Environmental policy and Incentives to Adopt Abatement Technologies under Endogenous Uncertainty

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(very preliminary, do not cite or quote).

Abstract

We compare a carbon tax and a cap and trade mechanism in their propensity to induce carbon-reducing technological adoption, when investments are undertaken under uncertainty on the demand or on the input cost sides. In our setting, both the variance of the shocks, and their correlation across firms, affect firm's profit. Through their technological choice, firms affect the variance and the correlation of the shocks they are exposed to; therefore, they consider this aspect in their decisions. We find that uncertainty associated to a given technology increases expected profits under a carbon tax, and under cap and trade as long as the shocks are not correlated across the firms; if, instead, shocks are perfectly correlated, uncertainty has no impact on profits. As a result, we show that, while under a carbon tax, all of the firms tend to have the same behavior in equilibrium (either of adoption, or non adoption), a cap and trade system induces asymmetric adoption.

1 Introduction

Market based environmental policy instruments, such as taxes and pollution permits, are widely advocated as effective means to solve pollution-related externalities. They have been shown to provide stronger incentives to promote abatement technologies (Jung, Krutilla and Boyd, 1996), and to be more effective in reducing emissions (Fowlie, Holland and Mansur, 2012). At the same time, however, it is well known that different instruments, even within the class of the market-based ones, produce different outcomes (see, for instance, Kempe and Soete 1990, and Perino and Requate, 2012).

Requate and Unold (2003) - henceforth R&U - analyze such differential impact of various policy tools on the incentives to adopt advanced abatement technology under perfect competition in the sector subject to environmental regulation. In particular, they compare a carbon tax to a system of tradable pollution permits, also known as *cap and trade,* in which each firm's emissions has to be covered by an equivalent amount of permits[1]. They find that, with initially symmetric firms, taxes tend to induce symmetric adoption, while permits may determine asymmetric adoption. Their result hinges upon the different impact of adoption on permits price under the two regimes. Under cap and trade, each firm deciding to adopt triggers a decline in the demand for permits, and, as a result, of the permits price; this reduces the net benefits from additional adoption. On the contrary, a carbon tax is fixed regardless of the level of adoption; therefore, all of the firms face the same net benefit from adoption, regardless of the other firms' adoption strategies. The analysis in R&U is carried out in an environment with no uncertainty[2].

An extensive literature delves into the relation between uncertainty and environmental policy instruments. A variety of contributions, including the seminal work by Weitzman (1974), analyze the regulatory ideal behavior, under uncertainty on firms' marginal abatement cost. Their general finding is (see also, for instance, Rotschild) that the optimal instrument depends on the shapes of the cost and of the benefit functions[3]. Differently from our contribution, however, these papers do not directly consider incentives for adoption of abatement technologies.

A somehow smaller literature explicitly considers technological adoption under alternative market-based policy instruments. Neuhoff & Weber (2010) analyze optimal cap-and-trade schemes with and without price controls when the regulator's optimal policy considers incentives for appropriate adoption of enhanced abatement technologies. Baldursson & Von der Fehr (2004) introduce the assumption of risk-aversion, and find that in a cap and trade scheme risk-averse firms' incentive to invest in abatement equipment depend on their initial market position; firms may find it convenient to invest in emission abatement to reduce their exposure to the stochastic permit price fluctuation if they are permits' potential buyers or to postpone investment and retain their allowances if they are potential sellers.

A set of paper model benefit and cost uncertainty in the option value framework. In a recent contribution, Chen and Tseng (2011) emphasize the value of volatility as a mean to increase earning opportunities, and find that a cap and trade system, in which permits prices are volatile, provides higher incentives to adoption.

Our paper is the first, to our knowledge, to recognize that the endogenous

[1] The regulator sets the total amount of permits (hence the total amount of emissions), and distributes them through one of the allocation mechanisms. Permits are then traded among firms at the market price.

[2] R&U build on Denicolò (1999), who studies the (marginal) incentives to innovate for a firm who is then entitled to reap the monopoly benefits from the innovation. He finds that taxes are superior to permits when the marginal damage associated to pollution is not too high. His results crucially hinge on the fact that the size of the innovation is not fixed, and depends on R&D expenditure.

[3] In particular, Weitzman shows that, when the marginal abatement costs are uncertain, a tax system is less (more) desirable than an alternative cap and trade system when the marginal benefits of reducing the externality are relatively steep (flat), as compared to the shape of the marginal cost function.

technological adoption choice has a fundamental impact on how uncertainty affects equilibrium profits, and, as a result, on the effects of adoption.

Consider, for instance, the case of two firms that are subject to fuel cost shocks[4], having to decide whether or not to adopt a low-carbon technology. We assume that, if the two firms share the same technology, then they are subject to correlated shocks. If, instead, their technology differs, their cost shocks turn less correlated (or uncorrelated whatsoever, depending on the extent of comovement between the costs of the two fuels). The impact of the level of correlation of uncertainty on the firm's profits (and, in turn, on the adoption choices) depends on the type of environmental policy chosen. Therefore, we consider the two most prominent market-based instruments, a carbon tax, under which each firm is charged a fixed tariff for each unit of emissions, and a cap and trade mechanism (such as the ETS system currently in place in Europe), where a fixed amount of tradable permits is allocated by the policymaker. For each of them separately, we analyze firms' expected profits if they adopt the low-carbon technology, and if they do not. We show that expected profits always depend on the level of uncertainty, and, under cap and trade, are also a function of the extent of correlation of uncertainty across firms. However, firms recognize that both the level of uncertainty, and the degree of correlation across the two shocks (and, as a result, their expected profits through the channel of uncertainty) are affected by firms' technological choice, and incorporate this consideration into their adoption decision. We then pin down firms' adoption choices, and derive the incentives to adopt low-carbon technologies induced by each mechanism.

We obtain a set of novel results on differential technological adoption across carbon tax and cap and trade. In our framework, absent environmental regulation, uncertainty increases ex ante expected profits[5]. This is preserved both under a carbon tax, where each firm's strategy has no impact on the level of tax, and under a cap and trade scheme when firms are subject to uncorrelated shocks (for example, restricting again attention to fuel cost shocks, if the firms have different technologies). On the contrary, under a cap-and-trade regulation, when uncertainty is perfectly correlated across the two firms (in our example, if they share the same technology), uncertainty has no impact on expected profits, as changes in the permits prices, following the realization of the shocks, fully balance the direct effects of the shocks on profits.

We find that, in order to exploit the benefits from uncorrelated uncertainty, firms, under cap and trade, may find it optimal to have different technologies. Therefore, under the (conservative) assumption that firms initially share the same technology, while the carbon tax calls for symmetric strategies of adoption or non-adoption across the various firms, cap and trade provides firms with an incentive to differentiate their adoption strategies, yielding to asymmetric adoption. This differential behavior across carbon tax and cap and trade turns more pronounced as uncertainty increases. This result, which is similar to Re-

[4] In the paper we will also consider demand/revenue shocks.

[5] More precisely, in our framework, the relevant condition ensuring that uncertainty increases expected profits is that realized marginal benefits are constant with emissions, while marginal costs are increasing (this is well known at least since Oi, 1961).

quate and Unold (2003), but for a different reason, is particularly striking in light of our assumption on the initial technological symmetry.

We finally investigate the impact of a feed-in-tariff that provide investors in zero-emission technologies with a buffer against price fluctuations. Given our focus on the differential impact of uncertainty across the various policy instruments, we assume, for simplicity, that the feed-in-tariff does not change the average return from the investment, but simply provides the investor with a fixed remuneration regardless of the market conditions[6]. While feed-in tariffs are becoming an increasingly popular way to promote renewable technologies both in Europe and in the United States, the prevaling view among economists is that the combination of feed-in tariffs with carbon tax/cap and trade leads to welfare losses (Bohringer and Rosendahl, 2010). Our results in this respect are less clear-cut. While a feed-in-tariff unambigously decreases technological adoption under a carbon tax system, its effects under a cap-and-trade system are subtler. By decreasing the level of uncertainty, the feed-in-tariff indeed reduces the incentives for asymmetric adoption. This can alternatively increase adoption (if, without the feed-in–tariff, there would have been no adoption), or reduce it (if, absent the tariff, full adoption would have prevailed).

