# Environmental policy and Incentives to Adopt Abatement Technologies under Endogenous Uncertainty

Federico Boffa Stefano Clò Alessio D'Amato

(very preliminary, do not cite or quote).

**Abstract**

This paper analyses how different types of environmental regulation influence the incentives to adopt a low-carbon technology when investments are undertaken under uncertainty. We compare a cap and trade scheme with a carbon tax system. We analyse how uncertainty impacts on the firms' expected profits in each regulatory framework. Our paper is the first, to our knowledge, to recognize that the endogenous technological adoption choice has a fundamental impact on how uncertainty affects equilibrium profits, and, as a result, on the effects of adoption. First of all, we find quite surprisingly that uncertainty impacts positively on firms' expected profits, more under carbon tax than under cap and trade. Moreover, we find that under a carbon tax each firm's expected profit depends only on its own uncertainty and symmetric firms will always make symmetric choices. To the contrary, under a cap and trade scheme each firms' expected profits depends on both firms' uncertainties but only when firms are heterogeneous, while under symmetry and perfectly correlated shocks, uncertainty has no impact on profits. We find that, in order to exploit the benefits from uncorrelated uncertainty, firms, under cap and trade, may find it optimal to differentiate their adoption strategies. While the carbon tax calls for symmetric strategies of adoption or non-adoption across the various firms, cap and trade tends to involve asymmetric strategies.

## 1 Introduction

Market based environmental policy instruments, such as taxes, pollution permits, and abatement subsidies, are widely advocated as effective means to solve pollution-related externalities. Their superior efficiency with respect to command-and-control, illustrated in a number of theoretical contributions (Zerbe 1970; Downing and White 1986; Milliman and Prince 1989; Kolstad, Ulen and Johnson, 1990, Jung, Krutilla and Boyd, 1996), and supported by Hahn and Stavins' (1999) evidence on the United States tradable permits markets, is further witnessed by their widespread use as policy tools, both in the United States,

and in Europe (Stavins, 2003). At the same time, however, it is well known that different instruments, even within the class of the market-based ones, produce different outcomes (Orr 1976, Kempe and Soete 1990).

Requate and Unold (2003) - henceforth R&U - analyze such differential impact of various policy tools on the incentives to adopt advanced abatement technology. 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. R&U conclude that it may be easier to achieve social optimum under permits than under taxes. The intuition behind their result has to do with the higher flexibility associated to the permits regime, which can produce, under an appropirate regulatory choice of the cap, an asymmetric outcome - something generally not achievable by a carbon tax[2]. R&U do not explore uncertainty.

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 environmental 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

[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] Denicolò (1999) finds the opposite results, that taxes may be superior to permits in providing incentives to innovation when the regulator can commit to retaining the same environmental policy before and after the innovation, and when the correction of the environmental externality does not require significant output contraction. In his setting, Denicolò assumes that there is an individual potential innovator, who enjoys monopoly on the innovative technology. Kehoane (1999) obtains a similar result.

[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.

market position; firms may find 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 technological adoption choice has a fundamental impact on how uncertainty affects equilibrium profits, and, as a result, on the effects of adoption. Uncertainty may be related to demand conditions or to input prices. Consider, as an example, two electric generators, initially sharing the same high-emission fuel, but supplying two different markets, that face cost-related uncertainty. Each of them has the option to switch to a low-emission fuel. If both of them, or neither of them, switches, they end up incurring perfectly correlated cost shock (on the assumption that both fuels' price is uniform across the two regions). On the other hand, if only one of the two firms adopts, shocks are imperfectly correlated, or even uncorrelated, depending on the extent of comovement between the two fuels.

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.

We analyze the mapping both between uncertainty and profit, and between the degree of correlation of shocks across the firms and profits in each of the two arrangements. We then derive the incentives to adopt low-carbon technologies induced by each mechanism under the assumption of risk neutrality on the part of the firms. Firms realize that their technological choice may affect the level of uncertainty as well its degree of correlation across them, and incorporate this consideration in their decision. Finally, we show that policies aimed at supporting renewable energy sources may also impact on the level of uncertainty, and, in turn, on the firms' adoption pattern.

We obtain a set of novel results on differential technological adoption across carbon tax and cap and trade. In our framework, increasing marginal costs ensure that, absent environmental regulation, uncertainty increases ex ante expected profits[4]. This is preserved under a carbon tax, where each firm's strategy has no impact on the level of tax, and hence on the rival firm's parameters. On the contrary, under a cap-and-trade regulation, when uncertainty is perfectly correlated across the two firms, the good realizations of the shock are associated to a simultaneous increase in the permit prices, whereas the opposite happens

[4] 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).

for bad realization of the shock. Changes in permit prices, resulting from the realization of uncertainty, neutralize the direct effect of uncertainty on profit under perfectly correlated shocks, and each firm's amount of production (and of emissions) is orthogonal to the shock. As a result, we show that under cap and trade, and perfectly correlated shocks, uncertainty has no impact on profits.

