

Procrastinating Reform: The Impact of the Market Stability Reserve on the EU ETS*

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Abstract

We study the impact of the market stability reserve (MSR) on price and emission paths of the EU ETS. From 2019 onwards, the MSR will adjust the number of allowances auctioned as a function of the size of the surplus, i.e. in times of a large surplus it shifts the issue date of allowances into the future. In a perfectly competitive allowance market the MSR only affects price and emission paths if the baseline equilibrium becomes unfeasible. If the MSR is binding, prices increase in the short run but drop in the medium run relative to the baseline. The MSR increases price variability if uncertainty over future allowance demand is resolved while there is a surplus. The long run cap is unaffected by both the MSR and overlapping climate policies. This contrasts the EU's objectives of improving the resilience of the EU ETS and increasing synergies with overlapping climate policies.

Keywords: Market stability reserve; cap-and-trade; EU ETS reform; price variability, overlapping policies

JEL codes: Q58; Q54

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1 Introduction

The EU Emissions Trading System (EU ETS) represents the backbone of the European Union's climate policy efforts and is the world's biggest operational cap-and-trade scheme. It covers about 45% of total greenhouse gas emissions of the 31 participating countries, pricing carbon since 2005. However, the EU ETS looks back on a mixed performance caused by institutional shortcomings and severe demand shocks (Ellerman et al., 2015). Currently, institutional as well as economic actors share the perception that the price of emission allowances is too low (Clò et al., 2013; Nordhaus, 2011).¹ This normative judgment is based on two main considerations, namely that estimates of the social cost of carbon tend to be substantially higher (Tol, 2009; Grosjean et al., 2016; Knopf et al., 2014; van den Bijgaart et al., 2016) and that prices would need to be much higher to steer investment towards low carbon technologies, e.g. in the energy sector (European Parliament, 2014, p. 5). The reason for low prices has been spotted in what is called the 'surplus' in the market: a glut relative to demand of roughly 1.8 billion allowances in 2015, which exists in the form of banked quantities on firm's accounts (Burtraw et al., 2014; Knopf et al., 2014; Sandbag, 2015). While we will not discuss the validity of these claims and causal relationships, they pushed the European Commission to propose a reform of the EU ETS, including a market stability reserve (MSR), scheduled to start operating by 2019 (European Parliament and Council, 2015).

The MSR will adjust the number of allowances auctioned in a particular year based on the size of the aggregate bank ('surplus') at the beginning of the previous year. If firms in total hold more than 833 million unused allowances in their accounts, the number of auctioned allowances is reduced over the course of a year by an amount equal to 12% of the size of the aggregate bank. These allowances are placed in the MSR and are thus temporarily set aside the market. They are re-injected in batches of 100 million per year as soon as the aggregate bank drops below 400 million. This mechanism continues until the reserve is depleted. Given its current design, the MSR is allowance-preserving in the long run and does not affect the overall EU climate target. The EU expects the MSR to spur investments in low-carbon technologies, increase synergies with climate policies overlapping the EU ETS and improve the its resilience towards demand shocks (European Parliament and Council, 2015). To investigate and analyze whether the MSR can live up to the EU's expectations, we model risk-neutral, symmetric firms in a frictionless market for emission allowances in continuous time. We apply dynamic optimization techniques to obtain the market equilibria for a reference scenario without the MSR as well as a scenario with the MSR. Comparing the outcomes

¹Prices on the spot market moved in a range of 5.50-8.50 EUR in 2015.

delivers novel and nuanced insights concerning the impact of the MSR on the functioning of allowance markets.

In the context of the EU ETS, firms may bank allowances, but are not allowed to borrow from future allocations. This imposes a constraint on inter-temporal optimization once the surplus is depleted. All the reserve does is shifting the auction dates of allowances to the future, temporarily reducing liquidity. Only if this reduction in liquidity imposes a binding constraint such that optimal emission paths of the reference scenario can no longer be realized, the reform will have an effect on the market equilibrium. Looking at such a sufficiently stringent MSR, price and emission effects turn out to be ambivalent. Although prices are higher than in the baseline in the short run, they are lower in the medium run. The reason lies in the allowance preserving nature of the reserve. In the long run, all allowances placed in the reserve are again released into the market, reducing scarcity of allowances in the medium run. The overall cap remains unchanged. Thus, the EU's objective to spur low-carbon investments by higher prices might not be achieved by the MSR.

We then elaborate on the MSR's effects under uncertainty concerning the demand for allowances. Demand shocks can be caused e.g. by the introduction of overlapping policies or business cycle effects. If the MSR is sufficiently stringent to affect prices and the shock occurs before the surplus in the market has been depleted, the MSR tends to amplify rather than reduces price variability. This finding runs counter to the stated objectives of increased resilience and improved synergies with other emission policies. The MSR does also not change the fact that climate policies overlapping the EU ETS have no direct impact on aggregate long-run emissions in the EU ETS.

Since the MSR as a quantity-based adjustment mechanism is a novelty, the literature studying this instrument is only just emerging. Based on the dynamic optimization framework of cap-and-trade systems with banking introduced by Rubin (1996), extended to include uncertainty by Schennach (2000) and recently applied to the EU ETS by Ellerman et al. (2015), the authors Fell (2016), Kollenberg & Taschini (2016) and Schopp et al. (2015) assess the impact of a MSR, but differ in several aspects from our paper. Kollenberg & Taschini (2016) and Fell (2016) consider perfectly competitive markets but allow the reserve to create and destroy allowances without limits, contrary to the actual policy design. Schopp et al. (2015) assume that banking by regulated firms is restricted by internal processes and that once their bank exceeds a given threshold, speculators with a higher discount rate enter the market, leading to higher volatility, lower prices and thus inefficiencies. Salant (2016) challenges this justification of a reserve and suggests that the observed price movements can be explained equally well by regulatory risk, doubting that the MSR is a suitable fix as a temporal shift of allocations is not capable of reducing inefficiencies when facing such institutional uncertainties.

The surplus would then in fact not be the root cause of current low prices.

The remainder of the paper is organized as follows: Section 2 presents the setup and the dynamic optimization equilibrium of a competitive allowance market in the deterministic baseline case based on Rubin (1996). The MSR is introduced in Section 3, where effects on price and emission paths are derived. Section 4 considers the impact of the MSR under uncertainty about the demand for allowances. The last section concludes. Proofs are relegated to the appendix.

2 The baseline case

We start by specifying and solving a baseline case (*B*) of an intertemporal allowance market with banking and without borrowing, which is well established in the literature (see e.g. Cronshaw & Kruse, 1996; Rubin, 1996; Schennach, 2000; Ellerman et al., 2015). The market stability reserve will be added in the next section.

There is a continuum of polluting firms with mass one in a perfectly competitive market for emission allowances, where each firm is characterized by an abatement cost function, $C_i(\alpha)$, with abatement $\alpha = u_i - e_i(t)$ being denoted by the difference in baseline emissions $u > 0$ and actual emissions of firm i at time t , $e_i(t) \in [0, u_i]$. The abatement cost function is assumed to be twice continuously differentiable and convex in abatement for all non-negative levels of abatement and emissions. It is assumed that $\partial C_i / \partial \alpha = C'_i(\alpha) > 0$ and $\partial^2 C_i / \partial \alpha^2 = C''_i(\alpha) > 0$ for all $\alpha \in [0, u_i]$ and $C''_i(u_i) = \bar{c} > 0$.

The time path of auctioned allowances $S_B(t)$ is set to decline at a constant rate $a > 0$, i.e. $S_B(t) = S_0 e^{-at}$, where $S_0 > 0$ is the number of allowances issued at $t = 0$.² Net sales of an individual firm, $x_i(t)$, can be both positive and negative, but in aggregate, sales of firms equal the number of allowances auctioned at time t ($\int_{i=0}^1 x_i(t) di = S_B(t) \geq 0$)³. In the baseline case, the time path of auctioned allowances is identical to the time path of allowances issued by the regulator for all t . Moreover, we assume the initial bank in the baseline case to be non-negative ($\int_{i=0}^1 b_i^0 di = b_B^0 \geq 0$) and finite, allowing the market to start with a surplus. Firms take the equilibrium price path of emission allowances $p(t)$ as given. Initial banks and time paths of individual banks $b_{B,i}(t)$ are allowed to differ between firms. We use the following equalities and notational conventions for aggregate values:

²The EU ETS exhibits a "linear reduction factor" which reduces the annual cap on emissions by a constant amount to be in line with the reduction target for 2030. Given that we use an infinite time horizon, a linear representation is not appropriate.

³We abstract from free allocation of issued allowances by the regulator and instead assume allocation via auctions only. Including free allocation would only shift profits of firms up but would not alter the equilibrium emission or price paths.

$u = \int_0^1 u_i di$, $b^0 = \int_0^1 b_i^0 di$, $b(t) = \int_0^1 b_i(t) di$, $x(t) = \int_0^1 x_i(t) di$ and $e(t) = \int_0^1 e_i(t) di$.

Definition 1 (Long-run scarcity) *A cap-and-trade scheme imposes scarcity in the long run if and only if there is a t_{scarce} for which it holds that*

$$\int_{s=0}^t S(s) ds + b^0 < \int_{s=0}^t u ds \quad \forall t \geq t_{scarce}.$$

The allowance market specified above satisfies this definition of long-run scarcity. In contrast to aggregate baseline emissions ($u \cdot t$), the aggregate number of allowances available is finite in the long run ($\lim_{t \rightarrow \infty} \int_0^t S_0 e^{-as} ds + b_B^0 = S_0/a + b_B^0$).

