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Summary

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Keywords: Carbon Markets, Price Stabilizing Mechanisms, Macroeconomic Recession

JEL Classification: Q5, Q55

The paper was presented at the 2016 IAERE and 2018 SIEP Conferences, the University of Nottingham (2016) and the Second International Workshop on the Economics of Climate Change and Sustainability (2018). We wish to thank the audience for useful comments and discussions. The usual disclaimers apply.

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Emissions Markets with Price Stabilizing Mechanisms: Possible Unpleasant Outcomes*

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May 31, 2019

Abstract

There is a large consensus that low levels of carbon price cannot provide adequate incentives to invest in cleaner technologies and abate emissions. Since carbon demand and price tend to decrease during recessions, economists and policy makers have proposed different types of price stabilizing mechanisms (PSM) for emissions markets to prevent carbon price from falling too low. We investigate the effects of a PSM on investments and emissions and show that when unfavorable macroeconomic conditions reduce emissions, adjusting the supply of allowances to sustain their price may inhibit investments. Moreover, when firms invest in an integrated abatement technology, not only can emissions increase - an effect previously examined in the literature - but a PSM can exacerbate this effect when an exogenous negative shock curbs the demand of carbon.

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1 Introduction

This paper investigates the effects of introducing price stabilizing mechanisms (PSMs) in carbon markets to prevent emission prices to fall too low in case of exogenous macroeconomic downturns.

"By capping overall greenhouse gas emissions from major sectors of the economy, the EU ETS creates an incentive for companies to invest in technologies that cut emissions. The market price of allowances - the 'carbon price' - creates a greater incentive the higher it is" (European Commission, 2013). This sentence testifies the widespread consensus that, overall, higher prices on emissions provide stronger incentives to invest in lower emission technologies. Such belief is one of the reasons that recently pushed the European Commission to introduce a market stability reserve (MSR), a measure aimed at reabsorbing excessive surplus of allowances in the EU ETS market and avoid their prices reaching too low levels.[1]

We analyse with a stylised model the theoretical foundation of this belief and discuss why this generally valid principle is subject to some exceptions. Based on the intuitions suggested by our framework, we then analyse few potential unintended effects of some forms of price stabilizing mechanisms (PSM) for emissions.

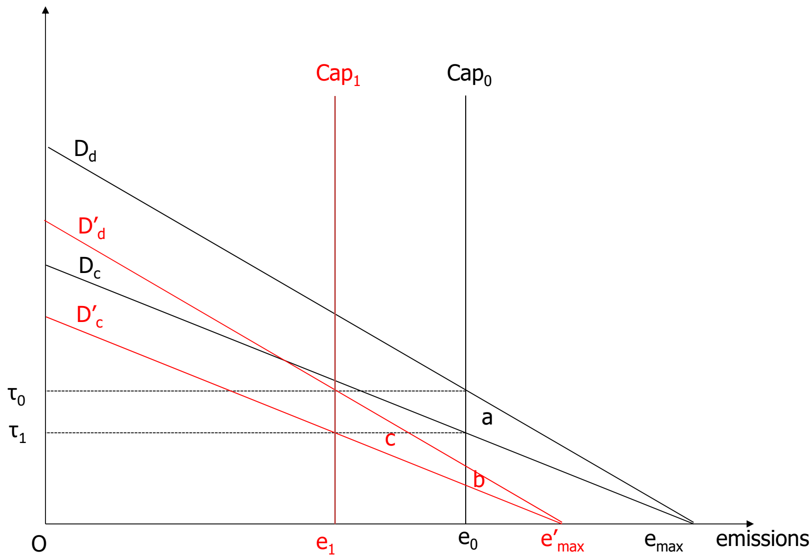
In order to understand how high carbon prices can stimulate investments in cleaner technologies, we consider a PSM that adjusts ex-post the emission cap to counterbalance negative shocks of aggregate demand. Let D_d and D_c be the aggregate demands of carbon emissions under two different types of abatement technology, namely a less efficient, or "dirty", technology, and a more efficient and "clean" one. Figure 1 depicts a situation in which the more efficient the abatement technology, the lower the cost of abating, the lower the demand of emissions. Cap_0 represents an initial emission cap, i.e. the total number of emission permits, defining the maximum level of pollution e_0 that firms can emit in the aggregate. The relative scarcity of permits with respect to the demand for emissions generates a price τ_0, if firms use the dirty technology, or τ_1, if they adopt the clean one.

