Clean technology adoption under Cournot competition*

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Abstract

In this paper we assess incentives for clean technology adoption by firms that compete *à la* Cournot in local product markets subject to a tradable emission permits regulation. Sanin and Zanaj (2011) show that permits prices may increase after clean technology adoption. Herein we show that, since strategic firms are able to predict such increase, this results in a non-innovation equilibrium (even for very low adoption costs). To the light of the previous result, we find a sufficient condition for the cap on emissions to ensure positive innovation incentives.

Key Words: environmental innovation, tradable emission permits, interaction *à la* Cournot.

JEL Classification: D43, L13, Q55

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1 Introduction

Herein we assess the incentives to invest in clean technologies of polluting firms with market power in their local output market, who participate in a region-wide tradable emissions permits (TEP) market. Firms compete *à la* Cournot producing a homogenous good and emissions as a by-product.[1] Due to such emissions, firms are subject to an environmental regulation that consists in the creation of a number of tradable emission permits that are then freely allocated to firms by each country regulator. Since permits are tradable, firms buy/sell permits in order to hold one permit per unit of emissions, at the end of the period.

This description corresponds to the way that sectors subject to international competition in the European Union (EU) are regulated *via* the EU-Emission Trading Scheme (ETS): to comply with the EU-wide CO_2 emission reduction objective (8%) established by the Kyoto Protocol, national allocation plans (NAPs) are established.[2] Those NAPs, after the EU Commission's approval, reflect the burden sharing rules decided through negotiation. In accordance with each NAP, each government allocates permits among firms operating in the country, permits that can then be traded internationally. Some of the firms receiving permits have market power in their local market, *e.g.* electricity utilities, but are price takers in the region-wide EU-ETS where firms from outside their local market participate. Those firms, all together, can push up or down the price of permits according to their behavior in the local output market. In such case, their interaction in the output market may influence the outcome in the permits market, even if due to the relative small size of the local output market in relation to the region-wide emissions market, they do not consider the possibility of exerting any influence in the permits market.

Regarding the investment decision, we suppose that firms can choose to produce with their (dirty) technology or to invest in a clean technology that decreases emission's intensity of output. Such definition of environmental innovation is inspired by Bréchet and Jouvet (2008) and it is very appropriate in the case of pollutants with the characteristics of CO_2, in which emission reduction can be best achieved by input substitution or by a more general change in the production process itself as opposed to investing in end-of-pipe technology.[3] We model the choice of technology as follows: in a first stage, firms choose the production technology and, in a second stage, they choose output production, and consequently, the number of permits to buy/sell.[4] We focus on the analysis of fulfilled expectations equilibria[5] (FEE) resulting from the game to derive the conditions for having positive innovation

[1] This can be due to the use of a polluting input or due to a polluting production process itself.

[2] http://ec.europa.eu/environment/climat/emission/implementation_en.htm

[3] Most literature on environmental innovation is concerned with end-of-pipe innovation (see for example Requate and Unold, 2003), which is not the most commonly used in the case of CO_2 reduction.

[4] This sequence of decisions follows the rule of the less irreversible decision.

[5] This concept, derived from Katz and Shapiro (1985), will be clarified in the following section.

incentives. The structure of the model is inspired by the technology-linked-markets setup proposed by Gabszewicz and Zanaj (2006, 2008) and the innovation game is inspired by Gabszewicz and Garella (1995) when modelling the decision of internalizing the production of an intermediate good.

Most of the literature on environmental innovation is devoted to the comparison of the innovation incentives under alternative pollution control rules. With the exception of Montero (2002), in general this literature considers the output market as competitive (Parry, 1998 and Requate, 1998). Montero (2002) defines innovation as investing in an R&D sector, which produces a (proportional) decrease in the separable cost of abatement per unit of R&D invested. In this context, he studies the impact of strategic interactions in the output market on innovation incentives when the market for tradable emission permits is cleared through (Nash) bargaining between two strategic firms. He finds that one firm's innovation decreases permits prices which, on one hand, reduces its production costs (direct effect) but, on the other hand, increases competition in the output market (strategic effect) due to the decrease in the rival's production costs. The incentives to innovate then depend on the net effect. Herein, as in Sanin and Zanaj (2011), the direct effect may be by itself positive or negative and therefore may add-up to the strategic effect. In this context, we show how innovation incentives depend on firms position in the permits market, on the rate of region-wide innovation and on output strategic interaction in the local markets, which in turn are a function of the constraint imposed by the cap. In particular, the cap on emissions will be more or less restrictive depending on the elasticity of output demand and, together with the increase on emissions efficiency due to the new technology, will determine whether the price of permits increases or not after innovation (Sanin and Zanaj, 2011). This last effect will benefit sellers or buyers, determining whether an innovation equilibrium arises or not. To the light of the previous result, we find a condition for the cap on emissions considered in each NAP to ensure positive innovation incentives.