Each firm solves the following optimization problem:

$$\min_{e_i(t), x_i(t)} \int_{t=0}^{\infty} [e^{-rt} C(u - e_i(t)) + p(t)x_i(t)] dt \quad (1)$$

$$s.t. : \dot{b}_i(t) = x_i(t) - e_i(t) \quad (2)$$

$$b_i(t) \geq 0 \quad \forall t. \quad (3)$$

The time horizon is assumed to be infinite since the end of the EU ETS - or rather the period of continuous banking of allowances - is not yet determined. Allowances of both Phase II (2008-2012) and Phase III (2013-2020) can be transferred to Phase IV (2021-2030) and transferability to subsequent phases has been codified (European Parliament and Council, 2003, Article 13). For the time beyond phase IV, explicit EU emission targets for 2040 and 2050 have already been formulated and climate policy is expected to be in place for the rest of the century. Any uncertainty about the continuation of the EU ETS, or rather the ability to bank emissions, is thus assumed to be captured by the discount rate r .⁴

The present-value Hamiltonian for firm i 's optimization problem then reads

$$H = e^{-rt} [C(u - e_i(t)) + p(t)x_i(t)] + \lambda_i(t) [x_i(t) - e_i(t)], \quad (4)$$

where $\lambda_i(t)$ is the co-state on the state equation (2). The resulting modified Lagrangian is given by

$$\mathcal{L} = e^{-rt} [C(u - e_i(t)) + p(t)x_i(t)] + \lambda_i(t) [x_i(t) - e_i(t)] - \mu_i(t)b_i(t), \quad (5)$$

where $\mu_i(t)$ is the multiplier function of the non-borrowing constraint (3).

⁴Given the long-run impact of the MSR, imposing a finite terminal time T might have a substantial impact on the intertemporal allocation of emissions and in particular on the effect of the MSR. While these aspects are very interesting, we leave the consideration of regulatory uncertainty with respect to the design of the EU ETS to future research and focus on identifying the impact of the MSR assuming the rules specified in the current legislation are permanent.

The corresponding necessary and sufficient conditions for an optimal solution yield ⁵.

$$\dot{b}_{B,i}(t) = x_i(t) - e_{B,i}(t), \quad (6)$$

$$\dot{\lambda}_{B,i}(t) = \mu_{B,i}(t), \quad (7)$$

$$\mu_{B,i}(t)b_{B,i}(t) = 0, \quad \mu_{B,i}(t) \geq 0, \quad b_{B,i}(t) \geq 0, \quad (8)$$

$$-e^{-rt}C'(u - e_{B,i}(t)) = \lambda_{B,i}(t), \quad (9)$$

$$-e^{-rt}p_B(t) = \lambda_{B,i}(t). \quad (10)$$

Note that the initial endowment of firm i , $b_{B,i}^0$, does not explicitly feature in conditions (6) to (10). It shifts profits up or down because it affects the net number of allowances bought by firm i , but not the equilibrium emission profile. Since initial endowments are the only dimension in which firms differ in our model and optimal emission paths do not depend on them, the emission paths of all firms will be the same in equilibrium. They can hence be represented by the path of aggregate emissions $e_B(t) = \int_{j=0}^1 e_{B,j}(t) dj$, where the subscript B indicates equilibrium values in the baseline scenario.

The price path is characterized by conditions (7), (8) and (10), which yield

$$\frac{\dot{p}_B(t)}{p_B(t)} = \begin{cases} r & \text{if } b_B(t) > 0 \\ r - \frac{e^{rt}\mu(t)_B}{p_B(t)} & \text{if } b_B(t) = 0. \end{cases} \quad (11)$$

While the price of allowances rises at the rate of interest r , firms are indifferent as to when they acquire or sell emission allowances as long as they can realize the optimal emission path (condition 8). Because banking of allowances is allowed, the equilibrium price will never increase at a rate greater than r . Firms would otherwise want to purchase more allowances today to sell them in the future, i.e. bank additional allowances. However, if in equilibrium the allowance price rises at a rate less than r , firms would like to borrow allowances. In most real world emission trading schemes, there are restrictions on borrowing.⁶ Hence, intertemporal

⁵For a description of sufficient conditions for this problem, see (Seierstad & Sydsaeter, 1987, p. 234)

⁶While explicit borrowing is not permitted in the EU ETS, some implicit borrowing is possible because allowances for year t were issued (in part) before the compliance date of the year $t - 1$ (Chevallier, 2012; Bertrand, 2014; Kollenberg & Taschini, 2016). In Phase II firms could effectively borrow up to one year's allocation, because allowances were issued for free at the beginning of each year. However, with an increasing share of allowances auctioned spread over the entire year, implicit borrowing has been considerably restricted in Phase III. Moreover, this mechanism is not possible between phases, i.e. allowances of Phase III could not be used for compliance in Phase II. In what follows, we assume that borrowing is not possible in the EU ETS, but discuss implications of relaxing this assumption.

arbitrage cannot prevent the allowance price from rising at a rate below the rate of interest which happens if the constraint on borrowing is binding (here: $b(t) = 0$).

Using conditions (6) to (10) and defining time τ_B as the instant when the aggregate bank equals zero for the first time ($\tau_B = \inf\{t : b_B(t) = 0\}$) the following set of equilibrium conditions arise:

$$p_B^0 e^{rt} = C'(u - e_B(t)) \quad \forall t < \tau_B, \quad (12)$$

$$\int_{t=0}^{\tau_B} e_B(t) dt = b_B^0 + \frac{S_0}{a}(1 - e^{-a\tau_B}), \quad (13)$$

$$\int_{s=0}^t e_B(s) ds \leq b_B^0 + \frac{S_0}{a}(1 - e^{-at}) \quad \forall t < \tau_B, \quad (14)$$

$$e_B(t) = S_0 e^{-at} \quad \forall t \geq \tau_B. \quad (15)$$

Condition (12) determines the optimal price and emission paths up to a constant shift parameter. The latter can be specified by using condition (13) which follows from the bank being empty at τ_B . Condition (14) ensures that there are always enough allowances available to realize the equilibrium emission path up to τ_B and condition (15) determines emissions at and after τ_B . Once the bank has been depleted, firms will never again have an incentive to bank, i.e. in the deterministic baseline case the banking phase is unique.⁷

3 The Market Stability Reserve

We now expand the model to investigate how the introduction of the EU ETS MSR affects equilibrium price and emission paths compared to the baseline case. Generally speaking, the MSR is a set of rules that, conditional on the state of the aggregate bank of allowances, $b(t)$, changes the allocation schedule relative to the baseline case. In contrast to (hard and soft) price collars that have been discussed in the literature at some length (Murray et al., 2009; Gröll & Taschini, 2011; Fell et al., 2012), there is no direct link to the price of allowances since the MSR is a purely quantitative instrument. The auctioning profile $S_{MSR}(b(t), t)$ is thus no longer exogenously given but a function of the aggregate bank $b(t)$, i.e. the time path of auctioned allowances is no longer identical to the time path of issued allowances with the MSR.

In the present model, the rules which have been adopted for the MSR in the

⁷See Schennach (2000) and Ellerman et al. (2015), also for proof that $\tau_B < \inf$

EU ETS (European Parliament and Council, 2015), are represented as follows⁸:

$$\dot{R}(t) = \begin{cases} \gamma b(t) & \text{if } b(t) > \bar{b} \\ -I & \text{if } b(t) < \underline{b} \wedge R(t) > 0 \\ 0 & \text{if } \textit{otherwise}, \end{cases} \quad (16)$$

where γ is the share of the aggregate bank determining the number of allowances stored in the MSR if the bank exceeds the threshold \bar{b} . A total of I allowances is taken out of the reserve and injected to the market, whenever the aggregate bank drops below \underline{b} . The MSR will be seeded with an initial stock of allowances $R^0 > 0$ as currently backloaded allowances together with other reserved amounts will be put directly into the reserve (European Parliament and Council, 2015). This does not change the total number of existing allowances, i.e. $b_B^0 = b_{\text{MSR}}^0 + R_0$.

Definition 2 (allowance preservation) *The MSR is allowance preserving if and only if the sum of allowances in the reserve, $R(t)$, total allocated allowances and initial bank with the MSR always equals the sum of total allocated allowances and initial bank in the baseline case.*

$$\int_{s=0}^t S_{\text{MSR}}(s) ds + b_{\text{MSR}}^0 + R(t) = \int_{s=0}^t S_B(s) ds + b_B^0 \quad \forall t \geq 0$$

The above rules of the EU ETS reform (European Commission, 2014; European Parliament and Council, 2015) and the guarantee that allowances in the reserve are transferred to future Phases imply that the reserve, $R(t) \geq 0$, is allowance preserving, i.e. no allowances are created or destroyed by the activity of the reserve mechanism.⁹ Note that Fell (2016) and Kollenberg & Taschini (2016) differ in their representation of the MSR. They do not require the MSR to be allowance preserving, which is the main driver for the differences in results. However, allowance preservation does not necessarily imply that aggregate emissions are not affected in the long run.

Definition 3 (emission preservation) *The MSR is emission preserving if and only if the cap-and-trade scheme exhibits long-run scarcity (see Definition 1) and the sum of the total number of allocated allowances and the initial bank with the MSR*

⁸Note that the time lag in the response of the MSR has been ignored for convenience.

⁹Article 13(2) of Directive 2003/87/EC as amended by Article 2(2) of European Parliament and Council (2015).

equal the total number of allocated allowances and the initial bank in the baseline case in the long run.

$$\int_{t=0}^{\infty} S_{\text{MSR}}(b(t), t) dt + b_{\text{MSR}}^0 = \int_{t=0}^{\infty} S_{\text{B}}(t) dt + b_{\text{B}}^0$$

This is equivalent to long-run depletion of the reserve ($\lim_{t \rightarrow \infty} R(t) = 0$).

