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Abstract

In October 2015 the European Parliament has established a market stability reserve (MSR) in the Phase 4 of the EU-ETS, as part of the 2030 framework for climate policies. In this paper we model the EU-ETS in presence of the Market Stability Reserve (MSR) as it is defined by that decision and investigate the impact that such a measure has in terms of permits price, output production and banking strategies. To do so we build an inter-temporal model in which polluting firms competing in an homogeneous good market are price takers in a permits market and face an uncertain demand. Our main finding is that the MSR succeeds in increasing the permits' price correcting an excess supply (and conversely decreasing it in case of excess demand). However, when the output demand is stochastic, the MSR may alter the arbitrage conditions that determine permits' prices. In some cases which depend on the extend of the demand variation, unintended effects on the price pattern appear. This in turns may adversely affect welfare. **Key words**: ETS; market stability reserve; MSR; banking.

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1 Introduction

Tradable emission permits (TEP) can achieve a given pollution reduction target in a cost-effective manner (Montgomery, 1972) and, in a dynamic perspective, if these markets have full temporal flexibility (fungibility), firms can optimally allocate abatement efforts across time (Cronshaw and Brown-Kruse, 1996). The attractiveness of TEP regulation in relation to environmental taxes is that the regulator is not required to have information regarding the production and abatement technologies available in the sector under regulation for the cost-effective equilibrium to arise. Such equilibrium is achieved through the market mechanism itself. However, there is a consensus on the fact that the European Emission Trading System (EU-ETS) is not working properly in this regard. Duncan (2016) analysis is unequivocal: *"Right now the ETS is like a car without an engine, we need to ensure it is fit to do the job it should and drive emissions reductions in Europe"*. In fact, several factors have contributed to the actual situation, in which the price of allowances is low with a very high surplus of permits, such as the economic crisis, the introduction of renewables and the use of Kyoto credits. The fact that the current cost of reducing emissions is low is not a good news since it suggests that the ETS may fail to induce a transformation away from fossil fuels. For all these reasons, the market design of the EU-ETS is being reformed on several issues, such as the speed at which the cap decreases, carbon leakage amendments, rules about innovation funds. So far, a step forward has been taken by creating a market stability reserve (MSR), by the Decision (EU) 2015/1814 of the European Parliament and of the Council.

"The purpose of the MSR is to avoid that the EU carbon market operates with a large structural surplus of allowances, with the associated risk that this prevents the EU ETS from delivering the necessary investment signal to deliver on the EU's emission reduction target in a cost-efficient manner" (EC 2017). The idea behind such reform is a flexibility mechanism that allows the supply of permits to be responsive to fundamental changes in permits demand (like technology advances or economic shocks). The mechanism works as follows: each year the EC publishes the number of allowances in circulation and, if the number is higher or equal than 833 million, 12% are placed in the reserve[1] (and consequently withdrawn from next year's auctions to the electricity sector). Instead, if the allowances in circulation are below 400 million, or if for six month the price is more than 3 times the average carbon price during the two preceding years, 100 million are released from the reserve. The number of allowances in circulation is defined as the number of allowances issued from 2008 (plus international credits used from 2008) until the year in question minus total emissions since 2008 and minus the number of allowances already in the stability reserve: i.e. firms accumulated banking of allowances. The first calculation of these allowances has been released in May 2017 and amounts to 1,693,904,897 allowances. In line with the agreed MSR rules, no reserve feed is triggered by the indicator published in

[1]In fact the text says that what is retired is the maximum between 12% of allowances in circulation and 100 Mt. The proposal of increasing this factor to 24% has been discussed but not approved yet.

2017. The next publication will be made in May 2018. This will result in the determination of the first reserve feed for the period January to August 2019. Moreover, "backloaded" allowances (900 million allowances withdrawn from the market at least until 2019), will be placed in the MSR's reserve as well as any remaining allowances not allocated by the end of the current trading phase, that is 2020.

Several scholars have studied similar flexibility mechanisms that to some extent are used in the Californian CO_2 market and the Regional Greenhouse Gas Initiative (RGGI).[2] Firstly, Pizer (2002) introduces the idea of a "safety valve" which consists in coupling a cap-and-trade system is with a price ceiling. As long as the allowance price is below the safety-valve price, this hybrid system acts like cap-and-trade, with emissions fixed but the price left to adjust. Instead, when the safety-valve price is reached the system behaves like a tax, fixing the price but leaving emissions to adjust. Later, Philibert (2008) and Burtraw, et al. (2009) have proposed a symmetric safety valve, also known as a price collar, which would limit price volatility on both the upside and the downside. Fell and Moregerstern (2010) extend this kind of analysis by introducing uncertainty and coupling the collar mechanisms to restrictions on banking and borrowing. They find that adding a price collar to the reserve borrowing proposal can reduce costs: a price collar can achieve costs almost as low as a tax but with less emissions variation. The price collar mechanisms outperform their safety valve counterparts in terms of expected abatement costs at the same level of expected cumulative emissions.

Traditionally, the literature has analyzed price flexibility measures whereas the EC has chosen instead to go for a quantity mechanism. Some recent papers have then analyzed this design. Schopp et al. (2015) show in a computational model that low EUA prices are observed because current supply exceeds current demand of the electric industry that use them to hedge emissions associated with existing 3 to 4 year power contracts. In this view, the MSR is a good solution since it affects the short-time price without touching to the long-run price signal. Similarly Trotignon et al. (2016) and Perino and Willner (2016) find that the MSR reduces the short-medium term price, fostering earlier emission reductions. This is precisely what Zetterberg et al. (2014) criticize, saying that the risk of price volatility is higher in the presence of the MSR due to the difficulty of predicting hedging needs. There is also a concern that the MSR will not erode the current surplus quickly enough with an excess supply present until 2028 (Mathews et al., 2015). Salant (2016) suggests that low hedging demand from the power sector is not compensated by other sectors expecting to buy low now and sell high later due to the lack of credibility of the survival of the system. In contrast, Fell's (2016) simulations find that the MSR can decrease price volatility (but that its performance is very sensitive to parameters). FTL-Lexecon (2017) suggests that alternative design would improve the performance of the market. Several results are put to a trial in an experimental setting by Holt and Shobe

[2]The RGGI covers emissions from the power sector in 9 States of the Unites States of America (Those states are Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island and Vermont) as from January 2009.

(2016), who find that there is little benefit associated to the MSR but that a price collar may instead enhance efficiency.

The paper closest to ours is Kollenberg and Taschini (2016) who model the adjustments in permits availability due to the existence of the MSR using a stochastic partial equilibrium framework. Their model and scope are very different from ours but some of the results are in line: the MSR substitutes private banking and reduces variability in allowance holdings by withdrawing (reinjecting) when the surplus is too high (low).

In this paper we consider a polluting sector subject to the EU-ETS in the presence of the MSR (like for instance the electricity sector). To this end, we study the MSR impact on banking strategies, allowances price and output production to assess to which extent private banking is crowded out by this mechanism. Differently from Kollenberg and Tashini (2016) we perform such exercise for different designs of the flexibility mechanism. We model a "fixed" rule, that is, for an MSR mechanism that is set independently of the banking already accumulated. This rule is similar to the backloading policy already in place in the EU ETS. We then compare it with a "proportional" rule in which the MSR withdraws a given percentage of the accumulated banking. Furthermore, we study uncertainty under the form of a shock on the output demand, to understand whether the MSR actually makes the EU ETS price more responsive to output changes with respect to no intervention. To our knowledge, this is the first paper that studies to which extent the proposed design of the MSR interacts with firms' market strategies under demand uncertainty. To do so, we assume that firms may delay banking as it was an "option", waiting for the MSR to regulate the market. We then calculate firms' optimal strategies under Cournot-like competion, when the regulator modifies the cap, and present a fully fledged analysis of output pricing and banking behavior.

Our main finding is that the MSR succeeds in increasing the permits' price when there is an excess supply (and conversely decreasing it in case of excess demand). However, when uncertainty on the output demand is factored in, the MSR may alter the perfect arbitrage conditions. In some cases which depend on the extend of the demand variation, dynamic inefficiencies in the price pattern appear. In particular, firms prefer to delay banking for wider valued of the demand variation compared to the no intervention case. This in turns may adversely affect not only producers' profits, but also consumers' surplus.

The paper is organized as follows. We first explain our modelling strategy (Section 2), then we develop the model under uncertainty (Section 3). We introduce the notion of delaying banking. We calculate how backloading and MSR modify it, including welfare effects (Section 4). Our main results are also presented by intuitive graphical illustrations. We conclude by pointing out some policy implications.

