ETS. Our primary aim is to compare and tease out the relative implications from various market conditions and design elements rather than providing plausible forecasts. Our simulation results should thus at best be seen as ballpark figures. Second, we compute an approximate solution which implies a second-order deviation with respect to the exact solution. Most of induced bias, however, cancels out by looking at the relative differences in the approximate solution's path levels across scenarios.

We consider several scenarios: the continuation of Phase III rules without reform (LRF 1.74); an increase in the linear reduction factor from 1.74% to 2.2% from Phase IV on (LRF 2.2); the same scenario with the MSR starting in 2019 (LRF 2.2 + MSR); and a sole, hypothetical increase in the LRF to 2.75% (LRF 2.75). The scenario LRF 2.2 + MSR is further divided into four sub-scenarios, depending on whether the firm is sophisticated, i.e. able to understand the interplay between its decisions in the competitive equilibrium and the MSR impacts over time (A) or not (N), and on whether the add-on cancellation mechanism is active (C) or not. For instance, LRF 2.2 + MSR AC and LRF 2.2 + MSR A respectively refer to a MSR with and without cancellations, whose impacts are anticipated and accounted for by the firm.

The reform in the reference case We begin with an assessment of the reform impacts in the reference case. The left (resp. right) hand side of Figure 5 depicts the price, banking and emissions paths in the four main scenarios under exponential (resp. logistic) myopia.[57] First note that all paths are ordered by their LRF, i.e. a higher LRF implies higher (resp. lower) price (resp. emission) levels at all points in time from 2018 on and a shorter banking period (though with higher banking levels). Second note that under exponential myopia price levels reach their peaks and emissions fall to zero the year the bank becomes empty. This always occurs a few years after the cap shrank to zero as a result of intertemporal cost minimization. As soon as the bank is nil, the annual required abatement effort is dictated by the difference between the current baseline and cap. As this difference shrinks over time, so do the required abatement and associated cost at the margin (i.e. the price) until they fall to zero when the baseline becomes zero. Third note that logistic myopia smooths out both the price peak and emissions drop to zero, and further generates a slightly distorted inverse U-shaped banking path relative to exponential myopia.

Relative to LRF 2.2, introducing the MSR first hikes the price and curbs emissions, irrespective of cancellations and the firm's sophistication. For instance, the MSR raises the price by

[57] Here we emphasize again that these are actual equilibrium paths along given realized baseline and supply paths, which yearly differ from the expectations the firm had about those.

c.a. 30% in 2050 under both types of myopia. Without cancellations, the opposite situation starts to hold in the 2060's as withdrawn permits are gradually being released, but this does not counterbalance the initial price increase. Under exponential (resp. logistic) myopia, this is attributable to permanent cumulated withdrawals in the order of 2 or 5 (resp. 5 or 8) $GtCO_2$ without or with cancellations on average (depending on the firm's sophistication). Therefore, the MSR is never cap neutral, i.e. it always reduces the cumulated volume of emissions allowed under the system, by an amount which yet varies depending on cancellations being on or not, and on the firm's myopia and sophistication.

Specifically, the four sub-scenarios in LRF 2.2 + MSR are depicted in Figure 6. We begin with exponential myopia on the left-hand side. First note that the price, banking and MSR intake paths are similar until the 2050's when the bank passes below the release threshold and set-aside permits may or may not return to the market depending on cancellations. From this point on, cancellations essentially induce higher price levels.[58] Second note that although the MSR eats away some portion of the bank, the latter nonetheless remains above the upper threshold until c.a. 2040, which means MSR intakes persist for two decades.[59] Third note that sophistication does not play a key role here though, as intuition suggests, it entails less cumulated withdrawals (with and without cancellations). This is because the firm is able to foresee that some permits will return to the market in the future, hence it banks less, which in turn implies that the MSR absorbs less permits and reinjects them sooner.[60]

Market outcomes are noticeably different under logistic myopia, essentially because the firm's degree of sophistication now matters more. First note that sophistication implies higher price levels – this effect wanes over time and holds irrespective of cancellations. Specifically, the price is doubled and jumps as high as €20 in 2018 in anticipation of the supply squeeze ahead and then even remains above the price level implied by LRF 2.75 until the late 2030's.[61] Second, coupled with a truncated time horizon, sophistication entails greater MSR intakes. Indeed, as the MSR cuts back on supply and reinjections are far off into the future, the firm only foresees a sizeable supply crunch over its planning horizon. This drives the current price

[58]Without cancellations, as the MSR continuously reinjects 100 million permits per year, the price is lower and drops to zero before the baselines are effectively zero. These reinjections induce a second banking period when the firm is sophisticated (see Perino & Willner (2016) for a similar effect) while the bank never becomes zero in the first place and then fluctuates around the release threshold when the firm is not sophisticated.

[59]Notice the two small banking upticks after both the intake and release thresholds are breached arise as the MSR suddenly stops aspirating permits or start reinjecting permits, respectively.

[60]Note that without cancellations and with sophistication, the MSR reinjects more permits than effectively withdrawn as the final MSR stock is less than the amount of permits the MSR is initially seeded with.

[61]Under exponential myopia the 2018 price surge exists with sophistication but is less salient.

and bank up, in turn augmenting future MSR intakes, and so forth.[62] Third and relatedly note that cancellations logically magnify this self-fulfilling prophecy effect.

In summary, the reform has endogenized the cumulated emissions cap which now depends on past and future market outcomes and essentially becomes a market outcome itself. As such it can be influenced by external factors like macroeconomic conditions or overlapping policies. Our analysis quantifies how it is also a function of the market participants' (bounded) rationality, here myopia and sophistication. The MSR responsiveness or ability to adjust cumulated supply mostly depends on when it stops taking in permits.[63] Because this happens no sooner than at least two decades after its launch, the MSR can retroactively curb some excess supply due to the 2008 economic downturn and past achievements of complementary policies. We now analyze how responsive it could be to similar circumstances in the future.

Demand shock 1: Renewable deployment We next assess the purported stabilizing capacity of the MSR in the face of an unanticipated, sustained increase or decrease in permit demand over time in the form of lower or higher build-ups of a renewable energy share (RES) in the Union energy mix than in the reference case. Table 3 specifies renewable deployments in the Low and High RES scenarios and Figure 3a depicts the resulting baseline paths.

Figure 7a depicts the price paths in these two scenarios with and without MSR under exponential myopia.[64] The MSR raises prices throughout in both scenarios, which underlines a key asymmetry inherent to its design: it is tailored to curb supply by sucking in permits rather than to expand it by releasing them back. A key responsiveness indicator to look at is the date at which the MSR stops withdrawing permits: relative to the reference case (2041), it is advanced in Low RES (2033) and postponed in High RES (2046). Note, however, that relative to the reference case, the induced responsiveness does not suffice in that 1.5 billion additional withdrawals cannot sustain a price higher than €30 in High RES and although withdrawals are reduced by 0.9 billion in Low RES, 4.2 billion permits are already cancelled and cannot return to the market to prevent the price from passing the €100 landmark. Thus the price divergence across Low and High RES continues to increase over time though it is slightly reduced, e.g. from €54 without MSR to €46 in 2050 with MSR.

Our results therefore suggest that the MSR capacity to dampen such a sustained divergence in the evolution of the permit demand over time would be limited. Specifically, if we think

[62] This induced snowball effect quickly slows down and is limited in magnitude since $R < 1$.

[63] By construction the date at which the MSR release supply matters less present cancellations.

[64] Our results are qualitatively similar under logistic myopia and available from the authors.

of renewable penetration as resulting from dedicated EU-wide or national policies, the MSR could only feebly puncture a future waterbed effect under High RES, and would fail to release the price pressure when these policies underachieve relative to their targets under Low RES. Turning cancellations off would slightly alter the latter observation as this would allow more permits to return to the market and reduce the price, but note this would not fundamentally change the MSR responsiveness per se, namely in this case when it starts to reinject permits.

Demand shock 2: Economic recession We now assess the market response to a short- to mid-term negative shock on economic activity from 2028 to 2037 which we parametrize on observed EU economic growth variations in the aftermath of the 2008 economic downturn between 2008 and 2017, i.e. a sudden and significant drop in activity at first, followed by a period of stagnation in the subsequent years and of slight recovery afterwards. The resulting path for the baseline emissions is reported in Figure 3a.