It is conceivable that allowances placed in the reserve, while not being destroyed, never leave it again, because the aggregate bank would not drop below \underline{b} for a sufficiently long time to empty it. This happens e.g. in Holt & Shobe (2016) and Richstein et al. (2015), i.e. although the MSR in their models is allowance preserving, it turns out not to be emission preserving. Both use finite time horizons that are too short for the reserve to be depleted. We do not assume that the MSR is emission preserving, but show that it naturally emerges as a feature of the equilibrium (Lemma 1).

The legislation enacting the MSR states that sending an investment signal for low-carbon investments is a key motivation for the implementation of the MSR (European Parliament and Council, 2015). In an earlier publication the European Parliament explicitly links investment signals to allowance prices - as does most of the environmental economics literature.¹⁰ We therefore interpret the investment objective to imply a desire to raise allowance prices and use the change in the price path as the criterion to assess the impact of the MSR.

The optimization problem of firm i under the MSR is identical to (1)-(3), because firms operate in a perfectly competitive market and do not take into account how their individual behavior affects aggregate outcomes, i.e. $e(t)$ and $S_{\text{MSR}}(b(t), t)$. The MSR only affects the set of feasible aggregate emission paths. The corresponding equilibrium conditions are:

$$p_{\text{MSR}}^0 e^{rt} = C'(u - e_{\text{MSR}}(t)) \quad \forall t < \tau_{\text{MSR}} \quad (17)$$

$$\int_{t=0}^{\tau_{\text{MSR}}} e_{\text{MSR}}(t) dt = b_{\text{MSR}}^0 + \frac{S_0}{a} (1 - e^{-a\tau_{\text{MSR}}}) + R^0 - R(\tau_{\text{MSR}}) \quad (18)$$

$$\int_{s=0}^t e_{\text{MSR}}(s) ds \leq b_{\text{MSR}}^0 + \frac{S_0}{a} (1 - e^{-at}) + R^0 - R(t) \quad \forall t < \tau_{\text{MSR}} \quad (19)$$

$$e_{\text{MSR}}(\tau_{\text{MSR}}) = S_0 e^{-a\tau_{\text{MSR}}} - \dot{R}(\tau_{\text{MSR}}), \quad (20)$$

where the subscript MSR indicates the equilibrium value or path of variables determined by the model and τ_{MSR} is defined analogously to τ_{B} , i.e. it is the

¹⁰"A low carbon price makes 'clean' investments unattractive." (European Parliament, 2014). However, note that incentives to adopt cleaner technologies might not be monotonic in the price of emissions (Perino & Requate, 2012).

point in time when the aggregate bank is depleted for the first time ($\tau_{\text{MSR}} = \inf\{t : b_{\text{MSR}}(t) = 0\}$). Note that in contrast to condition 15, condition (20) does not hold for all $t > \tau_{\text{MSR}}$. The banking phase is no longer unique if the MSR affects price and emission paths as we show below.

Proposition 1 *If the equilibrium emission path of the baseline case, $e_{\text{B}}^*(t)$, is feasible under the market stability reserve, both the equilibrium price and emission paths are unaffected by the MSR.*

$$e_{\text{MSR}}(t) = e_{\text{B}}(t) \quad \forall t, \quad (21)$$

$$p_{\text{MSR}}(t) = p_{\text{B}}(t) \quad \forall t. \quad (22)$$

- *In case of a binding non-borrowing constraint, this is the case if and only if,*

$$\int_{s=0}^t e_{\text{B}}(s) ds \leq b_{\text{MSR}}^0 + \int_{s=0}^t S_{\text{MSR}}(e_{\text{B}}(s), s) ds \quad \forall t \leq \tau_{\text{B}}. \quad (23)$$

- *In case of unrestricted borrowing, the MSR has no effect on equilibrium emission and price paths regardless of how it shifts the auctioning of allowances over time.*

Proposition 1 states that the introduction of the MSR only affects equilibrium price and emission paths if the baseline equilibrium is no longer feasible, i.e. if the MSR temporarily induces additional real scarcity. Feasibility of the equilibrium emission path means that at every point in time there are enough allowances available to firms to cover the path's emissions.¹¹ Scarcity is induced not by reducing the total number of allowances in the long run but by temporarily reducing liquidity in the market by storing allowances in the reserve.

Feasibility of the equilibrium emission path of the baseline case requires that the MSR is emission preserving. The equilibrium conditions (17) - (20) indeed ensure that this is always the case.

Lemma 1 *In a competitive, intertemporal allowance market without borrowing exhibiting long-run scarcity, the allowance preserving MSR is also emission preserving.*

The intuition is as follows: The only reason to bank allowances in a deterministic setting with a smooth baseline allocation path, $S_{\text{B}}(t)$, is intertemporal arbitrage in periods when the allowance price rises at the rate of interest. However, the finite total number of allowances available and hence the need for emissions to

¹¹ See Salant (2016) for a detailed discussion.

converge to zero in the long run induces firms to stop banking in finite time. The latter is a well established result in the literature (Rubin, 1996; Schennach, 2000; Ellerman et al., 2015). The urge to draw the bank down to zero implies that the lower threshold triggering injection of allowances from the MSR will be undercut sufficiently long to deplete the MSR. Hence, all allowances placed in the MSR at some point will be released eventually.

Nevertheless, if borrowing is restricted, firms might not be able to compensate for the temporary reduction in available allowances without adjusting their emission profile. Given the rules for the MSR, the following proposition holds:

Proposition 2 *If the equilibrium emission path of the baseline case, $e_B^*(t)$, is not feasible under the market stability reserve, then:*

- *in the short run (for all $t \leq \tau_{\text{MSR}}$, with $\tau_{\text{MSR}} < \tau_B$) the equilibrium emission path with the MSR is lower and the equilibrium price path higher than in the baseline case*
- *in the medium run (for an interval that starts at some point in time $t_{\text{cross}} \in [\tau_{\text{MSR}}, \tau_B]$ and ends at \bar{t}_3) the equilibrium emission path with the MSR is higher and the equilibrium price path lower than in the baseline case*
- *in the long run (for all $t > \bar{t}_3$) emission and price paths with and without a MSR are identical*
- *there are exactly two separate and bounded banking phases $[0, \tau_{\text{MSR}})$ and $(\underline{t}_3, \bar{t}_3)$ with $\tau_{\text{MSR}} < \underline{t}_3 < t_3 < \bar{t}_3$.*

Salant (2016) presents qualitatively similar results for multiple given allocation schedules. Proposition 2 confirms that his results carry over to the case of the MSR that adjusts the auctioning profile as a function of the size of the bank. The intuition is the same in both cases. If the MSR induces additional real scarcity in early periods of the scheme, emissions have to be cut relative to the equilibrium in the baseline case and allowance prices go up correspondingly. However, since the MSR is both allowance and emission preserving, any period of additional temporary scarcity implies that there is a period later on when scarcity is reduced relative to the baseline scenario. Thus for a while, emissions are higher and prices lower than they would have been without the MSR.

Figure 1 illustrates Proposition 2 by presenting the equilibrium paths of emissions, prices, the aggregate bank and the reserve for the scenarios with and without a MSR. Parameter values are chosen to broadly represent the state of the EU ETS

in 2019.¹² Taking a look at panel (a) of Figure 1, it is evident that the MSR shifts the allocation path (solid black line) relative to the baseline case without MSR (solid gray line). The MSR creates discrete jumps in the allocation path when its activity changes from reducing auctioned volumes to inactivity at t_1 as the aggregate bank undercuts the upper threshold (\bar{b}), from inactivity to injections at t_2 as the lower threshold \underline{b} is undercut and back from injections to inactivity as soon as the reserve is completely empty (t_3). Once the MSR is empty ($t \geq t_3$), allocation paths are identical in the two scenarios.

The MSR-induced reduction of auctioned volumes in the short run leads to a faster depletion of the aggregate bank (solid black line in panel (c)) relative to the baseline scenario (solid gray line) as well as the build-up of the reserve stock (dashed black line). This reduction of the aggregate bank implies that firms cannot realize the equilibrium baseline emission path. Firms respond by increasing their abatement efforts in order to counter at least some of the additional temporary scarcity induced by the MSR (see also Holt & Shobe, 2016). The dotted black line in panel (c) shows that the sum of private ($b(t)$) and regulatory ($R(t)$) banking increases compared to the baseline. Hence, while the introduction of the MSR reduces the number of allowances held in private banks, it increases the total number of allowances that are stored for future use.

As laid out in Proposition 2, relatively higher abatement during the first banking phase for all $t \in [0; \tau_{\text{MSR}}]$ leads to a higher path for the price of allowances (solid black line in panel (b)) in the short run. However, due to the non-borrowing constraint binding earlier with the MSR than without ($\tau_{\text{MSR}} < \tau_{\text{B}}$), the initially higher price path under the MSR starts to rise at a lower rate earlier than in the baseline case. While the baseline price path keeps rising at r until τ_{B} , the flatter slope of the price path with the MSR leads to an intersection with the baseline path (solid gray line) at t_{cross} and stays below until the end of the second banking phase at \bar{t}_3 . With the MSR still injecting after τ_{MSR} , this reversal in price levels leads to higher emissions in the medium run (see panel (a)).

Given the allowance preserving nature of the MSR, firms anticipate the sudden downward shift of the allocation path at $t = t_3$. As a consequence of banking still being allowed, they smooth this shift by accumulating a small bank (bank remains below the lower trigger level) for all $t \in (t_3; \bar{t}_3)$ (solid black line in panel (d)). Due to this smoothing, emission levels under the MSR approach those of the baseline scenario (panel (a)) with allowance prices under the MSR rising again at r (panel (b)), until the aggregate bank is depleted for good and price and emission levels with and without the MSR are the same. After $t = \bar{t}_3$, both the baseline and MSR

¹²The following abatement cost function is used: $C(u - e(t)) = (c/2)(u - e(t))^2$ if $e(t) \leq u$ and equals zero otherwise. Parameter values used: $a = 0.022$, $c = 0.05044$ (see Landis, 2015, Table 4), $S_0 = 1.9$ billion, $u = 1.9$ billion, $b^0 = 3$ billion, $R^0 = 1.5$ billion, $r = 0.1$, $\bar{b} = 833$ million, $\underline{b} = 400$ million, $\gamma = 0.12$, $I = 100$ million.

case are again identical, as the effects of the reserve vanish and the system returns to its baseline dynamics under an aggregate bank of zero.

