Fixed price vs Fixed Quantity with Different Timing of Auction: Incentives to Adopt Low-Carbon Technology under Uncertainty

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(very preliminary, do not cite or quote).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 consider four possible market design by combining a cap and trade scheme where either the quantity or the price of emissions is controlled with different timing of auction: an early auction where allowances are auctioned before uncertainty is revealed, and a late auction where allocation takes place after uncertainty is revealed. We analyse how uncertainty impacts on the firms' expected profits in each regulatory framework in order to determine under which market design the incentives of adoption are maximized. First of all, we find quite surprisingly that uncertainty impacts positively on firms' expected profits in all the cases except fixed quantity with early auction. Under late auction, uncertainty increases expected profits less under fixed quantity than under fixed price; and in this latter case uncertainty impacts positively on firms' expected profits more under late auction than under early auction. We conclude that the incentives to adopt are maximized under fixed price and late auction when uncertainty affects the low-carbon technology, while fixed quantity and early auction maximizes the incentives of adoption when uncertainty affects the carbon intensive technology. Finally, we apply these findings to some energy policy issues, concluding that the incentives to substitute nuclear power with gas plants instead of coal plants is maximized under a cap and trade scheme with price control where allowances are late auctioned. While adopt is maximized under fixed price and early auction when feed-in tariffs to renewable sources are in place.

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1 Introduction

Our paper analyzes the relative performances of a set of alternative regulatory schemes in terms of the incentives to adopt low-carbon technology. We focus on the role of uncertainty, and we identify which environmental policy design best fits frameworks with shifts in the generation mix (such as that currently being experienced by Germany), and with feed-in tariffs schemes adding to ETS regulations.

The policy objective of reducing carbon emissions has been introduced in Europe in 2003 through a cap and trade scheme -the so-called European Emissions Trading Scheme (ETS) - to induce through the adoption of low-carbon technologies. The ETS is a quantity-based mechanism where the regulator fixes *ex-ante* a limit to the amount of emissions that can be overally produced (the cap) and then allocates a corresponding amount of allowances among the regulated agents according to a pre-defined allocation rule. Firms need an allowance for any emission they produce. Whenever emissions exceed the amount of owned allowances, compliance occurs either by acquiring at the market price the required amount of allowances or by reducing emissions internally, for instance by adopting a low-carbon technology. Indeed, once carbon emissions are priced, traditional fossil fuels-based technologies become more expensive while low carbon technologies become indirectly more competitive and attractive.

With the current economic recession, the ETS has lost momentum. The reduction in electricity consumption and industrial production brought down the level of emissions. As a consequence, the demand for allowances has decreased, lowering the carbon price.[1]. 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).

To increase the effectiveness of this market-based instrument in promoting the adoption of low-carbon technology the EC proposed to support the carbon price through ex-post cap adjustment.[2]

[1] Carbon price within the ETS passed from 27 euros per tonn of CO2 in june 2008 to 12 euros per tonn in august 2011 (monthly average)

[2] 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. The Impact Assessment of this proposal estimated 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. 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).

A strategy paper published in 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. 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

On top of intervening on the ETS cap, the new ETS Directive 2009/29/EC establishes a progressive change in the main allocation rule: from the current grandfathering toward auctioning (Clò 2010). In 2010, the EC adopted an Auctioning Regulation where the administration, the format and other aspects of auctioning have been established. The timing of auctioning has not been entirely determined by the Auctioning Regulation. Whether allowances should be auctioned in the *future* or in the *spot* market has been open to debate. On one side, electricity producers demanded for early auction of *futures* allowances to cover their positions against long-term electricity supply contracts formulated even three years in advance. On the other side, the EC opted to limit early supply of allowances to grant scarcity of allowances and sustain the carbon price, thus opting for a late auction of *spot* allowances.

Within this framework, we can distinguish between four potential types of market design, derived by combining a cap and trade system where either the quantity or the price of emissions is controlled with different timing of auctioning. This paper investigates how the propensity of adopting a low-carbon technology can vary depending on the underlying market design when investments are undertaken under uncertainty. It first analyses how the impact of uncertainty on firms' expected profits varies under the four market designs; then it develops a comparative analysis aimed at determening under which market design the incentives of adoption are maximized.

The paper is structured in the following way: section 2 introduces the aim of the paper; section 3 discusses the relevant literature on the issues we are going to analyse is discussed. The model used to develop our analysis, the related assumptions, timing and settings are introduced in section 4. Sections 5 and 6 focus respectively on the late auction and early auction cases under fixed price, while sections 7 and 8 focus respectively on the late auction and early auction cases under fixed quantity. For each of these four cases, we derive market equilibria, we determine the firms' expected profits and we analyse how do they vary with a change in the uncertainty of the technology's return parameters. Section 8 develops a comparative analysis between the different cases, while some policy implications are derived in section 9. Section 10 concludes the paper by summarizing the main findings.

2 Aim of the paper

This paper analyses the performances of a set of regulatory designs in terms of incentives to adopt new technologies.

We analyse how adoption incentives vary under different timing of auctioning and different control mechanisms. Concering the timing of auctioning, we distinguish between an *early auction*, where allocation takes place before uncertainty is revealed (e.g auctioning *futures* permits) and a *late auction*, where allowances are auctioned after uncertainty is revealed (e.g. auctioning *spot* permits). Moreover we consider two alternative control mechanisms: first, a *cap & trade with quantity control* where the amountof emissions that can be produced is fixed while the price of the allowances varies. Second, a *cap & trade with price control* where the regulator fixes some limitations to the price fluctuations (a price floor and price cap, becoming a fixed price when the price cap equals the price floor) and then adjustes the quantity of tradable allowances after uncertainty is revealed to mantain the price at the desired level.

To summarize, we can define four different types of cap and trade market designs and we analyze how the decision to invest in low carbon technology varies in each of them. We are interested in analyzing under which conditions the incentives to adopt a clean technology under uncertainty are maximized.

	Late Auction	**Early Auction**
cap & trade with price control	**I**	**II**
cap & trade with quantity control	**III**	**IV**

In the light of the current trend of the European climate policy, we identify different issues to analyse in this paper. First, we question whether supporting the carbon price through *ex-post* quantity adjustments can be an effective strategy to promote adoption. Second, we analyze whether the timing of auctioning impact on prices and on decision to invest in order to determine whether limiting early auction of *futures* allowances in favour of a late auction of spot allowances can be an effective strategy to promote adoption.

The main findings of our analysis can be applied to some open policy issues. One of these concerns the future change in power generation mix in Germany. It is well known that the 2011 Fukushima nuclear disaster caused a unexpected energy policy reversal in several European countries. Among them, Germany announced its progressive nuclear phase-out.[3] As the German nuclear reactors are expected to shut down by 2022, they will have to be progressively substituted by other baseload technologies, mainly coal or gas-fired plants, where the gas price -being linked to the evolution of the oil market- is more volatile than the coal price and its future evolution can be considered more uncertain. Given this uncertainty, and being coal a more carbon intensive fuel than gas, we can question which market design would better promote the adoption of less carbon intensive gas plants rather than coal plants.

Moreover, we can apply this analysis to the case of renewable energy sources. National energy policies aimed at increasing the role of renewable technologies are in place in many countries and these may overlap with the European cap and trade scheme, calling for coordination. (Boorhinger and Rosendhal (2010), FIsher (2010), Philibert 2011). Thus, we question how overlapping instruments should be coordinated and, in particular, how should the ETS be designed to maximize the adoption incentives when direct subsidies to renewable technologies are already in place.