Figure 7b depicts the price paths present the recession with and without MSR under logistic myopia.[65] The price always plunges when the crisis hits and note that price variations during the recession are similar with and without MSR. That said, the MSR maintains a higher price throughout relative to LRF 2.75.[66] Also observe that the initial price drop is slightly smaller with the MSR, especially with a sophisticated firm (by c.a. 10%).[67] This effect is small as the MSR has limited room to curb much of the crisis-induced excess supply. Indeed, relative to the reference case, the MSR stops taking in permits one year later and only 850 million more permits are withdrawn and cancelled. As a result, present the MSR the maximum price with the crisis is €14 lower than without.[68] Our results therefore suggest that the MSR capacity to buffer a crisis of this magnitude would be limited.

Price corridor We finally compare the market outcomes under the MSR with those under an alternative control, namely a soft price corridor, or 'Price Stability Reserve', with a given set of parameters. Note that our aim is merely to highlight distinct implications between the two controls, not to provide a thorough comparative economic assessment. We consider both the reference and the demand shock 1 scenarios under exponential myopia.

[65] Our results are qualitatively similar under exponential myopia and available from the authors.

[66] However, note that the differences in price levels stem from the MSR-induced supply squeeze prior to the recession, but not from the MSR actions during the recession itself.

[67] This smaller price drop is almost nonexistent when the firm is not sophisticated.

[68] Should the crisis occur earlier on, the MSR would have more time to take in permits and more of the crisis-induced excess supply would be curbed. However, this would only marginally change our results as the MSR already withdraws permits for about 25 years after the start of the crisis in our case.

We begin with the reference scenario, whose outcomes are displayed on the left-hand side of Figure 8, where the price without control is below the floor until 2044. Introducing the PSR causes a €1 price uptick in 2018 when the firm is sophisticated and anticipates that the PSR will kick in and start reducing supply next year. In fact, the entire auction volume in 2019 is withdrawn but note this does not suffice to raise the price up to the floor. In the following years the price is pegged to the floor until 2031, which in turn implies that the PSR is not cap-neutral as c.a. 4 billion permits are permanently withdrawn.[69] From 2032 on, price paths start taking off from the floor as well as deviating from one another.

The take-off is simply due to past withdrawals that augment the firm's cumulated required abatement and drive the price above the floor – for otherwise the price path without sophistication would still be glued to the floor. The deviation is less straightforward and attributable to the fact that although the ceiling never binds, it might still affect the firm's anticipation of the future PSR-driven supply impacts in the competitive equilibrium.[70] The main piece of evidence is to note that because withdrawn permits never return to the market, cancellations should be inconsequential for the market outcomes, i.e. the PSR A and PSR AC equilibrium outcomes should be identical, which is however not the case here.[71]

Specifically, between 2020 and 2030, more permits are set aside than necessary for the floor to be met when the firm is sophisticated.[72] As it happens, in those years the firm foresees that the ceiling will be hit in the future, thereby increasing future supply. As this shrinks the firm's perceived required total abatement effort, and thus its current abatement decision, supply must be squeezed further for the floor to be attained today. This is more pronounced absent cancellations as more permits can potentially return to the market.[73] However, the firm's forecasts turn out to be wrong as the ceiling never binds after all and these additional set-aside permits are permanently withdrawn, which in turn induces higher price levels.[74]

We finally turn to the demand shock 1 scenario, whose outcomes are displayed on the right-hand side of Figure 8. In High RES, the PSR sustains a higher price signal than the MSR:

[69] This guided our selection of the PSR parameters as this roughly corresponds to the average cumulated withdrawals obtained in LRF 2.2 MSR N and LRF 2.2 MSR NC in the reference case.

[70] There is a large literature documenting the effects of non-binding price bands in a rational expectations equilibrium. To quote but a few pioneering pieces in the wider commodity storage context, see for instance Lee (1978), Salant (1983), Miranda & Helmberger (1988) or Wright & Williams (1988).

[71] Market outcomes are by contrast identical when the firm is not sophisticated (PSR N & NC).

[72] A second auction shutdown occurs in 2020 (with the price below the floor) when the firm is sophisticated.

[73] This effect is less marked the less permits the reserve is initially seeded with.

[74] Symmetrically, in alternative situations where the price floor is initially set below the market price and thus non-binding, it might still induce a price jump. This is because the firm anticipates that the floor might possibly bind in the future and thereby tighten supply, which drives the price up today.

the price is pegged to the floor until 2058 when it falls as some withdrawals would be needed for the floor to be met, but annual auction volumes become null. In total, the PSR withdraws 3.2 billion permits more than the MSR under identical conditions.[75] In Low RES, the PSR fails to contain the price increase, just as the MSR. Specifically, the soft ceiling is breached in 2053 as there too few permits left in the reserve to defend it due to cancellations.[76] In fact, the PSR is only active in 2019 when it sucks in the entire auction volume (c.a. 900 MtCO_2) and in 2053 when the reserve is entirely depleted (c.a. 300 MtCO_2).[77]

5 Related literature

Ellerman & Montero (2007) and Ellerman et al. (2015) apply the key tenets of efficient permit banking theory (Cronshaw & Kruse, 1996; Rubin, 1996; Schennach, 2000) to the U.S. Acid Rain Program and the EU-ETS, respectively, with the aim of investigating the efficiency of observed aggregate banking behaviors ex post, and find them to be at least partially efficient. Note, however, that both leave the question of the observed price dynamics mostly aside. For instance, in a similar approach to ours, Ellerman & Montero (2007) compare efficient banking paths implied by various pairs of interest rate and growth rate in counterfactual emissions to actual paths to guess at what pair might have governed banking behavior ex post. They observe a regime switch in actual banking behavior which they argue to be attributable to a change in the expected growth in counterfactual emissions and highlight the importance of changes in expectation and how they affect banking behavior.

Taking stock of this, we explicitly formulate firms' expectation about future counterfactual emissions as part of the model and provide a finer characterization of how these emissions evolve over time through a Kaya-like, calibrated decomposition. This allows us to replicate the observed banking behavior more satisfactorily. Additionally, we briefly tackle the issue of price formation and show that the formal adjunction of firm's myopia in the model can better pick up the yearly-averaged observed dynamics. Our calibrated estimates for the market's interest rate and myopia parameters contribute to the empirical literature dedicated to the EU-ETS (Ellerman et al., 2016; Hintermann et al., 2016; Fuss et al., 2018).

More generally, our paper primarily relates to the nascent literature dedicated to the MSR. Early papers considered the initial MSR design (Fell, 2016; Perino & Willner, 2016; Schopp

[75] Early withdrawals are so large that borrowing occurs in 2021 and persists throughout.

[76] Absent cancellations there would be enough permits in the PSR for the ceiling to hold – the MSR would also reduce the price somewhat, but as a mere result of the bank being mechanically drawn down to zero.

[77] The 2053 reinjection mechanically causes the sudden rise in the bank on Figure 8d.

et al., 2015) while more recent papers deal with the reinforced, final MSR with cancellations and a higher intake rate (Beck & Kruse-Andersen, 2018; Perino & Willner, 2017; Perino, 2018). In terms of modelling structure, the closest papers are Fell (2016) and Perino & Willner (2016). The key difference is the introduction of both myopia and limited sophistication, and the corresponding adjunction of novel solving procedures.

Specifically, Fell (2016) shows that the MSR reduces price variability and improves synergies with complementary policies by reducing 'ex-post over-allocations', albeit to a lesser extent than with a price collar.[78] The latter result aligns with our comparison of the MSR with a soft price collar. By contrast, Perino & Willner (2016) find that MSR preserves the cumulated cap and cannot reduce ex-post excess supply. Moreover, Perino & Willner specify the theoretical conditions under which the MSR cushions or amplifies price responses due to demand shocks relative to without control, and conclude that the MSR increases price variability. Similarly, Richstein et al. (2015) find that the initial MSR raises price volatility with an agent-based power market simulation model.[79] Our simulations suggest that price responses to shocks are slightly dampened under the final MSR relative to no MSR.