We find that, in order to exploit the benefits from uncorrelated uncertainty, firms, under cap and trade, may find it optimal to differentiate their adoption strategies. While the carbon tax calls for symmetric strategies of adoption or non-adoption across the various firms, cap and trade tends to involve asymmetric strategies; this result is particularly striking, as we (conservatively) assume that firms are initially symmetric. This differential behavior across carbon tax and cap and trade turns more pronounced as uncertainty increases (and as the benefits from getting uncorrelated shocks turn larger under cap and trade).

We finally investigate the impact of a feed-in-tariff that provide investors in zero-emission technologies with a buffer against price fluctuations[5]. 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 Timing and Setting

We consider two risk-neutral regulated firms, labelled as $i$ and $j$, operating as monopolists on the two different 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 to adopt the new technology. Adoption takes place whenever the differential profit in case of 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.

[5]We will assume, for simplicity, that the feed-in-tariff does not change the average return from the investment, but only acts as a buffer.

## 2.2 Assumptions

In the absence of environmental regulation, firms are not charged for their emissions, and their *cost function* is given by:

$$C(e_k) = c_k e_k + d_k \frac{e_k^2}{2}$$

where $k = i, j$. $c_k$ is the fuel cost and $d_k$ is a positive parameter. $c_k$ and $d_k$ differ depending on whether firm $k$ has adopted the new technology ($c_k^a$ and $d_k^a$), or it has not ($c_k^n$ and $d_k^n$). We omit the superscript 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.[6]

The unregulated profit maximization problem is given by:

$$\max_{e_k} \pi_k^u = (v_k - w_k) e_k - d_k \frac{e_k^2}{2} \quad (1)$$

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.

The markup $c_k$ is the realization of a stochastic parameter, distributed according to the (known) distribution functions $F(c_k^a)$, and $F(c_k^n)$ for the adoption and non-adoption cases, respectively. We may regard $c_k$ as being determined by volatile output or input prices. We assume distributions are uniform, with $c_k \in (\varepsilon_k, \overline{c}_k - \varepsilon_k)$, and $\varepsilon_k$ captures the level of uncertainty. $\varepsilon_k$ lies in the $\left(\underline{\varepsilon}_k, \frac{\overline{c}_k}{2}\right)$ interval (the larger $\varepsilon_k$, the smaller uncertainty; when $\varepsilon_k = \frac{\overline{c}_k}{2}$, then there is no uncertainty whatsoever). Also, we assume $\overline{c}_k^a > \overline{c}_k^n$.

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:

$$\max_{e_k} \pi_k^r = c_k e_k - d_k \frac{e_k^2}{2} - p e_k \quad (2)$$

where the superscript $r$ stands for regulated.

so that

$$e_k = \frac{c_k - p}{d_k} \quad (3)$$

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

In the baseline version of our model, the two firms are initially symmetric, and they face perfectly correlated shocks. Observe that uncertainty is placed on the net return side (gross return net of fuel cost) for each technology. As

[6] 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).

a result, it may stem alternatively from uncertainty on gross return or from uncertainty on fuel costs. Uncertainty on gross retrurns, in turn, is a function of both consumer's willingness to pay $v_k$. and of production-related subsidies. Both subsidies and uncertainty may be technology-specific.

Firms have two options to reduce emissions: they may restrict production, or, alternatively, they may adopt the low-carbon technology.

We make the following assumptions on the low-carbon technology:

**Assumption I.** $v_k^a > v_k^n$. The clean technology is associated to a lower emission intensity (and, as a result, to a higher per-emission value) with respect to the dirty technology

**Assumption II.** $E(c_k^a) > E(c_k^n)$. The linear benefit (net of the linear fuel cost) from adoption exceeds the benefits from the dirty technology. Assumption II ensures that there is room for adoption of the clean technology

**Assumption III.** $E\left(\frac{c_k^a}{d_k^a}\right) < E\left(\frac{c_k^n}{d_k^n}\right) = \frac{\bar{c}_k^a}{2d_k^a} < \frac{\bar{c}_k^n}{2d_k^n} \Rightarrow \frac{\bar{c}_k^a}{d_k^a} < \frac{\bar{c}_k^n}{d_k^n}$. Assumption III requires adoption to reduce 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 IV is necessary for Assumption III. 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.** $E(\pi_k^{u,n}) > E(\pi_k^{u,a})$. Assumption V establishes that adoption cannot be achieved absent environmental regulation.