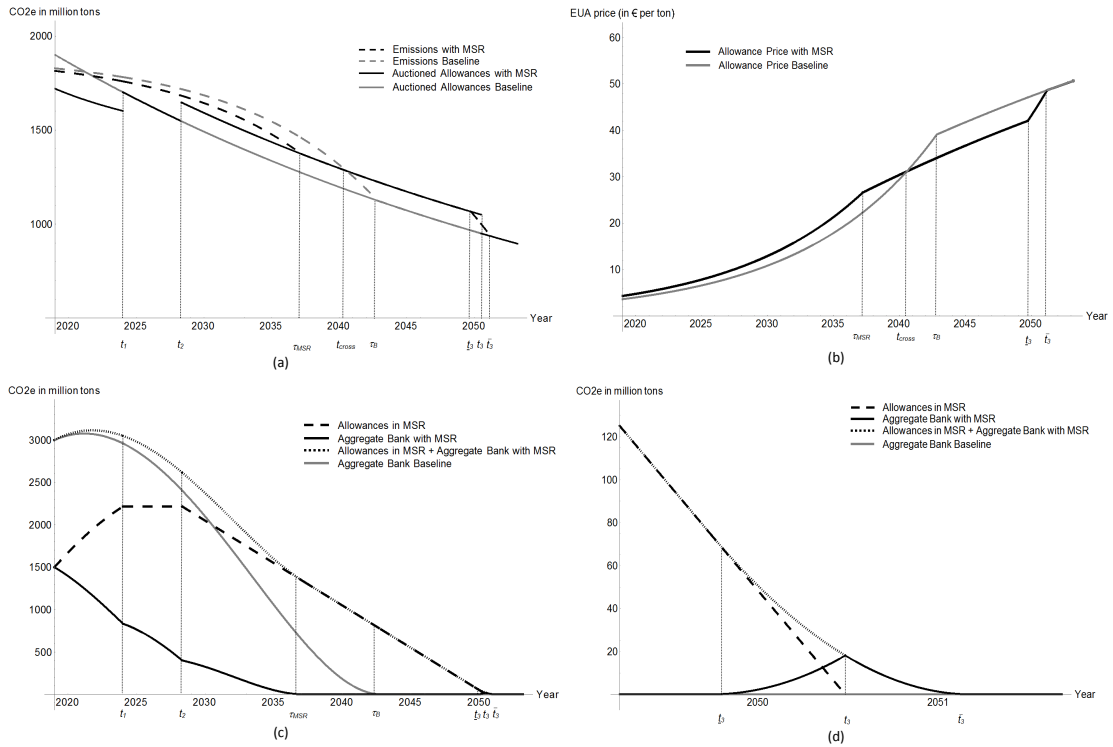


Figure 1: Comparison between baseline and MSR in deterministic setting. Panel (a) presents emission and allowance auction paths, panel (b) price paths, panel (c) aggregate banks and MSR and panel (d) zooms in on the evolution of the aggregate bank around t_3 .

The short-term price increase is a major motivation for introducing the MSR to the EU ETS. Propositions 1 and 2 reveal that in a deterministic setting and in the absence of additional market failures, this effect is possible but by no means guaranteed. Proposition 2 shows that even if the MSR increases prices in the short run, this has to be traded off against a drop in prices in the medium run. Hence, for investments with long lead and life times such as power plants, incentives to invest might be reduced by the MSR.

Real-world emissions trading schemes of course do not operate under such stylized conditions. We therefore now consider the effects of uncertainty over the demand for allowances.

4 The Effect of Uncertainty

Apart from stimulating investment in low-carbon technologies the MSR has also been implemented to achieve the following objectives: (a) to "make the EU ETS more resilient to supply-demand imbalances" and to (b) "enhance synergy with other climate and energy policies" (European Parliament and Council, 2015). Examples for the latter are substantial changes in the support for renewable energy (Fischer & Preonas, 2010), the phase out of nuclear energy of a large member state (Bruninx et al., 2013), EU-wide energy efficiency measures such as the light bulb ban (Perino & Pioch, 2016) or campaigns to induce climate friendly consumption patterns by households (Perino, 2015). Before we proceed by introducing demand shocks into the model, it is necessary to translate these objectives into specific criteria against which the MSR can be assessed. In what follows, we take the absolute size of the price response at the point in time when uncertainty is resolved as a measure of the resilience of the EU ETS to supply-demand imbalances, where smaller price changes induced by a given demand shock are considered to represent an increase in resilience.

A key critique of policies overlapping a cap-and-trade scheme is that they have no direct impact on emissions by industries participating in the system.¹³ We therefore take a direct net reduction in total emissions within the EU ETS induced by supplementary measures once the MSR is operational as the primary criterion to assess the existence of synergies. The question is, whether the MSR is still emission preserving in the presence of overlapping policies. Such policies reduce the demand for allowances, which in turn induces a price drop and hence a weaker investment signal. The absolute size of the price response when an overlapping climate policy is announced or implemented is therefore - analogous to the operationalisation of the "resilience" objective - used as a secondary criterion.

While in the final legislation the EC does not explicitly state that price and emissions paths are its criteria to assess the above objectives, we believe one would be hard pressed to find more relevant ones.¹⁴

Here, we focus on uncertainty affecting the demand for allowances caused e.g.

¹³See e.g. Fischer & Preonas (2010); Fowlie (2010); Goulder (2013) and Böhringer (2014). For intra-jurisdictional leakage effects of overlapping policies see Jarke & Perino (2015).

¹⁴This is in line with statements in a European Parliament briefing: "While the MSR mechanism will reduce the number of allowances in circulation for the period after 2020, it will not reduce the total number of allowances that will be issued in the long term. According to the Commission's impact assessment, placing allowances into the reserve should result in a medium-term increase in the carbon price, while longer-term prices will be determined by the cap." (European Parliament, 2014, p. 7). See also European Parliament and Council (2014): "The proposed reserve will complement the existing rules so as to guarantee a more balanced market, with a carbon price more strongly driven by mid- and long-term emission reductions and with stable expectations encouraging low-carbon investments".

by business cycles, technological progress or climate and energy policies overlapping the EU ETS. However, we do not consider changes in design and stringency of the cap-and-trade scheme itself.¹⁵ In concreto, we assume that there is a shock $\varepsilon(t)$ to the level of unregulated emissions u of the risk-neutral, representative firm. The abatement cost function under uncertainty is therefore

$$C(u + \varepsilon(t) - e_i(t)), \quad (24)$$

where the distribution of $\varepsilon(t) > -u$ is characterized by the density function $\phi(\varepsilon(t), t)$. Shocks are assumed to be persistent such that once they have occurred, the mean of unregulated emissions is permanently adjusted. The focus is therefore not on day-to-day fluctuations in the demand for allowances but on long-term structural changes.¹⁶

Firms face the following optimization problem

$$\begin{aligned} \min_{e_i(t), x_i(t)} \quad & E_0 \left[\int_{t=0}^{\infty} [e^{-\rho t} C(u + \varepsilon(t) - e_i(t)) + p(t)x_i(t)] dt \right] \\ \text{s.t. :} \quad & \dot{b}_i(t) = x_i(t) - e_i(t) \\ & b_i(t) \geq 0 \quad \forall t \end{aligned} \quad (25)$$

where $E_t[\cdot]$ is the expected value given all information available at time t and ρ is the interest rate inclusive of the asset-specific risk premium. The expected price path, given what is known at time t , satisfies (see Schennach, 2000)

$$E_t[\dot{p}(t)] = E_t[\rho p(t) - \mu_i(t)e^{\rho t}], \quad \forall t \geq \underline{t}, \quad (26)$$

which is the equivalent of condition (11) under uncertainty.¹⁷ If the borrowing constraint is not binding with certainty in an interval $[\underline{t}, \bar{t}]$, i.e. $E_t[\mu_i(t)] = 0$ for all $t \in [\underline{t}, \bar{t}]$, then the expected allowance price rises at rate ρ within this interval. If there is a positive probability that the borrowing constraint is binding, i.e. $E_t[\mu_i(t)] > 0$, the expected price will rise at a rate less than ρ over the respective interval.

In the presence of uncertainty over future demand for allowances, Proposition 1 is replaced by:

¹⁵Salant (2016) investigates the impact of regulatory uncertainty on allowance prices in the EU ETS.

¹⁶This is closely aligned with the EC's motivation: "[T]he establishment of a market stability reserve [...] would make the ETS more resilient to any potential future large-scale event that may severely disturb the supply-demand balance" (European Parliament and Council, 2014, p. 3).

¹⁷Note that the expected price path specified in condition (26) can only be observed if a futures market for allowances exists. The actual price path at any point in time will either rise at the rate of interest or be determined by $p_{\text{MSR}}(t) = C'(u + \varepsilon(t) - S_{\text{MSR}}(t))$. See Schennach (2000) and Pindyck (2001).