The paper is organized as follows. In Section 2 we present the assumptions and solve the sequential game played by the firms. In Section 3 we analyze equilibria and discuss the importance of the cap on emissions to induce an innovation equilibrium. Section 4 concludes.

2 The model

Inspired by the organization of the EU-ETS, we assume that there are n identical countries subject to a region-wide cap on emissions nS. All countries are assumed to be identical: each country, according to its NAP, allocates an amount S of permits for free to firms operating in its local market. Assume there are two strategic firms producing a homogenous good in each local market and that the production of the good generates emissions as a by-product.

A percentage α of S is allocated to firm i and a percentage $(1-\alpha)$ is allocated to firm j. These percentages are common knowledge. If permits received are not enough (or more than enough) to produce optimal output, firms trade in the market for permits (locally or regionally).

We assume that firms play a Cournot game in the local output market producing good y. Their technology is given by

$$y = K_l E, \quad l = i, j \tag{1}$$

where E stands for emissions (or use of permits) and K_l is firm's l productivity of emissions. Without innovation, emission's productivity is $K_l = 1, l = i, j$.[6] Firms can choose to implement a clean technology, *i.e.* a technology that would increase emission's productivity to K, with $2 \geq K > 1$, paying a fixed cost F.[7]

The choice of technology is modelled as a two-stages game: in the first stage firms simultaneously choose their production technology given their expectations regarding the level of adoption in the region (and consequently their expected price of permits q^e). Such choice is done by comparing their profits in the output market and in the permits market when using the clean technology (after paying the fixed cost of implementation F) as opposed to using the dirty technology. In the second stage firms choose how much to produce y^* and trade permits to maximize profits. We find the sub-game perfect Nash equilibria (SPNE) that are fulfilled expectations equilibria using backward induction. In our setup, a fulfilled expectation equilibrium is a permit market equilibrium (and the corresponding output market solution) in which the expectations of firms about the permit price are accomplished at the equilibrium of the game. As in Katz and Shapiro (1985), we find the conditions for an innovation (non-innovation or partial adoption) equilibrium to arise in a local market when firms expect a region-wide innovation (non-innovation or partial adoption) equilibrium and its corresponding permits price.[8]

2.1 Second stage: Cournot-Nash production game

Given the technology choice done in the previous stage and linear output demand, profits of firms are

$$\Pi_i(K_i, K_j, q^e) = (1 - K_iE_i - K_jE_j)K_iE_i - q^e(E_i - \alpha S); \tag{2}$$

$$\Pi_j(K_i, K_j, q^e) = (1 - K_iE_i - K_jE_j)K_jE_j - q^e(E_j - (1-\alpha)S). \tag{3}$$

[6] We could think of a relationship between the amount of input x used for production and emissions E of the type $E = \frac{1}{k}x$. Solving for x, we would obtain the technological relation between emissions and output in (1).

[7] We shall restrict $1 \leq K \leq 2$ to ensures the existence of equilibrium in the permits market by yielding positively sloped supply of permits.

[8] Nonetheless, we analyse the sets of parameters where a FEE does not exist in Appendix B.

where $K_i, K_j \in \{1, K\}$, $1 \leq K \leq 2$, $\alpha \in (0, \frac{1}{2})$ and where q^e is the expected permits price.

After computing the first order conditions (FOCs) and solving the system of equations we find the optimal use of permits

$$E_i(K_i, K_j, q^e) = q^e \frac{K_i - 2K_j}{3K_i^2 K_j} + \frac{1}{3K_i}; \quad (4)$$

$$E_j(K_i, K_j, q^e) = q^e \frac{K_j - 2K_i}{3K_i K_j^2} + \frac{1}{3K_j}. \quad (5)$$

The corresponding profits are

$$\begin{aligned} \pi_i(K_i, K_j, q^e) &= \frac{q^e\left(K_iK_j(2K_i - 4K_j - 4q^e + 9S\alpha K_iK_j) + q^e\left(K_i^2 + 4K_j^2\right)\right) + K_i^2K_j^2}{9K_j^2K_i^2}; \\ \pi_j(K_i, K_j, q^e) &= \frac{q^e\left(K_iK_j(2K_j - 4K_i - 4q^e + 9SK_iK_j(1-\alpha)) + q^e\left(K_j^2 + 4K_i^2\right)\right) + K_i^2K_j^2}{9K_j^2K_i^2}. \end{aligned} \quad (6)$$

2.2 First stage: technology adoption game

Herein we derive the Nash equilibria in the technology adoption game for given expectations on other firms' adoption and consequently on q^e.