Observe that the combination of Assumption II and Assumption IV 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 $e^c > \min\left(e_k^{*,a}, e_k^{*,n}\right)$, $\frac{\partial \pi_k^{u,a}(e^c)}{\partial e_k^a} < \frac{\partial \pi_k^{u,n}(e^c)}{\partial e_k^n}$[7]

# 3 Taxes

Under a carbon tax, the regulator sets a price for each unit of emissions generated by each firm. The decisions by the two firms are indipendent in this setting.

We also make the simplifying assumption that the carbon tax is set at a positive level $p < \min(\underline{\varepsilon}_k^a, \underline{\varepsilon}_k^u)$. This ensures that, whatever the realization of the return parameter, firms find it optimal to produce.

[7] Observe that conditions 1-3 imply that marginal abatement costs are intersecting (as in Perino-Requate, 2011).

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

$$\pi_k = c_k \frac{(c_k - p)}{d_k} - \frac{(c_k - p)^2}{2d_k} - p\frac{(c_k - p)}{d_k} = \frac{(c_k - p)^2}{2d_k} \tag{4}$$

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[8]:

$$E(e_k) = \int_{\varepsilon_k}^{\overline{c}_k - \varepsilon_k} \frac{c_k - p}{d_k} \left( \frac{1}{\overline{c}_k - 2\varepsilon_k} \right) dc_k = \frac{\overline{c}_k - 2p}{2d_k}$$

Expected profits are:

$$E(\pi_k) = \int_{\varepsilon k}^{\overline{c}_k - \varepsilon_k} \frac{(c_k - p)^2}{2d_k} \left( \frac{1}{\overline{c}_k - 2\varepsilon_k} \right) dc_k = \frac{\overline{c}_k^2 - \overline{c}_k\varepsilon_k + \varepsilon_k^2 - 3\overline{c}_k p + 3p^2}{6d_k}$$

Both expected emissions and expected profits depend positively on the firm's markup $c_i$ ($\frac{\partial E(e_i)}{\partial c_i} = \frac{1}{2d_i} > 0$; $\frac{\partial E(\pi_k)}{\partial c_k} = \frac{1}{6d_k}(2\overline{c}_k - 3p - \varepsilon_k) > 0$ if $p < \frac{(2\overline{c}_k - \varepsilon_k)}{3} \leq \frac{\overline{c}_k}{2}$), negatively on the carbon price $p$ ($\frac{\partial E(e_k)}{\partial p} = -\frac{1}{d_k} < 0$; $\frac{\partial E(\pi_k)}{\partial p} = \frac{-c_k + 2p}{2d_k} < 0$, since $p < \underline{\varepsilon}_k \leq \varepsilon_k \leq \frac{\overline{c}_k}{2}$ by construction.

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.

**Proposition 1** *Under a carbon tax, i) each firm's profits are affected only by its own net return parameter; and 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 differentiating expected profits with respect to $\varepsilon_i$, we obtain:

$$\frac{\partial E(\pi_k)}{\partial \varepsilon_k} = \frac{1}{3d_k} \left( \varepsilon_k - \frac{\overline{c}_k}{2} \right) < 0 \tag{5}$$

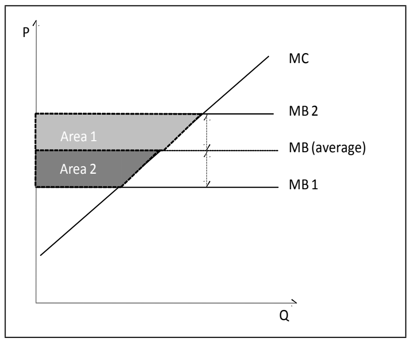
It follows immediatly that expected profits depend only on each firm's own uncertainty. Moreover, as $\varepsilon_k \leq \frac{\overline{c}_k}{2}$ by construction, a rise in uncertainty (that is, a reduction in $\varepsilon_k$) induces a rise in expected profits.

ii) Each firm finds it convenient to switch to the low-carbon technology whenever the initial investment $F$ is lower than the difference between expected profits from adoption and from non-adoption, that is, $F < E(\pi_k^a) - E(\pi_k^n)$. As an increase in uncertainty related to a given technology increases expected profits for that technology, it follows that, all else equal, an increase (a decrease)

[8] Notice that positive expected emissions require : $p < \frac{c_i}{2}$. We assume this is the case.

in the clean technology uncertainty $\varepsilon_k^a$ increases (decreases) expected profits, thereby increasing (decreasing) the expression $E(\pi_k^a) - E(\pi_k^n)$, and expanding (shrinking) the set of values of the fixed cost for which adoption is convenient. Conversely, an increase (a decrease) in uncertainty related to the carbon intensive technology $\varepsilon_k^n$ shrinks (expands) the set of values of the fixed cost that make adoption convenient. ■

Point i) is illustrated by the following graph.