2 Modelling strategy

2.1 Assumptions and notation

We consider n symmetric firms (indexed by $i = 1 \ldots .n$) that compete in quantities during three periods $(t = 0, 1, 2)$ where $(b - d\sum_{i=1}^{n} q_{i,t})$ is the inverse demand in t and c is the constant marginal costs. One (some) of the inputs used for production is polluting (e is the polluting intensity of output in t) and therefore firms are subject to environmental regulation based on TEP. A regulator fixes a yearly cap on emissions amounting to the pollution reduction target and sells an equivalent volume of permits in an auction. We denote $\alpha_t A$ is the amount of permits auctioned by the authority each period,[3] with $\alpha_{t+1} < \alpha_t \leq 1$. Firms are price takers in the TEP market whose price is σ_t. Firms maximize inter-temporal profits over three periods (by discounting with an interest rate denoted r), and decide optimal production $q_{i,t}$ and banking $z_{i,t}$.[4]

The regulator also stabilizes the market by setting a supply flexibility mechanism: depending on whether there are more (less) permits than those allowed by a given upper (lower) bound, the regulator will withdraw or inject additional allowances in the next period.

2.2 Benchmark modelling

The previous assumptions can be summarized as follows: each firm i maximizes inter-temporal profits:

$$\underset{q_{i,t},z_{i,t}}{Max} \qquad \Pi_i = \sum_{t=0}^{2} \frac{\pi_{i,t}}{(1+r)^t}, \tag{1}$$

$$s.t. \sum_{i=1}^{n}(eq_{i,t} + z_{i,t} - z_{i,t-1}) \leq \alpha_t A + x_t\,, \tag{2}$$

$$z_{i,2} = 0. \tag{3}$$

where for each period t :

$$\pi_{i,t} = (b - d\sum_{i=1}^{n} q_{i,t})q_{i,t} - cq_{i,t} - \sigma_t(eq_{i,t} + z_{i,t} - z_{i,t-1}). \tag{4}$$

We assume that banked permits are used in the subsequent period and that at the end of the regulatory period 2 there is no further incentive to bank.

[3]Notice that we consider the allocation A, the emission intensity e, demand b, d and cost parameter c as constant all along the regulatory period.

[4]Cronshaw and Brown-Kruse (1996), as well as Rubin (1996), show that, when the tradable emission permits market is competitive and all firms comply with the environmental regulation, allowing firms to save permits for future use increases inter-temporal efficiency, since firms can optimally allocate pollution abatement efforts across time.

Therefore, for every t, $z_{i,t-1}$ represent firm i banked permits at the end of $t-1$ that is unused permits at that date.[5]

The MSR can take different forms. If there is excess demand, that is banking below $\underline{Z}$ (in the EC decision 400Mt), the MSR rule leads to an injection of $\underline{a}$ permits (in the decision 100Mt). In case of excess supply, measured by banking exceeding a given threshold $\overline{Z}$ (in the proposal 800Mt), $-\zeta \sum_{i=1}^{n} z_{i,t-1}$ is the amount of permits withdrawn (in the decision 800Mt). Injection of permits is done in a fixed amount, whereas permits withdrawal is a fraction ζ of the gap between supply and demand, that is unused permits (in the decision ζ is 12%).

For sake of comparison between the MSR withdrawing rule and the backloading measure,[6] we also consider the case of a fixed amount of $-\overline{a}$ permits withdrawn. Finally, no intervention is needed when unused permits remain within the corridor defined by $\overline{Z}$ and $\underline{Z}$.

The regulatory intervention will thus be modeled as follows:

$$x_t = \begin{cases} \underline{a} & \text{if} \quad \sum_{i=1}^{n} z_{i,t-1} < \underline{Z}, \\ 0 & \text{if} \quad \underline{Z} \leq \sum_{i=1}^{n} z_{i,t-1} \leq \overline{Z}, \\ -\overline{a} & \text{if} \quad \sum_{i=1}^{n} z_{i,t-1} > \overline{Z}, \\ & \qquad \text{or} \\ -\zeta_t \sum_{i=1}^{n} z_{i,t-1} & \text{if} \quad \sum_{i=1}^{n} z_{i,t-1} > Z. \end{cases} \tag{5}$$

with $z_{i,2} = 0 \quad \forall i$.

The previous cases will be divided in two sub-cases: (i) the case in which the regulator reinjects $\underline{a}$ or withdraws an exogenous amount $-\overline{a}$, respectively and that we will call the "*fixed amount* rule"; (ii) the case in which the regulator withdraws a percentage of banking, ζ, that we call from now on the "*proportional to banking* rule". For simplicity, we will also label these rules as backloading and MSR respectively.

To assess the functioning of the policy intervention, the fixed withdrawal rule (or backloading) is formalized as follows:

$$\begin{array}{cc} t & \textit{Fixed withdrawal rule or Backloading} \\ 0 & \sum_{i=1}^{n}(eq_{i,0} + z_{i,0}) \leq \alpha_0 A, \\ 1 & \sum_{i=1}^{n}(eq_{i,1} + z_{i,1} - z_{i,0}) \leq \alpha_1 A - \overline{a}, \\ 2 & \sum_{i=1}^{n}(eq_{i,2} - z_{i,1}) \leq \alpha_2 A - \overline{a}. \end{array} \tag{6}$$

Equations (6) simply say that, in period 0, total permits auctioned must be enough to cover total emissions due to production and permits banked for period

[5] This hypothesis might seem in contrast with the literature on banking (see for instance Schennach 2000 where banking is dont at each period for the entire regulatory time span). However, the standard formulation and the one we choose result in the same optimal arbitrage equation, meaning that inter-temporal efficiency holds.

[6] As a short-term measure to resorb the allowance surplus, the Commission postponed the auctioning of 900 million allowances until 2019-2020.This backloading of auction volumes does not reduce the overall number of allowances to be auctioned during phase 3, only the distribution of auctions over the period.The auction volume is reduced by 400 million allowances in 2014; 300 million in 2015 and 200 million in 2016. The backloading was implemented through an amendment to the EU ETS Auctioning Regulation, which entered into force in 2014.

1. Then, in period 1, total permits auctioned considered the exogenous permits withdrawal must be enough to cover emissions and the net variation in the bank of permits. Finally, in period 2, auctioned permits (again minus withdrawal) must be enough to cover emissions considering that all banked permits must be exhausted.

The proportional withdrawal rule (or MSR) takes the form of a smooth adjustment of the cap, as described by the following conditions:

$$\begin{array}{cc} t & \textit{Proportional withdrawal rule or MSR} \\ 0 & \sum_{i=1}^{n}(eq_{i,0}+z_{i,0})\leq\alpha_0 A\ , \\ 1 & \sum_{i=1}^{n}(eq_{i,1}+z_{i,1}-z_{i,0})\leq\alpha_1 A-\zeta_1\sum_{i=1}^{n}z_{i,0}, \\ 2 & \sum_{i=1}^{n}(eq_{i,2}-z_{i,1})\leq\alpha_2 A-\zeta_2\sum_{i=1}^{n}z_{i,1}\ . \end{array} \tag{7}$$

Indeed the first equation is identical for both rules as the MSR does not operate in period 0. Then, the second equation above shows the MSR withdrawal as a percentage of the banked permits from period 0 and the third equation models the MSR withdrawal as a percentage of banked permits from period 0 and 1.

To solve the model we apply a two-step-solution (similarly to Chaton *et al.* 2015):

(i) considering permits price (σ_t) as exogenous, we first find the symmetric Nash equilibrium in quantities at each period by simply solving the system of FOCs given by $\frac{\partial \pi_{z_{i,t}}}{\partial q_{i,t}}=0$

$$q_t=\frac{b-c-e\sigma_t}{(1+n)\,d_t}; \tag{8}$$

(ii) secondly, we solve the system of FOCs given by $\frac{\partial \Pi_i}{\partial z_{i,t}}=0$ and the permits market clearing condition in equation, which gives the inter-temporal arbitrage condition defining the optimal banking strategies that maximize inter-temporal profits:

$$\sigma_0=\frac{\sigma_t}{(1+r)^t}. \tag{9}$$

Finally, solving the system of all equations resulting from (i) and (ii) gives the equilibrium values. Note that (ii) can be done because firms are non-strategic in the permits market. Finally, we check *ex post* (strict) positivity constraints and threshold restrictions that define the functioning of the intervention. In particular, although the equilibrium can be detailed by the equations below for any scenario, depending on the specific total inter-temporal permits supply, each case will be characterized by different constraints on the parameters to ensure positive quantity and output price, as well as banking. These constraints, detailed in the Appendix A.2, must be carefully checked when comparing the different cases to assess the impact of the policy.

2.2.1 Fixed amount rule or backloading

Recall that the quantity of permits injected ($x_t=\underline{a}$) or withdrawn ($x_t=-\overline{a}$) from the market in t. The benchmark is obtained with $\sum x_t=0$.