No firm adopts if and only if (iff) $F \geq \pi_l(K, 1, q^e) - \pi_l(1, 1, q^e) \equiv F_0(q^e)$, $l = i, j$; both firms adopt iff $F \leq \pi_l(K, K, q^e) - \pi_l(1, K, q^e) \equiv F_2(q^e)$, $l = i, j$; and only one firm adopts iff $F_2(q^e) \leq F \leq F_0(q^e)$, with

$$\begin{aligned} F_0(q^e) &= \frac{4(q^e - K)(1-K)q^e}{9K^2}; \\ F_2(q^e) &= \frac{4(1-K)q^e(q^e - q^eK - K + q^eK)}{9K^2}. \end{aligned} \quad (7)$$

Each firm participates in the market for permits as a buyer or a seller depending on the difference between their needs of permits for production, summarized in (4) and (5), and the endowment of permits they received for free, αS or $(1-\alpha)S$, respectively in each of the n local markets. Since we consider that all local markets in the region are identical, the previous implies that total supply (or demand) of permits is $n\left(\alpha S - \frac{(q^eK_i - 2q^eK_j + K_iK_j)}{3K_i^2K_j}\right)$ while region-wide demand (or supply) is $n\left(\frac{(q^eK_j - 2q^eK_i + K_iK_j)}{3K_iK_j^2} - (1-\alpha)S\right)$. The demand and supply of permits come from many industries and these industries are assumed to be of the same numerosity.

Equalizing demand with supply in the market for permits yields the price of permits

$$\begin{aligned} q_2^* &= \tfrac{1}{2}K(2 - 3KS); \\ q_1^* &= \frac{1}{2}\frac{K(3SK - K - 1)}{K - K^2 - 1}; \\ q_0^* &= \frac{(2-3S)}{2}. \end{aligned} \quad (8)$$

q_2^* if the two firms innovate in each local market, q_1^* if one firm innovates in each local market and q_0^* if none of them innovate. All permits price are positive if $KS \leq \frac{2}{3}$. Substituting the above expressions for permit prices in (4) and (5), one obtains the levels of emissions in all outcomes of the game, namely $(E_i^*(q_2^*), E_j^*(q_2^*))$; $(E_l^*(q_1^*), E_{-l}^*(q_1^*))$, $l = i, j$, and $\left(E_i^*(q_0^*), E_j^*(q_0^*)\right)$.

It is easy to see that equilibrium emissions' levels are always positive in the symmetric outcomes, whereas the asymmetric outcome of the game is only defined for $KS \in \left\{\frac{K-1}{2K-1}; \frac{2}{3}\right\}$. It is shown in Appendix A that in the previous set of parameters, profits are positive in all the outcomes of the game. Thus, our game is defined when

$$1 \leq K \leq 2 \quad \text{and} \quad KS \in \left\{\frac{K-1}{2K-1}; \frac{2}{3}\right\}. \tag{9}$$

Most literature on environmental innovation finds that, after implementing a clean technology, the price of permits decreases even when considering a non-competitive setting (see Montero, 2000). Here, as in Sanin and Zanaj (2011), the price of permits after innovation q_1^* may be higher or lower than the price without innovation. In particular, it will be higher than q_1^* when the pair $\{S, K\}$ is such that $S < \frac{2}{3(1+K)}$. This threshold makes the cap binding, restricting output production in equilibrium such that demand is met in its region of high demand elasticity (see Sanin and Zanaj, 2011 for details).

3 Equilibria analysis

In this section, we identify the fulfilled expectations innovation and non-innovation equilibria and in the following subsections we provide some comparative statics to analyze their characteristics. Through that process, we are able to disentangle innovation incentives as a function of output market characteristics and regulatory policy constraints. FEE can be found by imposing, for each case, the expected permits price to be equal to the realized permits price. Then,

Lemma 1 *A non-innovation FEE obtains if and only if $F \geq F_0(q_0^*)$; a partial adoption FEE obtains if and only if $F_2(q_1^*) \leq F \leq F_0(q_1^*)$ and an innovation FEE obtains if and only if $F \leq F_2(q_2^*)$, with*

$$\begin{aligned} F_0(q_0^*) &= \tfrac{(3S+2K-2)(3S-2)(1-K)}{9K^2}; \\ F_2(q_1^*) &= \tfrac{\left(K^2-3K+3K^2S+2\right)(3KS-K-1)(1-K)}{9(K^2-K+1)^2}; \\ F_0(q_1^*) &= \tfrac{\left(3KS-3K+2K^2+1\right)(3KS-K-1)(1-K)}{9(K^2-K+1)^2}; \\ F_2(q_2^*) &= \tfrac{\left(3K^2S-2K+2\right)(3KS-2)(1-K)}{9}. \end{aligned} \tag{10}$$