[3] For more details see, for instance, Euractiv at: http://www.euractiv.com/energy/germany-non-nuclear-2022-news-505222

3 Literature review

Our paper is connected to a first strand of literature which analyses the linkages between environmental policy instruments and incentives to technology adoption. This topic has been widely analyzed through a "discrete technology choice" model: once the environmental policy is in place, firms evaluate whether to adopt a certain technology which reduces the cost of compliance with the environmental regulation and which has a known fixed cost associated with it. A profit maximizing firm will find convenient to adopt whenever the initial investment is lower than the differential profits' increase in case of adoption.

Based on this model of adoption, different studies have developed a comparison across market based instruments, by questioning how they affect the diffusion rate of low carbon technologies and determining which of them maximizes the incentives of adoption. Indeed it has been widely recognized that alternative economic instruments impact differently on the innovation and diffusion of new technologies (Orr 1976, Kempe and Soete 1990).

We focus our analysis on market-based instruments, as their superior efficiency with respect to command and control has been extensively recognized (Zerbe 1970; Downing and White 1986; Milliman and Prince 1989; Kolstad et al. 1990, Jung et al. 1996). Theoretical comparisons among market-based instruments have found agreement only to a limited extent. By comparing how different instruments impact on the incentives for technology adoption at a firm-level (measured as an increase in producer surplus) Milliam and Prince (1989) found that a cap and trade scheme with auctioned permits would provide more incentive than emissions taxes, even with heterogeneous abatement costs (Milliman and Prince 1992). By applying the Milliam and Prince framework to a market-level where heterogeneous firms compete Jung et al. (1996) confirmed that auctioned permits provide the greatest incentives for adoption. In a subsequent paper, Parry (1998) shows that tax and emissions permits have similar efficiency properties under no uncertainty and linear damage function is linear.

These findings have been criticized by subsequent theoretical analyses. Based on the assumption that all firms adopt the new technology for a given exogenous price, the previous literature was not considering how a single firm's investment decision impacts on the market equilibrium, influencing indirectly the other firms' incentives to adopt. In particular, it has been argued that under a cap and trade scheme, as diffusion of low carbon technologies lowers the auction clearing carbon price, it reduces the incentives for further adoption (Requate and Unold (2003)). As carbon price decreases with adoption, some firms may free ride on other firms' investment decision, finding convenient not to adopt. This does not occur under a tax system where the carbon price does not vary. Thus, the firms finding convenient to adopt under carbon tax are at least as many investing under permits and thus taxes provide more incentives to adopt than other market-based instruments (Requate and Unold (2003)). The authors show also how the result may change depending on the timing the regulation entries into force.

By introducing endogenous carbon price, also Kehoane (1999) has argued that the incentives for adoption are inferior under cap and trade than under emissions taxes. The general result that taxes perform better than cap and trade has been confirmed by Denicolò (1999) who shows that, without uncertainty and under the assumption of convex environmental damage function, taxes are superior to permits if the regulator is committed to the regulation while taxes and permits are fully equivalent if the government can update these instruments after the technology diffusion has occurred. Our analysis adds uncertainty to their framework.

The literature has also discussed how environmental policies should be tailored when investment decisions are taken under uncertainty. Under a tax system, the regulator fixes the price and under this constraint the private parties determine the quantity of emissions, which is uncertain. Under a cap and trade scheme the quantity of emissions is known, while the price is not, thereby raising the problem of price volatility. One policy instrument can be more o less appropriate than another depending on specific circumstances. In particular, Weitzman (1974) demonstrated that when there is uncertainty the desirability of one instrument over the other depends on the shape of the marginal benefits and costs functions. In other words, when the MACs 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) compared with the shape of the marginal cost function. According to Rotchild & Stiglitz (1971), when environmental damages are convex higher uncertainty increases expected damages, thus calling for a quantity-based regulation which ensures emissions to a pre-defined level. On the other side, if environmental damage function' slope is small compared to the marginal abatement costs' slope, then a price-control mechanism should be adopted to reduce the risk of losses due to price volatility. These findings have been confirmed, among others, by Adar and Griffin (1976) and Fishelson (1976).

Also Baldursson & Von der Fehr (2004) explored the effects of uncertainty on market outcomes under different market-based instruments. They find that in a cap and trade scheme risk-adverse firms' incentive to invest in abatement equipment depend on their initial market position, and they 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 keep their allowances if they are potential sellers. As a consequence trade does not occur optimally and MACs are not equalized, making the quota system inferior with respect to a tax system, where the risk is transferred from the firm to the whole society, as marginal costs become fixed and environmental damages uncertain. The Baldursson & Von der Fehr (2004) conclusion depends partly on the risk-aversion assumption. However, it has been shown that uncertainty may limit the adoption of new technology also when firms are risk neutral (Gerosky 2000). It has been argued that when the convenience of investing in abatement technologies depends on the uncertain trend of resource price, there is an option value associated with delaying adoption (Pindyck (1991), Chao e Wilson (1993)). The incentive of postponing irreversible investment under uncertainty has been treated also by other authors (Hassett and Metcalf 1996, Saphore & Carr (2000), Xepapadeas (1999)).

Moreover, it is worth to mention that Bousquet & Cretì (2010) analyse how investments and capacity choice under environmental regulation depend on uncertainty in input price, finding that price variability leads to an expansion of the existing carbon intensive capacity. As uncertainty and price volatility increase, inefficiencies amplify and emission reduction become weaker.

Nehuoff & Weber (2010) explore the impact of price- and quantity-control instruments on both emissions-abatement efforts and private investment in technology innovation, focusing on how a change in innovation effectiveness influences the design of policy instruments. Consistently with the mainstream literature they find that when the slope of environmental damage function is high or when the innovation effectiveness increases, reducing marginal abatement costs, quantity-based instruments are superior to price-based ones in promoting technological innovation. Indeed, under these conditions the impact of uncertainty is higher on environmental damages than on MACs, thus a quantity-control mechanism reduces uncertainty. To the contrary, if innovation effectiveness decreases or if the slope of the environmental damage function is small, then price-control -which reduces uncertainty on the side of marginal abatement costs- is a superior mechanism.

Chen and Tseng (2011) compare the investment timing in the electricity sector between carbon tax and cap and trade, assuming that both input and output prices are idiosyncratic, as well as carbon price, and assuming price-taking firms. The authors compare the value of waiting with early profits which depend on price uncertainties and they show that, in financial options, volatility has a value because it increases option values and earning opportunities. As the carbon price does not vary under a tax system, the authors conclude that a cap and trade system where prices are volatile gives higher incentives to adoption.

Finally, another strand of literature focused on auction theory has shown how the market equilibrium and the related clearing price can vary depending on the timing and frequency of auction when bidding takes place under uncertainty or imperfect information (Milgrom and Weber (1982), McAfee and McMillan (1987), Bulow and Klemperer (2002), Mandell (2005)).

4 The Model

4.1 Assumptions

We consider two risk-neutral regulated firms, labelled as f and h. In the absence of regulation, the two firms use heterogeneous carbon intensive technologies, leading their product to be sold on two different markets. In the absence of regulation, firms are not charged for their emissions (e_k, $k = f, h$). The cost function is given by:

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

where c_m is the fuel average cost and d_k is a positive parameter. Ww assume that while the linear relation between costs and emissions accounts for the fuel input needed in production, the convex cost relation accounts for all the other inputs, for the capacity constraints and/or decreasing returns to scale related to production. Observe that the cost relation $C(e_k)$ may be regarded as stemming from the combination of a linear relation between quantity and emission which varies among technologies depending on their "carbon efficiency", and a convex cost function $C(q_k)$.[4]

The unregulated profit maximization problem is given by:

$$\max_{e_k} \pi_i = (v - c_m) e_k - d_k \frac{e_k^2}{2} \tag{1}$$

where v is the per-unit revenue (willingness to pay) and $(v - c_m) = c_k$ is the per-unit markup.