In a dynamic stochastic setting, Kollenberg & Taschini (2018) find that the initial MSR, as it merely reshuffles auctions, is largely irrelevant with risk-neutral firms as long as intertemporal equilibrium paths remain feasible, i.e. the bank is not suddenly emptied due to shocks.[80] This is because the MSR only affects the variability of the time of bank depletion, not its expected value. However, higher variability in long-term returns from banking matters for risk-averse firms. They thus bank less implying the short-term price is lower.[81] Tietjen et al. (2018) are further able to compute this endogenous risk premium by formally accounting for firms' hedging demand and investment decisions. Crucially, the premium depends on the temporal issuance of permits, and thus on related MSR impacts, which lead to higher prices in the short term and less investments in carbon-intensive capacities. Similarly, Schopp et al. (2015) consider an intertemporal market equilibrium in presence of emitters, hedgers and speculators (arbitrageurs). This results in a limited banking capacity for the market relative to efficiency, for once the bank exceeds hedging needs speculators with higher return requirements enter the market, which results in lower prices and higher volatility. They find that the initial MSR

[78] The reduction in ex-post excess supply may be driven by the assumption of a finite time horizon, which we relax, as permits do not all have time to return to the market.

[79] This also echoes with Holt & Shobe (2016)'s laboratory experiments showing that both welfare and price volatility may deteriorate under a MSR-like banking collar relative to no control.

[80] This is also the insight of Proposition 3 in Perino & Willner (2016).

[81] As Kollenberg & Taschini (2018) argue, cancellations in the final MSR would mitigate these inefficiences by reducing the risk associated with long-term returns of banked permits.

attenuates these inefficiencies and argue that its thresholds should be regularly updated to align with evolving hedging needs.[82]

The literature dealing with the final MSR is more recent and scarce. Since the cancellation provision endogenizes the cumulated cap, the main focus is on the quantification of the share of abatements resulting from different magnitude and timing of overlapping policies that is eventually cancelled, hence permanent. Perino (2018) provide back-of-the-envelope estimates for such long-term impacts of overlapping policies, with the general insight that the sooner the abatement occurs, the larger share thereof is rendered permanent.[83] Beck & Kruse-Andersen (2018) refine these estimates for both overlapping and national cancellation policies. Our paper also provides similar estimates, which further account for the impacts of uncertainty and bounded rationality on the part of the firms (myopia and limited sophistication).

Additionally, some papers go beyond the usual partial-equilibrium framework. For instance, Chaton et al. (2018) develop a three-period model where firms Cournot-compete in quantities on the output market. The MSR is found to raise permit prices by curbing supply, but Chaton et al. show that under stochastic output demand, the MSR may alter intertemporal arbitrage which may have unintended price impacts and adversely affect welfare. Bruninx et al. (2018) explicitly model the interaction between the power sector, the industry sector, the electricity market and the EU-ETS in presence of the (final) MSR. The main emphasis is placed on the power sector for which the MSR-driven permit price rise stimulates gas-coal fuel switching and green energy investments, but with limited impact on the average electricity price.

Finally, in a dynamic framework with cost uncertainty, Kollenberg & Taschini (2016) propose a cap adjustment policy responsive to aggregate banking de facto spanning the continuum between pure price and quantity controls. Firms' behaviors are endogenous with the policy and Kollenberg & Taschini identify the optimal adjustment rate numerically.[84] In a similar vein, Lintunen & Kuusela (2018) propose a Markov hybrid policy for annual cap adjustments which they show in a counterfactual analysis would have led to steadier price levels, lower emissions and higher welfare in the EU-ETS over 2009-2013.

[82] Relatedly, Richstein et al. (2015) find that the initial MSR is not cap neutral, which they argue is due to the selected MSR thresholds not being aligned with the hedging need of power producers.

[83] Relatedly, Perino & Willner (2017) evaluate three pre-final MSR design proposals.

[84] Gerlagh & Heijmans (2018) pin down an analytical form for the optimal rate in a two-period model.

6 Conclusion

We build a model of competitive intertemporal emissions trading under uncertainty tailored to the EU-ETS. Our first contribution is the introduction of two sources of bounded rationality on the part of regulated firms. First, they can have different types and degrees of myopia as they decreasingly account for estimated annual abatement efforts the farther away they look into the future. Second, they have different degrees of sophistication in understanding the interplay between the supply control's impacts and their own decisions in the competitive equilibrium over time. Accordingly, this necessitates two modelling novelties, specifically the implementation of an iterative procedure to derive expected equilibrium paths on the one hand and of a heuristic procedure to solve for the rational expectations equilibrium on the other. We counterbalance the associated modelling complexities by operationalizing a first-order approximation approach first suggested by Schennach (2000).

Our second contribution is the calibration of the market's interest rate, myopia and marginal abatement costs based on 2008-2017 market data to match observed price and banking paths. As a first attempt in the literature, we find reasonable parameter values and highlight the key role myopia can have in the price dynamics. As a third contribution, we assess the final market reform, essentially the impacts of the market stability reserve. We find that the MSR always reduces the cumulated cap (even without cancellations) and raises the permit price. We show how the MSR supply impacts depend greatly on the firms' types and degrees of myopia and sophistication. Our results indicate the reform has not completely addressed the governance issue as the MSR acts as temporary patch which is able to curb some excess supply induced by the 2008 economic downturn and past achievements of overlapping policies but displays limited responsiveness to similar shocks in the future. We also compare the performances of the MSR with those of a less peculiar supply-side control, a soft price collar.

Additionally, our modelling framework can serve as a good basis for an assessment of the MSR for the upcoming review in 2021, by extending our ex post analysis when additional data is available and investigating the impacts changing the MSR settings $\bar{b}$, $\underline{b}$, R and I ex ante. This could also be an opportunity to analyze more profound design changes in the MSR itself or the introduction of a price floor in lieu or on top of the MSR, e.g. via an auction reserve price, as is currently discussed (Newbery et al., 2018; Pahle et al., 2018). Additionally, although our model is herein purposely tailored to the EU-ETS, it is amenable to amendments and calibration to other systems, for instance the Regional Greenhouse Gas Initiative or the linked California-Québec ETS where other forms of price collars, intertemporal trading provisions and compliance cycles are in place. More broadly, our framework and the simulation results we obtain for the EU-ETS contribute to improving our understanding of the intertemporal performances of emissions trading systems in general – a topic which is high on the policy and research agendas (Ellerman et al., 2015, 2016; Fuss et al., 2018) – as well as the interactions between intertemporal trading and supply-side controls.

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Tables

Table 1: Projected trends of baseline emissions

Period	Climate Energy Package	2050 baseline	Baseline = 0 in
2008-2013	CEP#1 targets	57.5%	2115
2013-2017	CEP#2 targets	50.7%	2105
2018-2100	Reinforced CEP#2 targets	39.7%	2096

Note: 2050 baseline emissions given in relative terms w.r.t. 2008 verified emissions (2.12 $GtCO_2$).

Table 2: Calibration results based on 2008-2017 market data

Myopia type	Interest and myopia rates	Marginal abatement cost
No myopia	$r = 7.06\%$ (std.dev=52.9 $MtCO_2$)	$c = 5.53 \cdot 10^{-8}$ €/$(tCO_2)^2$ (std.dev=3.86 €/tCO_2)
Exponential	$r = 3\%^\star$ $\rho_e = 3.51\%$ (std.dev=46.4 $MtCO_2$)	$c = 5.63 \cdot 10^{-8}$ €/$(tCO_2)^2$ (std.dev=3.54 €/tCO_2)
Hyperbolic	$r = 3\%^\star$ $\rho_h = 4.71\%$ (std.dev=50.3 $MtCO_2$)	$c = 5.57 \cdot 10^{-8}$ €/$(tCO_2)^2$ (std.dev=3.75 €/tCO_2)
Logistic	$r = 3\%^\star$ $k = 5^\star$ $\Delta = 11.9$y (std.dev=72.4 $MtCO_2$)	$c = 5.90 \cdot 10^{-8}$ €/$(tCO_2)^2$ (std.dev=1.61 €/tCO_2)

Note: A $\star$ indicates parameters taken as given.