Firms are constrained by the regulation if the total intertemporal supply of permits auctioned $\Gamma = A(\alpha_0 + \alpha_1 + \alpha_2) + x_1 + x_2 > 0$ is lower than the overall emissions in the 3 periods, when the pollution constraint would not be binding:

$$\Gamma < \frac{ne}{(n+1)d} \times 3(b-c). \tag{10}$$

Whatever the functioning of the policy intervention under the fixed amount rule, the constraint (10) must hold. Notice that the regulator modifies the intertemporal cap as long as $x_1 + x_2 \neq 0$, that is the measure is not cap-preserving.

The **mainequilibrium valuesfor the fixed amount rule** are as follows:

$$q_0^* = \frac{1}{R}\left(\frac{\Gamma}{ne} + \frac{(R-3)(b-c)}{(n+1)d}\right), \tag{11}$$

$$z_0^* = \frac{A\alpha_0}{n} - \frac{1}{R}\left(\frac{\Gamma}{n} + \frac{(R-3)e(b-c)}{(n+1)d}\right), \tag{12}$$

$$z_1^* = -\frac{A\alpha_2 + x_2}{n} + \frac{1}{R}\left(\frac{(1+r)^2\Gamma}{n} - \frac{(R-3+r^2)e(b-c)}{(n+1)d}\right), \tag{13}$$

$$\sigma_0^* = \frac{1}{Re}\left(3(b-c) - \frac{(1+n)d\Gamma}{ne}\right), \tag{14}$$

where

$$R = \sum_{t=0}^{2}(1+r)^t. \tag{15}$$

Note that q_1^* and q_2^* and all other equilibrium variables have similar expressions (see Appendix A.1). In particular, σ_1^* and σ_2^* are obtained by intertemporal arbitrage (equation 9). Moreover, due to the structure of the three-period model, there is no banking at the final stage, that is $z_2^* = 0$.

Recalling that the total intertemporal permits supply is $\Gamma = A(\alpha_0 + \alpha_1 + \alpha_2) + x_1 + x_2$, we can easily compute equilibrium values for cap reduction ($x_1 = x_2 = -\overline{a}$), with two successive withdrawing periods succeeding each other), cap increase ($x_1 = x_2 = \overline{a}$) and compare them with the no intervention case ($x_1 = x_2 = 0$).[7]

Comparative statics can also be easily obtained. If the flexibility mechanism operates by reducing the cap, the equilibrium permits price increase. The mechanism at stake is as follows: banking increases, production decreases and so does the permits' demand, explaining the upward shift of the permits' price. The opposite occurs when the regulator reinjects permits (or $x_1 = x_2 = \overline{a}$).

2.2.2 Proportional to banking withdrawal rule or MSR

Recall that ζ_t is the percentage of banking withdrawn from the market at time t. Similarly to the fixed amount rule, firms are constrained by the regulation as

[7]Notice that the results hold when the cap is adjusted at period 1 only ($x_1 = -\overline{a}$ and $x_2 = 0$ or $x_1 = \overline{a}$ and $x_2 = 0$).

long as the total intertemporal permits supply is tight enough:

$$\Gamma_\zeta < \frac{ne}{(n+1)\,d} \times (3 - \zeta_1(1-\zeta_2) - 2\zeta_2)(b-c), \tag{16}$$

where

$$\begin{aligned} \Gamma_\zeta &= A\alpha_\zeta, & (17)\\ \alpha_\zeta &= \alpha_0(1-\zeta_1)(1-\zeta_2) + \alpha_1(1-\zeta_2) + \alpha_2. & (18) \end{aligned}$$

The main equilibrium values in the proportional rule are defined as follows (see Appendix A.1 for the other values):

$$q^*_{0,\zeta} = \frac{1}{D}\left(\frac{\Gamma_\zeta}{ne} + \frac{(R-3-\zeta_2 r)\,(b-c)}{(n+1)\,d}\right), \tag{19}$$

$$z^*_{0,\zeta} = \frac{A\alpha_0}{n} - \frac{1}{D}\left(\frac{\Gamma_\zeta}{n} + \frac{r\,(3+r-\zeta_2)\,e(b-c)}{(n+1)\,d}\right), \tag{20}$$

$$\begin{aligned} z^*_{1,\zeta} &= \frac{A}{D}\frac{(1+r)^2\,(\alpha_0\,(1-\zeta_1)+\alpha_1) - \alpha_2\,((1+r)+(1-\zeta_1))}{n} & (21)\\ &\quad - \frac{r\,(3+2r-(2+r)\,\zeta_1)\,e(b-c)}{D\,(n+1)\,d}, \end{aligned}$$

$$\sigma^*_{0,\zeta} = \frac{1}{De}\left((3-\zeta_1(1-\zeta_2)-2\zeta_2)(b-c) - \frac{(1+n)\,d}{ne}\Gamma_\zeta\right), \tag{22}$$

where

$$D = R - (1-\zeta_2)\,\zeta_1 - (2+r)\,\zeta_2 > 0. \tag{23}$$

Straightforward calculations show that increasing ζ_1 and/or ζ_2, that is the parameters which define the withdrawal rate, increase the permits price $\sigma^*_{0,\zeta}$ (and by arbitrage, also $\sigma^*_{1,\zeta}$ and $\sigma^*_{2,\zeta}$) compared to the no intervention case.[8]

3 Uncertainty on demand and the option to delay banking

In this Section we assume that there is a shock Δ on the market size at $t = 1$, that is, the demand intercept can be $b_m = b + \Delta$. If $\Delta > 0$ the demand increases, and conversely, if $\Delta < 0$ there is a recession. The demand variation occurs with a probability $(1-\lambda)$; we denote the expected demand as $E_b = \lambda b + (1-\lambda) b_m$.

Such uncertainty is resolved at $t = 1$, where either b or b_m realizes, until the second period.

We consider the decision on banking as a partially reversible investment. Firms could decide not to bank at period 0 and wait for the uncertainty regarding the level of demand to be resolved at period 1. This option to wait or

[8] Notice that by setting $\zeta_1 = \zeta_2 = 0$ in the equations defining the equilibrium, we get the no intervention case.

opportunity to delay the banking decision, denoted by DB, has a value that must be considered. Since there is no abatement in our model, firms bank permits only if they expect them to be more expensive in the future. In order to evaluate this option to delay we calculate the difference between the expected discounted profit when banking is positive at $t = 0$ ($z_0^* > 0$) denoted by $E(\Pi_i)$ and the expected discounted profit under the assumption that banking is delayed to $t = 1$ ($z_0 = 0$) denoted by $E(\Pi_i/z_0 = 0)$. Therefore, we have:

$$DB = \max(E(\Pi_i/z_0 = 0) - E(\Pi_i), 0). \tag{24}$$

The difference between those expected profits give us the expected gain due to delaying banking, which is considered as sequential investment (like in Majd and Pindyck, 1987).

We calculate the equilibrium under uncertainty on demand, by maximizing the expected discounted intertemporal profits. Similarly to the scenario under certainty, firms are constrained if the total offer of permits is low enough: $A \sum \alpha_t < \frac{n}{n+1} \times \frac{3(b-c)e+2\Delta e(1-\lambda)}{d}$. This constraint can be expressed in terms of $\Delta = b_m - b$. The total supply constraint gives a threshold Δ^c such that if $\Delta \geqslant \Delta^c$, the permits price is positive at each period:[9]

$$\Delta \geqslant \Delta^c = \frac{(n+1)\, dA}{2ne\,(1-\lambda)} \sum_{t=0}^{2} \alpha_t - \frac{3\,(b-c)}{2\,(1-\lambda)}. \tag{25}$$

The **main equilibrium values under uncertainty** and $z_0^* > 0$ are as follows:

$$\widehat{q}_0^* = q_0^* + \frac{2\,(1-\lambda)\,\Delta}{R\,(1+n)\,d}, \tag{26}$$

$$\widehat{z}_0^* = z_0^* + \frac{2\,(1-\lambda)\,\Delta e}{R\,(1+n)\,d}, \tag{27}$$

$$z_{1,b}^* = z_1^* + \frac{2e\,(1+r)\,(1-\lambda)\,\Delta}{d\,(1+n)\,(2+r)\,R}, \tag{28}$$

$$z_{1,bm}^* = z_{1,b}^* + \frac{\Delta er}{(n+1)\,(2+r)\,d}, \tag{29}$$

$$\widehat{\sigma}_0^* = \sigma_0^* + \frac{2\,(1-\lambda)\,\Delta}{eR}. \tag{30}$$

Notice that these values are calculated without any intervention modifying the cap, that will be introduced in the next Section. The variables with a hat represent expected values, whereas the others are realized values (once the uncertainty is resolved, that is when either b or b_m realizes).[10]

[9] In this Section, we assume $\alpha_0 = 1$, to simplify the calculations.