In the absence of price stabilizing instruments, any change on the demand side is accommodated by a variation in emissions price that does not affect the total amount of pollution. The areas below the demand curves on the left of $e_{\max}$ represent the "benefits" of pollution that firms lose when they must emit less than $e_{\max}$. Therefore, the gain from switching to the clean technology when the cap is set at Cap_0 is represented by the area between D_d and D_c, measured in the interval between e_0 and $e_{\max}$ (area a), where $e_{\max}$ represents the level of emissions that firms would choose in the absence of regulation.

Suppose now that an exogenous macroeconomic shock reduces the aggregate demand for

[1] Decision 2015/1814 of the European Parliament and of the Council.

Figure 1:



carbon emission from D_c to D'_c and from D_d to D'_d (depicted in red in Figure 1). This situation could happen, for instance, in times of recession, when a decrease in total consumption or other sources of market uncertainty induce a slowdown of industrial output. In this new scenario, the gain from switching to the clean technology is represented by b, which is strictly smaller than a. Hence, not surprisingly, a reduction in aggregate demand reduces the incentives to invest in emission-reducing technologies. However, if the regulator reacts reducing the aggregate cap from Cap_0 to Cap_1, it can "replicate" the pre-shock situation, since the firms' gain from switching to a cleaner technologies is given by the area $(c + b) = a$. In other words, by adjusting the cap, the regulator can modulate the incentives to invest by adjusting the market to the macroeconomic conditions.

Such analysis is simple and intuitive, but can lead to imprecise conclusions since it focuses only on the benefits of switching from the dirty to the clean technology, abstracting from the related investment costs and, ultimately, the firms' profits. We enrich the analysis above by describing the mechanisms through which automatic PSMs based on cap adjustments may bring about unintended effects.

In particular, we construct a simple theoretical model to investigate how PSMs might affect investments in abatement technologies during economic downturns. We argue that reducing the aggregate cap on permits during recession periods could discourage new investments in low emission technologies by weakening the financial status of the firms. Indeed, when unfavorable macroeconomic conditions reduce emissions because of weak demand, adjusting the emission permits supply to sustain the carbon price is a pro-cyclical measure which brings about higher compliance costs and further reductions of profits, unless the regulator can compensate firms by buying back their allowances.

Moreover, the impact of the PSM depends on the type of abatement technology considered.[2] In case of integrated abatement technologies, we argue that, even when an emission reducing investment is profitable, the required high carbon prices can lead to an increase of emissions. Interestingly, this circumstance is more likely to occur during recession periods if emissions prices are prevented from decreasing in response to lower demand.

The great attention to the effects of introducing stabilizing measures in carbon markets is testified by the extensive literature studying the EU ETS (Landis, 2015; Richstein et al., 2015; Schopp et al., 2015; Fell, 2016, Hepburn et al.,2016, Holt and Shobe, 2016; Kollenberg and Taschini, 2016; Perino and Willner, 2016 and Salant, 2016). Other papers deal with hybrid emissions trading systems characterized by bounds on the price or the quantity of abatement as measures to improve the governance of carbon markets (Grull and Taschini, 2011; Wood and Jotzo, 2011; Clò et al., 2013; de Perthuis and Trotignon, 2014; Hu et al., 2015 and Abrell and Rausch, 2017). However, to the best of our knowledge, this is the first paper in this strand of literature dealing with the interaction of PSMs in emission markets and exogenous macroeconomic downturns on firms' decisions about investments and emissions.