Table 3: Shares of renewable energy sources (RES) in EU28 energy consumption

RES	2020	2030	2050	2100
Low	20%	25%	36%	74%
Reference	22%	32%	55%	100%
High	24%	37%	69%	100%

Figures

Figure 1: Myopia weights M_τ under exponential, hyperbolic or logistic myopias

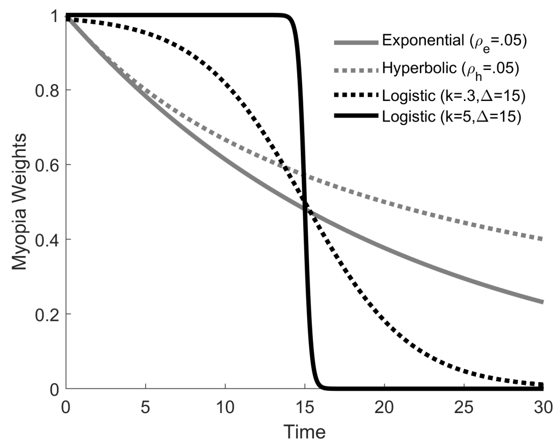
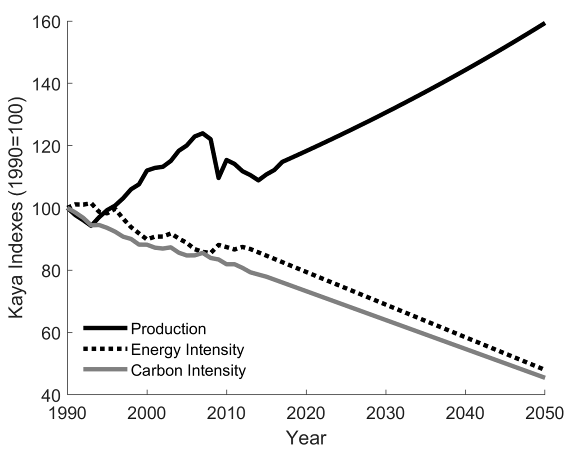


Figure 2: Baseline emissions and total emissions cap in the reference case

(a) Kaya Indexes



(b) Supply and Demand

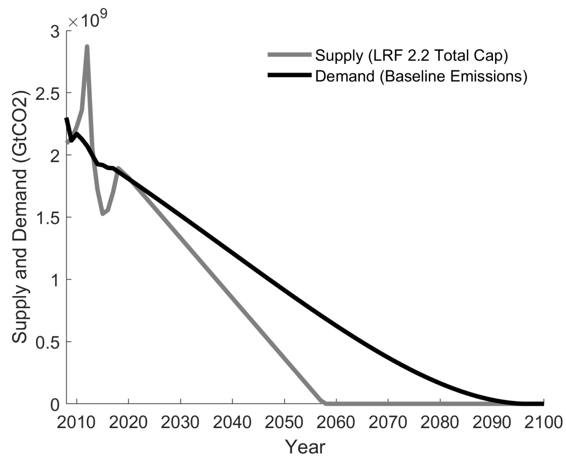


Figure 3: Baseline emissions and total emissions cap in alternative cases

(a) Baseline Emissions

(b) Total Emissions Cap

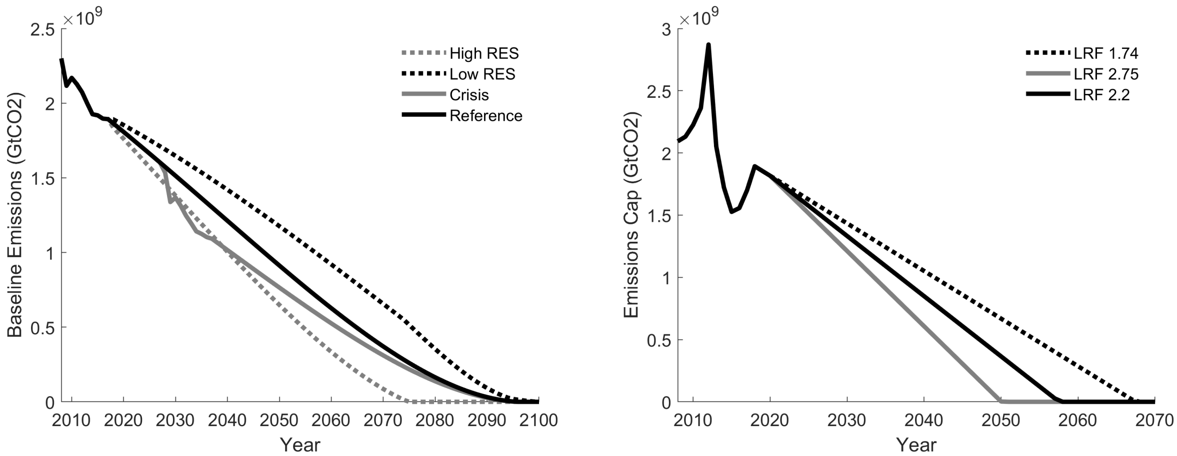


Figure 4: Calibration results based on 2008-2017 market data

(a) Banking

(b) Price

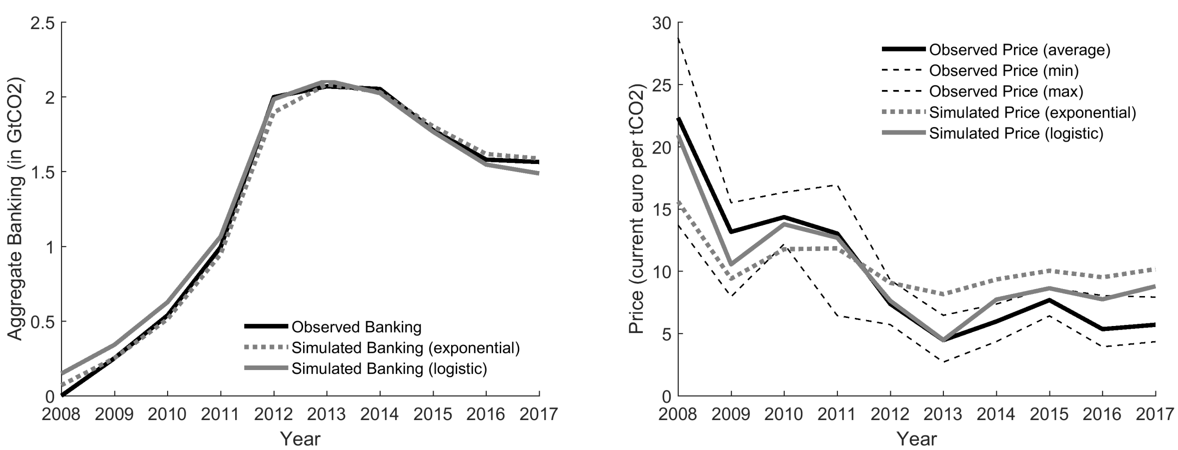
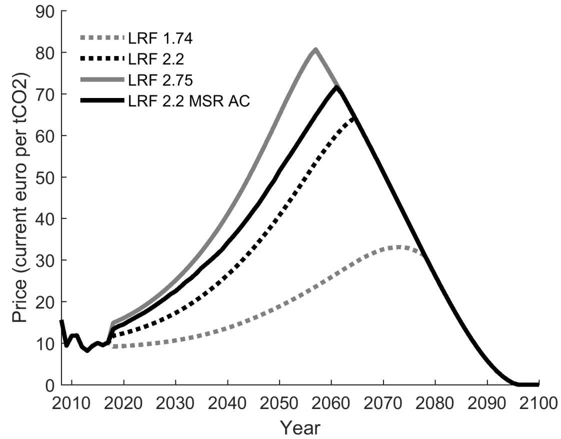
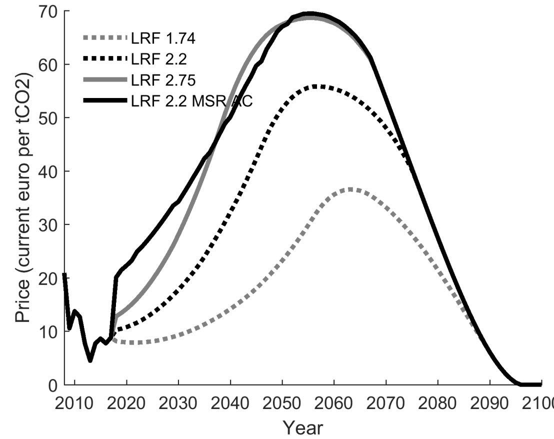


Figure 5: Price, banking and emission paths in the reference case

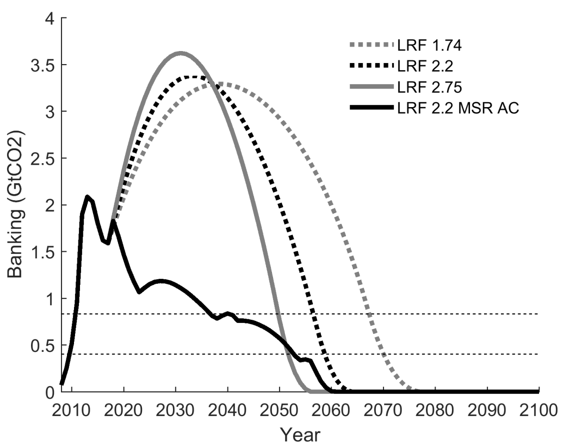
(a) Price (exponential)