Proposition 3 *Under uncertainty about future demand for allowances, the equilibrium price and emission paths are unaffected by the market stability reserve if and only if all equilibrium emission paths of the baseline case featuring a non-zero value of the density function ϕ are still feasible under the market stability reserve.*

- *In case of a binding non-borrowing constraint, this is the case if and only if,*

$$\int_{s=0}^t e_B(s, \varepsilon(s)) ds \leq b^0 + \int_{s=0}^t S_{MSR}(s, \varepsilon(s)) ds \quad (27)$$

$$\forall t \text{ and } \varepsilon(t) : \phi(\varepsilon(t)) > 0,$$

- *In case of unrestricted borrowing, the MSR has no effect on equilibrium emission and price paths.*

Proposition 3 implies that if shocks occur once the MSR has been depleted ($R(t) = 0$), i.e. in a situation where price and emission paths of both regulatory regimes are the same, the price response is the same in the MSR and the baseline scenarios unless the shock is large enough to render the MSR binding once more.¹⁸ Moreover, in the long run, the MSR has no impact on price and emission paths regardless of the size of any shock that might materialize.

Corollary 1 *Given the baseline allocation path $S_B(t) = S_0 e^{-at}$, there exists a finite \tilde{t} for which it holds that for all $t > \tilde{t}$ price and emission paths with and without the MSR are identical for all ϕ , i.e. the MSR is emission preserving. Hence, the MSR does not improve the ability of climate policies overlapping the EU ETS to affect long-run emissions within the EU ETS.*

Corollary 1 implies that the primary criterion for an improvement in synergies with overlapping climate policies is not met by the MSR.

For the remainder of this section, we focus on the absolute size of the price response at the instant uncertainty is resolved. This tests both for an increase in resilience of the EU ETS and the secondary criterion for an improvement in synergies with overlapping policies.

To identify the impact of a binding MSR on the price path, we turn to a more specific shock. Assume it is known that at time t_{shock} the parliament of a national

¹⁸Given the current specification of the EU ETS and the MSR, the latter can be considered unlikely. The MSR might not be depleted before the middle of the century. By then the cap can be expected to be at least 60-80 percent below current levels based on the EU's 2050 climate target. Hence, with the number of allowances auctioned each year below 600 million, the accumulation of an aggregate bank substantially above 833 million - to render the MSR both active and binding - would require a substantial demand shock.

government of a large EU member state or the EU itself is scheduled to decide on a policy overlapping the EU ETS affecting the future demand for allowances.

Here, the random variable ε takes one of two values $\{\varepsilon^L, \varepsilon^H\}$ (one of which might be zero) representing the possible outcomes of the vote with probabilities $1 - w^H > 0$ and $w^H > 0$ with $w^H \in (0, 1)$, respectively. Furthermore, assume that the MSR binds if $\varepsilon = \varepsilon^H$ but may or may not bind if $\varepsilon = \varepsilon^L$.¹⁹ Since for all $t > t_{shock}$ there is no risk, $\rho = r$ after the shock has occurred. The cap-and-trade scheme still induces scarcity in the market for allowances in the long run in both cases. While this setting is restrictive, it illustrates key properties of the MSR's impact on price and emission paths when uncertainty over the future demand for allowances is resolved and how the MSR affects the response of the EU ETS to overlapping (climate) policies.

Before uncertainty is resolved ($t < t_{shock}$) the impact of the MSR on expected price levels follows the general pattern described in Proposition 2. If the MSR is binding in at least one feasible future state of the world, then the MSR raises allowance prices above the baseline case without an MSR initially because there is an expected increase in the scarcity of allowances. Whenever the aggregate bank of allowances is zero, expectations about future shocks do not affect the level of the allowance price. The non-borrowing constraint binds and the allowance price is determined by $p_{MSR}(t) = C'(u - S_{MSR}(t))$. Again, there is a point in time $t_{cross} \in (\tau_{MSR}, \tau_B)$ where price paths with and without the MSR intersect. Note that whenever the aggregate bank is empty in both regulatory regimes and the MSR injects, then $p_{MSR}(t) = C'(u - S_{MSR}(t)) < p_B(t) = C'(u - S_B(t))$ since $S_{MSR}(t) = S_B(t) + I$ and $C'' > 0$. In the long-run, price levels are identical in the two regulatory regimes.

To understand how the MSR affects the price response at the point in time when uncertainty is resolved, t_{shock} , it helps to distinguish between different states of the system. First we consider a shock occurring when the aggregate bank is empty under both regulatory regimes but the MSR injects, i.e. it holds that $p_{MSR}(t) < p_B(t)$. The impact of the MSR on the absolute size of the price response to the shock at t_{shock} depends on the curvature of the marginal abatement cost function. More precisely,

Proposition 4 *If the anticipated resolution of uncertainty over $\varepsilon \in \{\varepsilon^L, \varepsilon^H\}$ occurs while the MSR is active ($R(t) > 0$) but after private banks have been depleted ($b_B(t) = b_{MSR} = 0$) and if $e_j(t) = S_j(t)$ with $j \in \{B, MSR\}$ holds both immediately before and after t_{shock} , then*

- $|\Delta p_{MSR}^i(t_{shock})| > |\Delta p_B^i(t_{shock})|$ if and only if $C''' < 0$,
- $|\Delta p_{MSR}^i(t_{shock})| = |\Delta p_B^i(t_{shock})|$ if and only if $C''' = 0$,

¹⁹Should the MSR not bind in case $\varepsilon = \varepsilon^H$, then Proposition 3 holds.

- $|\Delta p_{\text{MSR}}^i(t_{\text{shock}})| < |\Delta p_{\text{B}}^i(t_{\text{shock}})|$ if and only if $C''' > 0$,

where $|\Delta p_j^i(t_{\text{shock}})|$ is the absolute size of the price change induced by shock ε^i in regulatory regime j , formally $|\Delta p_j^i(t_{\text{shock}})| = |p_j^i(t_{\text{shock}}) - E[p(t_{\text{shock}})]|$.

Hence, for shocks occurring in the medium run, the immediate price response is smaller (larger) with the MSR than without if marginal abatement costs are convex (concave). The curvature of the marginal abatement cost function determines how a given change in aggregate abatement translates into a change in the equilibrium allowance price level. Given that in the relevant period the pre-shock price level is lower with the MSR and that convex marginal abatement costs are standard in the literature (Böhringer et al., 2009; Kesicki & Ekins, 2012; Landis, 2015), the MSR reduces the absolute size of immediate price responses to demand shocks. However, this is not a particular feature of an additional responsiveness to shocks provided by the MSR. Although the injection of allowances from the MSR causes the reduction in the price response, the injection itself is not a response to the shock but merely coincides with it.

For sufficiently large shocks triggering an extended banking phase with the aggregate bank passing one or both of the thresholds \underline{b} and \bar{b} (i.e. if $e_j(t) < S_j(t)$ with $j \in \{B, \text{MSR}\}$ for some period after t_{shock}), the responsiveness of the MSR might become relevant. A detailed analysis of this situation is beyond the scope of this paper as the impact of demand shocks on the incentives to bank are generally ambiguous with convex marginal abatement costs. After a shock occurring while $R(t_{\text{shock}}) = 0$ banking is triggered if the rate of change in the allowance price given $e(t) = S(t)$ would exceed the interest rate (condition (11)). However, $\partial \dot{p}/p/\partial u = -aS(t)(C'''C' - C''^2)/C'^2$ cannot be uniquely signed if the marginal abatement cost is convex ($C''' > 0$).

We now turn to what might be considered the most relevant case: shocks that occur during the initial banking phase, i.e. while firms still hold a strictly positive bank of allowances ($t_{\text{shock}} < \tau_{\text{MSR}}$). Given that the marginal abatement cost function is linear or convex with non-increasing convexity there is also an unambiguous result. In short: in absolute terms the price response tends to be larger with the MSR than without.

Proposition 5 *If the shock occurs during the initial banking phase ($t_{\text{shock}} < \tau_{\text{MSR}} < \tau_{\text{B}}$) and the MSR binds at least if $\varepsilon = \varepsilon^H$, then a sufficient but not necessary condition for the MSR to increase the absolute size of the price response ($|\Delta p_{\text{MSR}}^i(t_{\text{shock}})| > |\Delta p_{\text{B}}^i(t_{\text{shock}})|$, where $i = \{L, H\}$) is that the abatement cost function satisfies $C''' \geq 0$ and $C'''' \leq 0$. In this case, the expected price for all $t < t_{\text{shock}}$ is strictly higher than in the baseline.*

The above also holds for marginal increases in the stringency of the MSR, e.g. an increase in γ or a drop in \underline{b} or \bar{b} , that result in more allowances being stored in the reserve at τ_{MSR} .

The restrictions on the abatement cost function are not overly restrictive. Indeed, many (but not all) specifications used in the literature satisfy them. Marginal abatement costs are usually assumed to be increasing ($C'' > 0$) and either linear or convex ($C''' \geq 0$). Requiring that $C'''' \leq 0$ implies that the convexity of the marginal abatement cost function is not increasing in abatement. However, any finite degree of convexity is admissible. Moreover, $C'''' > 0$ does not imply that Proposition 5 does not hold, only that it is no longer guaranteed. In addition, in contrast to Proposition 4, Proposition 5 does already include the entire flexibility provided by the MSR. Hence, it holds for any size of shock that preserves that the EU ETS is binding in the long run.