The markup from selling their output on such markets depend on two stochastic and firm specific parameters, distributed acccording to the functions $F(c_f)$ and $F(c_h)$, where c_f and c_h are the firms' specific parameters and $F(c_f) \neq F(c_h)\ \forall c_f, c_h$. We can think of c_k as being determined by volatile output or input prices. We assume distributions are uniform, with $c_f \in (\varepsilon_f, c_f - \varepsilon_f)$ and $c_h \in (\varepsilon_h, c_h - \varepsilon_h)$, where $(c_f - \varepsilon_f) > (c_h - \varepsilon_h)$. The parameters ε_f and ε_h captures the level of uncertainty, through an inverse relation., i.e., larger ε_f and/or ε_h imply a smaller degree of uncertainty. Each firm ex ante knows the distribution, but not the realization, of both its own and the rival's productivity parameter. Notice that we model uncertainty on the revenue side but not on the (convex) cost side. As a result, our modeling strategy can be applied in all cases where output price volatility (e.g. determined by the state of the economy) *is* at stake.

When an ETS is in place, 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:

$$\max_{e_k} \pi_k = c_k e_k - d_k \frac{e_k^2}{2} - p e_k \tag{2}$$

so that

$$e_k = \frac{c_k - p}{d_k} \tag{3}$$

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

Facing a cap and trade, firms have the option to adopt a low-carbon technology, with the corresponding volatile markup-related parameter labeled as c_a and the corresponding distribution function being $F(c_a)$. The latter is assumed

[4] 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).

to feature a higher average productivity parameter, which measures, in some sense, the larger selling potential of new technologies (e.g. photovoltaics as compared to coal) - that is $c_a \in (\varepsilon_a, c_a - \varepsilon_a)$, $(c_a - \varepsilon_a) > (c_k - \varepsilon_k), k = f, h$. The new technology also affects firms' cost parameter that, in case of adoption is labelled as d_a. For the purpose of comparing adoption with non-adoption, we can assume that $d_f = d_h = 1$ for the existing technologies. Thus, If $d_a > 1$, the new technology features smaller carbon intensity and/or more significant capacity constraints and vice versa. Finally, adoption entails an intial investment F (fixed cost).

The above maximization problems might be useful to model several real life environmental issues. As we will discuss in a subsequent section, our model is suitable to exemplify the impact of different ETS design on the incentives for regulated firms to move from a mature energy technology (hydro, coal, gas, oil....) to a renewable one (such as wind), Indeed, the latter can be modelled through an increase in c_k and, at the same time, by a change in the cost parameter, implying larger capacity constraints (smaller scale), i.e. a value of $d_a > 1$. Our model can also be useful to assess the impact of policies stabilizing the output price (i.e. feed in tariffs) on the incentives to invest. The latter can indeed be modelled through a reduction in the related uncertainty (i.e. an increase in ε_a).

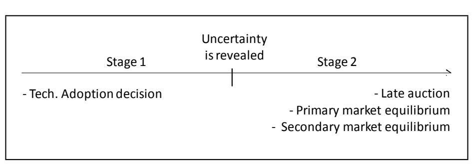
4.2 Timing and Setting

We analyze a two-stage game. At stage 1, each firm chooses whether to adopt the new technology. By assumption, the initial investment F must be undertaken under uncertainty, before getting to know the realization of the productivity parameters. Therefore, adoption takes place whenever the intial investment F is lower than the difference between the expected profit under adoption ($E(\pi_a)$) and non adoption ($E(\pi_k)$).

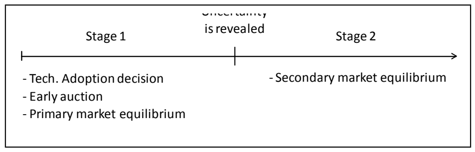
$$E(\pi_a) - F > E(\pi_k) \tag{4}$$

We consider two possible timing sequences, depending on the regulatory setting: early auction or late auction.

If a late auction is in place, at stage 1 firms only decide whether to adopt according to their expected profits. Then, after uncertainty is revealed, at stage 2 firms decide how much to produce and they buy the corrisponding amount of emission allowances in the public auction. Thus, both the primary and secondary market equilibria are derived.



If, instead, an early auction is in place, at stage 1 firms decide whether to adopt and simulteneously they buy allowances at the carbon market price before uncertainty is resolved, and the primary market equilibrium is derived; then, after the realization of the productivity parameter is revealed, firms decide how much to produce



Under early auction, firms' production decisions at stage 2 are constrained by the quantity of allowances acquired at stage 1. This is because we assume no resale in the second stage. No resale can be viewed as an extreme case where, for some reasons, trading of allowances does not take place after uncertainty is resolved even if it were allowed. This could happen when uncertainty is only systemic and it affects all firms symmetrically, making them either net buyers or net sellers once uncertainty is revealed. To the contrary, in case of idiosyncratic uncertainty, early auction with resale would tend to the late auction case. Therefore we focus on the two extreme cases: early auction with no resale and late auction, where the former mimics the case of early auction with resale under systemic uncertainty, while the latter mimics the case of early auction with resale under idiosyncratic uncertainty. Whenever uncertainty is characterized by both a systemic and an idiosyncratic component, then market equilibrium falls between the extreme cases we consider in this paper.

5 Fixed Price and Late Auction

We label the firm according to the chosen technology i. More specifically, as the adoption of the new technology implies that firms are symmetric, then $i = a$ if either firm f or h has adopted the cleaner technology. On the other hand, $i = f, h$ if the firm (f or h respectively) did not adopt the new technology.

Under fixed price and late auction, once uncertainty is revealed, the authority sells at a pre-determined price all the allowances required by the firms according to their realized return parameters. Indeed, under this regime, firms can buy at a given price a spot allowance for any emission they produce and they do not face any quantity constraint. This implies that firms' decisions are not inter-dependent.[5]

In the last stage, given a fixed price p, the optimal amount of permits is determined according to equation (3). By construction, the profit maximing optimal amount of permits equals the amount of produced emissions. Once the market equilibrium is derived, each firm i profits can be determined:

$$\pi_i = c_i \frac{(c_i - p)}{d_i} - \frac{(c_i - p)^2}{2d_i} - p\frac{(c_i - p)}{d_i} = \frac{(c_i - p)^2}{2d_i} \tag{5}$$

[5] *This case mimics closely the functioning of a carbon tax.*

In the first stage, when uncertainty is not yet revealed, firms have to decide whether to adopt a low-carbon technology according to their expected profits from adoption and non-adoption.