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 $c_k$. The figure above shows that, given the average marginal benefits, the increase in marginal profit under a good realization of the productivity parameter (Area 1) exceeds the reduction in marginal profit's under a symmetric bad realization of the same (Area 2).

As far as point ii) is concerned, observe that a firm may face differential changes in uncertainty between adoption and non adoption as a result both of structural (possibly technological) changes in the fuel input market, and of changes in the regulatory mechanisms.

We 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 provide investors in zero-emission technologies with a buffer against price fluctuations. We assume, for simplicity, that the feed-in-tariff does not change the average return from the investment, but only acts as a buffer against price fluctuation. In the real world, feed-in-tariffs also increase the average return from the investment. However, our results may be easily extended to encompass that situation as well, in particular by comparing two support scheme with the same expected return, one with uncertainty, and the other one without it. Using our result

in Proposition 1, we show that a feed-in-tariff that eliminates uncertainty on the remuneration reduces the incentives to adopt a zero-emission technology under a carbon tax. A zero-emission technology (such as, for instance, wind or photovoltaic) has no fuel cost; therefore, the only source of uncertainty may stem from the revenue side. As a result, by eliminating such uncertainty on the revenue side, the feed-in tariff unambigously decreases incentives towards adoption.

# 4 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.

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 they produce.

We start by analyzing the second stage. The permit price depends now on both firms' technologies, denoted as $i \in (n, a)$ and $j \in (ln, a)$. 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:

$$p^* = \frac{c_j d_i + c_i d_j - d_i d_j X}{(d_i + d_j)} \tag{6}$$

$$e_i^* = \frac{c_i (d_i + d_j) - (c_j d_i + c_i d_j - d_j d_i X)}{d_i (d_i + d_j)} \tag{7a}$$

$$e_j^* = \frac{c_j (d_i + d_j) - (c_j d_i + c_i d_j - d_j d_i X)}{d_j (d_i + d_j)} \tag{7b}$$

Equilibrium (ex post) profits are:

$$\pi_i^* = \frac{(c_i (d_i + d_j) - (c_j d_i + c_i d_j - d_i d_j X))^2}{2 d_i (d_i + d_j)^2} \tag{8a}$$

$$\pi_j^* = \frac{(c_j (d_i + d_j) - (c_j d_i + c_i d_j - d_i d_j X))^2}{2 d_j (d_i + d_j)^2} \tag{8b}$$

We now move to the first stage, before the resolution of uncertainty. We first analyze the case of lack of correlation across the realization of uncertainty for the two firms. This assumption arises when one firm decides to adopt, while the other chooses not to.

**Lemma 3** *Under cap and trade, when one of the firm adopts while the other does not, each firm's expected profits depend positively on the uncertainty of both firms' technology parameters ($\varepsilon_i, \varepsilon_j$).*

**Proof.** When firms are asymmetric and the realizations of the productivity parameters across the two firms are uncorrelated, each firm's expected value of emissions is given by:

$$E(e_i) = \int_{\varepsilon_i}^{\overline{c}_i-\varepsilon_i} \frac{c_i - p}{d_i}\left(\frac{1}{\overline{c}_i - 2\varepsilon_i}\right) dc_i = \frac{\overline{c}_i - \overline{c}_j + 2d_jX}{2(d_i+d_j)} \tag{8i}$$

where now $i \in (n,a)$ and $j \in (n,a) \backslash i$. The expected price is given by:

$$E(p) = \int_{\varepsilon_i}^{\overline{c}_i-\varepsilon_i} \frac{c_jd_i + c_id_j - d_id_jX}{(d_i+d_j)}\left(\frac{1}{c_i - 2\varepsilon_i}\right) dc = \frac{\overline{c}_jd_i + \overline{c}_id_j - 2d_id_jX}{2(d_i+d_j)} \tag{8j}$$

and the expected profits are:

$$E(\pi_i) = \int_{\varepsilon_i}^{\overline{c}_i-\varepsilon_i} \frac{\left(c_i(d_i+d_j) - (c_jd_i + c_id_j - d_jd_iX)\right)^2}{2d_i(d_i+d_j)^2}\left(\frac{1}{c_i - 2\varepsilon_i}\right) dc_i$$

$$E(\pi_i) = \frac{d_i}{2(d_i+d_j)^2}\left(X^2(d_j)^2 - Xd_j\overline{c}_j + Xd_j\overline{c}_i + \frac{(\overline{c}_j)^2 - \overline{c}_j\varepsilon_j + (\varepsilon_j)^2}{3} - \frac{\overline{c}_i\overline{c}_j}{2} + \frac{(\overline{c}_i)^2 - \overline{c}_i\varepsilon_i + (\varepsilon_i)^2}{3}\right) \tag{8k}$$