Other related papers are Earnhart and Segerson (2012) - who study the influence of firms' financial status on the effectiveness of environmental enforcement - Ghisetti et al. (2017) - who assess the role of financial barriers behind firms' adoption of environmental innovations - and Dardati and Riutort (2016) - who study how financial constraints affect investment behavior within a cap-and-trade system, showing empirically that investments are positively related to the market value of the permit holdings. Finally, we also contribute to the economic literature on optimal environmental policy and business cycle, whose results suggest to relax the cap on emissions during economic expansions and tightening it during recessions (Heutel (2012) and Doda (2016)).

The rest of the paper is organized as follows. In the next section, we derive a simple model that allows to analyze the effects of PSMs on the decision to invest in cleaner end-of-pipe technologies. Section 3 shows how PSMs can bring about more emissions when firms invest in integrated abatement technologies, while Section 4 provides some concluding remarks. The derivation of the main results is available in a final Appendix.

[2]The literature typically distinguishes *end of pipe* abatement technologies - which filter out the emissions generated through the production process - and *integrated* technologies - which generate less emissions through a more efficient processing.

2 Investments in cleaner technologies during macroeconomic downturns

Let $\pi(x) = px - c(x) - \frac{1}{\alpha}(s-e)^2$ be the profit of the representative firm operating in the market of good x. The demand for x is given by the exogenous price p.[3] $c(x) = \frac{1}{2}x^2 + F$ represents the production cost, where $F \geq 0$ is a fixed cost. Let s be the level of carbon gross emissions generated by the production of x, and $e \in [0, s]$ the level of final emissions allowed to the firm. The parameter $\alpha > 0$ describes an end-of-pipe abatement technology affecting the cost of cleaning gross emissions. Hence, $\frac{1}{\alpha}(s-e)^2$ represents the cost of reducing carbon emissions from s to e.

Assume that $s = x$. Then, the optimal production level is $x(e) = \frac{\alpha p + 2e}{\alpha + 2}$ and, substituting back into $\pi(x)$, we can write the optimal profit as a function of the regulated emission level e, that is:

$$\pi(e) = \frac{p^2\alpha}{2(\alpha+2)} + \frac{4p}{2(\alpha+2)}e - \frac{2}{2(\alpha+2)}e^2 - F.$$

This is increasing in e whenever $e < e_{\text{max}}$, where $e_{\text{max}} = p$ is the optimal level of emissions when the firm's emissions are not restricted by any form of regulation (i. e. when $e = s$). The derivative of $\pi(e)$ represents the firm's marginal emissions benefit, $MEB = \frac{2p}{\alpha+2} - \frac{2}{\alpha+2}e$, which is a downward sloping linear function of e, with MEB equal to zero when $e = e_{\text{max}}$ and MEB equal to $\frac{2p}{\alpha+2}$ when $e = 0$.

Note also that:

1. $\frac{\partial MEB}{\partial p} > 0$ for any level of e
2. $\frac{\partial MEB}{\partial \alpha} < 0$ when $e < e_{\text{max}}$

The MEB curve represents the firm's willingness to pay for a marginal increase of emissions, in the like of the demand for emissions depicted in Figure 1.[4] We use p, that is the inverse demand function of x, as a proxy for the macroeconomic conditions and interpret the first comparative statics result above as a confirmation of the intuition that emissions demand behaves pro-cyclically (Doda, 2014). In other words, the MEB increases when the demand of x increases.

Moreover, an increase in α, i.e. an investment that reduces the cost of end-of-pipe abatement, brings about a counter-clockwise movement of the MEB curve around its intercept on the horizontal axis, e_{max}. This is precisely the conventionally assumed effect of a technological innovation as the one depicted in Figure 1 and discussed in the Introduction.

[3] This is made for the sake of simplicity as our analysis would not change qualitatively if we used a more general inverse demand function $p(x)$ with $\frac{\partial p(x)}{\partial x} \leq 0$.

[4] The demand for emissions as function of the carbon price τ can be written as $e(\tau) = p - \tau\frac{\alpha+2}{2}$ (see the Appendix).