The results in Proposition 5 is driven by two main effects. The first is the link between the curvature of the marginal abatement cost curve, i.e. on how a given change in abatement translates into price adjustments, that also drives the results in Proposition 4. A binding MSR increases the price level during the initial banking phase (Proposition 2). Hence, the price response for any given adjustment in abatement is larger with the MSR than without if the marginal abatement cost curve is convex. The second is via the impact of the change in unregulated emission on the length of the initial banking phase ($\partial \tau_{\text{MSR}} / \partial u$). Typically the relationship is negative, i.e. higher unregulated emissions reduce the duration of the initial banking phase. However, for marginal abatement cost functions with an increasing degree of convexity ($C'''' > 0$), this can be reversed. This reversal occurs if and only if the increase (decrease) in unregulated emissions results in lower (higher) emissions for all $t \leq \tau_{\text{MSR}}$. Note that while the impact of changes in u on the price level in the initial banking phase is unambiguously positive ($\partial p_{\text{MSR}}^0 / \partial u > 0$) the impact on emissions is ambiguous. Unregulated emissions increase, but so does total abatement. The net effect on emissions depends on the shape of the marginal abatement cost function. If its convexity increases, equilibrium emissions drop in response to higher unregulated emissions which reduces scarcity of allowances causing the initial banking phase to expand. Hence, for marginal abatement cost functions with an increasing degree of convexity there are two countervailing effects that render the total effect of the MSR on the size of the price response ambiguous. This does not imply that the MSR necessarily reduces the price response but merely that an increase can no longer be guaranteed.

During the initial banking phase, a binding MSR is likely not to meet two of the objectives stated as justifications for the introduction of the MSR. The resilience of the EU ETS to supply-demand imbalances, as measured by the absolute size of price responses to anticipated but uncertain changes in allowance demand, decreases. As stated in Corollary 1, the emission preserving nature of the MSR rules out any direct impact on aggregate emissions within EU ETS sectors by overlapping climate policies (primary criterion) and Proposition 5 clarifies that also in terms of price responses (secondary criterion) the effect of the MSR is unlikely to

be the one hoped for.

The special case where the MSR does not bind for $\varepsilon = \varepsilon^L$ is worth mentioning. If conditions were identical at t_{shock} and $\varepsilon = \varepsilon^L$, the MSR would have no impact for all $t > t_{shock}$. However, for $\varepsilon = \varepsilon^H$, the MSR binds and hence Proposition 5 holds. Given the conditions stated there, prices increase more with the MSR than without after ε^H is realized. Hence, the expected allowance price prior to the resolution of uncertainty is higher with the MSR than in the baseline case. This induces additional abatement in the MSR regime and hence a bank that is above what it would have been for the allowance price path in the baseline regime. This in turn reduces scarcity of allowances at t_{shock} also in the case of $\varepsilon = \varepsilon^L$. The allowances price with the MSR hence drops below the price level in the baseline for the remainder of the initial banking phase if the low demand option realizes. The following Corollary holds

Corollary 2 *Given the conditions of Proposition 5 and that the MSR does not bind if $\varepsilon = \varepsilon^L$, then it also holds that*

$$p_{MSR}(t) > p_B(t) \quad \forall t < t_{shock}, \quad (28)$$

$$b_{MSR}(t_{shock}) + R(t_{shock}) > b_B(t_{shock}) \quad (29)$$

$$\Delta p_{MSR}^H(t_{shock}) > \Delta p_B^H(t_{shock}), \quad (30)$$

$$p_{MSR}^H(t_{shock}) > p_B^H(t_{shock}), \quad (31)$$

$$|\Delta p_{MSR}^L(t_{shock})| > |\Delta p_B^L(t_{shock})|, \quad (32)$$

$$p_{MSR}^L(t_{shock}) < p_B^L(t_{shock}). \quad (33)$$

Figure 2 illustrates Corollary 2 by presenting the price paths with (black) and without the MSR (gray).²⁰ With the MSR prices are initially ($t < t_{shock}$) higher as firms bank additional allowances in order to reduce scarcity in case of a high allowance demand implying a binding MSR. Once uncertainty is resolved, prices in both institutional settings jump to their new equilibrium levels. Directly after a positive demand shock, allowance prices are significantly higher with the MSR than without. Price paths intersect at t_{cross}^H . With low allowance demand, when by assumption the MSR is not binding, prices in both settings drop, but slightly more so in case with the MSR, because scarcity of allowances is somewhat lower due to the higher level of abatement prior to the shock. In the long run when banking has ceased, the price paths with and without the MSR are identical.

Using the example of the anticipated resolution of uncertainty, we show that the impact of the MSR on the size of the price response is generally ambiguous.

²⁰Parameter values that differ from those used in Figure 1 are given below. They are chosen to meet the assumptions made above and to produce a clear graph rather than to closely represent the EU ETS. Specifically: $r = 0.16$, $u = 1900$, $u_H = 2200$, $u_L = 1800$, $w_H = 0.8$, $R^0 = 500$ million, $\gamma = 0.08$.

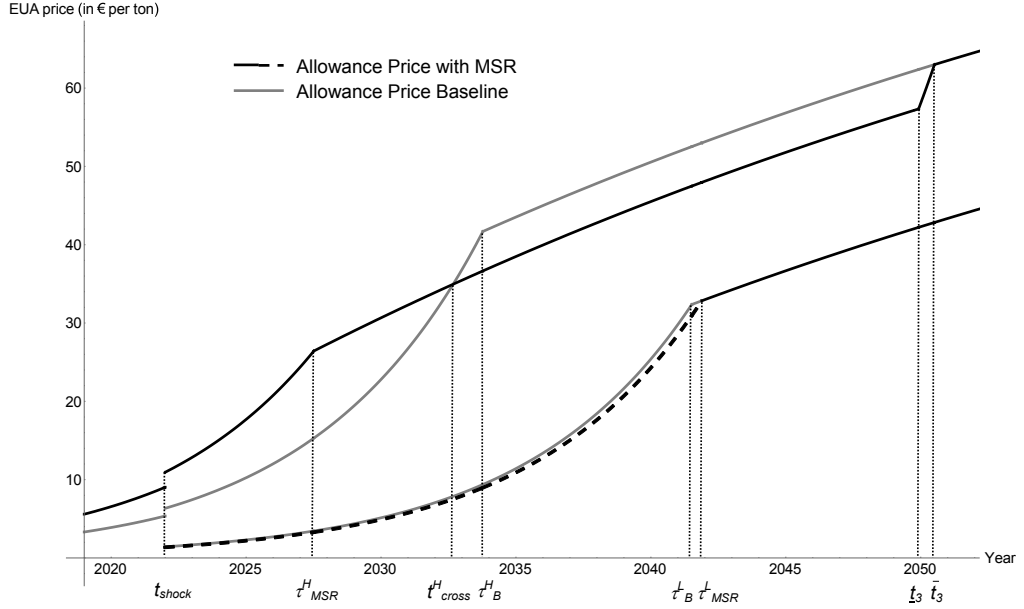


Figure 2: Comparison of allowance price paths with and without MSR in stochastic setting. The price path with the MSR following a negative demand shock (black dashed) is strictly below the path without the MSR for all $t \in [t_{shock}, \tau_{MSR}^L]$.

Under uncertainty over future allowance demand the introduction of a MSR raises the equilibrium price path in the short term if the MSR binds with positive probability in the relevant period. Moreover, if uncertainty is resolved during the initial banking phase, then the absolute size of the price response is larger with the MSR than without. A sufficient condition for this result is at least one feasible state of the world where the MSR binds and a linear or convex (with a non-increasing degree of convexity) marginal abatement cost function. The price response tends to be smaller with the MSR than without, if the shock occurs after the initial banking phase. The reason for this increase in resilience is the very fact that potentially undermines the investment objective of the MSR, i.e. that during this phase the price level with the MSR is lower than without.

The resilience of the EU ETS, as measured by the change in prices induced by shocks to the demand of allowances, is reduced by the MSR for a large class

of relevant shocks and abatement cost functions. Given that such demand shocks are a typical effect of overlapping climate policies and that long-run emissions are unaffected, the MSR does not increase but decrease synergies with overlapping climate policies during the initial banking phase.

5 Conclusion

Burdened by an excess supply of allowances in the form of a systemic 'surplus' (aggregate bank), the EU ETS is currently thought to not produce a sufficient price signal to trigger investment in low-carbon technologies. At the heart of a reform proposal to address these findings, the European Commission has devised a reserve mechanism that systematically postpones the issue date of allowances in times of high surpluses. One objective of the implementation of such a MSR is to increase scarcity in the market for allowances to reach higher price levels at an earlier date. This is hoped to induce firms to expand investment into low carbon technologies. Furthermore, the reserve should guard the system against demand shocks, i.e. reduce price variability by acting as a responsiveness mechanism when the aggregate bank moves outside a pre-defined trigger bandwidth. In this paper, we studied the effects of such an allowance-preserving reserve mechanism on equilibrium emission and price paths of market participants in a perfectly competitive market using a dynamic optimization framework.

Our key findings are: The MSR only affects price and emission paths if it induces additional temporary scarcity. In this case prices first rise above and subsequently drop below their baseline level. The impact of the MSR on the incentives to invest in low-carbon technologies is hence ambiguous and particular projects with long lead and life times might be negatively affected.

Increases in the resilience of the EU ETS to structural demand-supply imbalances and the synergies with overlapping policies achieved by the MSR are not apparent. Especially for shocks occurring while there is still a surplus of allowances the MSR tends to amplify, not dampen, the price response. Impacts on long-run emissions are ruled out since the MSR remains emission preserving given that shocks do not render the EU ETS redundant.

Taken together, our results cast serious doubt that the MSR as devised by the EU is an adequate tool to achieve the objectives stated by the EU. However, many questions remain to be answered: The effect of the MSR if low-carbon investments are explicitly modeled, the impact of options to revise the rules of the MSR (explicitly included in the legislation), the presence of additional market failures and more reliable quantification of the effects derived in this paper are likely candidates for future research.

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A Proofs

A.1 Proof of Proposition 1

Note that in (17)-(18) the exact time profile of $S(t)$ for all $t < \tau_B$ is irrelevant.

First part: Condition (23) ensures that the feasibility condition (19) is met. If the MSR is empty at τ_B given the optimal emission path under the baseline $R(\tau_B|e(t) = e_B(t)) = 0$, then conditions (12)-(15) and (17)-(20) coincide for all $t \leq \tau_B$. Note that (17) and (23) imply that this is always the case if the feasibility condition holds.

