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Policy Uncertainty and Investment in Low-Carbon Technology [*]

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Abstract

In the context of an emission trading scheme (ETS), we study how uncertainty over the environmental policy affects firms' investment in low-carbon technologies. We develop a three period sequential model that combines the industry and the electricity sectors and encompasses both irreversible and reversible investment possibilities for the firms. Additionally, we explicitly model the policy uncertainty in the regulator's objective function as well as the market interactions that give rise to an endogenous price of permits. We find that uncertainty reduces irreversible investment and that the availability of both reversible and irreversible technologies partially eliminates the positive effect of policy uncertainty on reversible technology found in previous literature. Furthermore, we provide a framework that allows to assess the efficiency of different implementations of the scheme.

JEL classification: D78, D80, L51, Q58
Keywords: Emission Trading Scheme, low-carbon investment, policy uncertainty, mechanism design, irreversible and reversible investment

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1 Introduction

Environmental issues have become a top priority due to the recent awareness of global natural constraints, and many policies have been developed to stimulate a more sustainable usage of resources. At a global governance level, the instruments chosen to reach sustainability and reduction of greenhouse gases (*GHG*) consist of market-based mechanisms such as emissions trading. Currently, the biggest Emission Trading Scheme is the European one (*EU ETS*). An Emission Trading Scheme (*ETS*) is a cap-and-trade system designed to create incentives for firms to invest in low-carbon technology, with the final goal of reducing carbon dioxide (CO_2) emissions. In practice, by allocating a certain amount of tradable emission permits for each of the energy-intensive installations covered by the scheme, the *ETS* places a limit on total CO_2 emissions. This system creates a market for these permits so that, given that firms have different marginal costs of abatement, some installations find it profitable to reduce their emissions and sell the unused allowances. This aggregate limit, or cap, and consequently the allocation of permits per each installation, is set by a regulatory authority periodically and at a decreasing rate. The periodicity of the cap decision allows the policy makers to update the limit according to the realized technology innovation path, to the actual investment process by firms and to possible government changes or priority revisions due to business cycles. Although this system entails a flexibility gain for the authority, it also leads to uncertainty over the future cap and the future market price of the allowances for the firms. As a consequence, given the long-term nature of investments in low-carbon technologies, the return on investment in abatement is also unknown at the time of investing. Thus, how does uncertainty over the policy decisions, driven by the periodicity of the cap, affect firms' investment in low-carbon technologies? More specifically, is the *ETS* efficient when firms do not know future levels of the cap?

1.1 Literature

Previous literature has attempted to address similar questions. Blyth, Bradley, Bunn, Clarke, Wilson, and Yang (2007) study how environmental policy uncertainty affects power sector investment in low carbon technology. Following the Real Option Theory, they develop a model of firm investment where firms can choose among different investments that are all irreversible. According to what the theory predicts,[1] they find that uncertainty over

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[1] See Dixit and Pindyck (1994).

the price of permits, i.e., the process that drives the future flow of profits, decreases irreversible investment. However this analysis presents several limitations. First of all, policy uncertainty is represented as an exogenous shock over the price of permits. This setting (an exogenous price and the absence of a policy objective function) rules out any consideration of the feedback effect from the firms to the policy maker, which is important from a policy design perspective. Secondly, it concerns only a portfolio choice: that is, the firms' production is held fixed, which eliminates a potential instrument to deal with future uncertainty. Finally, it focuses only on one of the sectors of the *EU ETS*, the power sector, and only one possible kind of investment in low-carbon technology - the irreversible one.

According to Shapiro and Varian (1999), a technology investment is comparable to an option when switching costs are high and therefore a technology lock-in effect comes into play. Namely, firms find themselves having little or no flexibility to switch to other technology solutions once they have implemented one of them. We extend this definition to the case when switching costs are not extremely high but firms simply do not find profitable to switch back to previous technology solution after having invested in new one. Following this extended definition, we can distinguish two kinds of investment specific to the power sector: an irreversible one, which means that once in place, it has to be used in production - such as renewable energy resources or energy efficiency - and a reversible one, which means that if the investment was made, the firm can still decide whether to use this technology for production or not - as is the case of fuel switching.

Differentiating between these two options is of vital importance for this research. In fact, in the analysis by Chen and Tseng (2011), reversible investment is found to increase with uncertainty. The investment they refer to takes the form of building up a gas plant, which allows power companies to use gas for production when the price of coal (the input cost plus the permit price) is higher than the gas price and vice-versa (fuel switching). This investment provides electricity generators with a precautionary instrument that helps to hedge the fuel price risk, and, therefore, the higher the uncertainty, the more they are inclined to build gas plants. However, the same criticisms made of Blyth, Bradley, Bunn, Clarke, Wilson, and Yang (2007) can be directed at this contribution. Here, uncertainty comes from the price of the permits and from fuel prices, leaving the regulatory part exogenous to the model. Moreover, the production is fixed, so there is only a substitution effect. And, finally, it considers only the power sector in isolation, with only one type of investment possibility - which, under the Shapiro and Varian (1999) definition, is the reversible one.

Colla, Germain, and Van Steenberghe (2012) take a step further in modeling this market, by introducing an objective function for the authority and endogenizing the price of the permits. They study the optimal environmental policy for the *EU ETS* in the presence of speculators in the market for allowances. However, in their setting, firms are homogeneous, with only the choice of irreversible investment, and uncertainty regards future demand for the firms' product, and not the policy rule.

1.2 Our Contribution

As in previous literature, we consider the current set up of the *EU ETS* as representative of a general *ETS*.[2] In this environment we propose combining uncertainty over the policy rule with both possibilities of reversible and irreversible investment. We therefore put forward a stylized but comprehensive setting where the two sectors regulated by the *EU ETS*, industry and electricity, have access to different low-carbon technologies. Industries have access only to an irreversible clean technology. On the other hand, power companies may use both an irreversible clean technology and a reversible technology, namely fuel switching: electricity generation firms can construct a gas plant but they still have the option to produce with the previously existing coal plant.[3] We explore the final effect of the interaction of these firms in the market in terms of aggregate investment. For this purpose, we develop a three-period sequential model. In the first period, two firms, representative of the two sectors, decide whether to invest in CO_2 abating technologies; in the second period, uncertainty over the relative preference of the authority over economic activity versus environmental concerns is realized and the regulator chooses the aggregate cap. Finally, firms decide on their production and fuels and the permits market clears.

To the best of our knowledge, no other model has put together both carbon-intensive industries and electricity generators, which is essential to capture the final behavior of the aggregate level of investment - both reversible and irreversible - in low-carbon technology. We also allow for output effects in addition to substitution effects, by letting the firms decide on production

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[2] Appendix A provides a description of the *EU ETS* to the extent relevant for the purpose of this analysis and explains the concept of policy uncertainty in this context. For further information regarding the EU ETS see Ellerman, Convery, Perthuis, and Alberola (2010) and Chevallier (2011).

[3] Irreversible clean technologies may refer to technologies which improve energy efficiency or, for power plants, to renewable energy sources (wind, solar, geothermal or biomass). We exclude the reversible technology possibility for the industry sector as it is not a feasible option for industrial production.

levels. Additionally, we clearly identify the uncertainty parameter in the regulator's objective function as the relative weight the authority puts on environmental concerns. This provides us with a feedback effect, since the regulator internalizes the effect of her choices on firms' investment decisions. Moreover, the political nature of uncertainty allows us to derive important policy implications regarding commitment incentives by policy makers. This is because this type of uncertainty can be directly influenced by the authority, as opposed, for instance, to demand uncertainty. Finally, our formulation allows to derive a closed form solution and therefore to clearly identify the effects of the different forces that play a role in this complex picture. Our model can thus be used as a benchmark to further include additional features of interest of the different *ETS* and study how the outcome varies with them.
Our results show that, given a balanced proportion of the two regulated sectors and an uncertainty process that follows a mean preserving spread, any degree of policy uncertainty, driven by the impossibility for the authority to fully determine *ex ante* the future values of the cap, decreases aggregate irreversible investment. Regarding reversible technology, if the policy makers are more environmentally concerned, uncertainty always reduces investment. When they are strongly biased towards the economic activity, however, uncertainty might increase investment in reversible technology, since it creates an option value for investing. This positive effect is partially nullified by the interplay with the irreversible technology.

The paper is organized as follows. Section 2 introduces the model while section 3 presents the methodology and the results. Finally, Section 4 concludes and sets the path for future research.