The expected value of emissions is given by[6]:

$$E\left(e_i\right) = \int_{\varepsilon_i}^{c_i-\varepsilon_i} \frac{c_i - p}{d_i} \left(\frac{1}{c_i - 2\varepsilon_i}\right) dc_i = \frac{c_i - 2p}{2d_i} \tag{6}$$

Expected profits are:

$$E\left(\pi_i\right) = \int_{\varepsilon_i}^{c_i-\varepsilon_i} \frac{\left(c_i - p\right)^2}{2d_i} \left(\frac{1}{c_i - 2\varepsilon_i}\right) dc_i = \frac{c_i^2 - c_i\varepsilon_i + \varepsilon_i^2 - 3c_ip + 3p^2}{6d_i} \tag{7}$$

Both expected emissions and expected profits depend positively on the firm's markup c_i, while they depend negatively on the carbon price p:

$$\frac{\partial E\left(e_i\right)}{\partial c_i} = \frac{1}{2d_i} > 0 \tag{8}$$

$$\frac{\partial E\left(e_i\right)}{\partial p} = -\frac{1}{d_i} < 0 \tag{9}$$

$$\frac{\partial E\left(\pi_i\right)}{\partial p} = \frac{-c_i + 2p}{2d_i} < 0 \tag{10}$$

$$\frac{\partial E\left(\pi_i\right)}{\partial c_i} = \frac{1}{6d_i}\left(2c_i - 3p - \varepsilon_i\right) > 0 \text{ if } p < \frac{\left(2c_i - \varepsilon_i\right)}{3} \leq \frac{c_i}{2} \tag{11}$$

where inequality (10) follows from $p < \frac{c_i}{2}$. Clearly if $d_a < 1$ expected emissions and expected profits from adoption change (in absolute terms) more rapidly compared to expected profits and expected emissions from non-adoption; the opposite is true when $d_a > 1$.

Moreover, while expected emissions do not depend on uncertainty expected profits do. Therefore we analyse how uncertainty, namely the uncertainty parameter ε_i, affects expected profits and, indirectly, the decision to adopt a low-carbon technology.

Lemma 1 *Under fixed price and late auction each firm's expected profits depend positively only on its own uncertainty.*

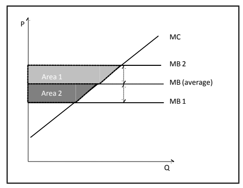
Proof By differentiating expected profits with respect to ε, we obtain:

$$\frac{\partial E\left(\pi_i\right)}{\partial \varepsilon_i} = \frac{1}{3d_i}\left(\varepsilon_i - \frac{c_i}{2}\right) < 0 \tag{12}$$

It follows immediatly that expected profits depend only on each firm's own uncertainty. Moreover, as the productivity realization varies within the range

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

$(\varepsilon_i, c_i - \varepsilon_i)$, ε_i cannot exceed $\frac{c_i}{2}$. As a result, when uncertainty decreases (i.e., ε_i increases), expected profits decrease as well. Vice-versa, expected profits increase when uncertainty increases. In other terms, higher uncertainty increases the firm's expected profits. This relation is illustrated by the following graphs.



Under price control, price does not vary by defintion and marginal costs do not shift, thus uncertainty impacts only on the firm's marginal benefits c_i. The higher the uncertainty (i.e., the lower ε_i), the larger the range where marginal benefits can vary. 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) is higher than the reduction in marginal profit's under an equal but opposite realization of the productivity parameter (Area 2). Thus, as uncertainty increases (i.e. ε_i decreases) expected profits increase as well as a consequence of the concavity of the profits function.

6 Fixed Price and Early Auction

Under early auction with no resale, the firm's production in the last stage is constrained by the amount of permits bought in the previous stage before the resolution of uncertainty, and denoted e_i^*. In the last stage the cost of emission allowances is sunk and it is not considered in the profit function. Therefore, each firm i maximizes:

$$\begin{aligned} \max_{e_i} \pi_i &= c_i e_i - d_i \frac{e_i^2}{2} \\ s.t.\ e_i &\leq e_i^* \end{aligned}$$

As a result:

$$e_i = \begin{cases} \frac{c_i}{d_i} \text{ if } \frac{c_i}{d_i} < e_i^* \\ e_i^* \text{ if } \frac{c_i}{d_i} > e_i^* \end{cases} \tag{13}$$

Whenever $e_i^* > \frac{c_i}{d_i}$ part of the acquired allowances will not be used (i.e $e_i^* - \frac{c_i}{d_i}$) and this constitutes an inefficiency that does not take place under late auction.

In the first stage, firms buy allowances weighting the second stage tradeoff between the prospect of availability in excess of its needs, and the alternative of being short of them. Thus, the expected value of emission is given by:

$$E(e_i) = \int_{\varepsilon_i}^{e_i^* d_i} \frac{c_i}{d_i}\left(\frac{1}{c_i - 2\varepsilon_i}\right) d_i c_i + \int_{e_i^* d_i}^{c_i - \varepsilon} e_i^* \left(\frac{1}{c_i - 2\varepsilon_i}\right) dc_i =$$

$$E(e_i) = \frac{1}{4d_i\varepsilon_i - 2c_i d_i}\left(d_i^2 e_i^{*2} + \varepsilon_i^2 + 2d_i\varepsilon_i e_i^* - 2c_i d_i e_i^*\right) \quad (14)$$

We now determine expected profits and then the optimal amount of permits that each firm will acquire in the early auction. Expected profits, expressed as a function of e_i^*, are obtained by combining these probabilities:

$$E(\pi_i) = \int_{\varepsilon_i}^{e_i^* d_i} \left(c_i \frac{c_i}{d_i} - \frac{c_i^2}{2d_i}\right)\left(\frac{1}{c_i - 2\varepsilon_i}\right) dc_i + \int_{e_i^* d_i}^{c_i - \varepsilon} \left(c_i e_i^* - \frac{d_i e_i^{2*}}{2}\right)\left(\frac{1}{c_i - 2\varepsilon_i}\right) dc_i - pe_i^* =$$

$$= \frac{(d_i e_i^*)^3 - \varepsilon_i^3}{6d_i(c_i - 2\varepsilon_i)} + \frac{e_i^*(c_i - \varepsilon_i)^2 - d_i e_i^{*2}(c_i - \varepsilon_i)}{2(c_i - 2\varepsilon_i)} - pe_i^* \quad (15)$$

Firms maximize expected profits with respect to the amount of permits to be bought ($\frac{\partial \pi_i}{\partial e_i^*} = 0$):

$$e_i^* = \frac{1}{d_i}\left(c_i - \varepsilon_i - \sqrt{2p(c_i - 2\varepsilon_i)}\right) \quad (16)$$

the optimal amount of permits acquired in the early auction is positive whenever:

$$p < \frac{(c_i - \varepsilon_i)}{2} \quad (17)$$

Given this condition, the optimal amount of allowances increases with uncertainty:

$$\frac{\partial e_i^*}{\partial \varepsilon_i} = \frac{1}{(c_i - 2\varepsilon_i)}\left(2\varepsilon_i - c_i + \sqrt{2p(c_i - 2\varepsilon_i)}\right) < 0 \quad (18)$$

This relation does not occur under late auction and it helps us to understand how uncertainty impacts on expected profits under early auction.

Lemma 2 *Under fixed price and early auction each firm's expected profits depend positively only on its own uncertainty.*

Proof By differentiating expected profits with respect to ε, we obtain:

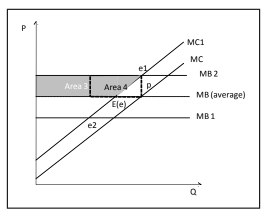
$$\frac{\partial E(\pi_i)}{\partial \varepsilon_i} = \frac{1}{6d_i(c_i - 2\varepsilon_i)^2}(\varepsilon_i - d_i e_i^*)^2(4\varepsilon_i - 3c_i + 2d_i e_i^*) \quad (19)$$

substituting from e_i^* we get:

$$\frac{\partial E\left(\pi_i\right)}{\partial \varepsilon_i}=-\frac{\left(c_i-2\varepsilon_i+2\sqrt{2}\sqrt{pc_i-2p\varepsilon_i}\right)\left(2\varepsilon_i-c_i+\sqrt{2}\sqrt{pc_i-2p\varepsilon_i}\right)^2}{6d_i\left(c_i-2\varepsilon_i\right)^2}<0 \tag{20}$$

which is always negative, as $2\varepsilon_i < c_i$ by construction, when equation (16) is verified.