When the firm has to decide whether to invest in a technology that increases α, it compares the cost and the benefit of such investment. The *marginal* effect of an increase of α on the emission benefit is:

$$\frac{\partial \pi(e)}{\partial \alpha} = \frac{(p-e)^2}{(\alpha+2)^2},$$

which is always positive. Therefore, emission benefits are increasing in α and the firm invests in α as long as $\frac{\partial \pi(e)}{\partial \alpha}$ is larger than the marginal cost of the investment in α.

Note that, in the relevant range $0 < e < e_{\max}$, $\frac{\partial^2 \pi(e)}{\partial \alpha \partial p} > 0$ and $\frac{\partial^2 \pi(e)}{\partial \alpha \partial e} < 0$. The first inequality suggests that the marginal benefits of investing in α can be lowered by a macroeconomic downturn that reduces p. The second inequality implies that a more stringent cap on carbon permits always increases the marginal benefit of investing in end-of-pipe technologies. Therefore, a reduction of e can counterbalance the negative effect induced by a contraction of p and a PSM can actually increase the benefit related to an investment in end-of-pipe technologies during a macroeconomic downturn. However, this does not imply that the firm would actually invest. In fact, despite the possible positive effect that a tighter cap has on the investment benefits, a reduction of e increases abatement costs and, consequently, reduces profits. This can be a serious issue during macroeconomic downturns and in the presence of fixed costs. Such concern is summarized by the following claim:

Claim 1 *During macroeconomic downturns a PSM can have pro-cyclical effects and hamper investments in cleaner technologies.*

To illustrate this claim, we provide a numerical example. We consider a discrete investment in an end-of-pipe technology that increases α from $\alpha_0 = 1$ to $\alpha_1 = 2$. Let Φ represent the fixed cost of such investment. We compare the investment contingent profits under three scenarios. The first represents a situation characterized by a high emissions demand ($p = 100$) and a high emissions cap ($e = 70$). The second scenario considers the case where the demand is lowered by a recession ($p = 80$) while the cap is unchanged ($e = 70$). Finally, in the third scenario, the emission cap is adjusted to the lower demand of permits in order to guarantee the same emission price of the first scenario. This requires $p = 80$ and $e = 50$ (see Figure 2). Table 2 summarizes the profits values under the three alternative scenarios, for both α_0 and α_1.

Table 1

	Scenario 1 $p = 100$ and $e = 70$	**Scenario 2** $p = 80$ and $e = 70$	**Scenario 3** $p = 80$ and $e = 50$
$\alpha_0 = 1$	$\pi = 4700 - F$	$\pi = 3166.\bar{6} - F$	$\pi = 2900 - F$
$\alpha_1 = 2$	$\pi = 4775 - F$	$\pi = 3175 - F$	$\pi = 2975 - F$

In the first scenario, the investment benefit, that is the difference between $\pi = 4775 - F$ and $\pi = 4700 - F$, is 75 and corresponds to the area labeled as a in Figure 2, i.e. the area between $MEB(e, \alpha_0, p = 100)$ and $MEB(e, \alpha_1, p = 100)$ in the interval $70 < e < 100$. Note that in this scenario the carbon price is 20 under α_0 and 15 under α_1.