2 The Model

We develop a model of three sequential periods, which encompasses the key elements of a cap-and-trade system. As in the actual market for permits, firms have to decide on their investment strategy before knowing with certainty the future amount of permits they will be entitled to. Once the cap is set and firms decide on their production levels, the price is endogenously determined by the interplay of firms' supply and demand of allowances. We abstract both from temporal trading and speculation, which allows us to focus on the direct market interactions between the firms and the regulator. For the same reason, we do not include demand side effects, by assuming that firms can always sell their production at a constant price. The model considers three different agents: a regulatory authority, or policy maker, and one firm from each of the two regulated sectors (industries and electricity producers). Given the large number of installations covered by this type of schemes (the *EU ETS* covers around 11 300 energy-intensive installations from 30 countries), and the fact that the allowances are traded on electronic platforms, it is difficult for any particular firm to exert significant market power in the market for permits. Therefore, we assume perfect competition amongst firms in this market.[4] Furthermore, we assume a continuum of homogeneous firms within each sector and therefore consider only a representative firm from each. This implies, in particular, that the price that prevails in the market will be determined, in our model, as the result of the interaction of the two firms, because it represents the actions taken by the entire market. Finally, all agents are risk neutral.

2.1 The regulator

As laid out in the introduction, we focus on the effect of having uncertainty over the policy maker's preferences. Although a long term target for the cap is set out in advance, the policy maker decides period by period on the actual limit in effect for that given trading period (phase), which might be tighter or looser than the average, according to the importance she puts in environmental concerns versus economic outcomes. This difference in preferences might derive from priority revisions resulting from business cycles,[5] unexpected changes in the technological innovation path, different political preferences of changing governments, or even the presence and influence of political lobbies. Considering that a standard payoff period for a low-carbon investment is between 15 and 20 years, when firms make their investment decisions, their payoff is uncertain - particularly, investment in low-carbon technology is more profitable if the forthcoming emission cap is tighter, and vice-versa.

Evidence of policy uncertainty in the context of the *EU ETS* is presented in the following figure. It depicts the information available to the firms in 2003 and the realized cap for the first and the second trading periods. In

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[4] This is true even though allowances are not distributed equally amongst firms: in the *EU ETS*, power companies receive a much higher share of allowances. However, the model can be extended to include some market power amongst the firms in the electricity generating sector.

[5] In particular, whenever there is an economic recession, the government in power might choose to loosen the cap, so as to bolster the economy.

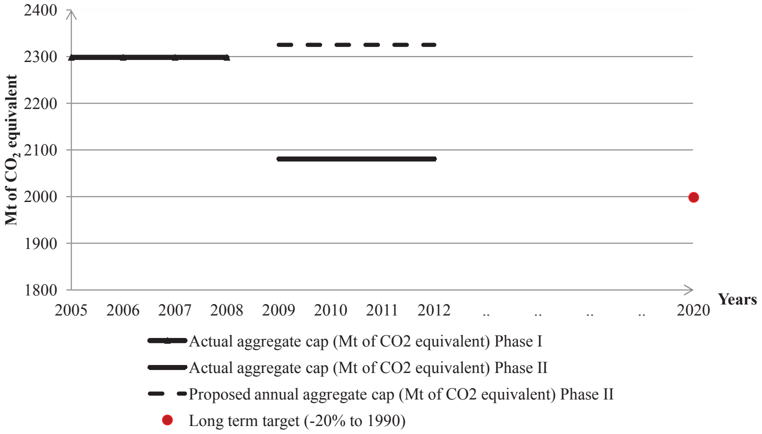

Figure 1: Annual aggregate cap as known in 2003. Source: European Commission.

fact, in 2003 firms were aware of the aggregate cap level for the first trading period (2005-2007) and they had expectations on the second phase cap (the dashed line). In 2007 the European Commission announced a second-phase cap significantly lower than the expected one due to the unforeseen over-allocation of the first phase. The difference between the expected cap for 2008-2012 (dashed line) and the realized one (the full line) proves evidence of the uncertainty around the future values of policy parameter, namely the aggregate cap.

We model this uncertainty through a parameter, $\tilde{\gamma}$, measuring the weight put by the policy maker on economic expansion, proxied by the firms' profits, while $(1-\tilde{\gamma})$ is the weight put on the disutility from CO_2 emissions. This preference parameter can take two values:

$$\tilde{\gamma} = \begin{cases} \gamma + \tau & \text{with probability } q \\ \gamma - \tau & \text{with probability } (1-q) \end{cases}$$

It can be high with probability q, or low with probability $(1-q)$. Firms know the value of q, γ and τ, but they do not know the exact realization of $\tilde{\gamma}$ *a priori*, namely when they make their investment decisions. This value becomes known by the firms only in the second period, when uncertainty is realized. The regulator sets the cap so as to maximize the following objective function:

$$R(\bar{e};\tilde{\gamma}) = \tilde{\gamma}\left[\sum_{i=1}^{2}\pi_i\right] - (1-\tilde{\gamma})\,\phi\bar{e} \qquad (1)$$

where $\sum_{i=1}^{2}\pi_i$ is the sum of the profits of the two representative firms and $\phi\bar{e}$ is the damage function that represents the disutility from CO_2 emissions, as described in Scott (1994) and Germain, Steenberghe, and Magnus (2004). This function consists of a parameter, ϕ, which quantifies not only the marginal immediate damage of CO_2 emissions for the ozone layer, but also comprises a measure of their long-run social and economic cost, due to climate change,[6] and $\bar{e}$, the cap set by the policy maker, which therefore corresponds to the total amount of CO_2 emitted by firms. We assume that the damage is linear in the emissions, so that the parameter represents their actual marginal cost.[7] In principle, tightening the cap has two effects: a substitution effect, as firms substitute from the carbon-intensive input towards cleaner technologies, and an output effect, because firms might find it profitable to decrease their production in order to decrease emissions.

2.2 The firms

We consider two representative firms: firm 1, from the power sector, and firm 2, from the industrial sector.[8] They differ in their productivity, α_i, their available choice of fuels, and their cost of investment in clean technologies, measured by k_i. In particular, the firm in the electricity sector may choose to invest among two types of low-carbon technologies:

- An irreversible clean technology (such as renewable energy sources, *RES*, or energy efficiency enhancing technologies) which we consider irreversible, since after investment takes place the firm is locked-in to its use.[9]

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[6] Such as the damage from the intensification of natural disasters, the decrease in clean water resources, or migration and restructuring due to the sea level rise.

[7] A linear damage function has been used in similar analyses (see, for example, Scott (1994) and Colla, Germain, and Van Steenberghe (2012)).

[8] For now, we assume throughout that both sectors have the same size. However, the model can easily be extended to include different shares among sectors.

[9] Regarding *RES*, since there are nearly no operating costs, once these investments take place, the firm always uses them.

- An irreversible technology, namely fuel switching in production, which requires building a second plant that produces using gas,[10] and paying a fixed cost, F. However, once the investment is made and uncertainty over the cap is resolved, the firm has the opportunity to switch back to the coal-using plant, if the realized cap was higher than the expected, given that operating costs of coal are always lower than those of gas. We assume that both plants are big enough so that the company operates with only one of them at a time according to the merit order. Accordingly, we consider the availability to switch between fuels a reversible technology. The investment decision is of a discrete nature: to build or not the new gas plant. We consider this option a low-carbon technology because gas releases only around 80% of the amount of CO_2 emitted by coal. This coupled with the fact that lower amounts of fuel are necessary, since the productivity of gas is usually much higher, leads to a much lower total level of emissions from production. The relevance of gas as energy source for power companies is illustrated in the table in Appendix B.

On the contrary, firm 2 has only the option to invest in the irreversible clean technology.[11] Both clean technologies are continuous variables.
The firms' profit functions can be described as:

$$\pi_1(a_1, e_1, G_1; \bar{e}) = \max\{\pi_{1,e}(a_1, e_1; \bar{e}), \pi_{1,G}(a_1, G_1; \bar{e})\} \tag{2}$$

$$\pi_{1,e}(a_1, e_1; \bar{e}) = \alpha_{1,e}(a_1 + \bar{a})e_1 - ce_1^2 - p(\bar{e})\left(e_1 - \frac{\bar{e}}{2}\right) - k_1 a_1^2 \tag{3}$$

$$\pi_{1,G}(a_1, G_1; \bar{e}) = \alpha_{1,G}(a_1 + \bar{a})G_1 - gG_1^2 - p(\bar{e})\left(\lambda G_1 - \frac{\bar{e}}{2}\right) - k_1 a_1^2 - F \tag{4}$$

for firm 1, where the profit will be the maximum between the profit using coal for production and the profit using gas for production, and

$$\pi_{2,e}(a_2, e_2; \bar{e}) = \alpha_{2,e}(a_2 + \bar{a})e_2 - ce_2^2 - p(\bar{e})\left(e_2 - \frac{\bar{e}}{2}\right) - k_2 a_2^2 \tag{5}$$

for firm 2. Each firm has a two-input production function, where one of them is a fossil fuel - coal (e_2), for firm 2, and coal (e_1) or gas (G_1) for firm

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[10] Almost all the existing coal plants burn pulverized coal in a boiler to generate steam which then drives a steam turbine. Replacing the existent coal-burners to burn gas would reduce consistently the efficiency of the gas plant. For instance, a retrofit gas plant would have an average of 37% efficiency whereas a new CCGT has on average 58% efficiency. Therefore almost all the companies build a new gas plant.