Second part: If unrestricted borrowing is allowed, the constraint on the state variable (3) has to be dropped. The set of constraints in (8) and hence the feasibility condition (14) are dropped as a result.

A.2 Proof of Lemma 1

Differentiating condition (17) with respect to time, rearranging and extending the right-hand side with $e_{\text{MSR}}(t)$ yields

$$\frac{C'(u - e_{\text{MSR}}(t))}{C''(u - e_{\text{MSR}}(t))} = -\frac{\dot{e}_{\text{MSR}}(t) e_{\text{MSR}}(t)}{e_{\text{MSR}}(t) r} \quad \forall t < \tau_{\text{MSR}}, \quad (\text{A.1})$$

which holds if and only if $b_{\text{MSR}}(t) > 0$ (see condition (11)). We now check whether it can be satisfied in the long run ($t \rightarrow \infty$) which is a necessary (but not sufficient) condition for the stock of allowances in the MSR to remain strictly positive in the long run.

First we consider the term on the right-hand side. In this deterministic setting the MSR is either depleted ($\lim_{t \rightarrow \infty} R(t) = 0$) or converges to a strictly positive size \bar{R} ($\lim_{t \rightarrow \infty} R(t) = \bar{R} > 0$) in the long run. This implies that the rate of change of emissions, i.e. the first term, converges to the rate of change of issued (and auctioned) allowances in the baseline, i.e. $\lim_{t \rightarrow \infty} -\frac{\dot{e}_{\text{MSR}}(t)}{e_{\text{MSR}}(t)} = a$, which is strictly positive but finite. Since there is a finite upper bound on the total number of allowances of $S_B^0/a + b_B^0$ emissions have to converge to zero ($\lim_{t \rightarrow \infty} e_{\text{MSR}}(t) = 0$), rendering the second term and hence the entire expression zero.

$$\lim_{t \rightarrow \infty} \left[-\frac{\dot{e}_{\text{MSR}}(t) e_{\text{MSR}}(t)}{e_{\text{MSR}}(t) r} \right] = \frac{a}{r} \lim_{t \rightarrow \infty} e_{\text{MSR}}(t) = 0$$

The limit of the left-hand side of (A.1) for $t \rightarrow \infty$ depends on how C' and C'' behave for $e(t) \rightarrow 0$. Both have been defined in Section 2: $C'(u - e_{\text{MSR}}(t)) > 0$ and $\lim_{e(t) \rightarrow 0} C''(u - e(t)) = \bar{c} > 0$. Hence, the left-hand side of (A.1) remains strictly positive for $e(t) \rightarrow 0$. Therefore (17) cannot be satisfied in the long run.

The bank will eventually be depleted and τ_{MSR} exists and is finite. Because $\underline{b} > 0$, the same holds for the MSR. As a result the MSR is not only allowance but also emission preserving in the sense of Definition 3.

A.3 Proof of Proposition 2

First part: Lemma 1 guarantees that a finite τ_{MSR} exists. By definition, the bank is strictly positive for all $t \leq t_2$. Hence, it holds that $\tau_{\text{MSR}} > t_2$.

If $\tau_{\text{MSR}} > t_3$, conditions (12)-(13) and (15) perfectly coincide with conditions (17)-(18) and (20), since $R(\tau_{\text{MSR}}) = \dot{R}(\tau_{\text{MSR}}) = 0$ in this case. Hence, $\tau_{\text{MSR}} > t_3$ would imply that $\tau_{\text{MSR}} = \tau_{\text{B}}$ and $e_{\text{MSR}}^*(t) = e_{\text{B}}^*(t)$ for all t . However, Proposition 2 considers the case where $e_{\text{B}}^*(t)$ is not feasible due to the MSR. It follows that $\tau_{\text{MSR}} \leq t_3$ and hence that $e_{\text{MSR}}^*(\tau_{\text{MSR}}) = S_0 e^{-a\tau_{\text{MSR}}} + I$.

The equilibrium emission path of the baseline case, $e_{\text{B}}^*(t)$, violates the feasibility constraint under the MSR at least once in the interval $[t_2, t_3]$. Hence, all emission paths at or above $e_{\text{B}}^*(t)$ are not feasible under the MSR. It therefore holds that $e_{\text{MSR}}^*(t) < e_{\text{B}}^*(t)$ and $p_{\text{MSR}}^*(t) > p_{\text{B}}^*(t)$ for all $t \leq \tau_{\text{MSR}}$.

Third and Fourth parts: Once the aggregate bank is depleted, the equilibrium price of allowances under the MSR does no longer rise at the rate of interest r , but at a lower rate. The non-borrowing constraint becomes binding and $e(t) = S_{\text{MSR}}(t)$. However, this holds only temporarily. At t_3 , the auctioning schedule $S_{\text{MSR}}(t)$ is discontinuous (it drops by I) as the MSR stops injecting allowances. If the bank was zero and emissions equaled the amount auctioned, the allowance price would make a discontinuous upward jump at t_3 . However, intertemporal arbitrage prevents the price from rising at a rate larger than r . Since the depletion of the MSR is perfectly foreseen, in equilibrium firms will bank allowances and the equilibrium price will rise at the rate r during a second banking interval $[\underline{t}_3, \bar{t}_3]$. Since the MSR is empty at the end of the second banking phase ($\bar{t}_3 \geq t_3$), it holds that $e_{\text{MSR}}^*(\bar{t}_3) = e_{\text{B}}^*(\bar{t}_3)$ and $p_{\text{MSR}}^*(\bar{t}_3) = p_{\text{B}}^*(\bar{t}_3)$.

The two banking phases are strictly separate, i.e. $\tau_{\text{MSR}} < \underline{t}_3$, because otherwise $\tau_{\text{MSR}} = \bar{t}_3 > t_3$. As has been shown above, this can only be an equilibrium if the MSR is non-binding. For all $t > \bar{t}_3$ the non-borrowing constraint is always binding since the price of allowances and hence marginal abatement costs for $e(t) = S_0 e^{-at}$ increase at a rate less than r , i.e. it holds that $\bar{t}_3 > 1/a \ln[(r+a)S_0/(ru)]$. This rules out a third banking phase.

Second part: As the aggregate bank and the MSR are empty in both scenarios for all $t \geq \bar{t}_3$, and the total number of allowances issued up to \bar{t}_3 is identical as well (the MSR is allowance and emission preserving), the result that $e_{\text{MSR}}^*(t) < e_{\text{B}}^*(t)$ and $p_{\text{MSR}}^*(t) > p_{\text{B}}^*(t)$ for all $t \leq \tau_{\text{MSR}}$ implies that for at least some t within $[\tau_{\text{MSR}}, \bar{t}_3]$ the opposite must hold. The point in time when emission and price paths with and without a MSR intersect, t_{cross} , has to be to the left of τ_{B} because

the slope of the price path in the baseline case is constant and lower than r for all $t > \tau_B$ and the price path with the MSR approaches from below at \tilde{t}_3 .

A.4 Proof of Corollary 1

The total number of allowances auctioned is finite ($\lim_{t \rightarrow \infty} \int_0^t S_0 e^{-as} ds + b_B^0 = S_0/a + b_B^0$). Hence, there exists a point in time \tilde{t}_1 when the total number of allowances available for future use drops below \underline{b} , implicitly defined by $S_0 e^{-r\tilde{t}_1}/a + b(\tilde{t}_1) + R(\tilde{t}_1) = \underline{b}$. This together with $\bar{b} > \underline{b}$ implies that the MSR will be empty at the very latest at $\tilde{t} = \tilde{t}_1 + R(\tilde{t}_1)/I$. Hence, for all $t \geq \tilde{t}$ the MSR cannot be binding regardless of the nature of any demand shock occurring. Price and emission paths are therefore identical with and without the MSR.

A.5 Proof of Proposition 4

If t_{shock} occurs while initially $b_j(t) = 0$, $R(t) > 0$ and $\dot{R} = -I$, then $e_B(t) = S_0 e^{-at} < e_{MSR}(t) = S_0 e^{-at} + I$. The price level prior to the shock (and any transitory banking phase) $p_j(t) = C'(u - S_j(t))$ is not the same under the two regulatory regimes ($p_B > p_{MSR}$). The price response is determined by

$$\frac{\partial p_j}{\partial u} = C''(u - S_j(t)) > 0. \quad (\text{A.2})$$

Whether this differs between the regulatory regimes depends on the curvature of the marginal abatement cost function,

$$\frac{\partial^2 p_j}{\partial u \partial S_j} = -C'''(u - S_j(t)). \quad (\text{A.3})$$

If the marginal abatement cost function is convex (concave) in the relevant range, then the price response under the MSR is smaller (larger) than in the baseline. If the marginal abatement cost function is linear ($C''' = 0$) in the relevant range, then the size of the price response is independent of the regulatory regime.

This also affects the condition that triggers transitory banking phases. Since the initial price level is lower under the MSR, the rate of change of the expected price level is higher under the MSR, everything else equal. Hence, unless the marginal abatement cost function is sufficiently convex, a banking phase to smooth an increase in the expected price is more likely under the MSR. This is relevant if shocks increase the (expected) demand for allowances.

A.6 Proof of Proposition 5

The abatement function $A(p) = C'^{-1}(u - e(t))$ has the following properties. $A' = 1/C'' > 0$ and $A'' = -C'''/(C'')^3$. Since $C'' > 0$ the latter implies that A'' and C''' have opposite signs unless they are both zero.