[10] The permits prices values for periods 1 and 2 are: $\sigma_{1,b}^* = \sigma_1^* - \frac{2(1-\lambda)\Delta}{e(2+r)R}$, $\sigma_{1,bm}^* = \sigma_{1,b}^* + \frac{2\Delta}{e(2+r)}$.

We also have to check that the arbitrage condition satisfied with $z_0 \geqslant 0$ and $z_1 \geqslant 0$. The following conditions must hold:[11]

$$2(1+r)\Delta(1-\lambda) + rR\max(0,\Delta) \leq$$
$$(2+r)(\tfrac{(n+1)dA}{ne}((1+r)^2\sum_{t=0}^{2}\alpha_t - \alpha_2 R) - (2r+3))r(b-c)\ , \tag{31}$$

$$\Delta \geqslant \underline{\Delta}_0 = \Delta^c + \frac{R}{2\,(1-\lambda)}(b-c-\frac{(n+1)\,dA}{ne})\frac{(n+1)\,dA}{ne}((1+r)^2\sum_{t=0}^{2}\alpha_t - \alpha_2 R)\ . \tag{32}$$

Positive quantities imply the following constraint:

$$\Delta < \overline{\Delta}_0 = \frac{(R-3)\,(b-c)}{2(1-\lambda)} + \frac{(n+1)\,d\Gamma}{2ne\,(1-\lambda)}. \tag{33}$$

The value of delaying the banking decision as an option. The previous equilibrium allow the calculation of the expected inter-temporal profits when firm decide to wait until period 1 to bank $E\,(\Pi_i/z_0=0)$ or when they don't (that is $E\,(\Pi_i)$). Under these hypotheses, the value of delaying banking DB is as follows:

$$DB = \frac{A^2 d\Lambda}{e^2 n^2} - \frac{((b-c)\,r\,(3+r) - 2\,(1-\lambda)\,\Delta)^2}{d(1+n)^2\,(1+r)\,(2+r)\,R},$$

where $\Lambda = \frac{(\sum\alpha_t)^2 - 2R\sum\alpha_t + R^2\alpha_0}{(1+r)(2+r)R}$.

DB is a quadratic function of the shock Δ (but also of b, c, A and of the probability of shock λ). To ease the calculations, we set $\alpha_0 = 1$.

The equation $DB = 0$ has two roots, namely $\underline{\Delta}_0[.]$ and $\Delta^{DB}[.]$:

$$\underline{\Delta}_0 = \overline{\Delta}_0 - \frac{(n+1)\,dA}{2ne\,(1-\lambda)}R, \tag{34}$$

$$\Delta^{DB} = \frac{(R-3)\,(b-c)}{2\,(1-\lambda)} + \frac{(n+1)\,dA}{2ne\,(1-\lambda)}(R - \sum_{t=0}^{2}\alpha_t). \tag{35}$$

Recall that:

1. for all $\Delta < \underline{\Delta}_0$ firms would borrow permits in the first period ($z_0 < 0$), but this strategy is discarded by the functioning of the EU ETS;

2. for all $\Delta > \overline{\Delta}_0$ firms don't produce in the first period ($q_0 = 0$) in order to gain profits when the demand is expected to be high.

Therefore, our analysis is conducted in the interval $\Delta \in [\underline{\Delta}_0, \overline{\Delta}_0]$. The graphical illustrations are obtained by using the following values: $b = 1.7$; $c = 1$; $e = 1$; $d = 1$; $\alpha_1 = 1$; $\alpha_2 = 0.9$; $\alpha_3 = 0.6$; $r = 0.05$; $\lambda = 0.5$; $n = 6$; $x_3 = 0$; $A = 0.18$.

[11] Note that $\Delta = 0$ gives the same constraints than in the case without demand uncertainty. This property also holds for the cases developed afterwards.

Straightforward computations show that for all $\Delta \in [\underline{\Delta}_0, \Delta^{DB}]$, the option to wait DB is positive. This means that the expected profits when there is no first period banking exceeds the expected profits when banking at $t = 0$. Therefore it would not be optimal for the firms to bank ($z_0 = 0$). The discontinuity in the banking decision implies that the carbon prices are not linked by the inter-temporal arbitrage equation. Therefore, for all $\Delta \in [\underline{\Delta}_0, \Delta^{DB}]$, the equilibrium carbon price at $t = 0$ is determined by the fundamentals of the current period only.[12] Moreover, as banking starts at $t = 1$,carbon prices at $t = 1$ and $t = 2$ are arbitraged.

Instead, for all $\Delta > \Delta^{DB}$, banking starts as from the first period ($z_0^* > 0$) . In this case, carbon prices follow the inter-temporal arbitrage equation (with $\widehat{\sigma}_0^*$ defined by equation 30

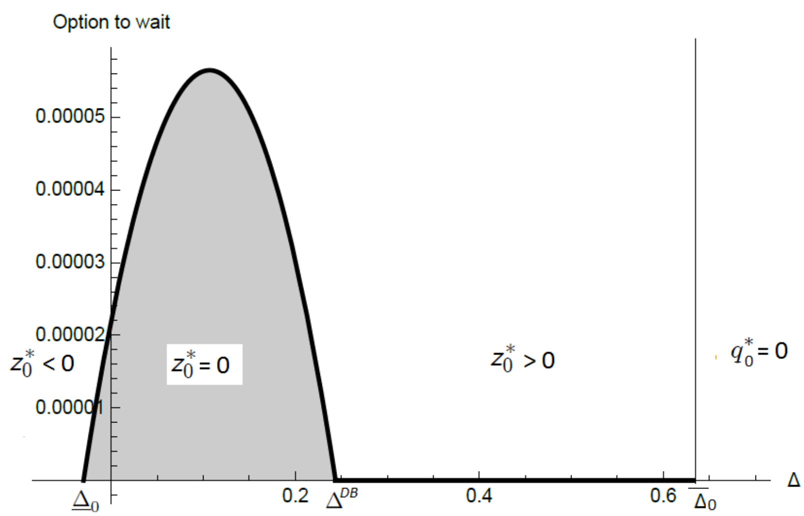


Figure 1. Delaying Banking as an option to wait

Notice that increasing the allocation, the discounting factor R or the jump probability λ (see the Figure 2) amplify the interval where the DB is positive, implying that the interval such that it is optimal to wait is broader, both for demand increase ($\Delta > 0$) and decrease ($\Delta < 0$) .

[12] In this case, $\sigma_0 = \frac{1}{e}\left((b-c) - \frac{(1+n)dA}{ne}\right)$.

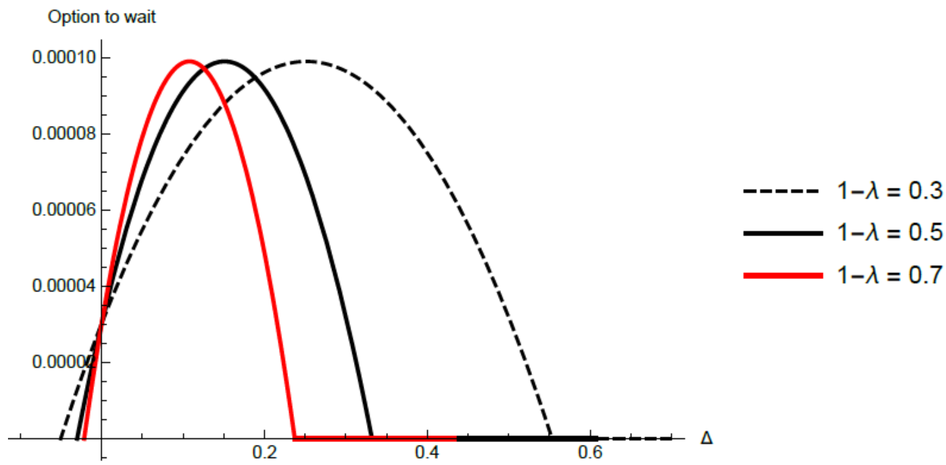


Figure 2. The impact of the jump probability on DB

4 Impact of backloading and MSR policies

The main driver of firms' choice in their banking strategy is demand uncertainty, as explained in the previous Section. We now look at the impact of the MSR and backloading on such strategies. To do so, we study how the intervention policies modify the DB equation and the interval under which it is optimal for firms to delay banking (Subsection 4.1). Then we analyze the impact on prices and welfare (Subsection 4.2).

To summarize our results, stabilization policies have two effects:

- they modify the demand variation interval under which firms prefer to delay banking until the second period;
- the shift of the demand variation thresholds such that banking is delayed creates inter-temporal inefficiencies, in particular on the CO_2 price.

All the result are analytically proved.[13] Whenever useful we illustrate them graphically. This is for instance the case for the impact of stabilization policies on consumers' surplus and firms' profits.

4.1 Delaying banking under stabilization policies

To simplify the analysis, we assume that the regulator only intervenes at $t = 1$. The cap is either tightened ($x_1 = -\overline{a}, x_2 = 0$) under backloading,or released ($\zeta_1 > 0$, $\zeta_2 = 0$) under proportional withdrawing (MSR), with respect to the benchmark case of no intervention.