[11] For example, a cooling system installed in a cement installation.

1 - and the other is clean technology - a_2 for firm 2 and a_1 for firm 1. Our measure of coal has a one to one correspondence with carbon dioxide (CO_2). We assume fossil fuels and clean technology as inputs complements and for mathematical tractability we consider a multiplicative production function. This complementarity is justified by technological considerations.[12] Given that the profit is expressed in monetary terms, these functions imply that the firms' profits are given by the revenues from their sales,[13] minus the costs of using gas or coal, which consist of the operating costs of the inputs plus the permits trading cost, and minus investment costs. The productivity of the combination of the inputs, which includes the price of the output, is given by α_i. Due to their physical properties $\alpha_{1,G} > \alpha_{1,e}$. Moreover, $\bar{a}$ represents the existing level of clean technologies for the two sectors. This formulation allows firms to set the level of investment in clean technology to zero, if optimal, still having a positive production level. We assume the same $\overline{a}$ for both sectors.

We assume convex costs of coal and gas, which assures that the profit functions are concave in the production inputs. The concave structure captures not only the price of the fuels, but also the storage costs of these inputs, as well as their opportunity cost - both of which increase exponentially for high quantities of fuels. Because the price of gas is historically on average higher than the price of coal, we also consider $g > c$.

The second part of the profit concerns the permit trading part which is the net demand for permits ($(e - \overline{e}/2)$ or $(\lambda G - \overline{e}/2)$) multiplied by the endogenous permits price ($p(\overline{e})$), which is a function of the total amount of allowances ($\overline{e}$). The cap is assumed to be shared equally amongst the firms,[14] and λ is the proportion of CO_2 emitted by one unit of gas, as compared to that of one unit of coal. If the net demand is positive, the firm is emitting more than what it is entitled to, and therefore is a net buyer of allowances. On the contrary, if a firm manages to decrease its emission level below its allocation of permits, then it is a net seller in the market for allowances.

Finally, $k_i a_i^2$ is the cost of investing in the irreversible technology. We as-

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[12] Renewables are intermittent energy resources and very difficult or costly to store, hence the aggregate supply of electricity always uses a mix of fossil fuels and *RES*. *EF*, on the other hand, are investments that make these fuels more productive, by reducing the energy wasted during the cycle, and must, therefore, always be used along with the latter.

[13] Since we assumed that firms can always sell their output.

[14] The *ex-ante* allocation does not affect efficiency, as the permit trading reallocates them efficiently; what matters is the aggregate level.

sume, as it is standard in the literature,[15] that the cost of investing in this technology is convex.

2.3 Timing

The agents' actions take place as follows: in the first period, the two firms make their investment decisions, according to their expectation of the forthcoming cap; in the second period uncertainty is realized and the policy maker decides on the aggregate amount of permits, by maximizing her objective function; and in the last period, firms set their production levels, so as to maximize profits, by adjusting their fuel choices. They trade permits and the market clears, giving rise to the equilibrium price of allowances. This timeline is set out in Fig.2.

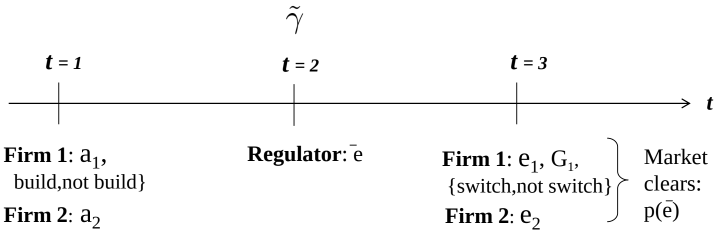

Figure 2: Timeline

3 Methodology and Results

In order to better isolate the mechanisms in effect, we first explore two reduced settings: one where only the irreversible investment (the choice of a_i) is available, which means that firms can improve their energy efficiency or invest in RES, and the alternative situation where only reversible investment for the electricity sector - investment in a gas plant - can be made.

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[15] After the seminal contribution of Montgomery (1972), several papers have assumed convex abatement costs - for example, Fell and Morgenstern (2009).

3.1 Irreversible Investment in Isolation

We start with the first case. When only irreversible investment is available, the firms' profit functions reduce to:

$$\pi_{i,e,s}(e,a;\bar{e_s}) = \alpha_{i,e}(a_i+\bar{a})e_{i,s} - ce_{i,s}^2 - p(\bar{e}_s)\left(e_i - \frac{\bar{e}_s}{2}\right) - k_i a_i^2 i = 1,2; s = h,l \tag{6}$$

where s stands for the realization of the state, which can be high ($\tilde{\gamma}_h = \gamma+\tau$) or low ($\tilde{\gamma}_l = \gamma - \tau$). In this reduced setting firms differ only on their productivity, α_i and their cost of abatement parameter, k_i.

We solve the model by backward induction. In $t = 3$, after the cap has been set and uncertainty is revealed, the firms decide on their output levels by adjusting their fuel (which consists here of coal, e_i), according to the observed cap. They do so by maximizing their last period profit, given by (6) net of sunk costs, with respect to the coal level, taking the price, the allocation and their first period choices as given. The resulting optimal level of coal is, then, given by:

$$e_{i,s}^*(p_s) = \frac{-p_s + \alpha_i(a_i+\bar{a})}{2c} \tag{7}$$

for $i = 1,2; s = h,l$, where the star indicates an equilibrium level and $p_s = p(\bar{e}_s)$. This optimal quantity depends positively on the productivity parameter $\alpha_{i,e}$, on the investment in clean technology a_i, and on its starting level $\bar{a}$. This happens because the marginal productivity of e_i is given by $\alpha_{i,e}(a_i+\bar{a})$, which makes the complementarity effect between inputs to be larger than the substitution effect.[16] Lastly, the optimal coal level depends negatively on the price for permits, p_s, and on the parameter measuring operating costs, c.

The two firms then exchange permits, according to their production needs, and the market clears. The equilibrium price is given by the following market clearing condition, for each of the two s states:

$$e_{1,s}^*(p_s) + e_{2,s}^*(p_s) = \bar{e}_s \tag{8}$$

which, solving for p_s, gives us the price that clears the market:

$$p_s^*(\bar{e}_s) = \frac{1}{2}\left[\alpha_1(a_1+\bar{a}) + \alpha_2(a_2+\bar{a}) - 2c\bar{e}_s\right] \tag{9}$$

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[16] This is true for any other choice of production function which embodies any (even very small) degree of complementarity between inputs.

This price depends negatively on $\bar{e}_s$ and c, and positively on the average productivity of coal. Intuitively, increases in the productivity of coal boost the demand for permits, thereby increasing its price. On the contrary, a decrease in operational costs c diminishes coal demand and consequently reduces the allowances' price. Finally, increases in the total amount of available permits $\bar{e}_s$ reduce their price, and vice-versa. This negative relation between $\bar{e}_s$ and p_s^* means, in particular, that the price level associated with $\tilde{\gamma}_h$, p_h, will be lower (or equal) than that associated with $\tilde{\gamma}_l$, p_l.

Next, we study the policy maker's behavior. In $t = 2$, she chooses the cap by maximizing her objective function, according to her type s, taking into account her effect on the firms' last period choices. Her objective function is given by:

$$R_s(\bar{e_s}) = \tilde{\gamma}_s \left[\sum_{i=1}^{2} \pi_i(a_i, e_i^*; \bar{e})\right] - (1 - \tilde{\gamma}_s)\, \phi \bar{e}_s \qquad (10)$$

where firms' profits are given by (8), substituting in the equilibrium values $e_{i,s}^*$.