■

Observe the stark difference with the tax mecanism; under cap and trade, the firms' expected profits depend positively on both firms' uncertainties $(\varepsilon_i, \varepsilon_j)$, as long as they are uncorrelated. The assumption of uncorrelated shock is a simplifying one. Indeed, our results hold even if such assumption is somewhat relaxed to imperfect correlation. Further discussion will be added when perfect correlation will be assumed, i.e. under perfect symmetry. Tha above result is clear if we look at the first derivatives:

$$\frac{\partial E(\pi_i)}{\partial \varepsilon_i} = \left(\frac{1}{3}\frac{d_i}{(d_i+d_j)^2}\right)\left(\varepsilon_i - \frac{\overline{c}_i}{2}\right) < 0 \tag{12a}$$

$$\frac{\partial E(\pi_i)}{\partial \varepsilon_j} = \left(\frac{1}{3}\frac{d_i}{(d_i+d_j)^2}\right)\left(\varepsilon_j - \frac{\overline{c}_j}{2}\right) < 0 \tag{12b}$$

which are both negative as $\varepsilon_i < \frac{\overline{c}_i}{2}$ and $\varepsilon_j < \frac{\overline{c}_j}{2}$ by construction.

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** *Uncertainty increases expected profits more under a carbon tax than under emissions trading.*

**Proof.** Comparing the derivatives of expected profits with respect to $\varepsilon_i$ under carbon tax and a cap and trade respectively, using equation (5) and equations (12a) and (12b) we can conclude that

$$\frac{\partial E(\pi_i)}{\partial \varepsilon_i}|_{FQ} = \left(\frac{1}{6}\frac{d_i}{(d_i+d_j)^2}\right)(2\varepsilon_i - c_i)$$

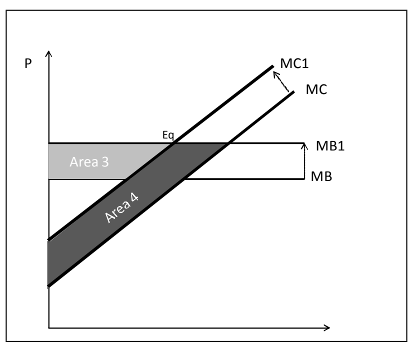
$$\frac{\partial E(\pi_i)}{\partial \varepsilon_i}|_{CT} = \frac{1}{6d_i}(2\varepsilon_i - c_i)$$

as a result,

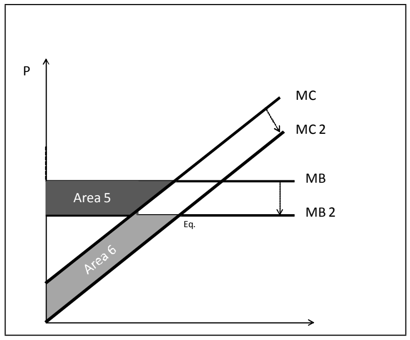
$$\begin{gathered}\frac{\partial E(\pi_i)}{\partial \varepsilon_i}|_{FQ} - \frac{\partial E(\pi_i)}{\partial \varepsilon_i}|_{CT} = \\ = \left(\frac{1}{6}\frac{d_i}{(d_i+d_j)^2}\right)(2\varepsilon_i - c_i) - \left(\frac{1}{6d_i}(2\varepsilon_i - c_i)\right) = \\ = \frac{d_i}{(d_i+d_j)^2} - \frac{1}{d_i} = \\ -\frac{d_j}{d_i}\frac{d_j+2d_i}{(d_i+d_j)^2} < 0\end{gathered}$$

■

Therefore, as uncertainty increases, expected profits increase more under carbon tax than under emissions trading. Indeed, as shown in the figure below, the potential marginal profit's increase (Area 3) is lower under a fixed cap than under a carbon tax, and the difference (Area 4) is caused by the marginal cost increase induced by the higher carbon price under quantity control. In fact, when the markup potentially grows firms have a higher willingness to pay for emissions, but since the overall quantity of emissions that can be produced is fixed, the higher demand for allowances increases the permits' price, shifting upward both firms' marginal costs.




To the contrary, under a cap and trade system the potential marginal profit reduction because of lower marginal benefits (Area 5) is counterbalanced by lower marginal costs induced by lower carbon price (Area 6).




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), each of them individually produces half of the emission cap $X$, regardless of the realization of the productivity parameter. As a result, equilibrium ex post emissions are:

$$e_k = \frac{X}{2}, \ k = n, a \tag{13}$$

and the equilibrium permits price is:

$$p^* = c_k - \frac{1}{2} X d_k, \ k = n, a. \tag{14}$$

Equilibrium profits are

$$\pi_k^* = \frac{1}{8} X^2 d_k, \ k = n, a \tag{15a}$$

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 summed up in the following Lemma.