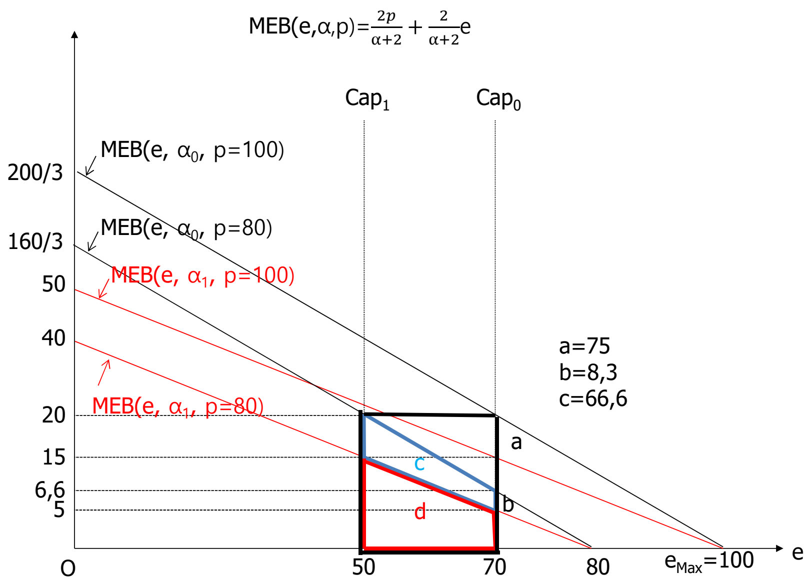
In the second scenario, characterized by a macroeconomic downturn and an unchanged supply of carbon permits, carbon prices are significantly lower, namely $6.\bar{6}$ under α_0 and 5 under α_1. Moreover we observe a reduction of the benefit of investing in the end-of-pipe technology which is now equal to $8.\bar{3}$, that is the difference between the profit under α_0, $\pi = 3166.\bar{6} - F$, and the profit under α_1, $\pi = 3175 - F$. Such benefit corresponds to the area between $MEB(e, \alpha_0, p = 80)$ and $MEB(e, \alpha_1, p = 80)$ in the interval $70 < e < 80$. As a consequence, if $8.\bar{3} < \Phi < 75$, the net investment benefit is positive under $p = 100$, but becomes negative when the decrease of demand brings about a reduction of the output price to $p = 80$.

The environmental regulator can restore the initial investment benefit by reducing e in response to a reduction of p. When $p = 80$ the cap on carbon permits that allows to pursue such objective is $e = 50$. Indeed, when $e = 50$ and $p = 80$, the carbon equilibrium prices are as in the first scenario, that is 20 under α_0 and 15 under α_1. Moreover, the original investment benefit is restored since it is now equal to $(2975 - F) - (2900 - F) = 75$, corresponding to the area between $MEB(e, \alpha_0, p = 80)$ and $MEB(e, \alpha_1, p = 80)$ in the interval $50 < e < 80$ (the sum of b and c in Figure 2).

However, restoring the original investment benefit comes at the cost of lower profits: for both α_0 and α_1 profits are higher under Scenario 2 than under Scenario 3. This is, of course, a reason for concern whenever the relatively heavier burden of the fixed costs makes the investment not viable. When this happens, firms can either resort to un-authorised emissions (if the expected cost of being caught is low) or exit the market. For instance, if $p = 80$, $2975 < F < 3166.\bar{6}$ and $\Phi < 8.334$, the firm would find it profitable to invest when $e = 70$ while negative profits could prevent investments if $e = 50$. Lower profits are the consequence of higher compliance costs due to a lower emissions cap. In Figure 2, such additional costs are identified by the areas d and $c + d$ which are equal to 200 and $266, 6$, respectively, that is the difference between the profits under Scenarios 2 and 3, evaluated for the cases of $\alpha = 2$ $\alpha = 1$.

In a more realistic scenario with heterogeneous firms and capacity constraints, we can expect a compounding effect for which, if the joint effect of a recession and a more stringent emissions cap push some firms out of business, the demand of permits decreases further, causing a new reduction of emissions price that, in turn, could induce the regulator to react by adopting an even tighter cap. Of course, the relevance of such issue depends on the

Figure 2:



firms financial conditions and other factors as, for instance, the availability of credit. In fact, firms could still invest and cover their temporary losses by either using their own assets or accessing financial markets. However, since these options might be severely restrained during recessions, tightening the cap can become a strongly pro-cyclical policy that can hamper investments in cleaner technologies.