The resulting equilibrium cap is a function only of the parameters describing the economy and a_i:

$$\bar{e}_s^* = \frac{(a_1 + \bar{a})\alpha_1\tilde{\gamma}_s + (a_2 + \bar{a})\alpha_2\tilde{\gamma}_s + 2\phi(\tilde{\gamma}_s - 1)}{2c\tilde{\gamma}_s}, s = h, l \qquad (11)$$

The optimal cap $\bar{e}_s^*$ depends positively on the weight the regulator puts on the economy, $\tilde{\gamma}_s$, and negatively on the marginal damage of emissions, ϕ, since $\tilde{\gamma}_s - 1 > 0$. Re-arranging the expression, it can be seen that the existence of a positive cap is guaranteed by the following maximum for the marginal damage parameter:

$$\phi < \frac{\gamma}{(1 - \gamma)} \frac{1}{2}[\alpha_1(a_1 + \bar{a}) + \alpha_2(a_2 + \bar{a})] \qquad (12)$$

which means the marginal damage has to be smaller than the average coal productivity in the market weighted by the relative preference of the regulator for the economy. As in Colla, Germain, and Van Steenberghe (2012), if the marginal damage of emissions is too large, the regulator is better off setting the cap to zero and having no production (and zero emissions). Therefore, for the rest of the analysis, we assume that ϕ is smaller than the threshold, and incorporate this condition in the following maximizations.

Finally, we study firms' investment decision in the first period. In $t = 1$, firms face uncertainty regarding the policy maker's preference parameter $\tilde{\gamma}$,[17] and, therefore regarding the cap and the market price for permits. They expect, with probability q, that the regulator is of a high type (i.e., more concerned about the economy), and therefore sets the associated cap, $\bar{e}_h$, and with probability $(1-q)$ that she is of a low type (more environmentally biased), and thus sets the associated cap, $\bar{e}_l$.[18] Therefore, they choose their investment levels by maximizing the following expected profit function with respect to a_i:

$$E(\pi_{i,e}(a_i;\bar{e})|\gamma,\tau,q) = q[\alpha_{i,e}(a_i+\bar{a})e^*_{i,h} - ce^{*2}_{i,h} - p(\bar{e_h})(e^*_{i,h} - \frac{\bar{e}_h}{2}) - k_i a_i^2 t]$$
$$+ (1-q)[\alpha_{i,e}(a_i+\bar{a})e^*_{i,l} - ce^{*2}_{i,l} - p(\bar{e}_l)((e^*_{i,l} - \frac{\bar{e}_l}{2}) - k_i a_i^2]$$
$$i = 1,2 \quad (13)$$

In doing so, for each of the two states they take into account the last period optimal levels of coal, the prices and the caps. Solving the first order conditions for a_i, we get the optimum investment level in clean technology, as a function of the expected price:

$$a_i^*(p_h,p_l) = \frac{\alpha_1[\bar{a}\alpha_1 - qp_h - (1-q)p_l]}{4ck_1 - \alpha_1^2}$$

Substituting in the equilibrium price we have:

$$a_i^* = \frac{(\alpha_{i,e}(-\alpha_{j,e}^2\hat{\bar{e}} + 2k_j[\overline{a}(\alpha_{i,e} - \alpha_{j,e}) + 2c\hat{\bar{e}}]))}{16ck_ik_j - 2\left(k_j\alpha_{i,e}^2 + k_i\alpha_{j,e}^2\right)} \quad (14)$$

for $i = 1,2, j = 3-i$, where $\hat{\bar{e}} = [q\bar{e}_h + (1-q)\bar{e}_l]$. This quantity is always positive as long as the following two conditions are maintained:

$$4ck_i - \alpha_{i,e}^2 > 0, i = 1,2 \quad (15)$$

$$[q\bar{e}_h + (1-q)\bar{e}_l] \geq \frac{-2k_j\bar{a}(\alpha_i - \alpha_j)}{(4ck_2 - \alpha_j^2)} \quad (16)$$

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[17] Although γ and τ are common knowledge, firms do not know whether the realization of $\tilde{\gamma}$ will be high or low.

[18] Although firms act as price takers and do not take into account their own effect on the price or the cap, they can assess exactly how these depend on the policy maker's preferences. So, they associate with each state s a certain level of permits, $\bar{e}_s$, and price $p(\bar{e}_s)$.

for $i = 1, 2, j = 3 - i$. The first condition regards the comparison between marginal costs and marginal productivity of a_i and e_i. The second one means that for a_i^* to be non-negative the expected cap cannot be too tight. This is because under such a cap level firms are better off setting e_i to zero, and consequently not producing. As long as these conditions are maintained, existence and uniqueness of a_i^* and e_i^* are guaranteed.
The derivative of a_i^* with respect to the expected cap, $[q\overline{e}_h + (1-q)\overline{e}_l]$, is always positive under the first condition. This effect takes place due to the complementarity with e_i, and means that also a_i^* depends negatively on the price of $e_{i,s}$. However, these effects are larger for $e_{i,s}^*$ than for a_i^*, so that the clean technology to coal ratio actually increases with increases in the price.[19] Additionally, a_i^* depends negatively on k_i, so that the firm with lower costs of abatement invests more in equilibrium, and *vice-versa*.
Substituting the equilibrium cap in the optimal levels of inputs and *vice-versa*, we find that both inputs increase with an increase in $\tilde{\gamma}_s$ and decrease with increases in ϕ, which carries over from their effect on the cap. The same substitution in conditions (12) and (16) shows (12) is always more binding, so that we take only this one. Thus, the conditions guaranteeing existence and uniqueness of non-negative equilibrium quantities are the following:

Condition 1

$$4ck_i - \alpha_{i,e}^2 > 0, i = 1, 2$$

Condition 2

$$\phi \leq \frac{\bar{a}\alpha(\gamma^2 - \tau^2)}{\gamma - \tau(1-2q) - (\gamma^2 - \tau^2)}$$

where $\alpha = min\{\alpha_1, \alpha_2\}$.

We finally investigate the effect of uncertainty on investment in clean technology. We do so by studying the effect of an increase in the spread of $\tilde{\gamma}_s$, which essentially means an increase in τ. We first assume that uncertainty follows a mean preserving spread (MPS) process, so that each of the possible states occurs with the same probability (i.e., $q = \frac{1}{2}$). Comparing the optimal values of a_i in the case of full information ($\tau = 0$) with those of uncertainty ($\tau \neq 0$), we find the that both at an aggregate level ($A = \sum_{i=1}^{2} a_i$) and at installation levels investment is always lower in the

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[19] Similar to the workings of the capital to labor ratio in most production functions.

latter case. Additionally, we find that $\frac{\partial a_i^*}{\partial \tau} < 0$, so that the investment levels monotonically decrease with uncertainty. This result is perfectly in line with the predictions of the Real Option Theory and derives from the fact that a higher level of irreversible investment implies less flexibility to deal with future uncertainty. Lastly, we consider a non-MPS, and find that, whenever $q < \frac{1}{2}$ the results are maintained, and for $q > \frac{1}{2}$, they only change whenever $\tau > \hat{\tau} = \gamma(2q-1)$. This means that increases in τ only have a positive effect on irreversible investment for the particular case where the probability that the realization is $\tilde{\gamma}_h = (\gamma + \tau)$ is very high, so that increases in τ mean increases in the average cap. Our results so far are summarized in the following propositions.

Proposition 1 *If the stochastic process follows a mean-preserving spread, irreversible investment is always lower under uncertainty than with full information, both at an aggregate level and at an installation level. Moreover, the higher the uncertainty, the lower the the investment.*

Proposition 2 *If the stochastic process does not follow a mean-preserving spread, and* $q < \frac{1}{2}$ *the results are maintained. If* $q > \frac{1}{2}$*, irreversible investment is lower in than in the certainty case if and only if* $\tau > \hat{\tau}$.

3.2 Reversible Investment in Isolation

In the second scenario we explore, firms do not have the option of investing in the irreversible technology, but the electricity generating company may take advantage of fuel switching. In this case, firm 1 and firm 2's profit functions are given by equations (2) to (5) setting a_i to zero.[20] The profits when using coal and gas for production are, respectively, given by:

$$\pi_{i,e}(e_i; \bar{e}) = \alpha_{i,e} e_i - c e_i^2 - p(\bar{e}) \left(e_i - \frac{\bar{e}}{2} \right), i = 1, 2 \tag{17}$$

$$\pi_{1,G}(G_1; \bar{e}) = \alpha_{1,G} G_1 - g G_1^2 - p(\bar{e}) \left(\lambda G_1 - \frac{\bar{e}}{2} \right) - F \tag{18}$$

Since this problem involves not only continuous decisions (the optimal levels of e_i and G_1), but also discrete choices by firm 1 (whether to invest in the

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[20] Since $\bar{a}$ is fixed, it becomes just an increase in productivity. So, we can set it to 1 without loss of generality, leaving the firms with a one-input production function.

gas plant in $t = 1$ and which plant to use in $t = 3$) we follow a somewhat different methodology for solving it.