The previous thresholds on the fixed innovation costs are non-linear functions of the improvement in efficiency K offered by the new technology and of the cap on emissions S, which together determine the elasticity of output demand at which firms are serving and would serve the local market after innovation. They determine the values of the pairs of $\{S, K\}$ for which the increase in profits in the output and in the permits market after innovation justify, or not, to cover the fixed cost F. Using the above thresholds of fixed costs (10), we build Fig 1 to display the configuration of parameters where the FEE arise.

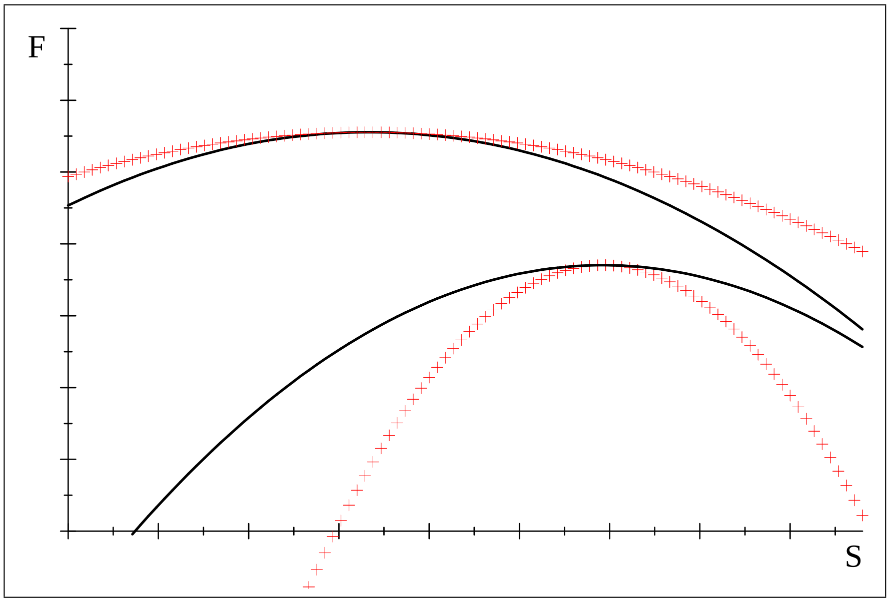

Fig 1: Map of FEE equilibria.

The upper dashed curve is the curve of $F_0(q_0^*)$ above which FEE non-innovation equilibria arise, while innovation equilibria arise for relatively small levels of fixed costs, i.e., below the last dashed curve: $F \leq F_2(q_2^*)$. For intermediate levels of fixed costs (area between the two full-line curves) a partial innovation equilibrium arises. These scenarios are result of the incentives to innovate dictated by the change in market share in the local output market and by the cost or revenue to buy or sell permits in the global permits market (as we will detail in Sections 3.1 and 3.2). From Fig 1, it is interesting to notice that the set of parameters where FEE partial equilibria arise shrinks as the total number of permits issued by the authority increases. Moreover, for very high S and low fixed cost of innovation, the FEE equilibria with full innovation are also not very likely because the for such high levels of S the corresponding output receipts for both firms is quite low. For these levels of S and F it is worth to notice that Cournot equilibria where the expectations of firms about permit prices are very likely to arise.

The FEE equilibria derived are unique for all relevant values of the pairs $\{K, S\}$ since it is easy to show that $F_0(q_0^*) > F_0(q_1^*)$ and $F_2(q_1^*) > F_2(q_2^*)$.Importantly, it also holds that

$$F_2(q_2^*) < F_2(q_1^*) < F_0(q_1^*) < F_0(q_0^*). \tag{11}$$

Then, there exists a set of parameters $F \in \{F_2(q_2^*); F_2(q_1^*)\} \cup \{F_0(q_1); F_0(q_0)\}$, where no FEE exists. In this set of parameters, the Cournot equilibrium of the production game exists but these Cournot equilibria are not FEE.[9] In these Cournot equilibria the expectations of firms about permit prices are not fulfilled. In this set, there can be a Cournot

[9] The existence of a Cournot equilibrium is guarantied by the standard concavity assumptions that our model satisfies.