[13]The detailed calculations of production, banking and welfare are available by the authors upon request, under Mathematica files.

4.1.1 Backloading

With $x_1 = -\overline{a}$, the thresholds such that it is optimal for firms to delay banking, with positive production in the first period, are modified as follows:

$$\underline{\Delta}_{0,x} = \underline{\Delta}_0 - \frac{d\,(n+1)\,\overline{a}}{2ne\,(1-\lambda)} < \underline{\Delta}_0, \tag{36}$$

$$\Delta_x^{DB} = \Delta^{DB} + \frac{d\,(n+1)\,\overline{a}}{2ne\,(1-\lambda)} > \Delta^{DB}, \tag{37}$$

$$\overline{\Delta}_{0,x} = \overline{\Delta}_0 - \frac{(n+1)\,d\overline{a}}{2ne\,(1-\lambda)} < \overline{\Delta}_0. \tag{38}$$

The interval under which it is optimal for firms to delay banking is wider with respect to the one without intervention: firms wait until the demand variation is stronger (both with demand boom and boost) to start banking (equations 36 and 37). Producing positive quantities in the first period shrinks (equation 38). Moreover, the DB value is modified as follows:

$$DB_X = DB + \frac{d\overline{a}(2A\,(R - \sum_t \alpha_t) + \overline{a})}{e^2 n^2\,(1+r)\,(2+r)\,R}. \tag{39}$$

In particular DB_X lies above DB when both are positive.

Backloading widens the interval over which is optimal to bank, whereas permits injection has the opposite effects of narrowing the interval of the demand variation under which firms do not bank.

Figure 3 illustrates these effects, as well as the injection case for comparison. The black line represents DB under the benchmark, the red line is DB_X with a fixed reduction of permits ($x_1 = -0.1, x_2 = 0$), and the dotted line represents the value of delaying banking under permits injection ($x_1 = 0.1, x_2 = 0$). This latter case has opposite but symmetric effects with respect to backloading. The demand variation interval over which firms bank shrinks.

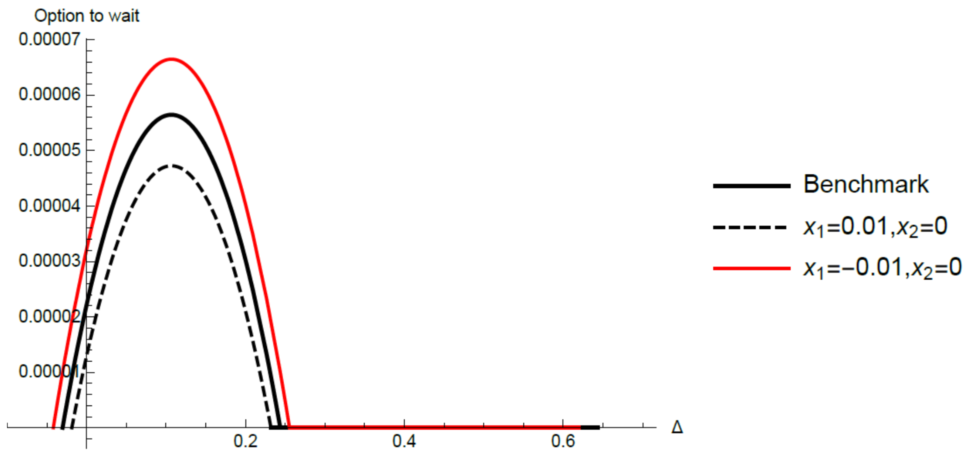


Figure 3. Fixed rules and DB

4.1.2 MSR

We study the impact on the interval variation such that it is optimal to delay banking under the MSR rule, with positive production in the first period. The critical thresholds are modified as follows:

$$\underline{\Delta}_{0,\zeta} = \underline{\Delta}_0, \tag{40}$$

$$\Delta_{\zeta}^{DB} = \Delta^{DB} + \frac{dA\,(n+1)\,((R-1)\left(\sum_0^2 \alpha_t - \zeta_1\right)\zeta_1)}{ne(1-\lambda)(R-2\zeta_1+\zeta_1^2)} > \Delta^{OW}, \tag{41}$$

$$\overline{\Delta}_{0,\zeta} = \overline{\Delta}_0 - \frac{dA\,(n+1)}{2ne\,(1-\lambda)}\zeta_1 < \overline{\Delta}_0. \tag{42}$$

The stability mechanism amplifies the values of the demand gap such that it is optimal to delay banking (equation 41) on the right side, for demand booms. The left threshold remains the same (equation 40). Positive quantities are obtained for a threshold value smaller than in the benchmark case (equation 42).

Let $\vartheta = (b-c)\,r\,(3+r) - 2\,(1-\lambda)\,\Delta$; the value of delaying banking writes as follows:

$$DB_{\zeta} = DB + \frac{\zeta_1 (Ad\,(1+n)\left(R - \sum_0^2 \alpha_t\right) - en\vartheta)}{de^2 n^2\,(1+n)^2\,R\,(R-\zeta_1)^2}$$
$$\times (Ad(1+n)((2R-\zeta_1)\sum_0^2 \alpha_t - R\zeta_1) + en\zeta_1\vartheta). \tag{43}$$

The term that adds up to DB is positive. Consequently $DB_\zeta > DB$ when both are positive, as Figure 4 illustrates. Also notice that the higher the withdrawal coefficient, the stronger the amplification effect.

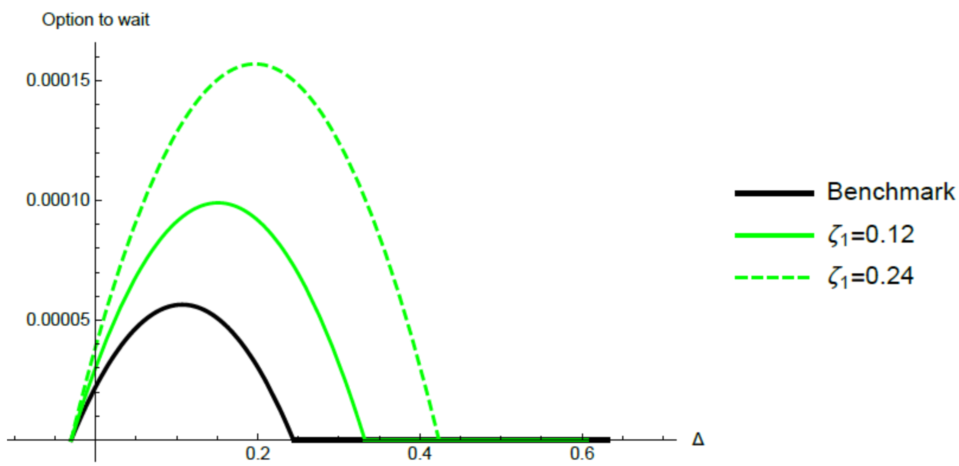


Figure 4. MSR (under different withdrawal coefficients) and DB

4.2 Impact of the stabilization policies on the carbon price

The impact on the CO_2 price can be calculated in the intervals of demand variation Δ .

4.2.1 Backloading

The following effects are at stake:

- If $\Delta \in \left[\underline{\Delta}_{0,x}, \Delta^{DB}\right]$, a backloading policy doesn't impact the banking behavior (there is no banking in either case), therefore there is no impact on the CO_2 price in $t = 0$. In the following periods, the cap reduction increases carbon prices. Notice that in the subinterval $\Delta \in [\underline{\Delta}_{0,x} \;\; , \underline{\Delta}_0]$ a backloading policy has no impact as borrowing is not allowed.

- If $\Delta \in [\Delta^{DB}, \Delta^{DB}_x]$, firms anticipate that the backloading policy will perfectly substitute private banking. Therefore they don't bank in the first period, which insulates the current allocation from the following ones. At $t = 0$, the current allocation is higher than its expected inter-temporal value. As a consequence, **over this interval, at** $t = 0$**, the permits'**

price is lower than the one without intervention. The profits maximising strategy is to produce instead of banking, to saturate the equilibrium constraint in the permits' market.[14]

- If $\Delta \in [\Delta_x^{DB}, \overline{\Delta}_0]$, firms bank as from the first period. Over this interval, the inter-temporal permits' allocation tightens the emission constraint. Therefore, the backloading policy increases CO_2 prices for all t.

The following tables detail the above-mentioned effects, by calculating the differences between the equilibrium prices after and before the intervention.