To begin with, we distinguish the possible behavior of the electricity company, with respect to its discrete choices. While with full information (i.e. price and cap known in $t = 1$) the power company invests in the new plant only if in the last period it is profitable to use gas instead of coal, under uncertainty this condition is maintained only under certain values of the fundamentals (τ, γ and ϕ). For other values, however, the company might not find it profitable to actually use gas, after having invested, depending of the realization of $\tilde{\gamma}$. In the latter case, if the regulator is more biased towards the environment ($\tilde{\gamma} = \tilde{\gamma}^l$), the cap is tighter, the permits' price is higher and, for given fuel prices, it is more profitable for the firm to produce by using gas, which requires it to hold a lower quantity of permits.[21] On the contrary, if the regulator is more willing to boost the economic activity $\tilde{\gamma} = \tilde{\gamma}^h$, the cap is higher, the allowances' price is lower, and the firm prefers to use the option to switch back to coal, given that $c < g$. Consequently, we distinguish between three possible cases, which correspond to the two discrete decisions of firm 1:

- *Case 1 (NI):* Firm 1 does not invest;
- *Case 2 (INS):* Firm 1 invests and never switches;
- *Case 3 (IS):* Firm 1 invests and

$$\begin{cases} \text{switches} & \text{if } \tilde{\gamma} = \tilde{\gamma}_h \\ \text{does not switch} & \text{if } \tilde{\gamma} = \tilde{\gamma}_l \end{cases}$$

Note what differentiates the last two cases are the fundamentals, namely the values of γ,τ and q, which are known by all agents from the first period, while what matters for the switching decision of the firm in the third case is particular realization of $\tilde{\gamma}$. We start by studying the two investment conditions: one assuming the fundamentals are such that firm 1 never switches after having invested - and so we compare firm 1's profit in the first two cases (*INS versus NI*); and another assuming that firm 1 might switch after the investment - for which we perform the comparison between firm 1's profit in third and first cases (*IS versus NI*).

The most interesting case, however, is the latter, since it involves the situation where the firm switches and takes advantage of the reversibility of the

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[21] Recall from Section II that gas emits less CO_2 than coal and it is also more productive.

technology. Thus, we assume the conditions are such that if the firm invests, it will switch to coal when $\tilde{\gamma} = \gamma + \tau$, and solve the model for this case. In order to find an equilibrium, we first assume it is not optimal for the firm to invest, and calculate the optimal quantities in a similar fashion to the case of only irreversible technology. The policy maker's cap is, thus, her best response to the quantities in the case where the firm is not investing in the gas plant, according to her type (h or l). We then assume it is optimal to invest and repeat the procedure.[22] All the equilibrium quantities, $e^*_{i,s}$, $\bar{e}^*_s$ and p^*_s, for each of the two cases (*NI* and *IS*), have the same properties as the ones derived above, and $G^*_{1,s}$ is analogous to the optimal level of coal. Additionally, we find that in equilibrium, firm 2's choices of $e^*_{2,s}$ are equal for both the *NI* and *IS* cases. The resulting expected profits for firm 1 are, therefore,

$$\begin{aligned} E[\pi_{1,NI}(e^*_s;\bar{e}^*_{s,NI})] = q[\alpha_{1,e}e^*_h - ce^{*2}_h - p^*_{h,NI}(e^*_h - \frac{\bar{e}^*_{h,NI}}{2})] \\ + (1-q)[\alpha_{1,e}e^*_l - ce^{*2}_l - p^*_{l,NI}(e^*_l - \frac{\bar{e}^*_{l,NI}}{2})] \quad (19) \end{aligned}$$

$$\begin{aligned} E[\pi_{1,IS}(e^*_h, G^*_l;\bar{e}^*_{s,IS})] = q[\alpha_{1,e}e^*_h - ce^{*2}_h - p^*_{h,SI}(e^*_h - \frac{\bar{e}^*_{h,SI}}{2})] \\ + (1-q)[\alpha_{1,G}G^*_l - gG^{*2}_l - p^*_{l,SI}(\lambda G^*_l - \frac{\bar{e}^*_{l,SI}}{2})] \quad (20) \end{aligned}$$

for $s = h, l$.[23]

In order to explore the firm's investment decision, we need to compare the two expected profits. However, since the firm is a price taker, it does not take into account its own effect on the price and the cap. Therefore, when the company makes its investment decision it does not compare the two expected profits described above directly.

Our equilibrium is, therefore, constructed in the following manner. We first assume it is an equilibrium for the representative firm to invest. This means all the continuum of firms invest, so that the equilibrium cap and price are $\bar{e}^*_{s,IS}$ and $p^*_{s,IS}$. Then, we check if this is the case; that is, if there does not exist any profitable deviation. We do so by comparing the profit

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[22] Notice that the cap set by the regulator in equilibrium is different depending on whether the firm invested or not. Due to market interactions, the optimal level of coal resulting from firm 2's profit maximization in this case might also be different from that of the case where firm 1 does not invest.

[23] The expected profit for firm 2 is analogous to the previous case.

of the representative firm when investing (and switching) with that of not investing, when the cap and the price are those prevailing assuming the firm is investing:

$$E[\pi_{1,IS}(e_h^*, G_l^*; \bar{e}_{s,IS}^*, p_{s,IS}^*)] - E[\pi_{1,NI}(e_h^*, e_l^*; \bar{e}_{s,IS}^*, p_{s,IS}^*)] > 0, s = h, l \quad (21)$$

We then repeat the procedure assuming it is an equilibrium not to invest, and compare:

$$E[\pi_{1,NI}(e_h^*, e_l^*; \bar{e}_{s,NI}^*, p_{s,NI}^*)] - E[\pi_{1,IS}(e_h^*, G_l^*; \bar{e}_{s,NI}^*, p_{s,NI}^*)] > 0, s = h, l \quad (22)$$

Considering, once again, a MPS we find that there is a threshold on F, F^{th}, such that, for $F < F^{th}$ firm 1 is better off investing, both when the cap is $\bar{e}_{s,IS}^*$ and $\bar{e}_{s,NI}^*$, and prices are $p_{s,IS}^*$ and $p_{s,NI}^*$. The opposite is true when $F > F^{th}$.[24]

We therefore find a unique equilibrium, given the fundamentals of the economy, consisting of the equilibrium quantities above, the system of beliefs of firms, given by q, the threshold for investment and the condition for switching, determined further below.

Finally, for easiness of interpretation, we analyze the equilibrium imposing restrictions on some of the parameters that are not central to our analysis. The calibration procedure is described in Appendix C. With these values, we plot equations (21) and (22). In Fig.3 we present the graph for the particular case of $\gamma = 0.5$ and $\phi = 280$, which in our framework describe a policy maker with balanced preferences.

The figure shows that, for $F < F^{th}$, the firm has a higher profit when investing in the gas plant, both when the cap is set optimally for this choice (positive part of the curve representing (21)) and when the cap is set optimally for *NI* (negative part of curve (22)). For $F > F^{th}$ the firm no longer has an incentive to invest: equation (21) becomes negative, and (22) positive, meaning that for any of the two caps, the firm is better off not investing.

The same procedure was followed to find an equilibrium in the case where the firm never switches to coal, once it has invested (*INS*). We find that the threshold for investing is larger since the company is willing to pay more for an investment that it is sure it will use. In a similar graph to that of Fig.3, this corresponds to a jump of the two curves to the right.

To complete the analysis for the reversible technology case, we find the conditions under which the firm switches. We proceed in the same manner as

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[24] We assume that, when indifferent, i.e., $F = F^{th}$, the firm invests.

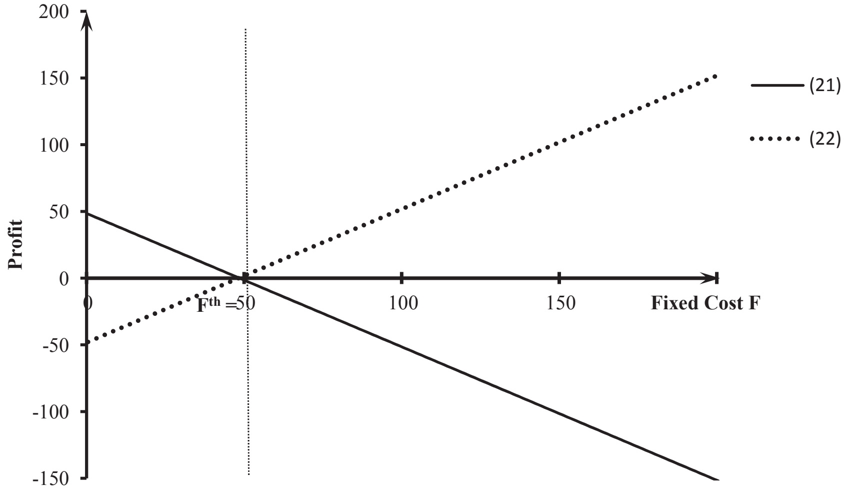

Figure 3: Investment decision for firm 1

before, by assuming an equilibrium in the last period, and then checking for profitable deviations. Additionally, and since the regulator can influence the firm's decision to switch because the cap is set before this, we compare her utility under each of the cases, to find unique conditions. We find that the switching decision depends on a the relative environmental preference of the regulator weighted by the marginal emission damage:

$$\varphi = \frac{(1-\gamma)}{\gamma}\phi \tag{23}$$

In particular, we find a critical point, φ^{th}, for which the switching decision depends on τ. Specifically:

1. If $\varphi < \varphi^{th}$, $\forall\tau$ whenever firm 1 invests it switches for a high realization;
2. If $\varphi > \varphi^{th}$, the firm switches only if $\tau > \tau^{th}$ (i.e., if the spread of the uncertainty parameter is very high).