2 The Model

2.1 Assumptions

We consider two risk-neutral regulated firms, labelled as i and j, operating on two perfectly symmetric (that is, subject to perfectly correlated demand shocks) markets i and j. We assume they are initially endowed with the same carbon intensive technology. Firms are subject to environmental regulation. We compare regulation through a carbon tax to regulation with a cap and trade.

The model *timing* consists of two stages.

In stage one, before the state of the world is revealed, each firm chooses whether or not to adopt a new carbon-reducing technology. Adopting firms incur a fixed cost F. As a result, adoption takes place whenever the differential expected profit under adoption exceeds the intial investment F.

Subsequently, in the interim stage, the state of nature is revealed, and uncertainty is resolved.

In stage two, firms select the optimal amount of production, and the permits price (under cap and trade) is determined.

In the absence of environmental regulation, firms are not charged for their

[6] Of course, the feed-in-tariff also increases the value the investor can draw from the project. For this reason, an equivalent interpretation of this setting would involve a comparison of a fixed subsidy accorded to the low-carbon technology, integrated by the variable remuneration (a system similar to the tender scheme currently envisioned by the European Union as a proper future support scheme), with a feed-in-tariff. In the subsidy/tender scheme, the risk rests on the producer, while in the traditional feed-in-tariff approach it is fully transferred to the policymaker.

emissions, and their *cost function* is given by:

$$C\left(e_k\right) = w_k e_k + d_k \frac{e_k^2}{2}$$

where $k = i, j$. w_k is the fuel cost and d_k is a positive parameter. w_k and d_k differ depending on whether firm k has adopted the new technology (w_k^a and d_k^a), or it has not (w_k^n and d_k^n). We omit the superscripts when the notation may be referred to both the adoption and the non-adoption cases. We assume that, while the linear relation between costs and emissions accounts for the fuel input needed in production, the convex cost component accounts for all the other inputs, for the capacity constraints and/or the production related decreasing returns to scale.[7]

The unregulated profit maximization problem is given by:

$$\max_{e_k} \pi_k^u = \left(v_k + \theta_k - w_k - \gamma_k\right) e_k - d_k \frac{e_k^2}{2} \tag{1}$$

where the superscript u stands for unregulated, v_k is the per-unit revenue (willingness to pay), w_k is the input (e.g., fuel) price, and $(v_k - w_k) = c_k$ is the per-unit markup. Let θ_k and γ_k denote two unobservable shocks that affect, respectively, the per-unit revenue and the fuel cost for firm k, γ_k. We assume that $\underline{\theta}_k < \theta_k < \overline{\theta}_k$, $\underline{\gamma}_k < \gamma_k < \overline{\gamma}_k$ and we denote the variances $VAR\left(\theta_k\right) \equiv \sigma_{\theta_k}^2$ and $VAR\left(\gamma_k\right) \equiv \sigma_{\gamma_k}^2$, and the correlation coefficient $\rho_{\theta_k, \gamma_k} = \frac{COV(\theta_k, \gamma_k)}{\sigma_{\theta_k} \sigma_{\gamma_k}}$, where COV stands for the covariance.

Under regulation, firms pay a price p for each unit of emission they produce, thus the profit maximizing function and the related optimal level of emissions respectively become:

$$\max_{e_k} \pi_k^r = \left(v_k + \theta_k - w_k - \gamma_k\right) e_k - d_k \frac{e_k^2}{2} - p e_k \tag{2}$$

$$e_k = \frac{\left(v_k + \theta_k - w_k - \gamma_k\right) - p}{d_k} \tag{3}$$

where the superscript r stands for regulated.

The introduction of a carbon price shifts the marginal cost function.

Observe that both sources of uncertainty θ_k and γ_k are placed on the net return side (gross return net of fuel cost) for each technology. θ_k represents volatility on gross returns, while γ_k represents volatility on fuel costs. The level of uncertainty over gross returns is affected both by the extent of changes in consumers' marginal willingness to pay, and by government subsides to production, which may be contingent on technologies. Therefore, even uncertainty on gross returns may be technology-specific.

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[7] Various papers have already combined the emissions-quantity linearity assumption with a quantity and a twice differentiable and convex cost function assumption (among others see Amundsen and Mortensen (2003), Bohringer and Rosendhal (2010), Fisher (2010)). A linear relation between emissions and quantity can also be found in IEA (2011) and Lenzen (2008).

We make the following crucial assumption:

Assumption Ia. The fuel cost shocks γ_i and γ_j across the two firms are perfectly correlated (i.e., $\rho = 1$), in two cases: i) if neither firm adopts the new technology; ii) if both firms adopt the new technology. On the contrary, if only one of the firms adopts, the shocks are uncorrelated ($\rho = 0$). This amounts to assuming that the correlation across the realizations of fuel price is perfect if the two plants use the same technology, and null if the technologies differ.

Assumption Ib. The gross return shocks θ_k are perfectly correlated across the two markets ($\rho = 1$), unless a fixed regulated remuneration (e.g., a feed-in tariff), not subject to uncertainty, is introduced in one of the two markets (or in both) by the policy-maker(s).

Assumption Ic. The shocks on returns are not correlated with the cost shocks, i.e., $COV\left(\theta_i, \gamma_i\right) = COV\left(\theta_i, \gamma_j\right) = COV\left(\theta_j, \gamma_i\right) = COV\left(\theta_j, \gamma_j\right) = 0$.

Observe that Assumptions Ia, Ib and Ic are stronger than needed, and made for expositional purposes only. Our results qualitatively continue to hold as long as the correlation of the cost shocks in case of symmetric adoption (that is, when both firms adopt), or symmetric non-adoption (i.e., when no firms adopt) is smaller than the correlation of the cost shocks in case of asymmetric adoption.

In addition, we make the following assumptions on the low-carbon technology:

Assumption II. $v_k^a - w_k^a > v_k^n - w_k^n$. The expected linear marginal benefit from adoption exceeds the expected linear marginal benefit from the dirty technology. Assumption II is a necessary condition for there to be room for technological adoption.

Assumption III. $\frac{v_k^a - w_k^a}{d_k^a} < \frac{v_k^n - w_k^n}{d_k^n}$. Assumption III requires adoption to reduce expected emissions absent environmental regulation, i.e., $e_k^{*,a} < e_k^{*,n}$, where $e_k^{*,a}$, $e_k^{*,n}$ are the ex post optimal emission levels under clean and dirty technologies respectively, absent regulation.

Assumption IV. $d_k^a > d_k^n$. Assumption V is necessary for Assumption IV. to hold. It prescribes that the clean technology, while being comparatively more efficient when emissions are limited, turns less efficient as emissions increase.

Assumption V. $E\left(\pi_k^{u,n}\right) > E\left(\pi_k^{u,a}\right)$. Assumption VI establishes that adoption cannot be achieved absent environmental regulation.

Assumption VI. $\left(v_k + \underline{\theta}_k - w_k - \overline{\gamma}_k\right) > 0,\ k = i, j$. This ensures that i and j find it optimal to produce a positive output regardless of the realization of the two shocks.

Observe that the combination of Assumptions II and III implies the following:

1. there exists an emission level $e^c \leq \min\left(e_k^{*,a}, e_k^{*,n}\right)$ such that $\frac{\partial \pi_k^{u,a}(e^c)}{\partial e_k^a} = \frac{\partial \pi_k^{u,n}(e^c)}{\partial e_k^n}$.

2. for $e^c < \min\left(e_k^{*,a}, e_k^{*,n}\right)$, $\frac{\partial \pi_k^{u,a}(e^c)}{\partial e_k^a} > \frac{\partial \pi_k^{u,n}(e^c)}{\partial e_k^n}$.