$\Delta \in t = 0$	
$[\underline{\Delta}_{0,x} \quad , \quad \underline{\Delta}_0]$	0
$[\underline{\Delta}_0 \quad , \quad \Delta^{DB}]$	0
$[\Delta^{DB}, \Delta_x^{DB}]$	$-\frac{Ad(1+n)(R-\sum \alpha_t)-en\vartheta}{e^2 nR} < 0$
$[\Delta_x^{DB}, \overline{\Delta}_{0,x}]$	$\frac{d(1+n)\overline{a}}{e^2 nR(R-1)} > 0$
$[\overline{\Delta}_{O,x}, \overline{\Delta}_O]$	$\frac{en\vartheta+d(1+n)(\Gamma-\overline{a})}{e^2 n(2+r)R}(1+r)^{t-1} > 0$

$\Delta \in t = 1, 2$	
$[\underline{\Delta}_{0,x} \quad , \quad \underline{\Delta}_0]$	$\frac{d(1+n)\overline{a}}{e^2 n(2+r)}(1+r)^{t-1} > 0$
$[\underline{\Delta}_0 \quad , \quad \Delta^{DB}]$	$\frac{d(1+n)\overline{a}}{e^2 n(2+r)}(1+r)^{t-1} > 0$
$[\Delta^{DB}, \Delta_x^{DB}]$	$\frac{d(1+n)(AR-\Gamma)-en\vartheta}{e^2 n(2+r)R}(1+r)^{t-1} > 0$
$[\Delta_x^{DB}, \overline{\Delta}_{0,x}]$	$\frac{d(1+n)\overline{a}}{e^2 nR}(1+r)^t > 0$
$[\overline{\Delta}_{O,x}, \overline{\Delta}_O]$	$\frac{en\vartheta+d(1+n)(\Gamma-\overline{a})}{e^2 n(2+r)R}(1+r)^{t-1} > 0$

Figure 5 illustrates these effects. The red line represents the DB value with backloading at period $t = 1$, whereas the benchmark is displayed in black. The interval over which there is no banking under the policy intervention is enlarged to focus on the effect of the CO_2 price decrease at $t = 0$.

[14]See equation (2).

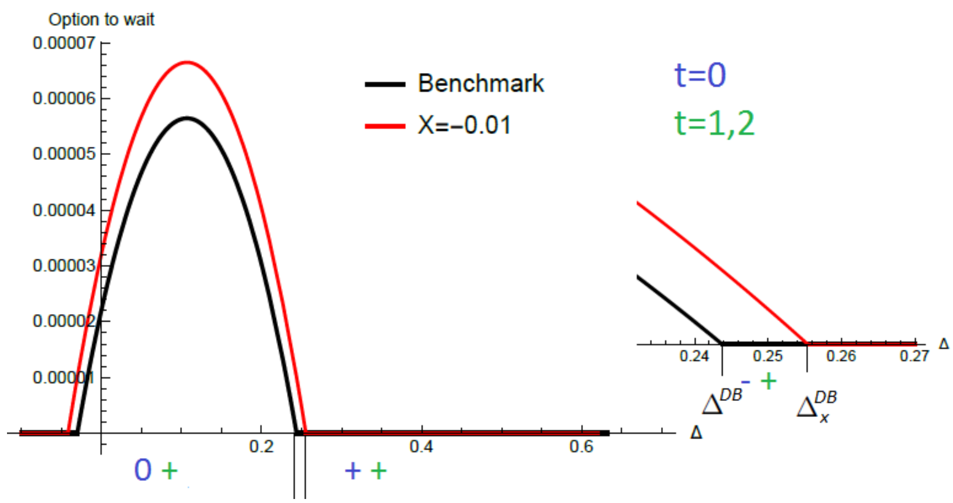


Figure 5. Backloading and impact on CO_2 prices

The short term inefficiencies in the first period are widened in Figure 6.

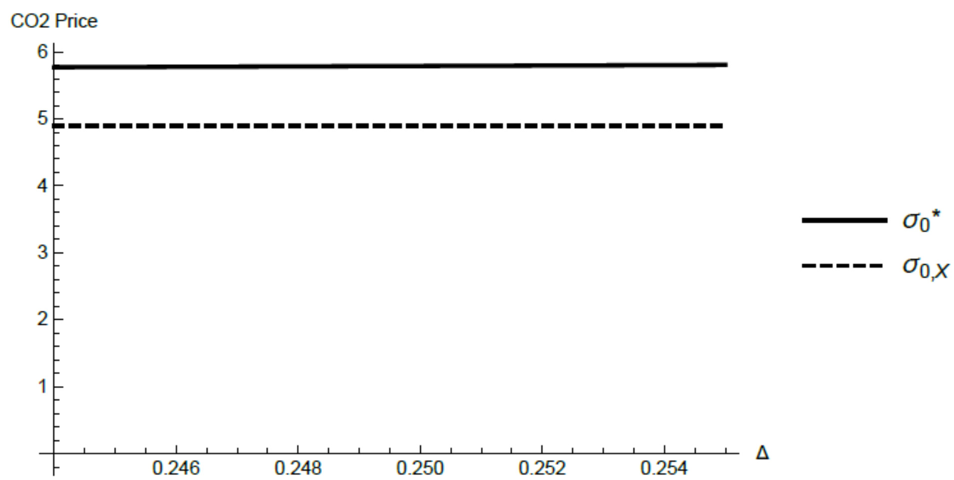


Figure 6. Carbon price: inefficient decrease

Figures 7.1 and 7.2 display the permits' price increase at periods 1 and 2, for all demand realizations (b and b_m):

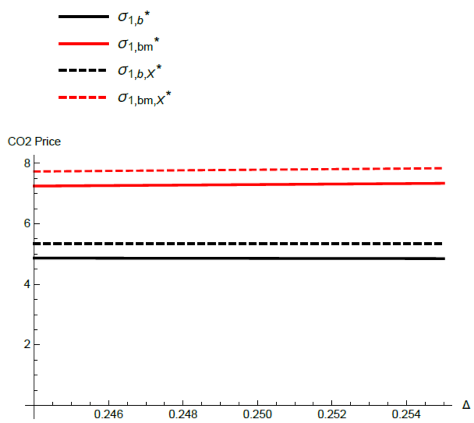


Figure 7.1 Carbon price increase

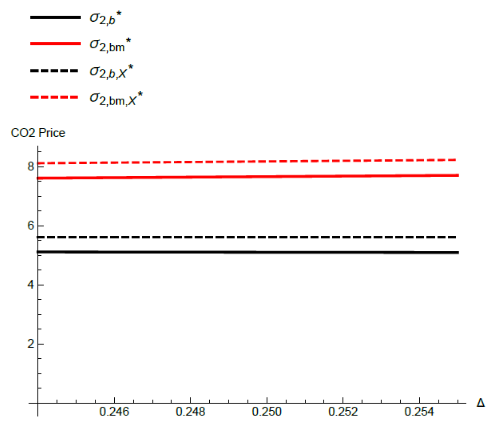


Figure 7.2 Carbon price increase

4.2.2 MSR

As in the previous case, the MSR (or proportional withdrawing) may create dynamic inefficiencies, depending on the extent of the demand variation:

- if $\Delta \in [\underline{\Delta}_0 \quad, \Delta^{DB}]$, the MSR policy does not impact the CO_2 price;
- if $\Delta \in [\Delta^{DB}, \Delta_{\zeta}^{DB}]$, at $t = 0$ **the MSR reduces the CO_2 price** over the interval where banking is inefficiently delayed with respect to the no-intervention case;
- if $\Delta \in \left[\Delta^{DB}, \overline{\Delta}_{0,\zeta}\right]$, the MSR rises CO_2 prices.

The detailed effects are as follows.

$\Delta \in t = 0$	
$\left[\underline{\Delta}_0 \quad , \quad \Delta^{DB}\right]$	0
$[\Delta^{DB}, \Delta_{\zeta}^{DB}]$	$-\frac{Ad(1+n)(R-\sum\alpha)-en((b-c)r(3+r)-2\Delta(1-\lambda))}{e^2nR} < 0$
$[\Delta_{\zeta}^{DB}, \overline{\Delta}_{0,\zeta}]$	$(1+r)^t \times \frac{Ad(1+n)(R-\sum\alpha)-en((b-c)r(3+r)-2\Delta(1-\lambda))}{e^2n(R-\zeta_1)} > 0$

$\Delta \in t = 1, 2$	
$\left[\underline{\Delta}_0 \quad , \quad \Delta^{DB}\right]$	0
$[\Delta^{DB}, \Delta_{\zeta}^{DB}]$	$(1+r)^t \times \frac{Ad(1+n)(R-\sum\alpha)-en((b-c)r(3+r)-2\Delta(1-\lambda))}{e^2nR} > 0$
$[\Delta_{\zeta}^{DB}, \overline{\Delta}_{0,\zeta}]$	$(1+r)^t \times \frac{Ad(1+n)(R-\sum\alpha)-en((b-c)r(3+r)-2\Delta(1-\lambda))}{e^2n(R-\zeta_1)} > 0$

Mixed interventions: proportional withdrawing and fixed injection. To reflect the full design of the EU decision on the stabilization mechanism, we consider the case of a fixed reinjection of permits and a proportional withdrawal. This case does not differ from the previous ones. There are still demand interval variation in which firms would bank without intervention but delay banking when the measure adjusting the cap are operational. Under the intervals where the optimal strategies differ, the permits' price decrease.