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

The payoff resulting when only one firm adopts and the othe does not can be easily shown to be, respectively:

$$\pi_s^n = \frac{1}{12} d_n \frac{2\varepsilon_a^2 + 2\varepsilon_n^2 + 6X^2 d_a^2 + 2c_a^2 + 2c_n^2 - 2\varepsilon_a c_a - 2\varepsilon_n c_n - 3c_a c_n - 6X c_a d_a + 6X d_a c_n}{(d_a + d_n)^2}$$

for the non adopting firm, and

$$\pi_s^a = \frac{1}{12} d_a \frac{2\varepsilon_a^2 + 2\varepsilon_n^2 + 6X^2 d_n^2 + 2c_a^2 + 2c_n^2 - 2\varepsilon_a c_a - 2\varepsilon_n c_n - 3c_a c_n + 6X c_a d_n - 6X c_n d_n}{(d_a + d_n)^2}$$

for the adopting firm. In order for asymmetric adoption to be indeed an equilibrium of the technology adoption game, we have to guarantee that the adopting firm does not have an incentive not to adopt, i.e.

$$F < F_h = \pi_s^a - \pi_n^*$$

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

$$F > F_l = \pi_a^* - \pi_s^n$$

We can now state and prove the following result:

**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 showing that it is indeed possible to have $F_h > F_l$. It is easily shown that:

$$F_h - F_l = -\frac{1}{8} \frac{(d_a - d_n)^2}{d_a + d_n} X^2 + \frac{1}{12} \frac{2\varepsilon_a^2 + 2\varepsilon_n^2 + 2c_a^2 + 2c_n^2 - 2\varepsilon_a c_a - 2\varepsilon_n c_n - 3c_a c_n}{d_a + d_n}$$

which is a maximum in $X = 0$ and is decreasing for $X > 0$. It gets to 0 for $X = \frac{1}{3}\sqrt{2}\frac{\sqrt{3}}{d_a - d_n}\sqrt{2\varepsilon_a(\varepsilon_a - c_a) - 2c_n(\varepsilon_n - c_n) + 2\varepsilon_n^2 + 2c_a^2 - 3c_a c_n}$ and is negative afterwards. A necessary condition to get $F_h - F_l > 0$ is therefore to have $F_h - F_l|_{X=0} = \frac{1}{12}\frac{2\varepsilon_a^2 + 2\varepsilon_n^2 + 2c_a^2 + 2c_n^2 - 2\varepsilon_a c_a - 2\varepsilon_n c_n - 3c_a c_n}{d_a + d_n} > 0$. As $\frac{\partial F_h - F_l|_{X=0}}{\partial \varepsilon_n} = 4\varepsilon_n - 2c_n$ is negative for all values of $\varepsilon_n < \frac{c_n}{2}$ and tends to 0 as $\varepsilon_n$ tends to $\frac{c_n}{2}$, and as it is easily shown that $F_h - F_l|_{X=0}$ is strictly positive in the limit case of no uncertainty (i.e. when $\varepsilon_n = \frac{c_n}{2}$), then we can conclude that it is indeed the case that $F_h - F_l|_{X=0} > 0$. Given that the necessary condition for $F_h - F_l > 0$ holds, it is also possible to assume a sufficintly low value of $X$, namely $X < \widehat{X}$, $F_h - F_l > 0$ for strictly positive values of $X$.

Comparative statics shows that an increase in both uncertainties (the one arising under no adoption and the one arising under adoption) bring about an

increase in the likelihood of asymmetric adoption to take place. This happens because the set of fixed costs values leading to no adoption shrinks ($F_h$ increases with uncertainty, i.e. with decreases in $\varepsilon_n$ and/or $\varepsilon_a$), and the same happens to the set of fixed costs leading to adoption by both firms (i.e. $F_l$ is reduced by increases in uncertainty).

$$\frac{\partial (F_h - F_l)}{\partial \varepsilon_n} = \frac{(2\varepsilon_n - c_n)}{6(d_a + d_n)} < 0, \ \frac{\partial F_h}{\partial \varepsilon_n} = \frac{1}{12} d_a \frac{4\varepsilon_n - 2c_n}{(d_a + d_n)^2} < 0, \ \frac{\partial F_l}{\partial \varepsilon_n} = -\frac{1}{6} d_n \frac{2\varepsilon_n - c_n}{(d_a + d_n)^2} > 0$$

$$\frac{\partial (F_h - F_l)}{\partial \varepsilon_a} = \frac{(2\varepsilon_a - c_a)}{6(d_a + d_n)} < 0, \ \frac{\partial F_h}{\partial \varepsilon_a} = \frac{1}{12} d_a \frac{4\varepsilon_a - 2c_a}{(d_a + d_n)^2} < 0, \ \frac{\partial F_l}{\partial \varepsilon_a} = -\frac{1}{6} d_n \frac{2\varepsilon_a - c_a}{(d_a + d_n)^2} > 0$$

■

This result 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 simmetric choices. Moreover, while under a carbon tax system an increase of uncertainty of non-adoption always reduces the convenience to adopt, under fixed quantity, an increase in uncertainty of non-adoption can promote adoption.