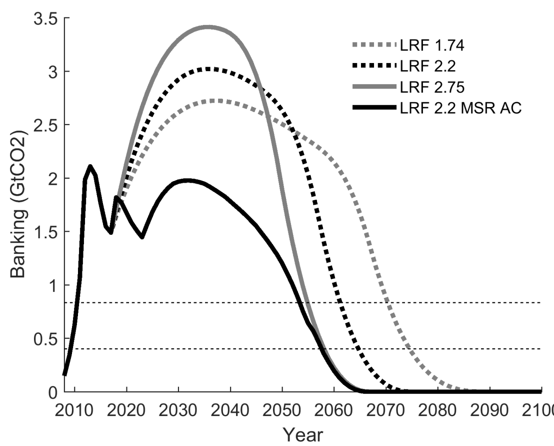
(b) Price (logistic)



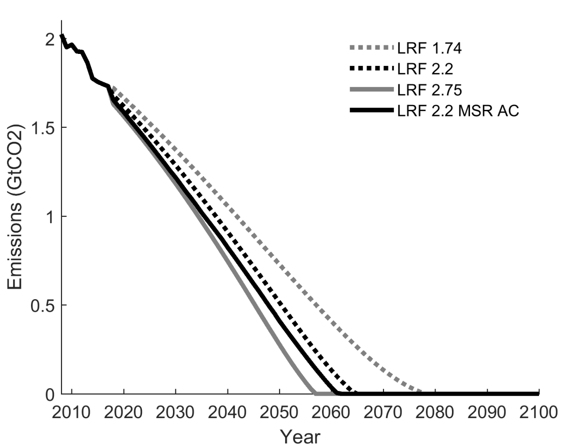
(c) Banking (exponential)



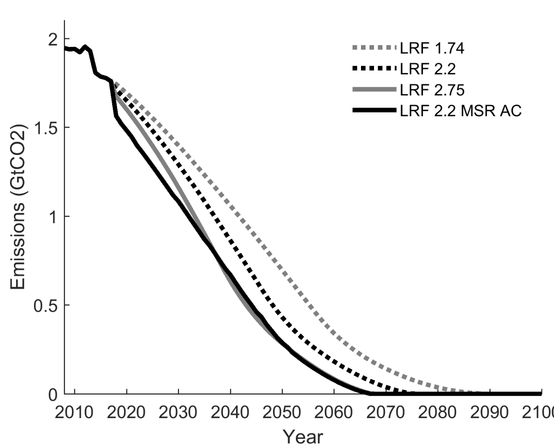
(d) Banking (logistic)



(e) Emissions (exponential)



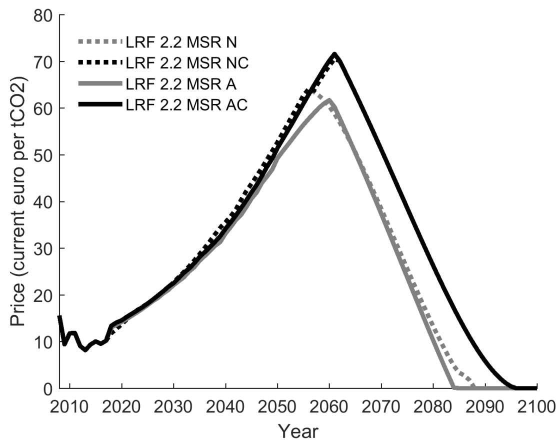
(f) Emissions (logistic)



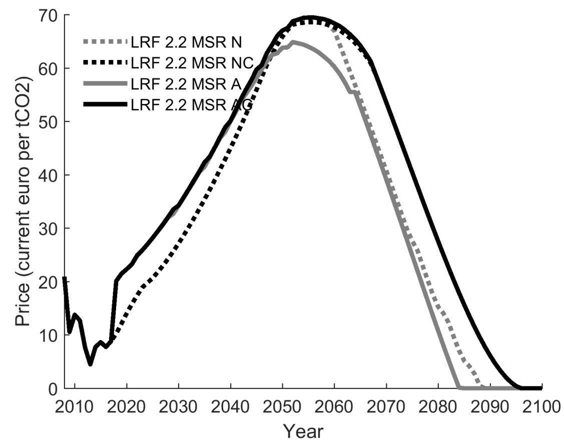
Note: LRF X = Linear reduction factor of X%; MSR AC = Anticipated MSR impacts, with cancellation.

Figure 6: Price, banking and withdrawal paths in the reference case

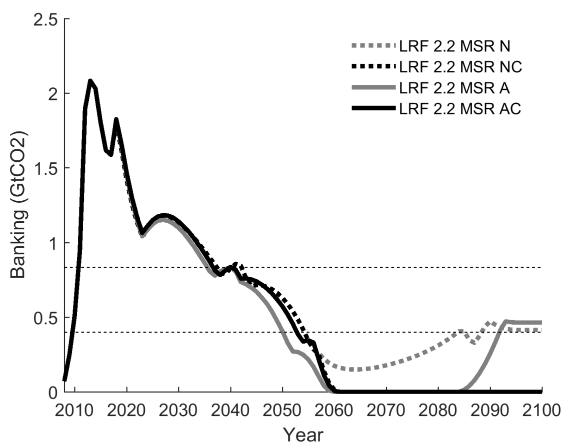
(a) Price (exponential)



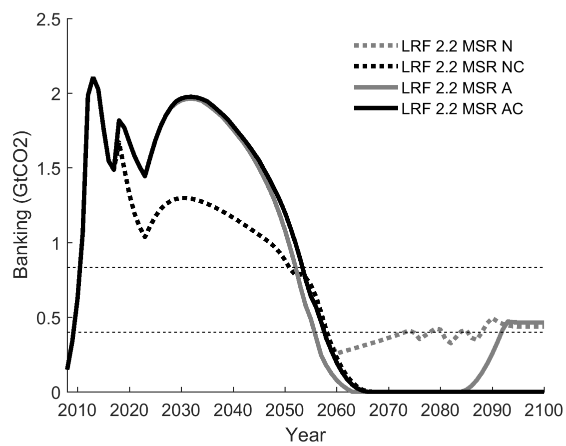
(b) Price (logistic)



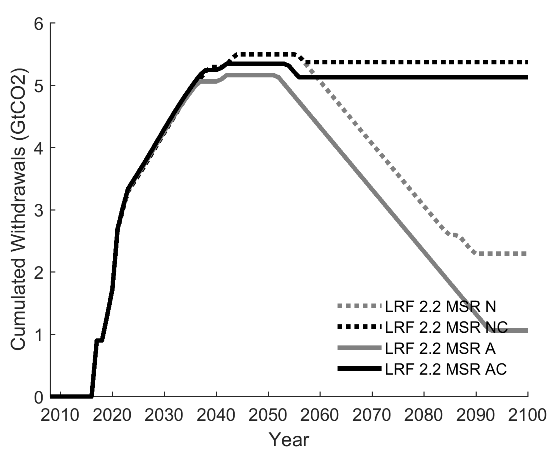
(c) Banking (exponential)



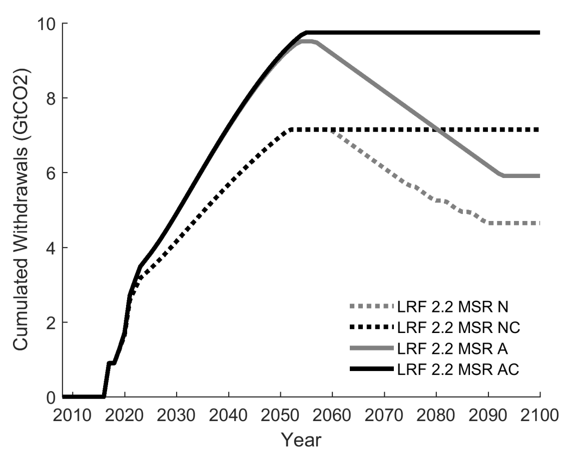
(d) Banking (logistic)



(e) Cumulated Withdrawals (exponential)