3. for $e^c > \min\left(e_k^{*,a}, e_k^{*,n}\right)$, $\frac{\partial \pi_k^{u,a}(e^c)}{\partial e_k^a} < \frac{\partial \pi_k^{u,n}(e^c)}{\partial e_k^n}$[8]

We now consider the incentives to adopt under a carbon tax and cap and trade regime, respectively.

2.2 Carbon Tax

Under a carbon tax, the regulator sets a price for each unit of emissions generated by each firm. The tax is invariant to the recorded amount of emissions.

We also make the simplifying assumption that the carbon tax is set at a positive level $p < (v_k + \underline{\theta}_i - w_k - \overline{\gamma}_i) < v_k - w_k$. This ensures that, whatever the realization of the return parameter, firms find it optimal to produce a positive level of output.

In stage two, given the tax p, the optimal amount of emissions is determined according to equation (3). Each firm k's profits is:

$$\max_{e_k} \pi_k^r = (v_k + \theta_k - w_k - \gamma_k)\, e_k - d_k \frac{e_k^2}{2} - p e_k \tag{4}$$

$$\frac{v_k + \theta_k - w_k - \gamma_k - p}{d_k} = e_k \tag{5}$$

$$\pi_k^r = \frac{1}{2 d_k}\left(p - v_k + w_k - \theta_k + \gamma_k\right)^2 \tag{6}$$

In stage 1, before the resolution of uncertainty, firms take their adoption decision by comparing adoption and non adoption profits.

The expected value of emissions is given by:

$$E(e_k) = E\left(\frac{v_k + \theta_k - w_k - \gamma_k - p}{d_k}\right) = \frac{v_k - w_k - p}{d_k}$$

Expected profits, obtained after expanding the previous expression, are:

$$E(\pi_i) = \frac{p^2 - 2pv_k + 2pw_k + v_k^2 - 2v_k w_k + w_k^2 + VAR(\theta_k) - 2COV(\theta_k, \gamma_k) + VAR(\gamma_k)}{d_i} =$$
$$= \frac{p^2 - 2pv_k + 2pw_k + v_k^2 - 2v_k w_k + w_k^2 + VAR(\theta_k) + VAR(\gamma_k)}{d_i}$$

Rewriting in terms of the markup $c_k = v_k - w_k$, we obtain:

$$E(e_k) = \frac{c_k - p}{d_k}$$
$$E(\pi_k) = \frac{p^2 - 2pc_k + c_k^2 + VAR(\theta_k) + VAR(\gamma_k)}{d_k}$$

[8] Observe that conditions 2-3 imply that marginal abatement costs are intersecting (as in Perino-Requate, 2011).

Expected profits are increasing in the variances of the shocks faced by the firm.

Profits increase with the firm's variance on both the revenue side, and on the cost side, while it decreases with the covariance across the two shocks.

Expected emissions and exected profits depend positively on the firm's expected markup $c_k = v_k - w_k$ ($\frac{\partial E(e_k)}{\partial c_k} = \frac{1}{d_k} > 0$; $\frac{\partial E(\pi_k)}{\partial c_k} = 2(c-p) > 0$ given that $c > p$ by assumption), negatively on the carbon price p ($\frac{\partial E(e_k)}{\partial p} = -\frac{1}{d_k} < 0$; $\frac{\partial E(\pi_k)}{\partial p} = 2(p-c) < 0$).

Observe that, for each technology, while expected emissions do not depend on uncertainty, expected profits do. We analyze the effect of uncertainty on expected profits and, as a result, on technological adoption. We initially focus on the case of absence of a feed-in-tariff.

Proposition 1 *Under a carbon tax,*

i) each firm's profits are affected only by the probability distribution of its own random variables;

ii) all else equal, an increase (respectively, a decrease) in the clean technology uncertainty increases (respectively, decreases) the incentives to adopt. Conversely, an increase (a decrease) in the dirty technology uncertainty decreases (increases) the incentives to adopt.

Proof. i) By inspecting the expression for expected profits for firm k:

$$E(\pi_k) = \frac{p^2 - 2pv_k + 2pw_k + v_k^2 - 2v_k w_k + w_k^2 + \sigma^2_{\theta_k} + \sigma^2_{\gamma_k}}{d_k} \tag{7}$$

we immediately see that they depend only on the uncertainty faced by the firm itself, and they are unrelated to the uncertainty faced by the rival firm.

ii) A firm decides to adopt the new technology if:

$$\frac{p^2 - 2pc_k^a + \left(c_k^2\right)^a + \sigma_{\theta_k^a} + \sigma_{\gamma_k^a}}{d_k^a} - F > \frac{p^2 - 2pc_k^n + \left(c_k^2\right)^n + \sigma_{\theta_k^n} + \sigma_{\gamma_k^n}}{d_k^n}$$

The impact of decision to switch to the low carbon technology on uncertainty is in this case limited to the cost-related uncertainty γ_k only (being revenue-related uncertainty $\theta_k$independent of the technological choice, in the absence of a feed-in-tariff). As a result, all else equal, a marginal increase in the cost-volatility of the clean technology $\sigma_{\gamma_k^a}$ increases the expected profit from adoption, and, as a result, it expands the range of fixed costs under which adoption takes place. Conversely, a decline in $\sigma_{\gamma_k^a}$ decreases the firm's profits from adoption, and, as a result, it restricts the range of fixed costs under which adoption takes place. Similarly, an increase (resp., a decrease) in uncertainty under non adoption $\sigma_{\gamma_k^n}$ increases (resp. decreases) the firm's profit from non adoption, and restricts (resp., increases) the range of fixed costs under which adoption takes place. ■

Under price control, marginal costs do not shift as carbon price does not vary contingent on the adoption or on the realization of the return parameter;

uncertainty therefore has only the direct impact on the firm's marginal net returns c_k.

We can now state the following:

Proposition 2 *Under a carbon tax, adoption is symmetric. Either both firms choose to adopt (if $F < E(\pi_k^a) - E(\pi_k^n)$, or none does (if $F < E(\pi_k^a) - E(\pi_k^n)$).*

Proof. Observe that the two firms face exactly the same alternatives. In particular, $E(\pi_i^n) = E\left(\pi_j^n\right)$ and $E(\pi_i^a) = E\left(\pi_j^a\right)$. It straightforwardly follows that they both take the same decision. ■

We now turn to considering the impact of a feed-in-tariff that provides investors in low-emission technologies with a buffer against price fluctuations. In the real world, the feed-in-tariff, besides hedging against price fluctuations, usually increases the revenue for the producer subject to it. To make the comparison meaningful, and to keep focusing on the effects of uncertainty, we compare the feed-in-tariff to an alternative support system consisting in a fixed subsidy accorded to the low-carbon technology, integrated by a variable remuneration subject to uncertainty on price (a system similar, for example, to the tender scheme currently envisioned by the European Union among the alternative support schemes under consideration). The feed-in-tariff is assumed to equal the expected revenue resulting from the application of the alternative support system (including the fixed subsidy and the variable component). This allows us to consider the feed-in-tariff as a scheme that does not alter the average expected return from the investment, but simply provides a certain return for the investment. In our model, the presence of a feed-in-tariff amounts to setting, in the firm's profit function, $\sigma^2_{\theta_k^a} = 0$. We can then state the following:

Proposition 3 *A feed-in-tariff reduces the incentives to invest in a low-carbon technology with respect to an alternative remuneration scheme ensuring an equal expected revenue, but subject to price uncertainty.*

Proof. Again by inspecting the inequality that determines the decision to adopt the low-carbon technology, we see that: $\frac{p^2 - 2pc_k^a + \left(c_k^2\right)^a + \sigma_{\theta_k^a} + \sigma_{\gamma_k^a}}{d_k^a} - F > \frac{p^2 - 2pc_k^n + \left(c_k^2\right)^n + \sigma_{\theta_k^n} + \sigma_{\gamma_k^n}}{d_k^n}$

As the feed-in-tariff is assumed not to modify the average net return from the investment c_k^a, its only effect is to drive down to zero $\sigma_{\theta_k^a}$. This has the effect of reducing the left-hand side, and reduces the incentives to adopt. ■

2.3 Cap and Trade

Under a cap and trade regime, the regulator sets a fixed amount of emissions X. We assume that the policymaker allocates the permits through a standard (first price) uniform auction in which the firms bid competitively, according to their valuation.