Higher uncertainty increases the amount of allowances acquired in the early auction. Each firm realizes additional profits whenever marginal benefits are higher than their average value (Area 3), while it faces a loss whenever the realization of the productivity parameter is worse than the average (Area 4). On average, the extra-profit the firm realizes when productivity has a good realization (Area 3) is higher than the profit loss in the opposite case (Area 4) making it optimal for the firm to increase the optimal amount of allowances when uncertainty increases. Firms tend to resolve the tradeoff between the risk of buying in excess and that of being short of allowances in favor of the former and, as uncertainty increases, the difference between the variation in marginal benefits and costs gets larger, implying that expected profits increase at a positive rate with uncertainty.



7 Fixed Quantity and Late Auction

Under late auction, each firm buys allowances in the last stage according to its needs. However, differently from the fixed price case, under fixed quantity firms are now subject to a constraint, since the sum of the their emissions cannot exceed a fixed cap X. This implies that under fixed quantity firms' choices become interdependent through the equilibrium on the permits market.

Label the two firms as $i = f, h$ and $j = f, h$, with $i \neq j$ under non adoption and as $i = a$, $j = a$ when firm i or firm j or both adopt the new technology.

First of all, we focus on expected profits under non adoption under the assumption that firms are asymmetric and the error terms are uncorrelated. This is the case when either no firm adopts or only one firm adopts (in the latter case either $i = a$ or $j = a$).For each of the two firms i, j we determine the demand for permits and, by summing (horizontally) the firms' demand functions, we obtain the market demand, which is a step function.

$$E=\begin{cases} \frac{d_j c_i+d_i c_j-p(d_i+d_j)}{d_i d_j} \text{ if } p\leq c_j \\ \frac{c_i-p}{d_i} \text{ if } c_i\leq p\leq c_j \end{cases}$$

If the cap is sufficiently strict, then only the most efficient firm operates in the market, otherwise both firms compete. We limit our analysis to this latter case where both firms compete. By equating the firms' aggregate demand function to the supply we get the equilibrium price and the resulting optimal level of permits each firm buys in the late auction:

$$p^* = \frac{c_j d_i + c_i d_j - d_i d_j X}{(d_i + d_j)} \tag{21}$$

$$e_i^* = \frac{c_i (d_i + d_j) - (c_j d_i + c_i d_j - d_j d_i X)}{d_i (d_i + d_j)} \tag{22a}$$

$$e_j^* = \frac{c_j (d_i + d_j) - (c_j d_i + c_i d_j - d_j d_i X)}{d_j (d_i + d_j)} \tag{22b}$$

Equilibrium profits are:

$$\pi_i^* = \frac{(c_i (d_i + d_j) - (c_j d_i + c_i d_j - d_j d_2 X))^2}{2d_i (d_i + d_j)^2} \tag{23a}$$

$$\pi_j^* = \frac{(c_j (d_i + d_j) - (c_j d_i + c_i d_j - d_j d_2 X))^2}{2d_j (d_i + d_j)^2} \tag{23b}$$

In the first stage firms have do decide under uncertainty whether to adopt a low carbon technology by comparing the expected profits from adoption and non adoption. By analysing how uncertainty affects expected profits under fixed quantity and, indirectly, the decision to adopt new technologies, we can state that:

Lemma 3 *When the Under fixed quantity and late auction each firm's expected profits depend positively on the uncertainty of both firms' technology parameters ($\varepsilon_i, \varepsilon_j$) when the realizations of the productivity parameters across the two firms are uncorrelated (i.e. firms' error terms are independent)*[7]*.*

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:

$$E(e_i) = \int_{\varepsilon_i}^{c_i - \varepsilon_i} \frac{c_i - p}{d_i} \left(\frac{1}{c_i - 2\varepsilon_i} \right) dc_i = \frac{c_i - c_j + 2d_j X}{2(d_i + d_j)} \tag{24}$$

The expected price is given by:

$$E(p) = \int_{\varepsilon_i}^{c_i - \varepsilon_i} \frac{c_j d_i + c_i d_j - d_i d_j X}{(d_i + d_j)} \left(\frac{1}{c_i - 2\varepsilon_i} \right) dc = \frac{c_j d_i + c_i d_j - 2d_i d_j X}{2(d_i + d_j)} \tag{25}$$

[7] the symmetric case is treated in the Appendix I

and the expected profits are:

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

$$E(\pi_i) = \frac{d_i}{2(d_i+d_j)^2}\left(\begin{array}{c} X^2(d_j)^2 - Xd_jc_j + Xd_jc_i + \\ +\frac{(c_j)^2-c_j\varepsilon_j+(\varepsilon_j)^2}{3} - \frac{c_ic_j}{2} + \frac{(c_i)^2-c_i\varepsilon_i+(\varepsilon_i)^2}{3}\end{array}\right) \tag{26}$$

Differently from the fixed price case, under fixed quantity, the firms' expected profits depend on both firms' uncertainties $(\varepsilon_i, \varepsilon_j)$ and the impact of each firm's uncertainty on expected profits results from:

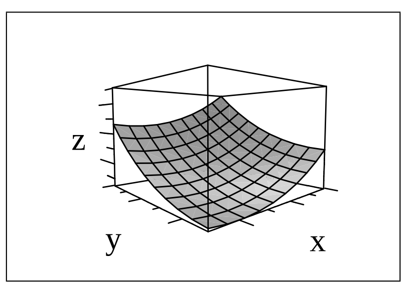
$$\frac{\partial E(\pi_i)}{\partial \varepsilon_i} = \left(\frac{1}{3}\frac{d_i}{(d_i+d_j)^2}\right)\left(\varepsilon_i - \frac{c_i}{2}\right) < 0 \tag{27a}$$

$$\frac{\partial E(\pi_i)}{\partial \varepsilon_j} = \left(\frac{1}{3}\frac{d_i}{(d_i+d_j)^2}\right)\left(\varepsilon_j - \frac{c_j}{2}\right) < 0 \tag{27b}$$

which are both negative as $\varepsilon_i < \frac{c_i}{2}$ and $\varepsilon_j < \frac{c_j}{2}$ by construction.

Moreover, the derivative of expected profits with respect to ε_i and depend differentially on the average level of the productivity parameter $(\frac{c_{i,j}}{2})$ in a negative way. Being the derivative negative, the impact of uncertainty on the expected profits increases with the average level of the productivity parameter $(\frac{c_{i,j}}{2})$. In our model, being $\frac{c_i}{2} > \frac{c_j}{2}$ by contruction, a variation of the uncertainty of the firm's i productivity parameter has a higher impact on both firms' expected profits than a variation of the uncertainty of the firm's j productivity parameters.

These findings are represented in the figure below.



Both firm's own and rival uncertainties impact positively on each firm's expected profits. This result differs from the fixed price case, where firms are not interdependent, and their expected profits depend only on its own uncertainty independently on the degree of asymmetry.