The effect of uncertainty on this reversible investment depends on the region of these parameters:

- If we are in the first case ($\varphi < \varphi^{th}$) and the firm always switches, then increases in the spread of $\tilde{\gamma}_s$ (τ) increase the threshold for investing, F^{th}, so that there is more investment in equilibrium. This effect can be seen in Fig.2 as a movement of all the curves to the right.

- Whenever $\varphi > \varphi^{th}$, and $\tau < \tau^{th}$, the firm does not switch, and, therefore, investing in the gas plant is equivalent to an irreversible investment.[25] Therefore, the effect of uncertainty is negative.[26]

- Finally, in the case where $\varphi > \varphi^{th}$ and $\tau > \tau^{th}$, the firm switches under the high realization of uncertainty, but increases in τ lead to decreases in investment.

Our results differ from those of Chen and Tseng (2011), where reversible investment always increases with uncertainty, due to the output effect: because firms are able to adjust their fuel quantities after uncertainty is resolved, they find it more profitable to decrease production than investing in a gas plant, if there is the possibility of a very low level of the cap, which follows from the existence of an environmentally-biased regulator ($\varphi > \varphi^{th}$) and a high level of uncertainty ($\tau > \tau^{th}$).

Proposition 3 *If firms are allowed to vary their output, reversible investment increases with uncertainty only for some values of the fundamentals of the economy.*

In a nutshell, if the authority is more biased towards the economy (either because the marginal damage is high, or γ is low), then uncertainty may have a positive effect on reversible investment, when it is considered in isolation. On the other hand, when the policy maker is more environmentally-oriented (either because γ is very high, or ϕ is low), uncertainty is never beneficial for investment.

3.3 Complete Environment

We now turn to the complete model, where both reversible and irreversible investments are available for the power generating firm, and the latter for the firm representative of the industrial sector. The procedure for solving is similar to that of subsection *3.2*, but incorporating the first period choices of a_i, as determined in subsection *3.1*.

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[25] This result is in line with the analysis of Blyth, Bradley, Bunn, Clarke, Wilson, and Yang (2007).

[26] In the analogous graph to the one in Fig.3, but for the comparison between NI and INS, which we do not present due to space restrictions, the two curves move to the left as τ increases, decreasing the threshold for investment.

Firms now have different optimal decisions on the level of clean technology according to the discrete reversible investment choice of firm 1: a_j^*, $j = INS, IS, NI$. This is because the power sector company adjusts its level of the irreversible technology, so as to maximize its profit, according to the productivity associated to the fuel it expects to use. Then, due to market interactions that affect the prevailing cap, we also allow firm 2 to decide on diverse levels of investment according to the fuel choices of firm 1, although in equilibrium, we find that they do not differ. This gives rise, in equilibrium, to three different levels of irreversible investment for firm 1, one for each of the three cases (*NI, IS, INS*) and only one for firm 2. When comparing these results with those of the model in subsection *3.1*, we find that $a^*_{1,INS} > a^*_{1;IS} > a^*_{1,NI} = a^*_{1,isol}$.[27] This means that the higher the probability of the firm using gas in production, the higher is the level of a_1^*.[28]

All the comparative statics for the equilibrium levels of the continuous variables above are maintained. In particular, aggregate investment in the irreversible technology always decreases with uncertainty, when the latter follows a mean preserving spread process.
As for the discrete choice of switching, we follow the procedure described before to find a threshold on $\frac{(1-\gamma)}{\gamma}\phi$, call it $\varphi^{th'}$, for which the decision to change fuels once invested depends on τ. Our results confirm that, also in the full setting, when the government is more biased towards the environment, $\varphi > \varphi^{th'}$, the power company switches whenever $\tau > \tau^{th}$, and uncertainty always decreases investment in the reversible technology. However, in the case of a government more incline towards economic activity, i.e. $\varphi < \varphi^{th'}$, where firm 1 decides to switch for any $\tau > 0$ after investing, the results change when the choice of the irreversible technology is included in the model. The present scenario is characterized by two features: firstly, for low levels of uncertainty the firm never invests; secondly, the positive effect of uncertainty on the reversible investment level, observed in isolation, vanishes for high levels of τ. Fig.4 depicts the threshold for investment, F^{th}, as a function of τ for a given $\varphi < \varphi^{th'}$ and it allows to identify these outcomes.[29] There are four regions of interest and, consequently, three additional thresholds for τ. For low levels of uncertainty, $\tau < \tau_1$, reversible investment increases with uncertainty as in subsection 3.2 but firms never invest. This is because, even if $F = 0$, the firm always has a lower profit

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[27] The level of a_2^* remains unchanged.

[28] This is because, on average, a_1 represents an addition to the productivity of the fuel.

[29] We again use the calibration described in Appendix C. We set again $\gamma = 0.5$ and now $\phi = 150$, such that the constraint on φ is satisfied.

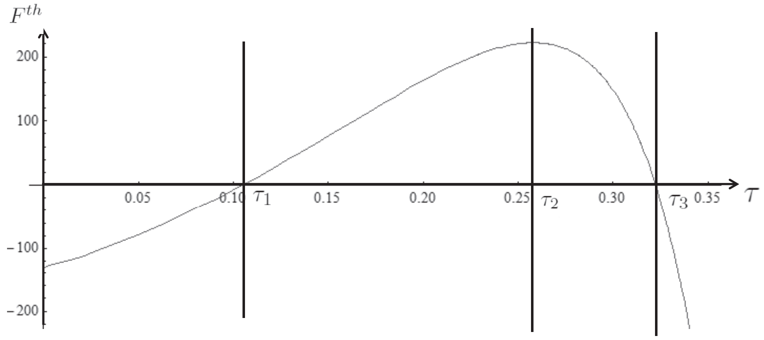

Figure 4: Investment in Reversible Technology

investing in the gas plant than not investing. This effect can be traced to the equilibrium behavior of the regulator: the introduction of the possibility of a_i in the firms' production functions allows the policy maker to lower the cap, since the same level of production can be attained emitting less CO_2. This lower limit on emissions, in turn, decreases both the equilibrium levels of $e_{1,s}$ and $G_{1,s}$ which, as set out before, decrease the firm's expected profit in different ways. Specifically, the firm's profit function $\pi_{1,G}$ is much more responsive to changes in $G_{i,s}$ than $\pi_{1,e}$ is to changes in $e_{1,s}$, so that $\frac{\partial \pi_{1,G}}{\partial \bar{e}} > \frac{\partial \pi_{1,e}}{\partial \bar{e}}$. Additionally, this relationship is not linear in $\bar{e}$: for higher values of the cap, the variation in profits is higher than for lower ones. Consequently, the introduction of a_i leads an economically biased authority to set a cap for which it is no longer profitable for the firm to invest in a gas plant. In the case of the more environmental policy maker described above, however, this effect is not enough to eliminate investment, due to the lower expected cap associated with this regulator type.

The second region refers to $\tau_1 < \tau < \tau_2$, where the power company invests in the reversible technology and uncertainty maintains the positive effect on investment found in subsection 3.2 as it represents a means to insure itself against future potential high permits price.