As a reminder, firms first choose their technology (before the revelation of the state of the world), and then, in the second stage, they buy the permits in the auction and produce.

We start by analyzing the second stage. The permit price depends now on both firms' technologies, denoted as $i \in (n, a)$ and $j \in (n, a)$. By equating the firms' aggregate demand function to the supply we get the equilibrium price and the resulting optimal level of emissions by each firm:

For firm i, the permits demand function, assuming perfect competition in the permits market, stems from equating to zero the marginal benefit from permits, and therefore from the following equation:

$$v_i + \theta_i - w_i + \gamma_i - d_i e_i - p = 0$$

It follows that:

$$\begin{aligned} e_i &= \frac{v_i + \theta_i - w_i - \gamma_i - p}{d_i} \\ e_j &= \frac{v_j + \theta_j - w_j - \gamma_j - p}{d_j} \\ E &= \frac{v_i + \theta_i - w_i - \gamma_i}{d_i} + \frac{v_j + \theta_j - w_j - \gamma_j}{d_j} - \frac{p\,(d_i + d_j)}{d_i d_j} \end{aligned}$$

By equating permits demand and permits supply, we obtain:

$$\begin{aligned} X &= \frac{v_i + \theta_i - w_i - \gamma_i}{d_i} + \frac{v_j + \theta_j - w_j - \gamma_j}{d_j} - \frac{p\,(d_i + d_j)}{d_i d_j} \\ p^* &= \frac{(v_i + \theta_i - w_i - \gamma_i)\, d_j + \left(v_j + \theta_j - w_j - \gamma_j\right) d_i}{(d_i + d_j)} - \frac{X d_i d_j}{(d_i + d_j)} \end{aligned}$$

This entails an amount of permits, for each of the two firms, equal to:

$$\begin{aligned} e_i &= \frac{1}{d_i + d_j}\left(\theta_i - \theta_j - \gamma_i + \gamma_j + v_i - v_j - w_i + w_j + X d_j\right) \\ e_j &= \frac{1}{d_i + d_j}\left(\theta_j - \theta_i - \gamma_j + \gamma_i + v_j - v_i - w_j + w_i + X d_i\right) \end{aligned}$$

The profit function is then the following:

$$\begin{aligned} \pi_i &= (v_i + \theta_i - w_i - \gamma_i)\, e_k - d_k \frac{e_k^2}{2} - p e_k = \\ &= e_i \left((v_i + \theta_i - w_i - \gamma_i) - d_i \frac{e_i}{2} - p \right) = \\ &= \frac{1}{2} \frac{d_i}{(d_i + d_j)^2} \left(\theta_i - \theta_j - \gamma_i + \gamma_j + v_i - v_j - w_i + w_j + X d_j\right)^2 \end{aligned}$$

By expanding the previous expression, we obtain:

$$
\begin{aligned}
E(\pi_i) &= \frac{1}{2}\frac{d_i}{(d_i+d_j)^2}\left(\theta_i-\theta_j-\gamma_i+\gamma_j+v_i-v_j-w_i+w_j+Xd_j\right)^2 \\
&\quad \frac{1}{2}\frac{d_i}{(d_i+d_j)^2}\left(\begin{array}{c} X^2d_j^2+2Xd_jv_i-2Xd_jv_j-2Xd_jw_i+2Xd_jw_j+VAR(\theta_i)+ \\ -2COV(\theta_i,\theta_j)-2COV(\theta_i,\gamma_i)+2COV(\theta_i,\gamma_j)+VAR(\theta_j)+ \\ +2COV(\theta_j,\gamma_i)-2COV(\theta_j,\gamma_j)+VAR(\gamma_i)-2COV(\gamma_i,\gamma_j)+VAR(\gamma_j)+ \\ +v_i^2-2v_iv_j-2v_iw_i+2v_iw_j+v_j^2+2v_jw_i-2v_jw_j+w_i^2-2w_iw_j+w_j^2 \end{array}\right)
\end{aligned}
$$

Rearranging, and substituting for the values of covariance, we may rewrite as follows:

$$
E(\pi_i)=\frac{1}{2}\frac{d_i}{(d_i+d_j)^2}\left(\begin{array}{c} X^2d_j^2+2Xd_jv_i-2Xd_jv_j-2Xd_jw_i+2Xd_jw_j+\sigma_{\theta_i}^2-2\rho_{\theta_i,\theta_j}\sigma_{\theta_i}\sigma_{\theta_j}+\sigma_{\theta_j}^2 \\ +\sigma_{\gamma_i}^2-2\rho_{\gamma_i,\gamma_j}\sigma_{\gamma_i}\sigma_{\gamma_j}+\sigma_{\gamma_j}^2+v_i^2-2v_iv_j-2v_iw_i+2v_iw_j+ \\ +v_j^2+2v_jw_i-2v_jw_j+w_i^2-2w_iw_j+w_j^2 \end{array}\right)
$$

As is clear from the previous expression, profits depend positively on the variance of the two parameters θ_i and θ_j, γ_i, γ_j, and negatively on the parameters' covariance across different firms. Observe that, under equal variance and perfect correlation for any of the two uncertain parameters, that is (taking, for instance, θ_i, but it could symmetrically be replicated for γ_i), if $\sigma_{\theta_i}^2=\sigma_{\theta_j}^2$ and $\rho_{\theta_i,\theta_j}=1$, then $-2\rho_{\theta_i,\theta_j}\sigma_{\theta_i}\sigma_{\theta_j}+\sigma_{\theta_i}^2+\sigma_{\theta_j}^2=0$. Therefore, in case of perfect correlation across the two firms, the variance has no impact on expected profits; the lower the correlation, the larger the impact of variance on expected profits.

Observe the stark difference with the tax mecanism; under cap and trade, each firm's expected profits depends positively on both firms' uncertainties $(\sigma_{\theta_i}^2,\sigma_{\theta_j}^2,\sigma_{\gamma_i}^2,\sigma_{\gamma_j}^2)$, and negatively on their correlation $\rho_{\theta_i,\theta_j}\sigma_{\theta_i}\sigma_{\theta_j}$ and $\rho_{\gamma_i,\gamma_j}\sigma_{\gamma_i}\sigma_{\gamma_j}$ As stated before, the assumptions of perfect correlation of the shocks in the case of same technology, and of non-correlation in the case of different technologies are made for expositional purposes, only. Indeed, for our results to hold, we only need that the cost shocks correlation when the firms share the same technology is larger than when they make different adoption choices.

We can at this point get an interesting insight based on the comparison of price and quantity instruments in terms of the impact of uncertainty on expected profits.

Lemma 4 *A unilateral increase in the uncertainty faced by an individual firm increases expected profits more under a carbon tax than under emissions trading*

Proof. We compare the derivatives of expected profits with respect to $\sigma_{\theta_i}^2$ and to $\sigma_{\gamma_i}^2$ under carbon tax and a cap and trade respectively. We see that:

$$
\begin{aligned}
\frac{\partial E(\pi_i)}{\partial\sigma_{\theta_i}^2}\Big|_{\text{Cap and Trade}} &= \frac{\partial E(\pi_i)}{\partial\sigma_{\gamma_i}^2}\Big|_{\text{Cap and Trade}}=\frac{1}{2}\frac{d_i}{(d_i+d_j)^2} \\
\frac{\partial E(\pi_i)}{\partial\sigma_{\theta_i}^2}\Big|_{\text{Carbon Tax}} &= \frac{\partial E(\pi_i)}{\partial\sigma_{\gamma_i}^2}\Big|_{\text{Carbon Tax}}=\frac{1}{d_i}
\end{aligned}
$$

The result follows by observing that $\frac{1}{2}\frac{d_i}{(d_i+d_j)^2} < \frac{1}{d_i}$. ■

Therefore, as uncertainty increases, expected profits increase more under carbon tax than under emissions trading.