When both firms adopt the same low carbon technology, they become symmetric and their expected profits no longer depend on uncertainty. Indeed, when both firms adopt the low-carbon technology, the firms share the same technology and thus the same realization of the productivity parameter; therefore, each of them individually produces half of the emission cap X, regardless of the realization of the parameter c_a (where the index a stands for adoption):

$$e_{a|i,j} = \frac{X}{2} \tag{28}$$

By equating the firms' aggregate demand function to the supply, the equilibrium price becomes:

$$p^* = c_a - \frac{X d_a}{2} \tag{29}$$

and both firms' expected profits in equilibrium become:

$$E\left(\pi_a\right) = \frac{1}{8} X^2 d_a \tag{30}$$

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, the average profit across all states equals the profit in the average state of the economy.

8 Fixed Quantity and Early Auction

We now turn to our last setting, where the environmental regulator sets the overall emissions cap and auction takes place before uncertainty is revealed.

In the last stage, each firm takes the amount of permits bought in the first stage e^* as given and chooses:

$$e_i = \begin{cases} \frac{c_i}{d_i} \text{ if } \frac{c_i}{d_i} < e^* \\ e^* \text{ if } \frac{c_i}{d_i} > e^* \end{cases}$$

In the first stage, firms simultaneously decide whether to adopt the low carbon technology and the amount of allowances to buy, according to the expected emissions and the expected profits, which are respectively given by:

$$\begin{aligned} E_{c_i}\left(e_i\right) &= \int_{\varepsilon_i}^{e_i^* d} \frac{c_i}{d_i} \left(\frac{1}{c_i - 2\varepsilon_i}\right) dc_i + \int_{e_i^* d}^{c_i - \varepsilon_i} e_i^* \left(\frac{1}{c_i - 2\varepsilon_i}\right) dc_i = \\ &= \frac{1}{4 d_i \varepsilon_i - 2 c_i d_i} \left(\left(d_i e_i^*\right)^2 + \varepsilon_i^2 + 2 d_i \varepsilon_i e_i^* - 2 c_i d_i e_i^*\right) \end{aligned} \tag{31}$$

and

$$E(\pi_i) = \int_{\varepsilon_i}^{e_i^* d_i} \left(c_i \frac{c_i}{d_i} - \frac{c_i^2}{2d_i} \right) \frac{1}{c_i - 2\varepsilon_i} dc_i + \int_{e_i^* d_i}^{c_i - \varepsilon_i} \left(c_i e_i^* - \frac{d_i (e)^2}{2} \right) \frac{1}{c_i - 2\varepsilon_i} dc_i - pe^*$$

$$E(\pi_i) = \frac{1}{c_i - 2\varepsilon_i} \left(\frac{(e_i^* d_i)^3 - (\varepsilon_i)^3}{6d_i^\gamma} + \frac{e_i^* (c_i - \varepsilon_i)^2 - d_i e_i^{*2} (c_i - \varepsilon_i)}{2} \right) - pe_i^* \quad (32a)$$

$$E(\pi_j) = \frac{1}{c_j - 2\varepsilon_j} \left(\frac{(e_i^* d_i)^3 - (\varepsilon_i)^3}{6d_i^\gamma} + \frac{e_i^* (c_i - \varepsilon_i)^2 - d_i e_i^{*2} (c_i - \varepsilon_i)}{2} \right) - pe_i^* \quad (32b)$$

Then, we determine each firm's demand of allowances as a function of the permits' price $\left(\frac{\partial \pi_{i,j}}{\partial e^*} = 0 \right)$:

$$e_i^* = \frac{1}{d_i} \left(c_i - \varepsilon_i - \sqrt{2p (c_i - 2\varepsilon_i)} \right) \quad (33a)$$

$$e_j^* = \frac{1}{d_j} \left(c_j - \varepsilon_j - \sqrt{2p (c_j - 2\varepsilon_j)} \right) \quad (33b)$$

By equating demand to supply we determine the equilibrium price of the early auction $\left(X = e_i^* + e_j^* \right)$:

$$p^* = \frac{\left(d_i (c_j - \varepsilon_j) + d_j (c_i - \varepsilon_i) - d_i d_j X \right)^2}{\left(d_i \sqrt{2 (c_j - 2\varepsilon_j)} + d_j \sqrt{2 (c_i - 2\varepsilon_i)} \right)^2} \quad (34)$$

Given the equilibrium price, the optimal amount of permits each firm acquires in the early auction is:

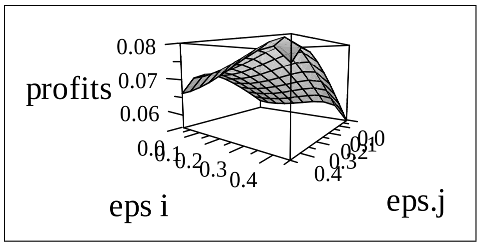
$$e_i^* = \frac{c_i - \varepsilon_i}{d_i} - \frac{\left(d_i (c_j - \varepsilon_j) + d_j (c_i - \varepsilon_i) - d_i d_j X \right) \sqrt{c_i - 2\varepsilon_i}}{d_i \left(d_i \sqrt{c_j - 2\varepsilon_j} + d_j \sqrt{c_i - 2\varepsilon_i} \right)} \quad (35a)$$

$$e_j^* = \frac{c_j - \varepsilon_j}{d_j} - \frac{\left(d_i (c_j - \varepsilon_j) + d_j (c_i - \varepsilon_i) - d_i d_j X \right) \sqrt{c_j - 2\varepsilon_j}}{d_j \left(d_i \sqrt{c_j - 2\varepsilon_j} + d_j \sqrt{c_i - 2\varepsilon_i} \right)} \quad (35b)$$

Finally, it is possible to analyze how uncertainty impacts on expected profits in equilibrium:

Lemma 4 *Under early auction and fixed quantity the relation between uncertainty and expected profits is not monotonic. When firms error terms are uncorrelated (i.e. asymmetric), both firms' expected profits might increase decrease with uncertainty, depending on the degree of uncertainty itself. The impact is, in absolute terms, lower for the firm with higher uncertainty.*

We can explain the non-monotonic relation between uncertainty and expected profits as the result of two opposite effects. First, as already seen under fixed quantity and late auction (equation 26), higher uncertainty increases expected profits. Moreover, as already seen under early auction and fixed price (equation 17), under early auction the optimal amount of allowances increases with uncertainty since the potential marginal profit's increase is higher than the marginal profit's reduction. However, being the total amount of emissions fixed, the higher demand of allowances brings up the permits' price, with a negative impact on expected profits. Given these counter-balancing effects, as uncertainty increases, exected profits first increase as far as the first effect is higher than the second, then they decrease. [8]



9 Comparisons

9.1 Late Auction vs Early Auction

We can now develop a comparative analysis aimed at determing under which market design the incentives to adopt are maximzed. In particular, we state the following proposition:

Proposition 5 *Under fixed price, a higher uncertainty increases expected profits both under late and early auction, but the increase is higher under late auction than under early auction.*

The proposition holds whenever:

$$\frac{\partial E(\pi_i)}{\partial \varepsilon_i}|_{L.A.} - \frac{\partial E(\pi_i)}{\partial \varepsilon_i}|_{E.A.} < 0 \tag{36}$$

which is always verified (for a formal proof see Appendix I).