It is worth noting that alternative policy options have been proposed to stabilize carbon prices (see, for instance, Grull and Taschini, 2011; Wood and Jotzo, 2011 and Clo et al., 2013). For instance, the regulator can commit to buy back any quantity of permits at a predetermined price, giving to the representative firm the possibility of choosing the level of e which is optimal for that price. Such price floor regime does not penalize investments in cleaner technologies during macroeconomic downturns. In fact, the regulator could buy back any permit at $\tau = 20$ if $\alpha_0 = 1$, or at $\tau = 15$ if $\alpha_1 = 2$. If p goes from 100 to 80 when such price floor is in place, the emissions demands shift down to $MEB(e, \alpha_0, p = 80)$ and $MEB(e, \alpha_1, p = 80)$, and the representative firm would find optimal to sell 20 units of e and emit $e = 50$ as in Scenario 3. Notice that the burden of such reduction is transferred to the regulator (i.e. to the society) who pays the firm 400, under $\alpha = 1$, and 300, under $\alpha = 2$, so that firm's profits are now greater than those arising under Scenario 2 and equal to $\pi = 3300 - F$ and $\pi = 3375 - F$, respectively. The analysis of the distributional effects due to the implementation of different PSMs is an interesting issue that deserve further investigation, but is beyond the scope of this paper.

In the following section, we discuss how preventing emission price to go below a certain level could imply another unintended outcome when firms invest in integrated abatement technologies.

3 Integrated abatement technologies, environmental quality and macroeconomic downturns

Assume that $s = \frac{1}{\omega}x$ is the level of carbon gross emissions *generated* by the production of x, where $\omega \geq 1$ is the parameter of production cleanliness. Different than the previous section, this assumption describe situations in which the firm can invest in a more efficient technology that *generates* less emissions thanks to an increase of ω, rather than filtering it away at the end of the production process through α.

Under this specification of s, the marginal emissions benefit is:

$$MEB = \frac{2\omega p}{\alpha\omega^2 + 2} - \frac{2\omega^2}{\alpha\omega^2 + 2}e,$$

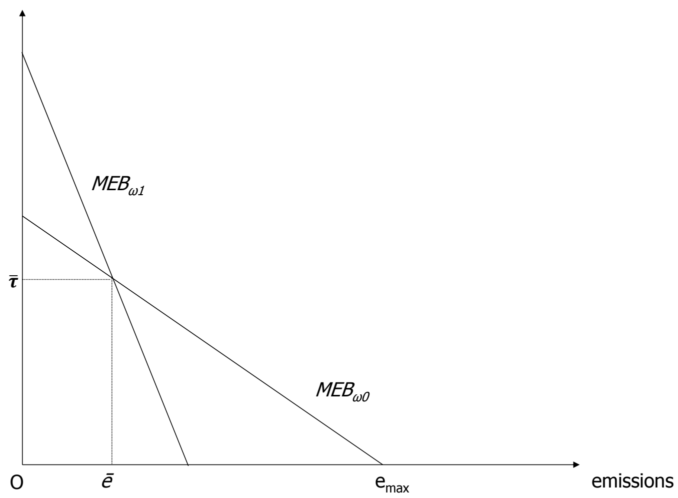
implying that $\frac{\partial MEB}{\partial \omega} < 0$ when $\hat{e} < e$, with $\hat{e} = \frac{p(2-\alpha\omega^2)}{4\omega}$. Note that $0 < \hat{e} < e_{\max}$, so that the effect of an increase of ω, say from ω_0 to ω_1, determines a clockwise rotation of the MEB curve as it is represented in Figure 3.[5]

The possibility of intersections between the marginal abatement curves representing different integrated technologies has been pointed out by several authors (Amir et al., 2008; Bauman et al., 2008; Baker et al., 2008 and Brechet and Meunier, 2014). The intuition is relatively simple: a technological progress that increases the emission coefficient ω, decreases the optimal level of unregulated emissions $e_{\max} = \frac{p}{\omega}$ so that the horizontal intercept shifts to the left in Figure 3. Moreover, when ω increases, an extra abatement of emissions from s to e becomes more "expensive" since it applies on more units of output, which explains the greater steepness of the MEB curve.