The permit market induced by cap and trade mitigates (and neutralizes in the case of perfect correlation) the effects of the shocks.

We can easily observe that, when both firms take the same decision (either of adoption or of no adoption), and therefore they face exactly the same expected benefits, the same expected costs, and the same realization of the productivity parameters, each of them individually produces half of the emission cap X, regardless of the realization of the productivity parameter. Indeed, given $\theta_i = \theta_j$ and $\gamma_i = \gamma_j$, $v_i = v_j$, $w_i = w_j$, $d_i = d_j$

$$\begin{aligned} e_i &= \frac{1}{d_i + d_j}\left(\theta_i - \theta_j - \gamma_i + \gamma_j + v_i - v_j - w_i + w_j + Xd_j\right) = e_j \\ &= \frac{1}{d_i + d_j}\left(\theta_j - \theta_i - \gamma_j + \gamma_i + v_j - v_i - w_j + w_i + Xd_i\right) = \frac{1}{2}X = e_k, \ \ k = n, a \end{aligned}$$

and the equilibrium permits price is:

$$p^* = c_k - \frac{1}{2}Xd_k, \ \ k = n, a. = \tag{8}$$

$$(v_k + \theta_k - w_k - \gamma_k) - \frac{Xd_k^2}{2} \tag{9}$$

Equilibrium profits are

$$\pi_k^* = \frac{1}{8}X^2 d_k, \ \ k = n, a \tag{10a}$$

Higher variability in the symmetric firms' production parameters causes a change in the firm's marginal benefits, inducing an adjustment in the clearing carbon price, while output remains the same. As a result, uncertainty has no impact on expected profits, either under adoption and non adoption, if the firms follow the same strategy concerning the chosen technology. This result is stated in the following Lemma.

Lemma 5 *Under a fixed cap, uncertainty has no positive impact on each firm's expected profit if the variances across the two firms are the same, and if realization of firms' uncertainty is perfectly correlated across the two firms.*

Consider the case of perfect correlation across firms both as far as the revnue shcok, and as far as the cost shocks are concerned. Then, $\rho_{\theta_i,\theta_j} = 1$ and $\rho_{\gamma_i,\gamma_j} = 1$. This implies that $COV(\theta_i, \theta_j) = \sqrt{\sigma_{\theta_i}\sigma_{\theta_j}}$ and $COV(\gamma_i, \gamma_j) = \sqrt{\sigma_{\gamma_i}\sigma_{\gamma_j}}$. As a result,

$$E(\pi_i) = \frac{1}{2}\frac{d_i}{(d_i+d_j)^2}\begin{pmatrix} X^2d_j^2 + 2Xd_jv_i - 2Xd_jv_j - 2Xd_jw_i + 2Xd_jw_j \\ +\sigma_{\theta_i}^2 - 2\sigma_{\theta_i}\sigma_{\theta_j} + \sigma_{\theta_j}^2 + \sigma_{\gamma_i}^2 - 2\sigma_{\gamma_i}\sigma_{\gamma_j} + \sigma_{\gamma_j}^2 + \\ +v_i^2 - 2v_iv_j - 2v_iw_i + 2v_iw_j + v_j^2 + \\ +2v_jw_i - 2v_jw_j + w_i^2 - 2w_iw_j + w_j^2 \end{pmatrix}$$

Restricting our attention to the random parameters, we get:

$$+\sigma_{\theta_i}^2 - 2\sigma_{\theta_i}\sigma_{\theta_j} + \sigma_{\theta_j}^2 + \sigma_{\gamma_i}^2 - 2\sigma_{\gamma_i}\sigma_{\gamma_j} + \sigma_{\gamma_j}^2$$

Proof. On the assumption that $\sigma_{\theta_i}^2 = \sigma_{\theta_j}^2$ and $\sigma_{\gamma_i}^2 = \sigma_{\gamma_j}^2$, the expression is driven down to zero. Therefore, uncertainty under perfect correlation of the shocks has no impact. ■

As is clear from the previous expression, profits depend positively on the variance of the two parameters θ_i and θ_j, γ_i, γ_j, and negatively on the parameters' covariance across different firms.

This depends on the lack of an interrelation across the two firms' decisions. Under a fixed cap, the emission price adjustment mechanism induces an increase in emission prices that equalizes profits across the different states. Differently from the carbon tax case, under cap and trade a variation of uncertainty impacts on firms' expected profits only when firms are asymmetric. In our setting featuring perfectly symmetric firms ex ante, the only possible source of asymmetry can be the technology adoption choice. In what follows, we will investigate if asymmetric technology adoption is possible given our assumptions of symmetry.

Assuming no feed-in-tariff (and, as a result, perfect correlation between σ_{θ_i} and σ_{θ_j}), the payoff resulting when only one firm adopts and the other does not can be easily shown to be, respectively:

$$\pi_i^a|j^n = \frac{1}{2}\frac{d_i^a}{\left(d_i^a + d_j^n\right)^2}\left(\begin{array}{c} X^2\left(d_j^n\right)^2 + 2Xd_j^n v_i^a - 2Xd_j^n v_j^n - 2Xd_j^n w_i^a + 2Xd_j^n w_j^n + \\ +\sigma_{\gamma_i}^2 - 2\rho_{\gamma_i,\gamma_j}\sigma_{\gamma_i}\sigma_{\gamma_j} + \sigma_{\gamma_j}^2 + v_i^{a2} - 2v_i^a v_j^n - 2v_i^a w_i^a + \\ +2v_i^a w_j^n + v_j^{n2} + 2v_j^n w_i^a - 2v_j^n w_j^n + \left(w_i^a\right)^2 - 2w_i^a w_j^n + \left(w_j^n\right)^2 \end{array}\right)$$

for the non adopting firm, and

$$\pi_j^n|i^a = \frac{1}{2}\frac{d_j}{\left(d_i + d_j\right)^2}\left(\begin{array}{c} X^2\left(d_i^a\right)^2 + 2Xd_i^a v_j^n - 2Xd_i^a v_i^a - 2Xd_i^a w_j^n + 2Xd_i^a w_i^a + \sigma_{\gamma_i}^2 - 2\sigma_{\gamma_i}\sigma_{\gamma_j} + \sigma_{\gamma_j}^2 + \\ +v_j^2 - 2v_i^a v_j^n - 2v_j^n w_j^n + 2v_j^n w_i^a + \left(v_i^a\right)^2 + 2v_i^a w_j^n - 2v_i^a w_i^a + \left(w_j^n\right)^2 - 2w_i^a w_j^n + \left(w_i^a\right)^2 \end{array}\right)$$

for the adopting firm.

We start by considering the case without a feed-in-tariff.

Proposition 6 *Under cap and trade, in an ex-ante perfectly symmetric setting,*

i) we may observe asymmetric adoption;

ii) incentives towards asymmetric adoption increase as uncertainty related to both technologies increases.