Higher uncertainty increases firm's expected profits under both late and early auction. However, under early auction firms tend to resolve the tradeoff between the risk of buying in excess and that of being short of allowances in favor of the former. Since a higher uncertainty increases the optimal amount of permits that might not be used in the next stage, it also raises the inefficiency related to the early auction case. This inefficiency does not occur under late

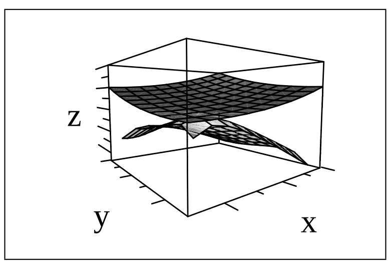
[8] Like in the fixed quantity and late auction case, When firms are symmetric and the realizations of the mark-up parameters across the two firms become perfectly correlated, firms'expected profits do not depend anymore on any of the firms' uncertainty (see Appendix II).

auction. Therefore, as uncertainty in the low-carbon technology adoption increases, expected profits increase under both late and early auction, but given the same variation of uncertainty, profits increase more under late auction than under early auction.

We now compare how uncertainty impacts on expected profits under early and late auction when the quantity of emissions is fixed[9]. We state the following proposition:

Proposition 6 *Under fixed quantity, expected profits are lower under early auction than under late auction and, as uncertainty increases, expected profits increase more under late auction than under early auction when the realizations of the productivity parameters are uncorrelated across the two firms.*

Under fixed quantity, the equilibrium price in early auction is higher than the expected price in late auction. This is because, under early auction firms tend to overpurchase allowances. However, being the cap fixed, they cannot increase the amount of acquired allowances, thus the higher demand increases price, reducing expected profits with respect to the late auction case. Therefore the expected profits under early auction are lower than expected profits under late auction. Moreover, when firms are asymmetric, under late auction higher uncertainty increases both firms' expected profits. Under early auction, higher uncertainty for the firm i impacts differently on firms'expected profits, first increasing and then decreasing both of them, with a lower impact on the firm with higher uncertainty. The figure below shows that both firms' expected profits under early auction are lower than profits under late auction, and the difference gets larger as uncertainty increases.



9.2 Fixed Price vs Fixed Quantity

We now compare the cases of late auction under fixed price and fixed quantity In order to understand under which market design the incentives to adopt new technologies are maximized, we analyse how a variation of uncertainty impacts on expected profits under fixed quantity and fixed price, and we obtain the following:

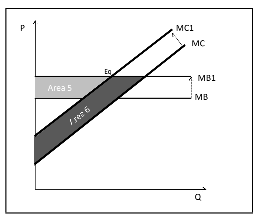
[9]Under late auction, the level of emissions that will be produced by the two firms, the corresponding amount of permits to be acquired and the equilibrium price will be defined only in the last stage, after uncertainty is revealed. Therefore, in order to compare late auction with early auction we focus on the first stage when uncetrainty affects expected profits and the propensity to adopt a new technology

Proposition 7 *Under late auction uncertainty increases expected profits more under fixed price than under fixed quantity.*

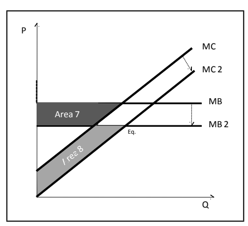
We compare the derivatives of expected profits with respect to ε_i in late auction under fixed price and fixed quantity respectively, using equation (12) and equations (27a) and (27b)[10].

$$\frac{\partial E(\pi_i)}{\partial \varepsilon_i}|_{FQ,LA} - \frac{\partial E(\pi_i)}{\partial \varepsilon_i}|_{FP,LA} < 0 \tag{37}$$

Therefore, as uncertainty increases, expected profits increase more under fixed price than under fixed quantity. Indeed, as shown in the figure below, the potential marginal profit's increase (Area 5) is lower under fixed quantity than under fixed price, and the difference (Area 6) 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 fixed quantity the potential marginal profit reduction because of lower marginal benefits (Area 7) is counterbalanced by lower marginal costs induced by lower carbon price (Area 8).



Finally we turn to the case where the average level of the technology's return parameter changes.

Proposition 8 *When the average level of the firm's markup related to the low-carbon technology' increases, both firms' i and j incentives to adopt are maximized under fixed price, while the incentives to adopt are maximized under fixed quantity when the average level of the firm's markup related to the carbon intensive technology' increases*

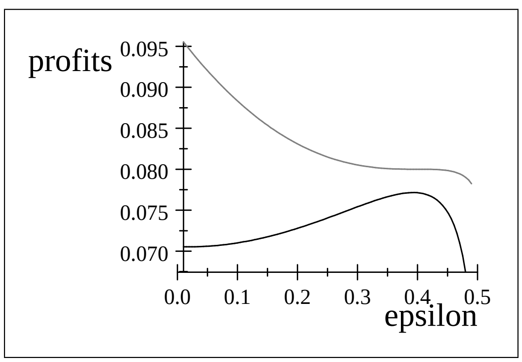
[10] For a formal proof see Appendix II

Under fixed price, an increase of the firm's i markup related to the carbon intensive technology increases firm's i expected profits from non-adoption, thus lowering the convenience to adopt. Firm's j both adoption and non-adoption expected profits remain unchanged and the incentives to adopt do not vary. To the contrary, under fixed quantity an increase of the firm's i markup related to the carbon intensive technology increases market price. Therefore, under non-adoption firm i increases its market share but it faces higher price -thus realizing lower expected profits than under fixed price- while firm j reduces its non-adoption expected profits more than under fixed price, as it loses market share and it faces higher prices. To summarize, when a carbon intensive technology increases its average performance, firm's i non-adoption profit increases more under fixed price than under fixed quantity, while firm's j non-adoption profits decrease more under fixed quantity than under fixed price, implying that both firms' incentives to adopt are maximized under fixed quantity. Vice-versa, when the markup related to the low-carbon technology increases, incentives to adopt are maximized under fixed price.

We can now state the following result with respect to the case where early auction is chosen.

Proposition 9 *Under early auction expected profits are higher under fixed price than under fixed quantity.*

This result, which can be deduced by combining the results of the previous analyses, is illustrated by the following graph:



Under early auction higher uncertainty increases the optimal amount of permits under both fixed price and quantity. However, under fixed quantity this higher demand impacts on price, first highering and then lowering expected profits.

Finally, the conclusions reached from the comparative analysis between fixed price and fixed quantity under late auction hold under early auction as well: when uncertainty related to the low-carbon technology increases, both firm's i and j incentives to adopt are maximized under fixed price; while when uncertainty related to the carbon intensive technology increases, both firm's i and j incentives to adopt are maximized under fixed quantity.

10 Policy Implications

By combining the findings reached in the comparative analysis, we can drive this general conclusion:

Proposition 10 *When uncertainty related to the low-carbon technology is relatively large, both firm's i and j incentives to adopt are maximized under fixed price and late auction; the same incentives are maximized under fixed quantity and early auction when uncertainty related to the carbon intensive technology is relatively large.*

This analysis has confirmed 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. On the other side, this strategy may imply higher administrative costs as it requires a continuous monitoring of the energy market and a corrisponding intervention within the ETS.

Moreover, 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 from our main results that the incentives to adopt gas-fired plants instead of coal plants would be maximized under a fixed price environmental regulation where allowances are subject to late auction. In this context, limiting early auction of futures allowances in favour of a late auction of spot allowances is an effective strategy to promote adoption of a low carbon alternative to nuclear energy under uncertainty.