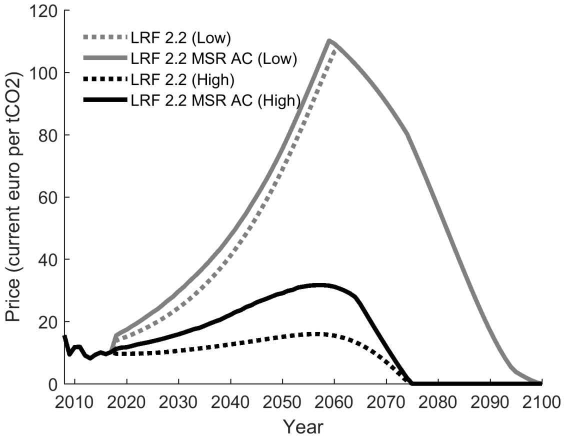
(f) Cumulated Withdrawals (logistic)



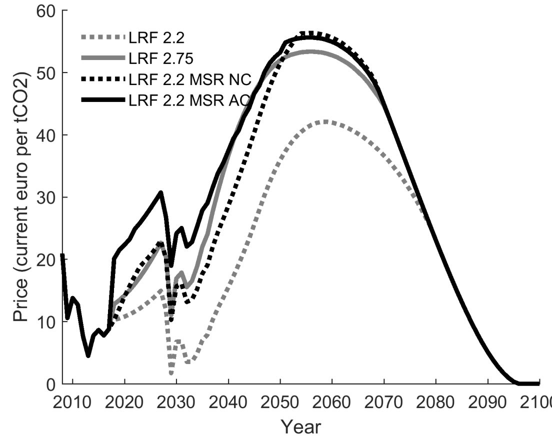
Note: A = Anticipated MSR impacts; N = Non-anticipated MSR impacts; C = with cancellation.

Figure 7: Price, banking and withdrawal paths in demand shocks 1 and 2

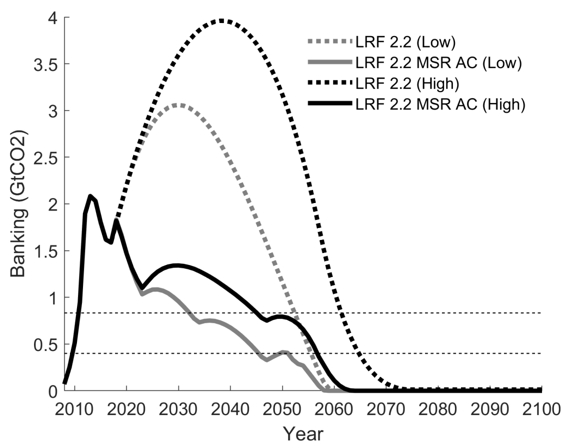
(a) Price (Shock 1)



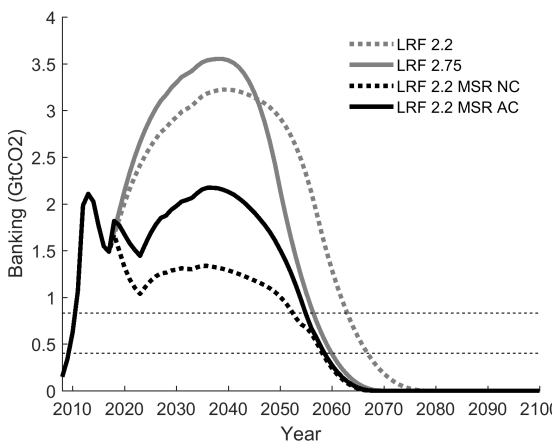
(b) Price (Shock 2)



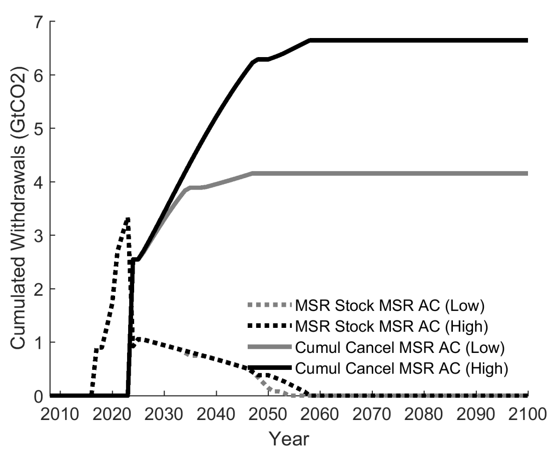
(c) Banking (Shock 1)



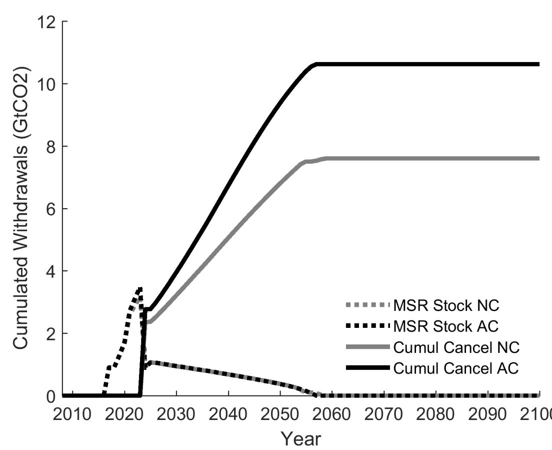
(d) Banking (Shock 2)



(e) Cumulated Withdrawals (Shock 1)



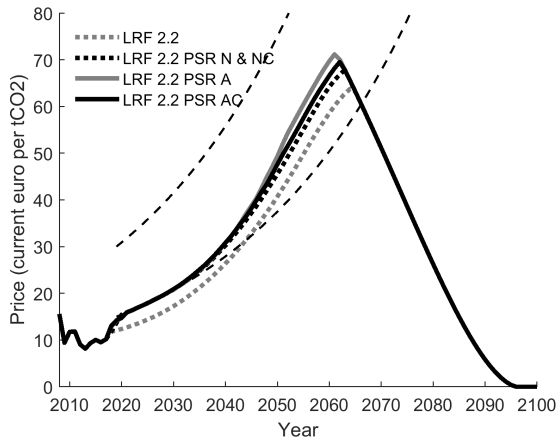
(f) Cumulated Withdrawals (Shock 2)



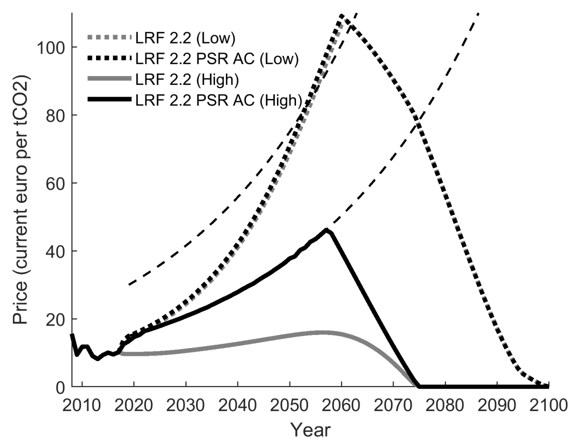
Note: The scenario with shock 1 (resp. 2) is obtained under exponential (resp. logistic) myopia.

Figure 8: Price, banking and withdrawal paths under a price corridor (PSR)

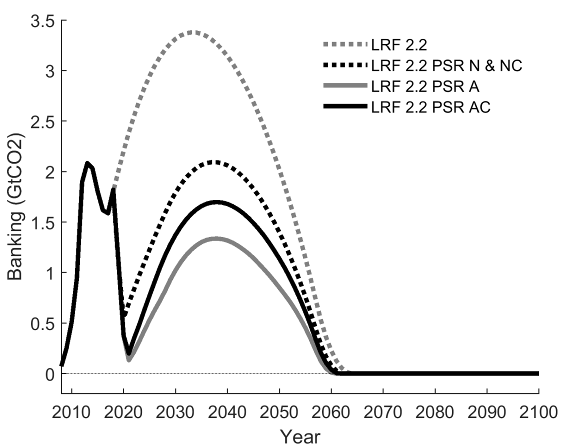
(a) Price (Reference)



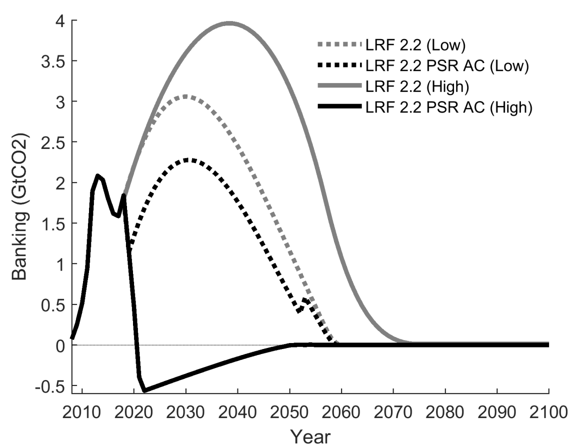
(b) Price (Shock 1)