The intersection of the MEB curves has interesting implications in terms of environmental regulation, as it implies that pushing the emissions price above a certain critical level can bring about higher emissions when firms innovate as compared to when they do not (see for instance Perino and Requate, 2012; Brechet and Meunier, 2014 and Dijkstra and Gil-Molto, 2018). In Figure 3, this circumstance occurs when the emissions price lies above the threshold value $\bar{\tau} = \frac{p\omega_0\omega_1}{\omega_0+\omega_1}$, corresponding to the emission level where the two *MEB*

[5] In Figure 3, $\bar{e} = \frac{p(2-\alpha\omega_0\omega_1)}{2(\omega_0+\omega_1)}$. Note that $\bar{e}$ coincides with $\hat{e}$ when we consider marginal changes of ω, that is when $\omega_1 \to \omega_0$.

Figure 3:



functions cross each other.[6]

This observation has an interesting corollary in terms of our analysis of the effects of a price stabilising mechanisms. In our model, the exogenous macroeconomic conditions are proxied by p, with high levels of p corresponding to a growing and wealthy economy, and low levels of p corresponding to business cycle contractions, with slowdowns in the economic activities. Since $\bar{\tau}$ is increasing in p, it decreases during a macroeconomic contraction. Therefore, if the regulator commits to avoid that the emission price decreases below a minimum level τ^*, the "likelihood" that innovation increases emissions is greater during recession periods, in the sense that if $\bar{\tau}$ decreases, the range of parameters for which $\bar{\tau} < \tau^*$ is larger.

Claim 2 *When a PSM prevents emission price to decrease, a macroeconomic downturns can increase the chances that emissions increase after an investment in integrated abatement technology.*

Our stylised model is clearly not able to evaluate formally the probability that $\bar{\tau} < \tau^*$. But the observation above suggest that further research is needed to explore these circumstances.

4 Conclusions

Our paper explores the effects of price stabilising mechanisms in relation to the macroeconomic conditions. We use a stylised model that accommodates different types of abatement technologies and describes firms' behavior in relation to the evolution of total demand.

[6]By substituting $\hat{e}$ back into the MEB function we get $\hat{\tau} = \frac{p\omega}{2}$. Note that $\bar{\tau} \to \hat{\tau}$ as $\omega_1 \to \omega_0$.

Our results suggest that automatic price stabilizers could have unintended consequences in terms of incentives to invest in abatement technologies. Moreover, even when investments do materialise, the impact on total emissions is ambiguous, particularly during an economic recessions. This calls for more attention to the pro-cyclical nature of some types of PSMs.

To the best of our knowledge, virtually all institutions that established a carbon market have also put in place complementary policies to reduce the burden on firms and consumer, while keeping the right incentives for emission abatement. For instance, the European ETS system foresees free allocations (mainly for energy intensive industries) and the use of international credits. The European Fund for Strategic Investment also provided guarantees to boost investment in the field. Moreover, a share of the revenues from the sale of allowances can be used to co-finance large-scale demonstration projects (e.g. in the EU through the NER300 programme[7], the Innovation Fund [8] or other member state specific funds), which can foster the development of cheaper and more effective technologies. Hence, the results of our paper should not be considered as evidence against the use of a PSM.

The aim of our paper is rather to highlight the importance of analysing and designing climate policies taking into account the existing macroeconomic policy tools and the overall industrial policy strategy. Failing in this, can not only unnecessarily aggravate the burden of emission abatement, but also hamper the achievement of ambitious environmental goals. In our view, the impact of the business cycle deserves further research, since some countries may not have the necessary fiscal space to respond with sufficiently strong countercyclical measures in time of crisis.

We believe that our results have also political economy implications. A procyclical environmental tool can erode the political support for environmental policies, and induce some governs to backtrack their commitments to international agreements.

[7] For an overview, see http://ec.europa.eu/clima/policies/lowcarbon/ner300/index_en.htm

[8] For an overview, see https://ec.europa.eu/clima/policies/innovation-fund_en

Appendix

In this appendix we derive the results for the more general formulation that incorporates both the end-of-pipe technology - parametrised through α - and the integrated technology - parametrised through ω. The representative firm maximise its profits, given by $\pi(x) = px - c(x) - \frac{1}{\alpha}(s-e)^2$, taking into account emission regulation. The production cost is set for simplicity as $c(x) = \frac{1}{2}x^2 + F$, $F > 0$ and $s = \frac{1}{\omega}x$. The results discussed in Section 2 simply require that $\omega = 1$.