When $\tau > \tau_2$, however, uncertainty has a negative effect over investment in the reversible technology. This is derives from the negative impact of uncertainty over the irreversible investment. Since the profit of the firm using gas is more sensitive to changes in the level of the clean technology, a_{IS}, than the the profit when using coal, it decreases faster as a_{IS} diminishes. This effect now prevails over the hedging motive and reversible investment decreases with uncertainty. Thus for $\tau_2 < \tau < \tau_3$, the firm still invests but the higher the uncertainty the less the investment made is. Additionally, for $\tau > \tau_3$ the firm does not find it profitable to invest, for any fixed cost F. The following proposition summarizes this result:

Proposition 4 *In a comprehensive setting with output variation the introduction of irreversible investment decisions partly eliminates the possibility of a positive effect of uncertainty on reversible investment found for governments biased towards the economy.*

We further study the second threshold for τ, which is derived as the value for which $\frac{\partial \pi_{IS}}{\partial \tau} = 0$, and captures the point where there is a change in the sign of the effect that uncertainty has over reversible investment. Fig.5 plots this threshold for different levels of γ and for a given marginal damage $\phi = 50$.

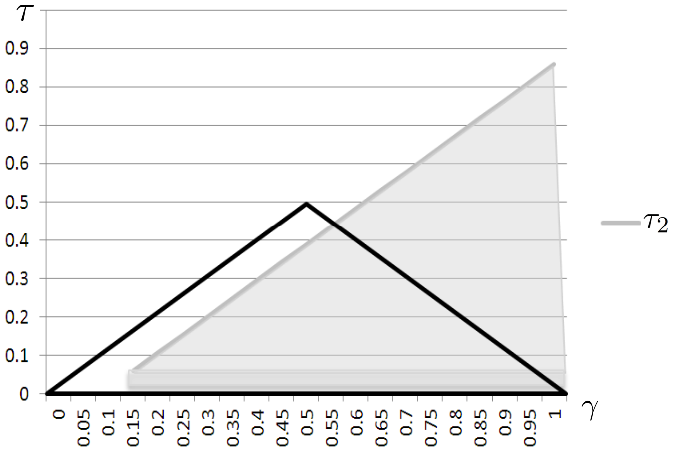

Figure 5: Threshold for positive effect

If τ is below the threshold, namely within the shaded area, uncertainty leads to a higher investment level. On the contrary, for τ higher than the threshold uncertainty has a negative effect on investment. The triangle delimitates the maximum τ possible for each value of γ, so that τ has a positive effect on reversible investment only in the shaded area under the triangle. Note that τ_2 is increasing with γ. This means that for policy makers more biased towards the economy,[30], the higher their bias, measured by γ for given ϕ, the higher the maximum level of uncertainty that stimulates investment.

The main results of the complete model can be summarized in the following table.

Parameters	**Preferences**	**Uncertainty Reversible**	**Uncertainty Irreversible**
$\varphi > \varphi^{th'}$	Environment	Negative	Negative
$\varphi < \varphi^{th'}$	Economy	Positive if $\tau < \tau_2$	Negative
		Negative if $\tau > \tau_2$	Negative

Table 1: Final effect of uncertainty on investment

In a setting which mimics the real world interaction in investment decisions, these results mean that if the authority has clear long run environmental goals such as the Kyoto Protocol, policy uncertainty is not likely beneficial for any type of investment in low-carbon technology. As described this effect takes place through two channels: the feedback effect of the regulator and the interaction with the irreversible clean technology.

Our analysis abstains from any welfare considerations, and focuses solely on understanding the channels through which uncertainty affects investment. From a welfare perspective, however, this uncertainty may be beneficial, if it acts as a stabilizer for the economy, of if the flexibility it entails allows to adjust to the current state of technological process. Understanding which effect prevails would require further analysis which is beyond the scope of this paper.

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[30] Recall that we are in the case of $\varphi > \varphi^{th'}$

4 Conclusion

In the context of a carbon dioxide Emission Trading Scheme, we study how uncertainty over the policy rule, driven by periodicity of the aggregate cap, affects firms' investment in low-carbon technologies. We formulate a three period sequential model that puts together the two sectors regulated by the European scheme and encompasses both irreversible and reversible investment possibilities for the firms. Additionally, we explicitly model the policy uncertainty as the relative priority the regulator puts on economic activity with respect to environment concerns and we assume that it follows a mean preserving spread process.

The Real Option Theory results carry over to our enlarged framework as far as irreversible investment is concerned. Namely, we find uncertainty always reduces investment levels. Regarding reversible investment taken in isolation, our results differ with respect to previous literature. Specifically, allowing firms to change their production *ex post* provides them with an additional instrument to cope with uncertainty (output effect), which mitigates to some extent the positive effect of uncertainty in reversible investment. Finally, in a complete setup, we show that introducing the additional possibility of irreversible investment partially eliminates the potential positive effect of policy uncertainty on reversible technology. The negative effect of uncertainty on irreversible investment carries over to the profitability of the reversible one, so that for higher levels of uncertainty this effect becomes negative.

To sum up, we find that only when policy makers are concerned primarily with economic expansion, relative to environmental issues, a small level of uncertainty might increase reversible investment, by making it a profitable opportunity. This situation might take place in developing countries, where often growth concerns relegate environmental issues to the background. On the contrary, in the case of the European Union, where we observe a higher environmental awareness, with clear long run green policy goals, policy uncertainty most likely has a negative effect on all investment in low-carbon technology. In this case the introduction of commitment mechanisms that reduce long-term uncertainty would help to create the right incentives to reach the CO_2 reduction target of the policy. These could consist, for example, of the setting of a long-term limited range for the cap, which would be enforceable by law, thereby binding future governments. These mechanisms should however guarantee the minimum flexibility required to adjust to unforeseen changes of the technological process or to stabilize economic shocks.

A number of extensions to the model are currently under implementation, both as a robustness check, and to further analyze the workings of this market. First, in order to verify the robustness of the results, we are in the process of developing a numerical analysis which uses alternative specifications for the profit functions of the firms, as well as for the damage function in the regulator's problem. Furthermore, we wish to add welfare considerations to the current analysis, using the regulator's objective function as proxy for the aggregate welfare. Both *ex-ante* and *ex-post* welfare will be explored to provide normative considerations. The analysis is limited in the sense that we do not consider additional exogenous shocks in production which might alter the optimal policy function of the regulator. However, this would require a dynamic analysis which is beyond the scope of the paper.

Appendix A: The EU ETS and Policy Uncertainty

Launched in 2005, the *EU ETS* is a market based approach that relies on the companies' cost differential of reducing emissions. The current scheme involves two sectors: power companies and carbon-intensive industries. Industries covered include factories producing cement, lime, glass, brick, pulp and paper, oil refineries, coke ovens, iron and steel.[31] Each of these installations receives annually an allocation of permits which corresponds to the total amount of CO_2 it is entitled to emit during the production processes. At the end of a specified trading round, each participant is required to hold permits representing its total emissions for the period.[32] Companies that exceed their quotas are allowed to buy unused permits from those that have excess supply, as a result of investment in abatement or of reduction in their production level. These permits are called European Union Allowances (EUA) and are traded in a specific platform, one EUA corresponding to the right to emit one ton of CO_2. Participants who do not meet this requirement are subject to financial penalties.

Until 2008 the authority opted for a grandfathering type of allocation, namely based on historical emissions levels, but from 2013 the scheme will move towards an allocation rule based on benchmarking and auctioning. The total amount of the allocated permits constitutes the cap. Both the

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[31] Petro-chemical and aviation will be part of the scheme in 2012-2013.

[32] From the second phase of the scheme, firms are allowed to bank and borrow their permits among different periods and phases of the scheme, namely to smooth the usage of their permits inter-temporally.

cap and the allocation are set by the regulatory authority. Until 2008 the allocation decision was a competence of national authorities through the National Allocation Plans, while from 2013 this competence has been centralized at the European level. The authority decides on the level of the cap period by period but considering long run targets. These periods are called *phases* and they differ in length. The three following figures depict for each of these phases the information available to firms regarding the future aggregate cap.

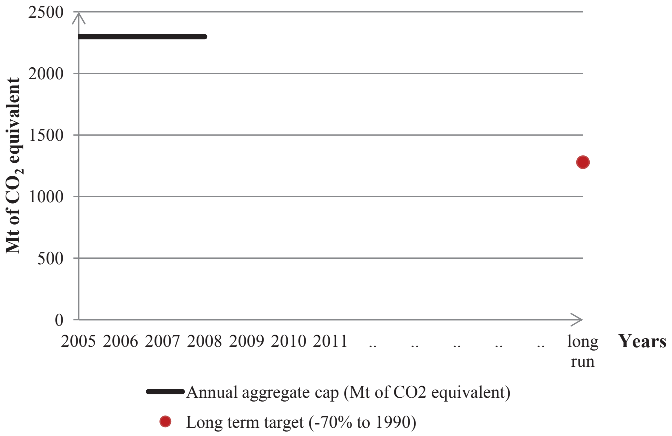

Figure 6: Annual aggregate cap as known in 2003. Source: European Commission.