Proof. The first part of the Proposition can be proved by looking at profits. In order for asymmetric adoption to be indeed an equilibrium of the technology adoption game, we have to guarantee that the adopting firm (suppose i) does not have an incentive not to adopt, i.e.,

$$\pi_i^a|\pi_j^n - \pi_i^n|\pi_j^n > F$$

and, at the same time, that the non adopting firm (suppose j) does not have any incentive to adopt, i.e.,

$$\pi_j^a|\pi_i^a - \pi_j^n|\pi_i^a < F$$

Therefore, it has to be that

$$\pi_j^a|\pi_i^a - \pi_j^n|\pi_i^a = \underline{F} < F < \overline{F} = \pi_i^a|\pi_j^n - \pi_i^n|\pi_j^n$$

A necessary and sufficient condition for asymmetric adoption to be a feasible option for some values of the fixed cost is the following:

$$\underline{F} = \pi_j^a|\pi_i^a - \pi_j^n|\pi_i^a < \pi_i^a|\pi_j^n - \pi_i^n|\pi_j^n = \overline{F}$$

It can be shown that:

$$\begin{aligned}
\pi_i^a|j^n &= \frac{1}{2}\frac{d_i^a}{\left(d_i^a + d_j^n\right)^2}\left(\begin{array}{c} X^2\left(d_j^n\right)^2 + 2Xd_j^n\left(v_i^a - v_j^n\right) - 2Xd_j^n\left(w_i^a - w_j^n\right) + \\ +\sigma_{\gamma_i}^2 + \sigma_{\gamma_j}^2 + \left(v_i^a - w_i^a\right)^2 + \left(v_j^n - w_j^n\right)^2 + \\ 2\left(v_i^a - w_i^a\right)\left(w_j^n - v_j^n\right) \end{array}\right) = \\
&= \frac{1}{2}\frac{d_i^a}{\left(d_i^a + d_j^n\right)^2}\left(\left(v_i^a - v_j^n - w_i^a + w_j^n + Xd_j^n\right)^2 + \left(\sigma_{\gamma_i}^2 + \sigma_{\gamma_j}^2\right)\right) \\
\pi_i^n|j^n &= \frac{1}{8}X^2 d_i^n \\
\pi_j^a|i^a &= \frac{1}{8}X^2 d_j^a \\
\pi_j^n|i^a &= \frac{1}{2}\frac{d_j^n}{\left(d_i^a + d_j^n\right)^2}\left(\begin{array}{c} X^2\left(d_i^a\right)^2 + 2Xd_i^a\left(v_j^n - v_i^a\right) - 2Xd_i^a\left(w_j^n - w_i^a\right) + \\ +\sigma_{\gamma_i}^2 + \sigma_{\gamma_j}^2 + \left(v_i^a - w_i^a\right)^2 + \left(v_j^n - w_j^n\right)^2 + \\ +2\left(v_j^n - w_j^n\right)\left(w_i^a - v_i^a\right) \end{array}\right) = \\
&= \frac{1}{2}\frac{d_j^n}{\left(d_i^a + d_j^n\right)^2}\left(\left(v_j^n - v_i^a + w_i^a - w_j^n + Xd_i\right)^2 + \left(\sigma_{\gamma_i}^2 + \sigma_{\gamma_j}^2\right)\right)
\end{aligned}$$

Denote $v_i^a - w_i^a - \left(v_j^n - w_j^n\right)$ as τ, we have:

$$\begin{aligned}
\overline{F} &= \pi_i^a|j^n - \pi_i^n|\pi_j^n = \\
&= \frac{1}{2}\frac{d_i^a}{\left(d_i^a + d_j^n\right)^2}\left(\tau^2 + X^2\left(d_j^n\right)^2 + 2\tau X d_j^n + \left(\sigma_{\gamma_i}^2 + \sigma_{\gamma_j}^2\right)\right) - \frac{1}{8}X^2 d_i^n \\
\underline{F} &= \pi_j^a|i^a - \pi_j^n|\pi_i^a = \\
&= -\frac{1}{2}\frac{d_j^n}{\left(d_i^a + d_j^n\right)^2}\left(\left(\tau^2 + X^2\left(d_i^a\right)^2 - 2Xd_i^a\tau\right) + \left(\sigma_{\gamma_i}^2 + \sigma_{\gamma_j}^2\right)\right) + \frac{1}{8}X^2 d_j^a
\end{aligned}$$

$\underline{F} = \pi_j^a|\pi_i^a - \pi_j^n|\pi_i^a < \pi_i^a|\pi_j^n - \pi_i^n|\pi_j^n = \overline{F}$ requires:

$$\frac{1}{2}\frac{d_i^a}{\left(d_i^a + d_j^n\right)^2}\left(\tau^2 + X^2\left(d_j^n\right)^2 + 2\tau X d_j^n + \left(\sigma_{\gamma^a}^2 + \sigma_{\gamma^n}^2\right)\right) - \frac{1}{8}X^2 d_i^n >$$

$$-\frac{1}{2}\frac{d_j^n}{\left(d_i^a + d_j^n\right)^2}\left(\left(\tau^2 + X^2\left(d_i^a\right)^2 - 2X d_i^a \tau\right) + \left(\sigma_{\gamma^a}^2 + \sigma_{\gamma^n}^2\right)\right) + \frac{1}{8}X^2 d_j^a$$

$$\frac{1}{2}\left(\sigma_{\gamma^a}^2 + \sigma_{\gamma^n}^2 + d^a d^n X^2 + \tau^2\right) > \frac{1}{8}X^2$$

As the solution to the above inequality is a non-empty set, point i) is proved.

ii) Remember that asymmetric adoption requires $\underline{F} < F < \overline{F}$. We show that that an increase $\sigma_{\gamma_i}^2$ and $\sigma_{\gamma_j}^2$ increase $\overline{F}$, while decreasing $\underline{F}$, thereby expanding the set the range of fixed costs under which asymmetric adoption is an equilibrium. Since, $\frac{\partial \overline{F}}{\partial \sigma_{\gamma^a}^2} = \frac{\partial \overline{F}}{\partial \sigma_{\gamma^n}^2} = \frac{1}{2}\frac{d^a}{(d^a+d^n)^2}$, that is, $\overline{F}$ increases with uncertainty. Similarly, $\frac{\partial \underline{F}}{\partial \sigma_{\gamma^a}^2} = \frac{\partial \underline{F}}{\partial \sigma_{\gamma^n}^2} = -\frac{1}{2}\frac{d_j^n}{\left(d_i^a+d_j^n\right)^2}$, that is, $\underline{F}$ decreases with uncertainty. An increase in uncertainty therefore unambiogusly expands the set of fixed costs for which asymmetric adoption is an equilibrium. ■

Finally, notice that our result on asymmetric adoption is particularly striking, as it refers to firms that are initially symmetric. Also, it substantially differs from the carbon tax case where initially symmetric firms make always symmetric choices. Moreover, while under a carbon tax system an increase of uncertainty of non-adoption always reduces the convenience to adopt, under a cap-and-trade mechanism, an increase in uncertainty of non-adoption can promote adoption.

Incidentally, observe that, for $F < \underline{F}$, both firms adopt in equilibrium, while, for $F > \overline{F}$, no firm adopts in equilibrium.

To conclude, when firms are initially symmetric, an increase in the uncertainty of adoption increases expected profits of adoption only when firms are asymmetric. Thus, under a fixed cap, an asymmetric adoption (i.e. adoption by a single firm) can be induced not only by the Requate-Unold effect of carbon price reduction but also by an effect related to the existence of uncertainty and the impact of the adoption choice of one firm on the uncertainty borne by the other when firms are not symmetric ex post. Indeed, only in case of asymmetry both firms'expected profits increase as uncertainty increases, while if nobody adopts or if both firms adopt, a variation of uncertainty has no impact on their expected profits. This does not take place in the carbon tax case where, independently on the degree of firms'heterogeneity, an increase in the uncertainty of adoption always increases the incentives to adopt.