Under no regulation, $e = s$ and the firm maximizes $\pi = px - \frac{1}{2}x^2 - F$, setting $x_{\max} = p$, so that $e_{\max} = \frac{p}{\omega}$, and

$$\pi_{\max} = \frac{1}{2}p^2 - F.$$

In the case of environmental regulation we have instead:

$$\frac{\partial \pi(x)}{\partial x} = p - x - \frac{2}{\alpha}(s-e)\frac{1}{\omega} = 0,$$

from which we obtain the optimal production level $x(e) = \omega\frac{\alpha p\omega + 2e}{\alpha\omega^2+2}$. Substituting this back into $\pi(x)$ we can write the optimal profit as a function of the emission level e, that is:

$$\pi(e) = \frac{1}{2}\frac{p^2\alpha\omega^2}{\alpha\omega^2+2} + \frac{1}{2}\frac{4p\omega}{\alpha\omega^2+2}e - \frac{1}{2}\frac{2\omega^2}{\alpha\omega^2+2}e^2 - F,$$

which is always increasing in p, and increasing in e whenever $e < e_{\max} = \frac{p}{\omega}$. Therefore,

$$MEB = \frac{\partial \pi(e)}{\partial e} = \frac{2\omega p}{\alpha\omega^2+2} - \frac{2\omega^2}{\alpha\omega^2+2}e$$

which is a downward sloping linear function of e with $MEB = 0$ when $e = e_{\max} = \frac{p}{\omega}$.

By inverting the MEB function we can write the demand of emission as $e(\tau) = \frac{p}{\omega} - \tau\frac{\alpha\omega^2+2}{2\omega^2}$, where τ represents the emissions price.

The partial derivatives of the MEB function show that:

$$\frac{\partial MEB}{\partial p} = \frac{2\omega}{\alpha\omega^2+2} > 0 \qquad \text{for any level of } e;$$

$$\frac{\partial MEB}{\partial \alpha} = -2\omega^3\frac{p - e\omega}{(\alpha\omega^2+2)^2} < 0 \qquad \text{for } e < e_{\max} = \frac{p}{\omega};$$

$$\frac{\partial MEB}{\partial \omega} = \frac{4p - 2\alpha\omega^2 p - 8\omega e}{(\alpha\omega^2+2)^2} < 0 \qquad \text{for } \hat{e} = \frac{p(2-\alpha\omega^2)}{4\omega} < e,$$

where $\hat{e}$ is always smaller than $e_{\max} = \frac{p}{\omega}$ and it is greater than zero when $\alpha\omega^2 < 2$.

The partial derivatives of $\pi(e)$ are

$$\frac{\partial \pi(e)}{\partial \alpha} = \frac{\omega^2}{(\alpha\omega^2 + 2)^2}(p - e\omega)^2,$$

and

$$\frac{\partial \pi}{\partial p} = \frac{p\alpha\omega^2}{\alpha\omega^2 + 2} + \frac{1}{2}\frac{4\omega}{\alpha\omega^2 + 2}e,$$

which are both positive, and

$$\frac{\partial \pi(e)}{\partial \omega} = \frac{2(2e + p\alpha\omega)(p - e\omega)}{(\alpha\omega^2 + 2)^2}$$

which is positive when $e \leq e_{max} = \frac{p}{\omega}$.

Further we can show that

$$\frac{\partial^2 \pi(e)}{\partial \alpha \partial p} = 2\frac{\omega^2}{(\alpha\omega^2 + 2)^2}(p - \omega e)$$

and

$$\frac{\partial^2 \pi(e)}{\partial \alpha \partial e} = -2\frac{\omega^3}{(\alpha\omega^2 + 2)^2}(p - \omega e)$$

which are, respectively, positive and negative as long as $e < e_{\max} = \frac{p}{\omega}$.

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