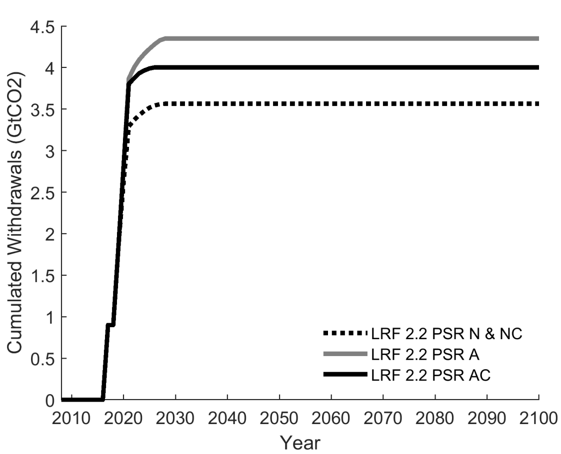
(c) Banking (Reference)



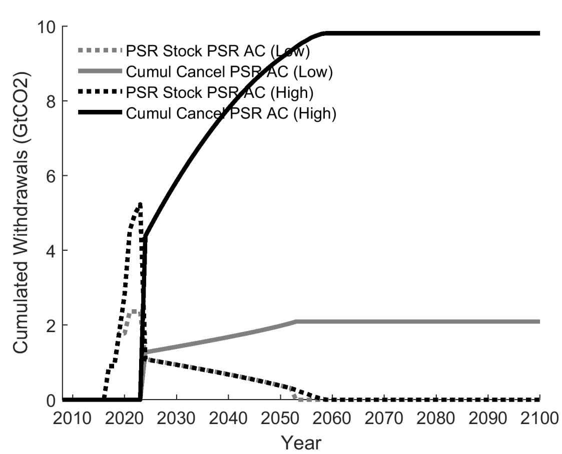
(d) Banking (Shock 1)



(e) Cumulated Withdrawals (Reference)



(f) Cumulated Withdrawals (Shock 1)



Note: The two scenarios (reference on the LHS; shock 1 on the RHS) are obtained under exponential myopia.

References

Beck, U. & Kruse-Andersen, P. (2018). *Endogenizing the Cap in a Cap-and-Trade System: Assessing the Agreement on EU-ETS Phase 4*. Arbejdspapir 2018:02, De Økonomiske Råd.

Bel, G. & Joseph, S. (2015). Emission Abatement: Untangling the Impacts of the EU ETS and the Economic Crisis. *Energy Economics*, **49**, 531–9.

Böhringer, C., Löschel, A., Moslener, U. & Rutherford, T. F. (2009). EU Climate Policy up to 2020: An Economic Impact Assessment. *Energy Economics*, **31**, S295–305.

Borenstein, S., Bushnell, J., Wolak, F. A. & Zaragoza-Watkins, M. (2016). *Expecting the Unexpected: Emissions Uncertainty and Environmental Market Design*. Working Paper 20999, National Bureau of Economic Research.

Bréchet, T. & Jouvet, P.-A. (2008). Environmental Innovation and the Cost of Pollution Abatement Revisited. *Ecological Economics*, **65**(2), 262–5.

Bredin, D. & Parsons, J. (2016). Why is Spot Carbon so Cheap and Future Carbon so Dear? The Term Structure of Carbon Prices. *Energy Journal*, **37**(3), 83–107.

Bruninx, K., Ovaere, M. & Delarue, E. (2018). *A First Analysis of the Market Stability Reserve in the European Emission Trading System*. TME Working Paper EN2018-19, KU Leuven.

Burtraw, D., Holt, C. A., Palmer, K. L., Paul, A. & Shobe, W. M. (2018). *Quantities with Prices*. Working Paper 18-08, Resources for the Future.

Cafiero, C., Bobenrieth, E. S., Bobenrieth, J. R. & Wright, B. D. (2011). The Empirical Relevance of the Competitive Storage Model. *Journal of Econometrics*, **162**(1), 44–54.

Chaton, C., Cretì, A. & Peluchon, B. (2015). Banking and Back-Loading Emission Permits. *Energy Policy*, **82**, 332–41.

Chaton, C., Cretì, A. & Sanin, M.-E. (2018). Assessing the Implementation of the Market Stability Reserve. *Energy Policy*, **118**, 642–54.

Clò, S., Battles, S. & Zoppoli, P. (2013). Policy Options to Improve the Effectiveness of the EU Emissions Trading System: A Multi-Criteria Analysis. *Energy Policy*, **57**, 477–90.

Cretì, A. & Joëts, M. (2017). Multiple Bubbles in the European Union Emission Trading Scheme. *Energy Policy*, **107**, 119–30.

Cronshaw, M. B. & Kruse, J. B. (1996). Regulated Firms in Pollution Permit Markets with Banking. *Journal of Regulatory Economics*, **9**(2), 179–89.

Deaton, A. & Laroque, G. (1992). On the Behaviour of Commodity Prices. *Review of Economic Studies*, **59**(1), 1–23.

Deaton, A. & Laroque, G. (1996). Competitive Storage and Commodity Price Dynamics. *Journal of Political Economy*, **104**(5), 896–923.

Doda, B. L. (2016). How to Price Carbon in Good Times... And Bad! *Wiley Interdisciplinary Reviews: Climate Change*, **7**(1), 135–44.

Ellerman, A. D., Marcantonini, C. & Zaklan, A. (2016). The European Union Emissions Trading System: Ten Years and Counting. *Review of Environmental Economics & Policy*, **10**(1), 89–107.

Ellerman, A. D. & Montero, J.-P. (2007). The Efficiency and Robustness of Allowance Banking in the U.S. Acid Rain Program. *Energy Journal*, **28**(4), 47–71.

Ellerman, A. D., Valero, V. & Zaklan, A. (2015). *An Analysis of Allowance Banking in the EU ETS*. Working Paper RSCAS 2015/29, European University Institute.

European Commission (2015). *Impact Assessment SWD(2015) 135*. Brussels, 15.7.2015.

European Commission (2018). *Communication C(2018) 2801*. Brussels, 15.5.2018.

European Parliament and Council (2018). *Directive (EU) 2018/410*. OJ L 76, 19.03.2018.

Fell, H. (2016). Comparing Policies to Confront Permit Over-Allocation. *Journal of Environmental Economics & Management*, **80**.

Fell, H., Burtraw, D., Morgenstern, R. D. & Palmer, K. L. (2012a). Soft and Hard Price Collars in a Cap-and-Trade System: A Comparative Analysis. *Journal of Environmental Economics & Management*, **64**(2), 183–98.

Fell, H., MacKenzie, I. A. & Pizer, W. A. (2012b). Prices versus Quantities versus Bankable Quantities. *Resource & Energy Economics*, **34**(4), 607–23.

Fuss, S., Flachsland, C., Koch, N., Kornek, U., Knopf, B. & Edenhofer, O. (2018). A Framework for Assessing the Performance of Cap-and-Trade Systems: Insights from the European Union Emissions Trading System. *Review of Environmental Economics & Policy*.

Gerlagh, R. & Heijmans, R. J. R. K. (2018). Regulating Stock Pollutants, mimeo.

Grosjean, G., Acworth, W., Flachsland, C. & Marschinski, R. (2016). After Monetary Policy, Climate Policy: Is Delegation the Key to EUETS Reform? *Climate Policy*, **16**(1), 1–25.

Grüll, G. & Taschini, L. (2011). Cap-and-Trade Properties under Different Hybrid Scheme Designs. *Journal of Environmental Economics & Management*, **61**(1), 107–18.

Grüne, L., Semmler, W. & Stieler, M. (2015). Using Nonlinear Model Predictive Control for Dynamic Decision Problems in Economics. *Journal of Economic Dynamics & Control*, **60**, 112–33.

Hasegawa, M. & Salant, S. W. (2015). The Dynamics of Pollution Permits. *Annual Review of Resource Economics*, **7**, 61–79.

Heutel, G. (2012). How Should Environmental Policy Respond to Business Cycles? Optimal Policy under Persistent Productivity Shocks. *Review of Economic Dynamics*, **15**(2), 244–64.

Hintermann, B., Peterson, S. & Rickels, W. (2016). Price and Market Behavior in Phase II of the EUETS: A Review of the Literature. *Review of Environmental Economics & Policy*, **10**(1), 108–28.