Finally, we can use our results to assess the impact of cap and trade on the desirability of feed-in-tariffs as a way to incentivize adoption. As for the case of the carbon tax, let us assume that the feed-in-tariff, consisting in a fixed per-unit revenue granted to the investor in the low-carbon technology, is compared to an alternative support system characterized by the same expected return, but subject to price fluctuations. In our model, this amounts to setting, in the firm's profit function, $\sigma_{\theta_k^a}^2 = 0$. Results are in this case subtler than those obtained under fixed price. Without a feed-in tariff, uncertainty on gross returns is perfectly correlated across the two firms, regardless of whether or not they adopted the carbon-reducing technology. By adding a feed-in-tariff, revenue uncertainty for the non-adopting firm starts to increase both firms' profits in case of asymmetric adoption, thereby providing a stronger incentive towards asymmetric adoption. We therefore prove the following:

Proposition 7 *A feed-in-tariff for the low-carbon technology increases the incentives towards asymmetric adoption, with respect to an alternative remuneration scheme ensuring an equal expected revenue, but subject to price uncertainty*

Proof. We show that a feed in tariff increases $\overline{F}$ and decreases $\underline{F}$, thereby increasing the benefits from asymmetric adoption. As a result of the feed-in tariff, the threshold value of the fixed cost above which no firm adopts, $\overline{F}$ and the threshold value of the fixed cost below which both firms adopt, $\underline{F}$, are defined as follows:

$$
\begin{aligned}
\overline{F} &= \pi_i^a|j^n - \pi_i^n|\pi_j^n = \\
&\frac{1}{2}\frac{d_i^a}{\left(d_i^a + d_j^n\right)^2}\left(\tau^2 + X^2\left(d_j^n\right)^2 + 2\tau X d_j^n + \left(\sigma_{\gamma_i}^2 + \sigma_{\gamma_j}^2 + \sigma_{\theta_j}^2\right)\right) - \frac{1}{8}X^2 d_i^n \\
\underline{F} &= \pi_j^a|i^a - \pi_j^n|\pi_i^a = \\
&-\frac{1}{2}\frac{d_j^n}{\left(d_i^a + d_j^n\right)^2}\left(\left(\tau^2 + X^2\left(d_i^a\right)^2 - 2X d_i^a \tau\right) + \left(\sigma_{\gamma_i}^2 + \sigma_{\gamma_j}^2 + \sigma_{\gamma_j}^2\right)\right) + \frac{1}{8}X^2 d_j^a
\end{aligned}
$$

Notice that the only difference between this case and that with no feed-in tariff is the term $\sigma_{\theta_j}^2$, which appears now, while it did not appear before. Without a feed-in-tariff, indeed, the two shocks θ_j and θ_j have the same distribution (and therefore the same variance), and are perfectly correlated regardless of the firms' adoption choices. It follows that $\rho_{\theta_i,\theta_j} = 1$ and $COV(\theta_j, \theta_j) = \rho_{\theta_i,\theta_j}\sigma_{\theta_j}\sigma_{\theta_j} = \sigma_{\theta_j}\sigma_{\theta_j}$. Therefore, the three terms where revenue-related uncertainty appeared, $VAR(\theta_i) + VAR(\theta_j) - 2COV(\theta_j, \theta_j) = \sigma_{\theta_i}^2 + \sigma_{\theta_j}^2 - 2\sigma_{\theta_j}\sigma_{\theta_j} = \sigma_{\theta_i}^2 + \sigma_{\theta_i}^2 - 2\sigma_{\theta_i}\sigma_{\theta_j} = 0$ cancelled out. Now, $VAR(\theta_i) = 0$, as a result of the feed-in-tariff. This implies that $2COV(\theta_j, \theta_j) = 0$, and $VAR(\theta_i) = \sigma_{\theta_i}^2$ remains there, without cancelling out. Since, $\frac{\partial \overline{F}}{\partial \sigma_{\theta_j}^2} = \frac{1}{2}\frac{d_i^a}{\left(d_i^a + d_j^n\right)^2} > 0$, and $\frac{\partial \underline{F}}{\partial \sigma_{\theta_j}^2} = -\frac{1}{2}\frac{d_j^n}{\left(d_i^a + d_j^n\right)^2}$, our result follows. ■

3 Discussion

This analysis has some interesting implications for several topics within the European energy and environmental debate.

First, our results are relevant in the light of the current debate revolving around the European Emissions Trading Scheme (ETS), the cap and trade scheme launched in 2005 to promote a cost-effective reduction of emissions in

EU. Since its inception in 2005, the actual carbon price has, on several occasions, dipped beneath the level required to promote abatement of emissions (EC 2010, Helm 2008). At the time the Climate Package was approved and the ETS cap was fixed for the third trading period, a 30€/ton carbon price was expected. However, economic recession has caused a reduction of ETS emissions, resulting in a reduction of the ETS carbon price below 10€/ton (first quarter 2012) and in a huge surplus of allowances that will be carried over to future years. The European Commission (EC) argued that this significant reduction of the carbon price has lowered the effectiveness of the ETS in promoting low carbon technologies. According to the EC "A lower carbon price acts as a much less powerful incentive for change and innovation" (EC 2010, p.6). Given these shortcomings several options to support the ETS carbon price have been proposed and are currently under discussion. In 2010, the EC officially proposed to further reduce both the European 2020 emissions target and the ETS cap during the future trading period 2013-2020, in order to sustain the carbon price and restore the incentives to innovation[9]. According to the EC "the lower cost of meeting the 20% target and the lower than expected carbon prices in the EU ETS have reduced the incentives for innovation generated by the climate and energy package. Moving to a 30% target would restore these incentives" (EC 2010b, p. 4). Furthermore, a strategy paper published on February 2011 by European Commission proposed to "set aside" 500-800 million permits from the amount due to be allocated in the scheme to counter a potential price slide that would occur in case of emissions reduction through energy efficiency interventions[10]. As a third option, it has been proposed to create an independent central authority entrusted with the possibility to correct the supply of allowances by acting like a central bank to maintain the carbon price within a pre-determined fluctuation band (De Perthius 2011). In the same way the European Central Bank can create and supply money to pursue an inflation target, a Carbon Central Bank should have the possibility to control the supply of allowances in order to pursue a carbon price stability target. This could be pursued through the introduction within the ETS of a mechanism for a reversible and continuous adjustment of the ETS cap according to transparent and pre-determined rules whenever the carbon price were to vary significantly from a desired range, compatible with EU emission reduction targets. While these mechanisms are supposed to support the ETS carbon price by intervening on the quantity of supplied allowances, a floor to the carbon price could be introduced. This fourth option could be implemented in many ways: a regulatory authority could be entrusted to buy back allowances at the given price floor (Helburn 2006), a reserve price could be set for public auctions (Neuhoff and Grubb 2006) or the payment of a fee

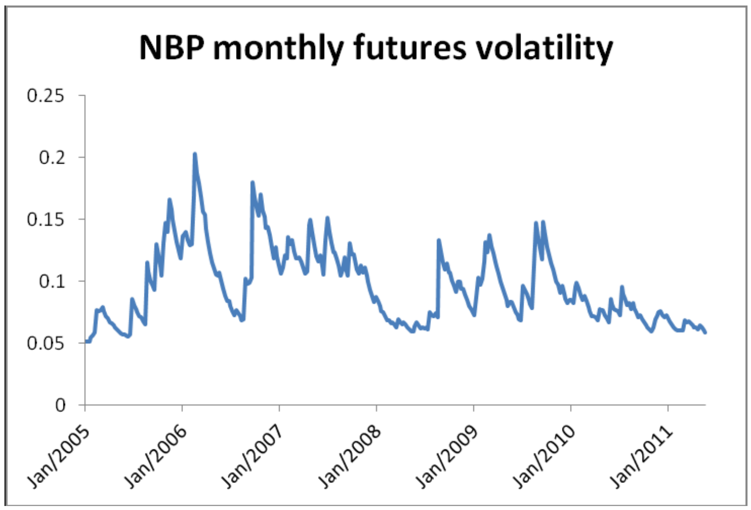
[9] in the Impact Assessment of this proposal, the PRIMES model estimated that that by lowering the target from -20% to -30% the CO2 price would almost double and its annual average during the decade 2010-2020 would pass from 16€/ton to 30€/ton, thus making convenient the development of new innovative technologies – such as the Carbon Capture and Storage – and favoring the moving toward a low carbon economy

[10] According to the Commission's impact assessment of the Energy Saving Directive, EU energy efficiency measures could be so effective in cutting emissions over the next decade that the demand of allowances could slump and prices fall by 44 per cent to 14€/ton

equal to the difference between the real carbon price and the price floor could be envisaged. (Wood and Jotzo 2009). In detail, the UK will introduce a price floor from 1 April 2013. The price floor will have the following characteristics: it will apply to the power sector and the floor will start at around £16 per tonne of carbon dioxide (tCO2) and follow a linear path to target £30/tCO2 in 2020 (both in 2009 prices). The British national price floor does not intervene on the ETS cap, which remains unchanged. This measure consists in an ex-post price adjustment which can be considered a carbon tax. Indeed, anytime the carbon price falls below the determined floor, the British power installations will have to pay to the British national government a carbon tax equal to the difference between the carbon price floor and the real carbon price. In this way, firms will end up paying at least the carbon price floor, even if the real carbon price falls beneath it.