Figure 8 illustrates this case. The DB value under proportional withdrawing and fixed injection is displayed in red. We compare it both with the no intervention benchmark (in black) and the case of withdrawing at time $t = 1$ only (in green).[15]

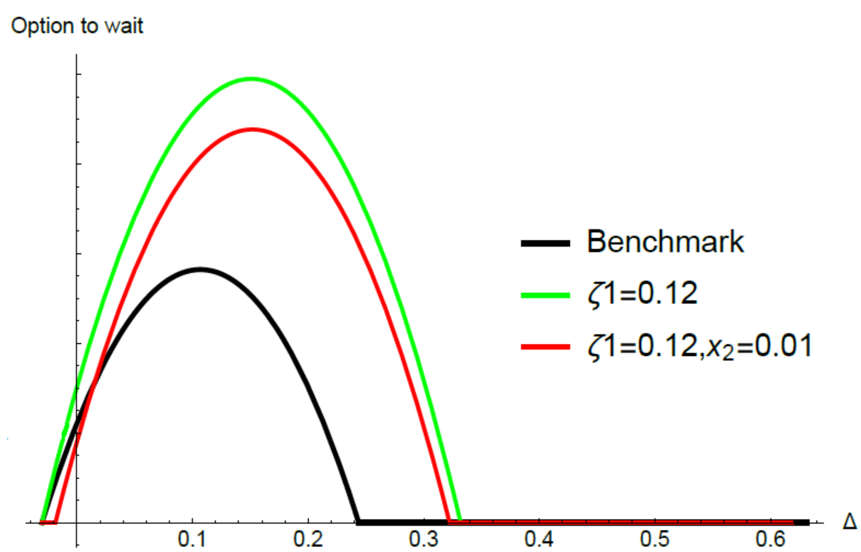


Figure 8. Mixed interventions and DB

4.2.3 Stabilization policies and welfare

The calculations above allows to calculate firms' profits and consumer welfare.

Over the demand interval variation where there is no banking, firms' profits follow the demand variation as firms produce up to saturating the permits' constraint. For higher expected demand variations, firms start banking at $t = 0$. In this case, first period production decreases and, due to Cournot competition, firms' profit increases much faster. Banking supports firms' profits maximising strategies which consist in adjusting to the demand increase (banked permits release the environmental constraint). With respect to the no intervention case, we see that if the cap becomes more stringent, firms profit is shifted below the benchmark case due to higher permits price.

As for the consumers' surplus, the demand increase dominates all the other effects, which explains why it increases. High permits price and lower production

[15]The permits withdrawn and injected do not compensate each other, to ensure that the policy modifies the overall cap.

with respect to the no intervention case explain why consumer surplus lies always below the no intervention case when the permits' supply is restricted. At the value of demand variation such that there is a discontinuity in banking decisions, consumers' surplus is discontinuous too, due to a jump in production.

Over the interval of demand variation where banking is delayed due to the cap modification, firms profits remain almost constant instead of increasing, and the consumer surplus changes the slope at the point where the banking decision changes and increases more slowly than in the no intervention case. However, consumer surplus slightly increases even in the zone of zero banking as demand increases too.

Figures 9.1 and 9.2 illustrate these effects. The no intervention case is displayed in black, the backolading in red. We have added injection (dotted line), to see mirror effects when the cap increases.

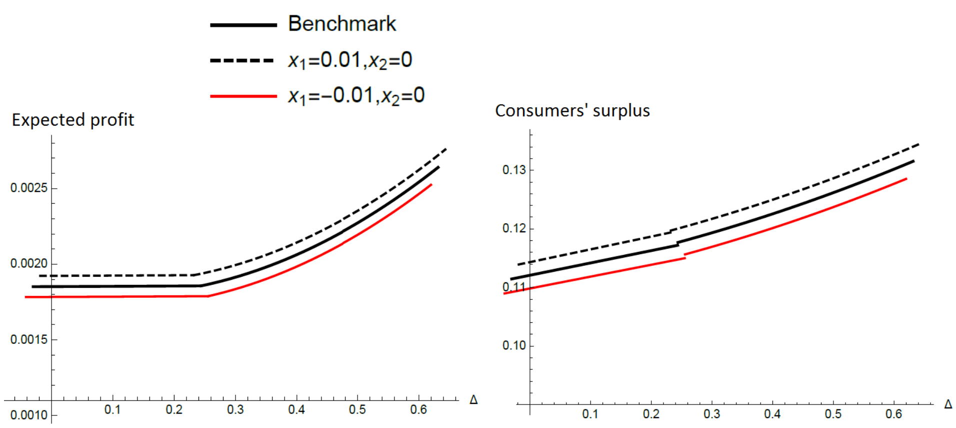
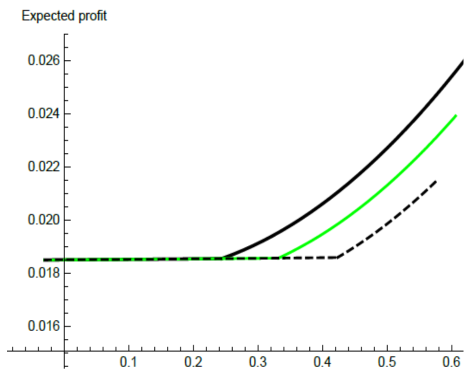


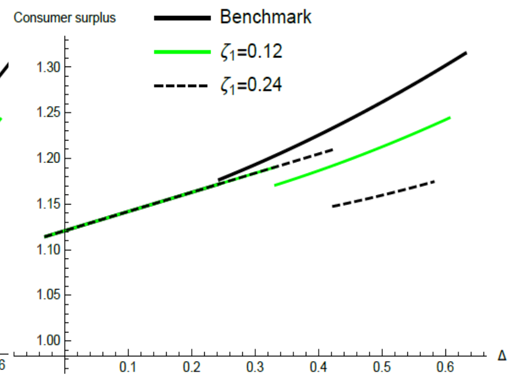
Figure 9.1 Fixed rules: firms' profit

Figure 9.2 Fixed rules: consumers' surplus

Under the MSR rule, the expected profits and consumer surplus display the same properties than in the case of the fixed withdrawal. Similar inefficiencies arise at $t = 0$ when private banking is discouraged.

In Figure 10, we focus on the impact of the increase of the withdrawing parameter, which is actually under discussion. The benchmark case is represented by the black line, the case of withdrawal at 12% by the green line and the case where the parameter is doubled is represented by the dotted line. We easily see that the higher the withdrawing parameter, the stronger the MSR effect. The discontinuity in the consumer surplus at the value of Δ where firms start banking is in this case very neat.





Figures 10.1 MSR: firms' profits under different withdrawing rates

Figure 10.2 MSR: consumers' surplus under different withdrawing rates

5 Conclusions

The MSR, as it is to be implemented, withdraws (or reinjects) a percentage of allowances in circulation. Contrarily to what is expected, withdrawing permits does not simply crowds out private banking it affect production decisions, permit prices and output prices. Most importantly, the stabilization policy interaction with the uncertainty on output demand generates (under some conditions) an option to delay banking permits. To the light of our results, we conclude that policy makers should be aware of eventual unintended effects of the measures adjusting the cap, as they modify firms' banking strategies. As long as banking is discouraged and it is replaced by some form of supply restriction, the permits price may not increase as it should. Simulating the effect of the MSR under demand shocks seems to be a critical factor to ensure the success of the EU ETS quantitative flexibility mechanisms.

As Burtraw (2015) affirmed: *"Theory and some evidence suggest that, so far, the MSR will have a limited effect in fixing the problem directly. However, to the credit of EU regulators, the MSR signals that the doctor has not given up on the patient. The European Union has a long-term commitment to emissions trading—the MSR may buy enough time for prices in the ETS to recover as the economy recovers. If that does not happen, I believe the European Union may ultimately replace the MSR with a more direct and simpler instrument—a reserve price in auctions for emissions allowances that will instill a minimum price in the market"*. In the follow up of our work, we would like to compare the impact of a price floor on firms' banking behavior, or to include investment decisions (that would impact pollution intensity) in firms' strategies.