Finally, our findings can also be applied to the case of renewable energy sources and the related supporting schemes. First, 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 fixed price. Moreover, feed-in tariffs ensure a certain economic return and, thus, reduce the markup uncertainty in case of adoption, (i.e., increase ε_a). Thus, as expected profits tend to increase with uncertainty, the overlapping between climate and energy policies and instruments might imply a decrease in expected profits from adoption. However, when uncertainty decreases, expected profits from adoption decrease more under late auction than under early auction. Therefore the incentives to adopt a low-cartbon technology are less penalized under early auction. We can conclude that when a feed-in tariff is in place the choice of an ETS scheme featuring fixed price and early auction migh be the most suitable choice.

11 Summary and Conclusions

This paper is intended as a first step in the investigation of the linkages between the EU ETS market design, timing of auctioning, and the incentives towards adoption of cleaner technologies. Modeling uncertainty, we could underline some novel and counterintuitive results in terms of which market design better promotes technology adoption when investments have to be taken under uncertainty. We can summarized the roadmap and the main finding of this research.

We have first analysed the four market design cases, focusing on how uncertainty impacts on expected profits in each of them. In particular we have found that under fixed price, an increase of uncertainty of the firm's technology return parameter impacts positively on its expected profits under both late and early auction. This implies that, under fixed price, higher uncertainty related to the low-carbon technology's return parameter increases expected proftis from adoption, highering the convenience of adoption under both allocation rules.

Under fixed quantity, the sum of firms' emissions cannot exceed a a fixed cap X. This constraint makes firms' strategies inter-dependent and this constitutes the main difference from the fixed price case, where firms' choices are independent. Given this interdependence, under fixed quantity each firm's expected profits may depend on the uncertainty of both firms' technology return parameters. In particular, under late auction, each firm's expected profits depends positively on the uncertainty of both firms' technology parameters when firms are asymmetric, while expected profits do not depend on the uncertainty of any of the firms' technology parameters when firms are symmetric. To the contrary, under early auction and fixed quantity there is not a monotonic relation between uncertainty and expected profits. When firms are asymmetric, as uncertainty related to one technology increases, both firms' expected profits first increase and then decrease. Also under early auction, expected profits do not depend on uncertainty when firms are symmetric.

The analysis has also developed a comaparative analysis between the market design cases, to determine under which scheme and under which cirucmstances incentives to adoption are maximized. In particular, by comparing late and early auction, we have found that under both fixed price and fixed quantity a higher uncertainty in the firms' productivity parameters increases firms' expected profits more under late auction than under early auction. This implies that when uncertainty affects more the performance of low carbon technologies, incentives to adopt are maximized under late auction, while early auction should be preferred to promote adoption when uncertainty has a higher impact on the carbon intensive technology's performance.

Moreover, by comparing fixed price with fixed quantity we have found that, under late auction, uncertainty increases expected profits more under fixed price than under late auction, while this is not always true under early auction. Nevertheless, in this latter case expected profits are always higher under fixed price, implying that when uncertainty affects more the performance of low carbon technologies both firms' incentives to adopt are maximized under fixed price, while fixed quantity should be preferred to promote adoption when uncertainty has a higher impact on the carbon intensive technology's performance. In the light of this analysis we have concluded that the incentives to adopt are maximized under fixed price and late auction when uncertainty affects more the low-carbon technology, while fixed quantity and early auction maximizes the incentives of adoption when uncertainty affects more the carbon intensive technology.

Finally, we have applied these findings to some energy policy issues to derive some normative implications. As Germany announced its progressive nuclear phase-out, the incentives to adopt gas-fired plants instead of coal plants will be maximized under a fixed price type of environmental regulation where allowances are late auctioned. Moreover this framework helped us to analyse how overlapping energy and environmental instruments should be coordinated: how should the ETS be designed to ensure effectiveness when direct subsidies to renewable technologies are already in place. In particular, we have found that, when a feed-in tariffs to renewable sources are in place, the incentives to adopt are maximized under fixed price and early auction.

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A Appendix I

Recalling that:

$$\frac{\partial E\left(\pi_i\right)}{\partial \varepsilon_i}|_{FP,LA} = \frac{1}{6d_i}\left(2\varepsilon_i - c_i\right)$$

$$\frac{\partial E\left(\pi_i\right)}{\partial \varepsilon_i}|_{FP,EA} = -\frac{\left(c_i - 2\varepsilon_i + 2\sqrt{2}\sqrt{pc_i - 2p\varepsilon_i}\right)\left(2\varepsilon_i - c_i + \sqrt{2}\sqrt{pc_i - 2p\varepsilon_i}\right)^2}{6d_i\left(c_i - 2\varepsilon_i\right)^2}$$

We verify that:

$$\frac{\partial E(\pi_i)}{\partial \varepsilon_i}|_{FP,LA} - \frac{\partial E(\pi_i)}{\partial \varepsilon_i}|_{FP,EA} < 0$$

The above inequality can be shown to always hold, as:

$$\begin{aligned}
&= \frac{1}{6d_i}(2\varepsilon_i - c_i) - \left(-\frac{\left(c_i - 2\varepsilon_i + 2\sqrt{2}\sqrt{pc_i - 2p\varepsilon_i}\right)\left(2\varepsilon_i - c_i + \sqrt{2}\sqrt{pc_i - 2p\varepsilon_i}\right)^2}{6d_i\left(c_i - 2\varepsilon_i\right)^2}\right) = \\
&= (2\varepsilon_i - c_i) - \left(-\frac{\left(c_i - 2\varepsilon_i + 2\sqrt{2p}\sqrt{c_i - 2\varepsilon_i}\right)\left(2\varepsilon_i - c_i + \sqrt{2p}\sqrt{c_i - 2\varepsilon_i}\right)^2}{(c - 2\varepsilon)^2}\right) = \\
&= -2\frac{p}{(c_i - 2\varepsilon_i)^2}\left(12\varepsilon_i(\varepsilon_i - c_i) + 3c_i^2 - 2\sqrt{2}\sqrt{p}\left(c_i - 2\varepsilon_i\right)^{\frac{3}{2}}\right) = \\
\sqrt{p} &< \frac{12\varepsilon_i(\varepsilon_i - c_i) + 3c_i^2}{2\sqrt{2}\left(c_i - 2\varepsilon_i\right)^{\frac{3}{2}}} \\
p &< \left(\frac{12\varepsilon_i(\varepsilon_i - c_i) + 3c_i^2}{2\sqrt{2}\left(c_i - 2\varepsilon_i\right)^{\frac{3}{2}}}\right)^2 \\
p &< \frac{9(c_i - 2\varepsilon_i)}{8}
\end{aligned}$$

Which is always verified given the condition $p < \frac{(c_i - 2\varepsilon_i)}{2}$ required for the optimal amount of allowances under early auction being prositive.

B Appendix II

Recalling that:

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

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

We verify that:

$$\frac{\partial E(\pi_i)}{\partial \varepsilon_i}|_{FQ} - \frac{\partial E(\pi_i)}{\partial \varepsilon_i}|_{FP} < 0$$

Indeed, it is easily shown that:

$$
\begin{aligned}
& \left(\frac{1}{6}\frac{d_i}{\left(d_i+d_j\right)^2}\right)\left(2\varepsilon_i-c_i\right)-\left(\frac{1}{6d_i}\left(2\varepsilon_i-c_i\right)\right)= \\
= \quad & \frac{d_i}{\left(d_i+d_j\right)^2}-\frac{1}{d_i}= \\
& -\frac{d_j}{d_i}\frac{d_j+2d_i}{\left(d_i+d_j\right)^2}<0
\end{aligned}
$$