Holt, C. A. & Shobe, W. M. (2016). Price and Quantity Collars for Stabilizing Emission Allowance Prices: Laboratory Experiments on the EUETS Market Stability Reserve. *Journal of Environmental Economics & Management*, **80**, 69–86.

Joltreau, E. & Sommerfeld, K. (2018). Why Does Emissions Trading under the EU Emissions Trading System (ETS) Not Affect Firms' Competitiveness? Empirical Findings from the Literature. *Climate Policy*, 1–19, forthcoming.

Jordà, O., Knoll, K., Kuvshinov, D., Schularick, M. & Taylor, A. M. (2017). *The Rate of*

Return on Everything, 1870-2015. Working Paper 24112, National Bureau of Economic Research.

Kaganovich, M. (1985). Efficiency of Sliding Plans in a Linear Model with Time-Dependent Technology. *Review of Economic Studies*, **52**(4), 691–702.

Kling, C. & Rubin, J. (1997). Bankable Permits for the Control of Environmental Pollution. *Journal of Public Economics*, **64**(1), 101–15.

Koch, N., Grosjean, G., Fuss, S. & Edenhofer, O. (2016). Politics Matters: Regulatory Events as Catalysts for Price Formation under Cap-and-Trade. *Journal of Environmental Economics & Management*, **78**, 121–39.

Kollenberg, S. & Taschini, L. (2016). Emissions Trading Systems with Cap Adjustments. *Journal of Environmental Economics & Management*, **80**, 20–36.

Kollenberg, S. & Taschini, L. (2018). Dynamic Supply Adjustment and Banking under Uncertainty: the Market Stability Reserve, mimeo.

Kydland, F. E. & Prescott, E. C. (1977). Rules Rather than Discretion: The Inconsistency of Optimal Plans. *Journal of Political Economy*, **85**(3), 473–91.

Laffont, J.-J. & Tirole, J. (1996). Pollution Permits and Compliance Strategies. *Journal of Public Economics*, **62**(1), 85–125.

Landis, F. (2015). *Final Report on Marginal Abatement Cost Curves for the Evaluation of the Market Stability Reserve*. Dokumentation 15-01, ZEW Mannheim.

Lee, D. R. (1978). Price Controls, Binding Constraints, and Intertemporal Economic Decision Making. *Journal of Political Economy*, **86**(2), 293–301.

Lintunen, J. & Kuusela, O.-P. (2018). Business Cycles and Emission Trading with Banking. *European Economic Review*, **101**, 397–417.

Lucas, R. E. & Prescott, E. C. (1971). Investment Under Uncertainty. *Econometrica*, **39**(5), 659–81.

Marcantonini, C. & Ellerman, A. D. (2015). The Implicit Carbon Price of Renewable Energy Incentives in Germany. *Energy Journal*, **36**(4), 205–39.

Marcantonini, C. & Valero, V. (2017). Renewable Energy and CO_2 Abatement in Italy. *Energy Policy*, **106**, 600–13.

Miranda, M. J. & Helmberger, P. G. (1988). The Effects of Commodity Price Stabilization Programs. *American Economic Review*, **78**(1), 46–58.

Muth, J. F. (1961). Rational Expectations and the Theory of Price Movements. *Econometrica*, **29**(3), 315–35.

Naegele, H. & Zaklan, A. (2017). *Does the EU ETS Cause Carbon Leakage in European Manufacturing?* Discussion Paper 1689, DIW Berlin.

Newbery, D. M., Reiner, D. M. & Ritz, R. A. (2018). *When is a Carbon Price Floor Desirable?* Cambridge Working Paper in Economics 1833, Energy Policy Research Group.

Newell, R. G. & Pizer, W. A. (2003). Regulating Stock Externalities under Uncertainty. *Journal of Environmental Economics & Management*, **45**(2), 416–32.

Newell, R. G., Pizer, W. A. & Zhang, J. (2005). Managing Permit Markets to Stabilize

Prices. *Environmental & Resource Economics*, **31**(2), 133–57.

Pahle, M., Burtraw, D., Flachsland, C., Tietjen, O. & Edenhofer, O. (2018). Perserving the Environmental Integrity of the EU ETS through a CO_2 Minimum Price, mimeo.

Perino, G. (2018). New EU ETS Phase IV Rules Temporarily Puncture Waterbed. *Nature Climate Change*, **8**, 262–4.

Perino, G. & Willner, M. (2016). Procrastinating Reform: The Impact of the Market Stability Reserve on the EU ETS. *Journal of Environmental Economics & Management*, **80**, 37–52.

Perino, G. & Willner, M. (2017). EU ETS Phase IV: Allowance Prices, Design Choices and the Market Stability Reserve. *Climate Policy*, **17**(7), 936–46.

de Perthuis, C. & Trotignon, R. (2014). Governance of CO_2 Markets: Lessons from the EUETS. *Energy Policy*, **75**, 100–6.

Pindyck, R. S. (1993). The Present Value Model of Rational Commodity Pricing. *Economic Journal*, **103**(418), 511–30.

Pizer, W. A. & Prest, B. (2016). *Prices versus Quantities with Policy Updating*. Working Paper 22379, National Bureau of Economic Reasearch.

Richstein, J. C., Chappin, E. J. & de Vries, L. J. (2015). The Market (In-)Stability Reserve for EU Carbon Emission Trading: Why It Might Fail and How to Improve It. *Utilities Policy*, **35**, 1–18.

Roberts, M. J. & Spence, A. M. (1976). Effluent Charges and Licenses under Uncertainty. *Journal of Public Economics*, **5**(3), 193–208.

Rubin, J. D. (1996). A Model of Intertemporal Emission Trading, Banking and Borrowing. *Journal of Environmental Economics & Management*, **31**(3), 269–86.

Salant, S. W. (1983). The Vulnerability of Price Stabilization Schemes to Speculative Attack. *Journal of Political Economy*, **91**(1), 1–38.

Salant, S. W. (2016). What Ails the European Union's Emissions Trading System? *Journal of Environmental Economics & Management*, **80**, 6–19.

Samuelson, P. A. (1971). Stochastic Speculative Price. *Proceedings of the National Academy of Sciences*, **68**(2), 335–7.

Schennach, S. M. (2000). The Economics of Pollution Permit Banking in the Context of Title IV of the 1990 Clean Air Act Amendments. *Journal of Environmental Economics & Management*, **40**(3), 189–210.

Schopp, A., Acworth, W., Hauptmann, D. & Neuhoff, K. (2015). *Modelling a Market Stability Reserve in Carbon Markets*. Discussion Paper 1483, DIW Berlin.

Seifert, J., Uhrig-Homburg, M. & Wagner, M. (2008). Dynamic Behavior of CO_2 Spot Prices. *Journal of Environmental Economics & Management*, **56**(2), 180–94.

Slechten, A. (2013). Intertemporal Links in Cap-and-Trade Schemes. *Journal of Environmental Economics & Management*, **66**(2), 319–36.

Stranlund, J. K., Costello, C. & Chávez, C. A. (2005). Enforcing Emissions Trading when Emissions Permits are Bankable. *Journal of Regulatory Economics*, **28**(2), 181–204.

Tietjen, O., Lessmann, K. & Pahle, M. (2018). *Carbon Pricing in Electricity Markets under*

Uncertainty: The Impact of Risk Aversion and Futures Market. Working Paper, Postdam Institute for Climate (PIK), presented at WCERE 2018.

Trück, S. & Weron, R. (2016). Convenience Yields and Risk Premiums in the EU-ETS – Evidence from the Kyoto Commitment Period. *Journal of Futures Markets*, **36**(6), 587–611.

Tvinnereim, E. (2014). The Bears Are Right: Why Cap-and-Trade Yields Greater Emission Reductions than Expected, and what that Means for Climate Policy. *Climatic Change*, **127**(3), 447–61.

Weitzman, M. L. (1978). Optimal Rewards for Economic Regulation. *American Economic Review*, **68**(4), 683–91.

Weitzman, M. L. (2018). *Prices or Quantities Dominate Banking and Borrowing*. Working Paper 24218, National Bureau of Economic Research.

Wright, B. D. & Williams, J. C. (1982). The Economic Role of Commodity Storage. *Economic Journal*, **92**(367), 596–614.

Wright, B. D. & Williams, J. C. (1988). The Incidence of Market-Stabilising Price Support Schemes. *Economic Journal*, **98**(393), 1183–98.