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 born 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.

We now proceed to a comparison of how the fixed costs thresholds vary with uncertainty under the two regulatory settings. Recall that under a carbon tax adoption takes place if

$$F < F_p = E(\pi_a) - E(\pi_i)$$

that is if fixed costs are lower than the expected gains in profits, where $F_p = \frac{c_a^2 - c_a\varepsilon_a + \varepsilon_a^2 - 3c_a p + 3p^2}{6d_a} - \frac{c_n^2 - c_n\varepsilon_n + \varepsilon_n^2 - 3c_n p + 3p^2}{6d_n}$. It is easily shown that a decrease in $\varepsilon_n$ (i.e. an increase in uncertainty under no adoption) leads to an decrease in adoption incentives (i.e. a lower $F_p$), while the opposite happens when $\varepsilon_a$ decreases, i.e.uncertainty under adoption increases. This is easily seen from the following comparative statics results:

$$\frac{\partial F_p}{\partial \varepsilon_n} = -\frac{1}{6} \frac{2\varepsilon_n - c_n}{d_n} > 0$$

$$\frac{\partial F_p}{\partial \varepsilon_a} = \frac{1}{6}\frac{2\varepsilon_a - c_a}{d_a} < 0$$

As

$$\frac{\partial F_l}{\partial \varepsilon_n} - \frac{\partial F_p}{\partial \varepsilon_n} = \frac{1}{6} d_a \left(d_a + 2d_n\right) \frac{2\varepsilon_n - c_n}{d_n \left(d_a + d_n\right)^2} < 0$$

we can conclude that a decrease in uncertainty under no adoption increases $F_p$ more than $F_l$, so that the incentives for both firms to adopt increase more under a carbon tax. On the other hand, a decrease in uncertainty under adoption leads to an increase in incentives towards adoption (by both firms) under a cap and trade system and to a decrease in the corresponding incentives under a carbon tax. This last result must anyway take into account that under a cap and trade system it might well be the case that one firm adopts, while this is not possible under a carbon tax.

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. Results are in this case subtler than those obtained under fixed price. Here, the feed-in tariff, by decreasing uncertainty, decreases the incentives for asymmetric adoption, and pushes towards a symmetric behavior. This can alternatively mean full adoption, for sufficiently low values of the fixed cost $F$ (in this case the feed-in-tariff would entrail an increase in adoption), or no adoption, for higher values of the fixed cost $F$ (in this case, the feed-in-tariff reduces adoption).

## 5 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, viceversa, 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 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 (ECa 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 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 European Commission (EC) "A lower carbon price acts as a much less powerful incentive for change and innovation" (EC 2010a, p.6). Given these shortcomings several options to support the ETS carbon price by intervening either on the ETS cap (target reduction -30% and set-aside of allowances) or directly on the carbon price (price floor) have been proposed and are currently under discussion. In particular, 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. 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). 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.

Finally, our results might also be of interest in other 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, 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.

## 6 References

## References


[1] Adar Z., J.M. Griffin, Uncertainty and the choice of pollution control instruments, *Journal of Environmental Economics and Management*. 3 (1976) 178–188.

[2] Amundsen E. and Mortensed J. (2001). The Danish Green Certificate System: some simple analytical results. *Energy Economics* 23. 489 509

[3] Baldursson, F. M., & von der Fehr, N.-H. M. (2004). Price volatility and risk exposure: on market-based environmental policy instruments. *Journal of Environmental Economics and Management*, 48(1), 682-704.

[4] Bohringer C., Rosendhal K. E. (2010). Green promotes the dirtiest: on the interaction between black and green quotas in energy markets. *Journal of Regulatory Economics*, 37:316–325

[5] Bousquet, Alain and Creti, Anna, Input Choice under Carbon Constraint (November 30, 2010). Bocconi Legal Studies Research Paper No. 40. Available at SSRN: http://ssrn.com/abstract=1718268

[6] Bulow, J., Klemperer, P., 2002. Prices and the winner's curse. *RAND Journal of Economics,* 33(1), 1–21.