Directive *2003/87/EC* set the goal of achieving an 8% reduction in emissions of greenhouse gases by 2008 to 2012 compared to 1990 levels, and established a long-run goal of reducing emissions of greenhouse gases by approximately 70% compared to 1990 levels. The only cap set precisely was that of the first phase, 2005-2007 (Fig.1). This means that each regulated firm had to plan its long term investment, which has a payback period estimated in around 15 years, without knowing the aggregate cap level, and therefore its allocation of allowances, from 2008 onwards, but assuming a tighter cap in the future given the long term reduction goal (-70% compared to 1990 levels).

In 2007, the cap for the period 2008-2012 was set to 2177MtCO_2, thereby correcting the previously announced one (dashed line in Fig.2). As reported by the EU Press Release IP/07/1614 of 26/10/2007, the European Commis-

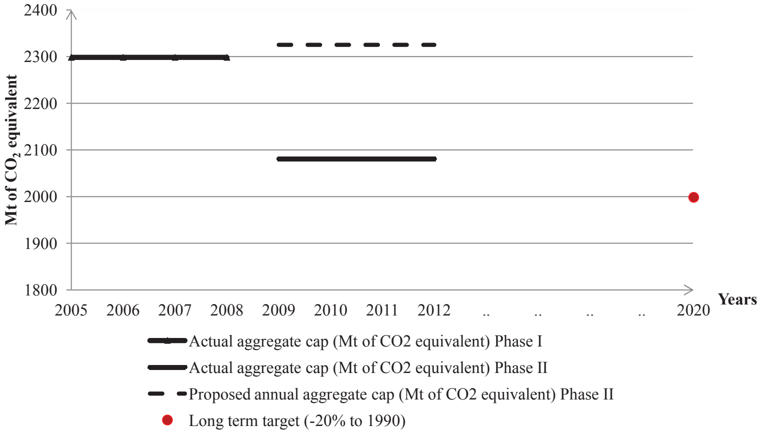

Figure 7: Annual aggregate cap as known in 2007. Source: European Commission.

sion also made a unilateral commitment that Europe would cut its emissions by at least 20% of 1990 levels by 2020, to be implemented "through a package of binding legislation". Although this implies a higher commitment of authorities towards lower emissions, also in this phase economic agents were uncertain about the cap level after 2012. Moreover the unexpected revision dictated by the over-allocation from the first phase increased even more the perceived volatility of the future cap level.

Finally, as shown in Fig.3, for the period 2013-2020, the cap corresponds to a trajectory. Specifically, it "will decrease each year by 1.47% of the average annual total quantity of allowances issued by the Member States in 2008-2012", according to directive *2010/634/EU*, starting with a cap of 2039MtCO_2. However, after 2020, the cap level is still unclear: it is stated that "this annual reduction will continue beyond 2020 but may be subject to revision not later than 2025". As underlined above, given the long term nature of low-carbon investments (around 15 years), this uncertainty over the policy instrument, the cap, may affect aggregate investment.

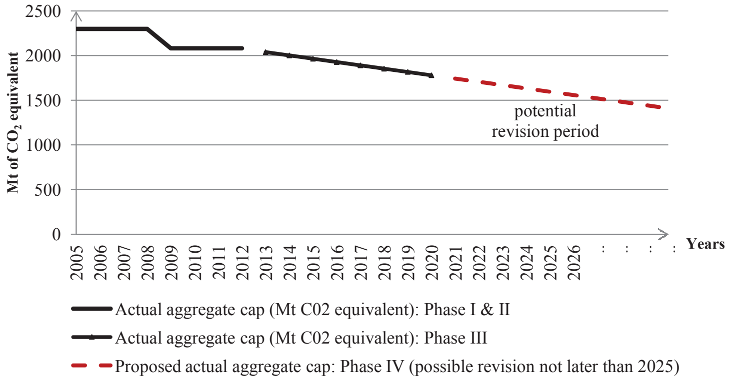

Figure 8: Annual aggregate cap as known in 2010. Source: European Commission.

Appendix B: Gas transition in the European power sector

For the choice of reversible investment we used the possibility for electricity generating firms to produce with gas or coal, according to which is more profitable. The following table reports the percentage of coal and gas used in the production mix of the power sector in different European countries in 1990 and 2010. Coal is clearly substituted out, mostly by gas, in all the countries considered. This is not only a feature of the European Union, but a worldwide trend of employing gas in the electricity generation process. The reason for this is exactly the switching motive previously laid out.

Percentage of coal and gas in the energy mix (1990-2010)				
	Coal		Gas	
	1990	2010	1990	2010
Germany	58%	44%	7%	13%
Italy	17%	14%	19%	53%
Spain	40%	11%	1%	32%
United Kingdom	65%	28%	1%	46%

Table 2: Coal and gas in the energy mix. Source: Enerdata and IEA.

Appendix C: Calibration

We present the parameter restrictions used for the interpretation of the results. As previously pointed out, this calibration exercise is dictated by the complexity of the analytical solutions.

Given the richness of information provided by the UK Government Department of Energy and Climate Change, we take the British market as a benchmark for the calibration of the parameters that are country dependent.

Productivity. We calibrate three different productivity parameters: one for the power sector when the plant is run by using coal ($\alpha_{1,e}$), one when the plant produces by using gas($\alpha_{1,G}$), and, finally, one for the industries sector which produces always by using coal (α_2). We consider the productivity of gas (output per 1000 cubic meters), adjusted for the thermodynamic efficiency of an average gas power plants, to be equal to 11 MWh/dam^3 (calorific value=40). For the coal, the adjusted productivity is set at 6.68 $MWh/tonne$. As mentioned in Section III, these parameters include also the price of the output. This means, for instance, that to calibrate ($\alpha_{1,e}$) we have to multiply the productivity of a power plant using coal by the retail price of electricity. For the first two parameters, ($\alpha_{1,e}$) and ($\alpha_{1,G}$), we use the Energy Prices and Taxes Statistics of the International Energy Agency, and take the annual average UK retail prices excluding taxes (in pounds per kWh) as a proxy for the price of electricity. Specifically, the annual average of UK end-of-use electricity price from 2006 to 2010 is 137 Euro per MWh (applying the current exchange rate). For the industrial sector we choose four industries regulated by the *ETS*: Steel, Cement, Pulp and Aluminium,[33] and we construct an industrial sector productivity index. Therefore (α_2)is the defined as $\sum_{j=1}^{4} p_j \nu_j$, where j is the industry index, p_j is the output price of industry j, and ν_j is the output per ton of coal ratio for industry j. Industry data is taken from sector associations while average output prices are collected from London Metal Exchange. The particular values follow. Cement UK industry: $\nu = 0.78$, $p = 70$ Euro/t; Steel UK industry: $\nu = 1$, $p = 400$ Euro/t; Aluminium UK industry: $\nu = 0.7$, $p = 1800$ Euro/t; Pulp EU industry:[34] $\nu = 0.83$, $p = 480$ Euro/t. Summing up, the three adjusted productivity parameters are the following: $\alpha_{1,e} = 339.9$, $\alpha_2 = 528.25$, $\alpha_{1,G} = 509.6$, and they are consistent with the observed fact that gas is more productive than coal.

Inputs Cost. As mentioned in previous sections, $C(e)$ and $C(G)$ are the

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[33] The latter will be included in the scheme in 2013.

[34] Due to absence of pulp production in the UK we use EU data as the ETS is a European Market.

operating costs of the fuels and we assume them to be convex in order to comprise not only the price of fuels, but also the storage and opportunity costs. As a proxy for c and g, we use UK government statistics on average prices of fuels purchased by the major UK power producers:[35] $c = 62$ $Euro/t$ and $g = 185.9$ $Euro/dm^3$.

Emission Factor. λ is the proportion of CO_2 emitted by one unit of gas, as compared to that of one unit of coal. Given that the amount of CO_2 generated by one unit coal equals 2.86 ton and the CO_2 emitted by gas is 0.0019 t/m^3, after the required measurement transformations, we get that the relative emission produced by one cubic meter of gas is 0.8.

Investment Costs for Irreversible Investment. k_2 and k_1 represent the cost that industries incur in to improve their energy efficiency and that power companies have to pay to invest in renewables, respectively. As evidence suggests that these values differ considerably depending on the technology, we do not assign any value to these parameters and we let them be restricted only by the conditions indicated in the Section IV.

Finally note that, given the stylized three period nature of the model, most of the model parameters do not have a direct correspondent to reality, where the time horizon is more extend and involves several repetitions of investment and production decisions.

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[35] Given that the average annual prices of coal purchased by the manufacturing industry in the UK is very close to the cost of coal paid by power producers, we use the same average for both sectors.

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