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7 Appendices

Appendix A.1 Equilibrium values

Benchmark modelling

Exogenous case. The other equilibrium values not presented in the text for shortness are:

$$q_1^* = \frac{1}{R}\left(\frac{(1+r)\,\Gamma}{ne} + \frac{r^2(b-c)}{(n+1)\,d}\right), \tag{44}$$

$$q_2^* = \frac{1}{R}\left(\frac{(1+r)^2\,\Gamma}{ne} - \frac{\left(R-3+r^2\right)(b-c)}{(n+1)\,d}\right). \tag{45}$$

Endogenous rule. The other equilibrium values not presented in the text for shortness are:

$$q_{1,\zeta}^* = \frac{1}{D}\left(\frac{(1+r)\,\Gamma_\zeta}{ne} + \frac{\left(r^2 + r\left((1-\zeta_2)\,\zeta_1 + \zeta_2\right)\right)(b-c)}{(n+1)\,d}\right), \tag{46}$$

$$q_{2,\zeta}^* = \frac{1}{D}\left(\frac{(1+r)^2\,\Gamma_\zeta}{ne} - \frac{r\,(3+2r-(2+r)\,\zeta_1)\,(1-\zeta_2)\,(b-c)}{(n+1)\,d}\right). \tag{47}$$

Equilibrium under uncertainty

Exogenous rule.

$$\sigma_{2,b}^{*} = \sigma_2^{*} - \frac{2\,(1+r)\,(1-\lambda)\,\Delta}{e\,(2+r)\,R}, \tag{48}$$

$$\sigma_{2,bm}^{*} = \sigma_{2,b}^{*} + \frac{2\,(1+r)\,\Delta}{e\,(2+r)}, \tag{49}$$

$$= \sigma_2^{*} + \frac{2\,(1+r)\,(\lambda+(2+r)\,(1+r))\,\Delta}{e\,(2+r)\,R}, \tag{50}$$

$$q_{1,b}^{*} = q_1^{*} + \frac{2\,(1-\lambda)\,\Delta}{(3+r\,(3+r))\,(2+r)\,(1+n)\,d}, \tag{51}$$

$$q_{1,bm}^{*} = q_{1,b}^{*} + \frac{r\Delta}{(2+r)\,(1+n)\,d}, \tag{52}$$

$$q_{2,b}^{*} = q_2^{*} + \frac{2\,(1+r)\,(1-\lambda)\,\Delta}{R\,(2+r)\,(1+n)\,d}, \tag{53}$$

$$q_{2,bm}^{*} = q_{2,b}^{*} - \frac{r\Delta}{(2+r)\,(1+n)\,d}. \tag{54}$$

Endogenous rule.

$$\sigma_{2,b,\zeta}^{*} = \sigma_{2,\zeta}^{*} - \frac{(1-\zeta_1)\,(1-\zeta_2)\,(2-\zeta_2)\,(1+r)\,(1-\lambda)\,\Delta}{e\,(2+r-\zeta_2)\,D}, \tag{55}$$

$$\sigma_{2,bm,\zeta}^{*} = \sigma_{2,b,\zeta}^{*} + \frac{(2-\zeta_2)\,(1+r)\,\Delta}{e\,(2+r-\zeta_2)}, \tag{56}$$

$$q_{1,b,\zeta}^{*} = q_{1,\zeta}^{*} + \frac{(1-\zeta_1)\,(1-\zeta_2)\,(2-\zeta_2)\,(1-\lambda)\,\Delta}{(1+n)\,(2+r-\zeta_2)\,dD}, \tag{57}$$

$$q_{1,bm,\zeta}^{*} = q_{1,b,\zeta}^{*} + \frac{r\Delta}{(2+r-\zeta_2)\,(1+n)\,d}, \tag{58}$$

$$q_{2,b,\zeta}^{*} = q_{2,\zeta}^{*} + \frac{(1+r)\,(1-\zeta_1)\,(1-\zeta_2)\,(2-\zeta_2)\,(1-\lambda)\,\Delta}{(1+n)\,(2+r-\zeta_2)\,dD}, \tag{59}$$

$$q_{2,bm,\zeta}^{*} = q_{2,b,\zeta}^{*} - \frac{r\,(1-\zeta_2)\,\Delta}{(2+r-\zeta_2)\,(1+n)\,d}. \tag{60}$$

Appendix A.2 Equilibrium constraints

Exogenous rule.

Withdrawal case. When $nz_0^{*} < \underline{Z}$ and $nz_1^{*} < \underline{Z}$, the MSR reinjects permits. The absence of arbitrage opportunities given by (9) holds if $z_0^{*} \geqslant 0, z_1^{*} \geqslant 0$, i.e.

$$A \geq \frac{ne}{(n+1)\,d} \times \frac{(R-3)\,(b-c)}{\alpha_0 R - \sum_{t=0}^{2}\alpha_t} + \frac{x_1+x_2}{\alpha_1 R - \sum_{t=0}^{2}\alpha_t} \tag{61}$$

and

$$A \geqslant \frac{ne}{(n+1)\,d} \times \frac{(2r+3)\,r(b-c)}{(1+r)^2\sum_{t=0}^{2}\alpha_t - \alpha_2 R} + \frac{(2+r)\,x_2 - (1+r)^2\,x_1}{(1+r)^2\sum_{t=0}^{2}\alpha_t - \alpha_2 R}. \quad (62)$$

Backloading case. The withdrawal case is defined by $x_1 < 0$ and $x_2 < 0$, if $nz_0^* > \overline{Z}$ and $nz_1^* > \overline{Z}$. The constraints associated to this case are as follows:

$$A > \frac{ne}{(n+1)\,d} \times \frac{(R-3)\,(b-c)}{\alpha_0 R - \sum_{t=0}^{2}\alpha_t} + \frac{x_1 + x_2}{\alpha_1 R - \sum_{t=0}^{2}\alpha_t} + \frac{R\overline{Z}}{\alpha_1 R - \sum_{t=0}^{2}\alpha_t}, \quad (63)$$

$$\begin{aligned} A \quad > \quad & \frac{ne}{(n+1)\,d} \times \frac{(2r+3)\,r(b-c)}{(1+r)^2\sum_{t=0}^{2}\alpha_t - \alpha_2 R} + \frac{(2+r)\,x_2 - (1+r)^2\,x_1}{(1+r)^2\sum_{t=0}^{2}\alpha_t - \alpha_2 R} \\ & + \frac{R\overline{Z}}{(1+r)^2\sum_{t=0}^{2}\alpha_t - \alpha_2 R}. \end{aligned} \quad (64)$$

Endogenous case. The absence of arbitrage opportunities given by (9) holds if $z_0 \geqslant 0, z_1 \geqslant 0$, i.e.

$$A \geq \frac{ne}{(n+1)\,d} \times \frac{(3+r-\zeta_2)\,r\,(b-c)}{D_{z0}} + \frac{\overline{Z}\,(R - \zeta_1\,(1-\zeta_2) - (2+r)\,\zeta_2)}{D_{z0}}, \quad (65)$$

since $nz_0^* > \overline{Z}$ and

$$A \geq \frac{ne}{(n+1)\,d}\frac{r\,(3+2r-(2+r)\,\zeta_1)\,(b-c)}{D_{z1}}, \quad (66)$$

where[16]

$$\begin{aligned} D_{z0} &= \Big((1+r)^2 + (1+r)\,(1-\zeta_2)\Big)\,\alpha_0 - (1-\zeta_2)\,\alpha_1 - \alpha_2, & (67) \\ D_{z1} &= (1+r)^2\,((1-\zeta_1)\,\alpha_0 + \alpha_1) - ((1+r) + (1-\zeta_1))\,\alpha_2. & (68) \end{aligned}$$

No intervention case. The constraints such that there is no intervention, that is $\underline{Z} < nz_0^* < \overline{Z}$ and $\underline{Z} < nz_1^* < \overline{Z}$ are as follows:

$$\frac{R\underline{Z}}{\alpha_1 R - \sum_{t=0}^{2}\alpha_t} < A - \frac{ne}{(n+1)\,d} \times \frac{(R-3)\,(b-c)}{\alpha_0 R - \sum_{t=0}^{2}\alpha_t} < \frac{R\overline{Z}}{\alpha_1 R - \sum_{t=0}^{2}\alpha_t}, \quad (69)$$

$$\begin{aligned} \frac{R\underline{Z}}{(1+r)^2\sum_{t=0}^{2}\alpha_t - \alpha_2 R} \quad < \quad & A - \frac{ne}{(n+1)\,d} \times \frac{(2r+3)\,r(b-c)}{(1+r)^2\sum_{t=0}^{2}\alpha_t - \alpha_2 R} \\ < \quad & \frac{R\overline{Z}}{(1+r)^2\sum_{t=0}^{2}\alpha_t - \alpha_2 R}. \end{aligned} \quad (70)$$

[16] Notice that $D_{z0} > 0$ and for $r \in [0,1]$, $0 \leq \alpha_2 \leq \alpha_1 \leq \alpha_0 \leq 1$ we have $D_{z1} > 0$. Given the structure of the MSR in the proportional rule, (65) does not depend on ζ_1 and the constraint (66) is independent from ζ_2.

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