[7] Carraro C. and Soubeyran A. (1996). Environmental taxation, market share, and profits in oligopoly. Chapter of the book Carraro C., Katsoulacos Y. Xepapadeas A. (eds.), 23-44, Kluwer Academic Publishers

[8] Fishelson G. (1976), Emission control policies under uncertainty, *Journal of Environmental Economics and Management*, 3, 189–197.

[9] Fisher C. and Preonas L. (2010), Combining Policies for Renewable Energy - Is the Whole Less than the Sum of Its Parts?. *Resources for the Future Working Paper* DP 10-19

[10] Geroski, P.A. (2000), "Models of Technology Diffusion", Research Policy 29:603-626.

[11] Hahn, R., Stavins, R. (1999) What Has the Kyoto Protocol Wrought? The Real Architecture of International Tradable Permit Markets. Washington, D.C.: American Enterprise Institute Press.

[12] Hassett, K.A. and G.E. Metcalf (1996), "Can Irreversibility Explain the Slow Diffusion of Energy Saving Technologies?", Energy Policy 24: 7-8.

[13] Jung, C., K. Krutilla, and R. Boyd (1996) 'Incentives for advanced pollution abatement technology at the industry level: An evaluation of policy alternatives.' *Journal of Environmental Economics and Management* 30(1), 95–111

[14] Innes, R. (2003). Stochastic pollution, costly sanctions, and optimality of emission permit banking. *Journal of Environmental Economics and Management* 45 (2003), 546–568

[15] International Energy Agency (2011). CO2 emissions from combustion - Highlights. IEA statistics, Paris

[16] Lenzen, M. (2008) Life cycle energy and greenhouse gas emissions of nuclear energy: a review. *Energy Conversion and Managment* 39, 2178-2199

[17] Kemp, R. and L. Soete. (1990), "Inside the 'Green Box:' on the economics of technological change and the environment," in: Freeman, C. and L. Soete, eds., New Explorations in the Economics of Technological Change (Pinter, London).

[18] Kolstad, C., Ulen Th. S. and G.V. Johnson (1990), 'Ex-Post Liability for Harm vs. Ex-Ante Safety Regulation: Substitutes or Compliments?' *American Economic Review*, 80, 888–901

[19] Mandell, S. (2005). "The choice of multiple or single auctions in emissions trading." Climate Policy 5(1): 97-107

[20] McAfee, R.P., McMillan, J., 1987. Auctions and bidding. Journal of Economic Literature 25, 699–738.

[21] Milgrom, .R., Weber, R.J., 1982. A Theory of auctions and competitive bidding. Econometrica 50(5), 1089–1122.

[22] Milliman, S. R., and R. Prince (1989). Firm incentives to promote technological change in pollution control. *Journal of Environmental Economics and Management* 17: 247–265

[23] Orr, L. (1976), "Incentive for Innovation as the Basis for Effluent Charge Strategy", American Economic Review 66:441-447.

[24] Parry, I.W.H (1998), Pollution regulation and the efficiency gains from technological innovation, *Journal of Regulatory Economics* 14, 229–254

[25] Perino, G., Requate T. (2012), Does more stringent environmental regulation induce or reduce technology adoption? When the rate of technology adoption is inverted U-shaped, *Journal of Environmental Economics and Management,* in press

[26] Philibert, C. (2008), Price caps and price floors in climate policy - a quantity assessment, *International Energy Agency Information Paper*

[27] Philibert, C. (2011), Interactions of Policies for Renewable Energy and Climate, *International Energy Agency Working Paper*

[28] Pindyck, R. (1991), "Irreversibility, uncertainty, and investment", Journal of Economic Literature 29:1110-1152.

[29] Rothschild, J.E. Stiglitz (1971), Increasing risk: I. A definition, *Journal of Economic Theory,* 2 , pp. 225–243.

[30] Saphores J.-D.M., P. Carr (2000) Pollution reduction, environmental uncertainty and the irreversibility effect, Mimeo, Department of Economics/GREEN, Universite´ Laval

[31] Stavins, R. (2003). Experience with Market Based Policy Instruments. *Handbook of Environmental Economics,* 1, 355–435

[32] Weber, T.A. and K. Neuhoff, Carbon markets and technological innovation (2010), *Journal of Environmental Economics and Management*, 60, 115-132.

[33] Weitzman, M.L. (1974), Prices vs. quantities, *Review of Economic Studies* 41, 477–491

[34] Xepapadeas A. (1999) Environmental policy and firm behavior: abatement investment and location decisions under uncertainty and irreversibility, Mimeo, Department of Economics, University of Crete, 1999.

[35] Zerbe, R.O. (1970), "Theoretical Efficiency in Pollution Control", Western Economic Journal 8:364-376.