We now consider the case where uncertainty is resolved during the initial banking phase ($t_{shock} < \tau_{MSR}$). Using the abatement function $A(p) = C'^{-1}(u - e(t))$, $\dot{R}(t) = I$ and $b_{MSR}^0 + R^0 = b_B^0$ conditions (17) to (20) yield

$$u\tau_{MSR} - \int_{t=0}^{\tau_{MSR}} A(p_{MSR}^0 e^{rt}) dt - b_B^0 - \frac{S_0}{a}(1 - e^{-a\tau_{MSR}}) + R(\tau_{MSR}) = 0 \quad (A.4)$$

$$u - A(p_{MSR}^0 e^{r\tau_{MSR}}) - S_0 e^{-a\tau_{MSR}} + I = 0 \quad (A.5)$$

The case without the MSR is represented by setting $R(\tau_{MSR}) = I = 0$. Using Cramer's rule, the following comparative statics hold

$$\frac{\partial p_{MSR}^0}{\partial u} = \frac{\tau_{MSR}}{\int_{t=0}^{\tau_{MSR}} A'(p_{MSR}^0 e^{rt}) e^{rt} dt} > 0, \quad (A.6)$$

$$\frac{\partial p_{MSR}^0}{\partial b_B^0} = -\frac{1}{\int_{t=0}^{\tau_{MSR}} A'(p_{MSR}^0 e^{rt}) e^{rt} dt} < 0, \quad (A.7)$$

$$\frac{\partial p_{MSR}^0}{\partial R(\tau_{MSR})} = \frac{1}{\int_{t=0}^{\tau_{MSR}} A'(p_{MSR}^0 e^{rt}) e^{rt} dt} > 0, \quad (A.8)$$

$$\frac{\partial \tau_{MSR}}{\partial u} = \frac{\tau_{MSR} A'(p_{MSR}^0 e^{r\tau_{MSR}}) e^{r\tau_{MSR}} - \int_{t=0}^{\tau_{MSR}} A'(p_{MSR}^0 e^{rt}) e^{rt} dt}{\int_{t=0}^{\tau_{MSR}} A'(p_{MSR}^0 e^{rt}) e^{rt} dt Z}. \quad (A.9)$$

where $Z = aS_0 e^{-a\tau_{MSR}} - rA'(p_{MSR}^0 e^{r\tau_{MSR}}) p_{MSR}^0 e^{r\tau_{MSR}} = \dot{e}(\tau_{MSR}) - \dot{S}(\tau_{MSR})$. Note that (A.8) is based on a liberal interpretation of $R(\tau_{MSR})$. Formally, $R(\tau_{MSR})$ depends on τ_{MSR} and hence is endogenous, not exogenous. However, $R(t)$ as such is a function of both endogenous variables and exogenous parameters. Especially the design parameters of the MSR, \underline{b} , \bar{b} , γ and I affect the number of allowances in the MSR at τ_{MSR} . An increase in $R(\tau_{MSR})$ is here taken to represent an increase in the stringency of the MSR, e.g. an increase in γ or a drop in \underline{b} or \bar{b} . The results therefore not only apply to the introduction of the MSR but also to marginal increases in its stringency.

For (A.9) the sign is ambiguous in general but not for a large set of relevant cases. It holds that $e(\tau_{MSR}) = S(\tau_{MSR})$ but that $e(t) > S(t)$ for t just below τ_{MSR} (otherwise the bank would not get depleted at τ_{MSR}). Hence, $\dot{e}(\tau_{MSR}) - \dot{S}(\tau_{MSR}) < 0$ and the denominator of (A.9) is negative.

To determine the sign of the numerator, assume that $A'' = 0$ (i.e. the marginal abatement cost curve is linear, $C''' = 0$). In this case A' is a constant and the

numerator simplifies to $A'(\tau_{\text{MSR}} e^{r\tau_{\text{MSR}}} - \int_{t=0}^{\tau_{\text{MSR}}} e^{rt} dt)$. When viewing the two terms in the brackets as geometric objects, it becomes apparent that the rectangle $\tau_{\text{MSR}} e^{r\tau_{\text{MSR}}}$ has a strictly larger area than the integral. The latter is a proper subset of the former. A similar argument holds for all $A'' > 0$ and for $A'' < 0$ that meet the following sufficient (but not necessary) condition: $A'(p_{\text{MSR}}^0 e^{rt}) e^{rt} = e^{rt}/C''(u - e(t))$ is constant or monotonically increasing for all $t \leq \tau_{\text{MSR}}$. For example, if C'' is linear ($C'' = l\alpha + z$), then $l \geq 0$ and $z \geq 0$ is a sufficient but not necessary condition for $\frac{\partial \tau_{\text{MSR}}}{\partial u} < 0$. Note that $C'' > 0$ for all non-negative levels of abatement already implies that $z \geq 0$. This implies that C''' can take any constant positive value l ($C'''' = 0$) and still satisfy the above condition.

To identify how the price response to a shock in unregulated emissions u is affected by the MSR, we need to identify the sign of

$$\frac{\partial^2 p_{\text{MSR}}^0}{\partial u \partial R(\tau_{\text{MSR}})} = - \frac{\frac{\partial p_{\text{MSR}}^0}{\partial u} \int_{t=0}^{\tau_{\text{MSR}}} A''(p_{\text{MSR}}^0 e^{rt}) e^{2rt} dt + \frac{\partial \tau_{\text{MSR}}}{\partial u} A'(p_{\text{MSR}}^0 e^{r\tau_{\text{MSR}}}) e^{r\tau_{\text{MSR}}}}{\int_{t=0}^{\tau_{\text{MSR}}} A'(p_{\text{MSR}}^0 e^{rt}) e^{rt} dt} \quad (\text{A.10})$$

For $A'' = 0$ this is unambiguously positive, because the first summand in the numerator becomes zero and $\frac{\partial \tau_{\text{MSR}}}{\partial u} < 0$ in this case. For all $A'' < 0$ the first summand in the numerator is negative, but for A'' sufficiently small, $\frac{\partial \tau_{\text{MSR}}}{\partial u} > 0$. For $A'' > 0$ the first summand in the numerator is negative and once it becomes sufficiently large, it could outweigh the negative second summand.

Hence, given identical conditions at t_{shock} , for all marginal abatement cost functions that are neither of increasing convexity (i.e. $C'''' \leq 0$) nor too concave, the impact of (a tightening of) the MSR on the response to a shock in unregulated emissions is positive ($\frac{\partial^2 p_{\text{MSR}}^0}{\partial u \partial R(\tau_{\text{MSR}})} > 0$). With (a tighter) MSR, prices changes are in absolute terms larger than without.

The resolution of uncertainty at t_{shock} is anticipated. At the instant t_{shock} , the co-state variable $\lambda(t)$ has to meet the following condition (Goeschl & Perino, 2009):

$$\lim_{t \rightarrow t_{\text{shock}}} \lambda(t_{\text{shock}}) = E[\lambda(t_{\text{shock}})] = w^H \lambda^H(t_{\text{shock}}) + (1 - w^H) \lambda^L(t_{\text{shock}}), \quad (\text{A.11})$$

where superscript H represents the value of the co-state if $\varepsilon = \varepsilon^H$ and L if $\varepsilon = \varepsilon^L$. The intuition for condition (A.11) is as follows: If the (expected) value of the co-state jumped, firms would have an incentive to shift purchases of allowances either forward or backward in time. However, by assumption the shock occurs when the bank is strictly positive, i.e. the expected allowance price rises at rate ρ and hence firms are ex-ante indifferent between purchasing an additional allowance just before or just after the shock occurs. Jumps in $E[\lambda(t)]$ (but not in $\lambda(t)$) are therefore ruled out by the no-arbitrage condition. Because $\lambda(t) =$

$-e^{rt} p_j(t)$, it also holds that $\lim_{t \rightarrow t_{shock}} p_j(t_{shock}) = E [p_j(t_{shock})] = w^H p_j^H(t_{shock}) + (1 - w^H) p_j^L(t_{shock})$.

Assuming identical conditions at t_{shock} , the expected allowance price before t_{shock} is higher with the MSR than without since condition (A.8) holds at least for $\varepsilon = \varepsilon^H$. Given identical conditions at t_{shock} , it holds that $\partial E [p(t_{shock})] / \partial R > 0$. Note that an increase in $E [p_{MSR}(t_{shock})]$ results in higher prices and hence in lower emissions for all $t < t_{shock}$. The bank of allowances held by firms at t_{shock} is therefore increasing in $E [p_{MSR}(t_{shock})]$. Because $\frac{\partial p_{MSR}^0}{\partial b_B^0} < 0$ this dampens the change in the expected price. The dampening will always be a second order effect, as otherwise the initial deviation in $E [p_{MSR}(t_{shock})]$ will be reversed. Hence, $\partial E [p(t_{shock})] / \partial R > 0$ holds even after taking into account that conditions at t_{shock} are not the same with and without the MSR.

Hence, it holds that for marginal abatement cost functions that are neither linear or convex with a non-increasing degree of convexity, a (tighter) MSR increases the prices response to an anticipated resolution of uncertainty at t_{shock} , given that $b_j(t_{shock}) > 0$ for $j = \{B, MSR\}$.

A.7 Proof of Corollary 2

Assume $t_{shock} < \tau_{MSR}$ and the MSR is not binding if and only if $\varepsilon = \varepsilon_L$. This implies that for identical conditions at t_{shock} , the price response to $\varepsilon = \varepsilon_L$ with and without the MSR are identical. Given that $\frac{\partial^2 p_{MSR}^0}{\partial u \partial R(\tau_{MSR})} > 0$ and the MSR binding in case of $\varepsilon = \varepsilon_H$, this implies that $E [p_{MSR}(t_{shock})] > E [p_B(t_{shock})]$. Again, the precautionary banking dampens the change in the expected price change ($\frac{\partial p_{MSR}^0}{\partial b_B^0} < 0$) but does not reverse it. Specifically, equations 28 to 33 hold.