These several options proposed within the European climate policy agenda show the increasing political interest in introducing within the ETS a mechanism for stabilizing the carbon price or, at least, to reduce its market fluctuation, as it would be ensured by a carbon tax. With respect to this political goal our analysis has shown that, under high uncertainty, while cap and trade tends to call for asymmetric adoption, a carbon tax yields to symmetric choices (either of full adoption or of no adoption), thus confirming that, under some circumstances, the incentives to adopt a low-carbon technology under uncertainty can be maximized through a environmental regulation based on price controls, implying indirectly that the EC proposal of supporting carbon price through ex-post quantity adjustments of the ETS cap can be an effective strategy to promote low-carbon technologies.

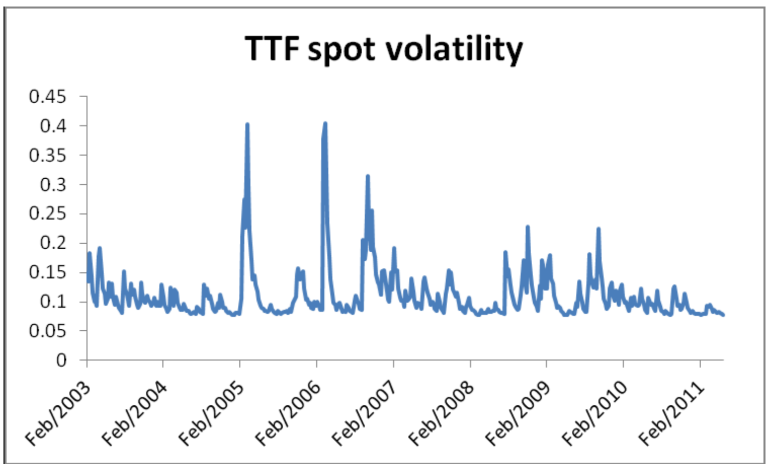
Our results might also be of interest in other energy policy issues, such as the case of the nuclear phase-out Germany is currently undergoing. Being coal and gas plants the closest alternatives to nuclear power, it is relevant to consider that historycally coal price volatility was consistently below the volatility expereiced in gas and oil markets due to the reasonably elastic coal supply (IEA, IEF, IMF and OPEC 2011). Despite the financial crisis caused a peak in coal price volatility, making it considerably more volatile than they were before the crisis, coal price is expected to continue to be less volatile than gas price.



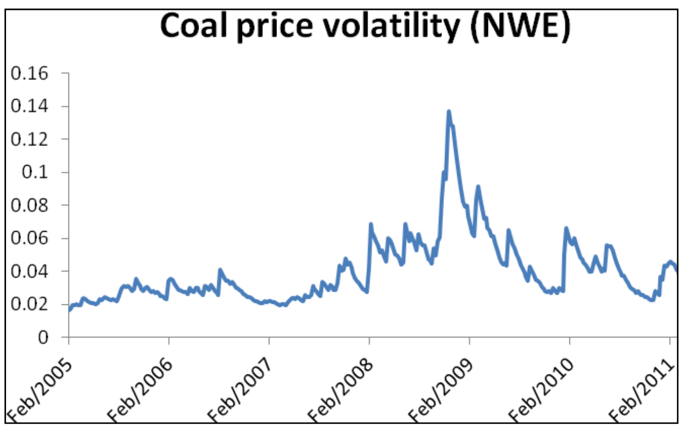
Given the different volatility between gas and coal price and being their future performance of gas power plants more uncertain than that related to coal plants, our results support the view that a full phase-out of coal generators in favor of natural gas-fuelled power plants would be likely only under a carbon tax; a cap and trade system would call for only partial adoption, at least for a larger parameters range.

Finally, our findings can also be applied to the case of renewable energy sources and the related supporting schemes. Feed-in tariffs are becoming an increasingly popular way to promote several renewable technologies, such as photovoltaic, biomass or wind power in several European Member States.

We have shown that renewable technologies such as solar and wind do not face uncertainty on the side of the "fuel combustion" marginal costs while they face uncertainty on the side of the revenues (uncertainty on the price and the quantity that can be produced). It is therefore impossible to determine ex-ante whether uncertainty related to a switch from fossil fuels to renewables is likely to increase or decrease. However, when renewables supporting schemes are in place, uncertainty related to renewables sources is likely to change. First, feed-in tariffs to renewable sources increase their expected return (highering the low-carbon technology markup parameter).Thus, our results suggest that adoption is expected to be maximized under a carbon tax system. Moreover, feed-in tariffs



TTF spot volatility
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Feb/2003
Feb/2004
Feb/2005
Feb/2006
Feb/2007
Feb/2008
Feb/2009
Feb/2010
Feb/2011


Coal price volatility (NWE)
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Feb/2005
Feb/2006
Feb/2007
Feb/2008
Feb/2009
Feb/2010
Feb/2011

ensure a certain economic return and, thus, reduce the markup uncertainty in case of adoption. Thus, as expected profits tend to increase with uncertainty, the feed-in tariffs might imply a marginal decrease in expected profits from adoption (and thus on the incentive to adopt) under a carbon tax system, while under a cap-and-trade system they can alternatively increase adoption (if, without the feed-in–tariff, there would have been no adoption), or reduce it (if, absent the tariff, full adoption would have prevailed).

4 Concluding Remarks

Our analysis has emphasized that endogenous technological adoption affects the impact of uncertainty on profits. The gist of our results consists in the differential mapping, both between uncertainty and profits, and between the extent of correlation of uncertainty and profit, entailed by carbon tax and cap and trade. When firms choose their technology, they sure consider such implication on profits; this yields to a different adoption pattern under a carbon tax and under a cap a trade.

In particular, we have shown that, under a carbon tax, each firm's expected profit depends only on its own uncertainty. Uncertainty impacts positively on firms' expected profits, therefore higher uncertainty of adoption increases the incentive to adopt, and vice-versa. We can conclude that initially homogeneous they end up making symmetric choices.

Under cap and trade, uncertainty impacts positively on expected profit only when the shocks undergone by the firms are uncorrelated, that is, under our assumption, when they took asymmetric adoption choices. In this case, each firm's expected profit depends on both firms' uncertainty. Moreover, differently from the carbon tax case, an increase of uncertainty both of adoption or non-adoption increases the incentive to make asymmetric choices. As a consequence, increasing uncertainty of adoption may interestingly lead to lower adoption (moving from a situation of full adoption to one of asymmetric adoption), while, vice-versa, an increase in the uncertainty related to the traditional technology may end up increase the incentives to adopt (moving from no adoption to asymmetric adoption).

Our analysis, while not having the goal of providing a welfare ranking of the two instruments, has shown that, under high uncertainty, while cap and trade tends to call for asymmetric adoption, a carbon tax yields to symmetric choices (either of full adoption or of no adoption).

Finally, our results might be of interest in some policy issues, such as the current debate about the introduction of a price stabilization mechansim with the ETS or the nuclear phase-out Germany is currently undergoing. Being coal and gas plants the closest alternatives to nuclear power, and being their future performance of gas power plants more uncertain than that related to coal plants, we can conclude that a carbon tax might provide additional incentives towards large-scale adoption of natural gas-based technologies. We have also shown that, in the case of a transition towards a carbon tax, feed-in-tariffs would have a negative impact on adoption.

5 References

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