equilibrium (symmetric or asymmetric) depending on the expectations of firms regarding q^e. An asymmetric Cournot equilibrium arises if one of the firms believes wrongly that q_2^* (or q_0^*) will prevail in the global permit market, while the other expects q_1^*, which is the price that indeed prevails. The levels of fixed costs corresponding to this set are neither low enough (*i.e.* $F \in \{F_2(q_2^*); F_2(q_1^*)\}$) to induce the correct expectation that an asymmetric equilibrium will prevail; nor high enough (*i.e.* $F \in \{F_0(q_1); F_0(q_0)\}$) to induce the correct expectation that a non-innovation equilibrium will prevail at the global permit market. It is also possible that a non innovation Cournot equilibrium arises if one firm expects q_2^* to prevail and the other expects q_0^* (and none of the firms has incentive to innovate). In any case, these errors in expectations can be corrected in a learning process if the interaction among firms is durable[10]. A more detailed analysis of the nonexistence of FEE is provided in Appendix B.

3.1 Non-innovation FEE

In this section, we investigate the non-innovation FEE, as stated in Lemma 1. In particular we study how the policy variable S influences the threshold $F_0(q_0^*)$ (that leads to a non-innovation FEE when $F \geqslant F_0(q_0^*)$):

$$\frac{\partial F_0(q_0^*)}{\partial S} = \frac{2\,(K-2+3S)\,(1-K)}{3K^2} < 0. \tag{12}$$

The previous equation shows that, as the cap on local emissions become less binding, *i.e.* S increases, incentives to innovate decrease. We can then state the following proposition

Proposition 2 *A policy choice that increases the number of permits S, increases the size of the permit (and consequently the output) market leading to a decrease in the incentives to invest in clean technologies.*

Let us now decompose the difference in profits before and after innovation, in the output market and the permits market for $K \to 2$. In Figure 2 and 3 the dashed red curve represents profits without innovation whereas the dotted green curve represents profits when the firm is the only one innovating. The thick curve represents the difference between the latter and the former situation. In Figure 2 we see that, without innovation and in an elastic demand case, as S (and consequently output production) increases, revenues in the output market also increase. Instead, when the firm is the only one that implements the clean technology, it becomes the larger Cournot producer and therefore output revenues become decreasing in S. Such decrease is due to the provoked decrease in the elasticity of its residual output demand. Hence, innovation increases output revenues, but such increase is a decreasing function of S.

[10] In a different setup dedicated to networks Katz and Shapiro (1985) have similar results. They also define equilibria that are FEE and others where the expectations of consumers on the newtwork size is not correct.

Figure 3 shows the *cost* in the permits market if the firm is the buyer ($\alpha = \frac{1}{3}$). For S sufficiently low (elastic demand), the price of permits increases after innovation. Then, the buyer's costs are higher after innovation than before (thick line is positive for small S). Gathering Figure 2 and 3 we see that, in the case of an elastic demand, innovation incentives in the output market are counterbalanced with the incentives in the permits market for the buyer of permits since the permits' price increase after innovation. Instead, it can be easily shown that incentives to innovate in the permits market are always positive for the seller (and decreasing with S).

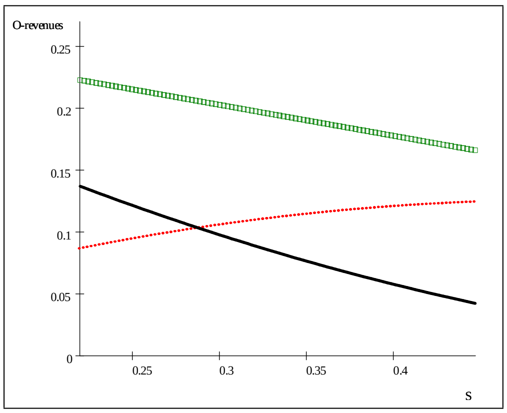

Figure 2: Output revenues

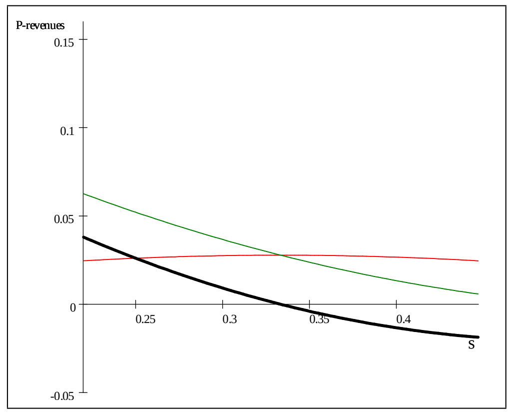

Figure 3: Cost of permits

By fixing S, the authority is indirectly capping production which determines the elasticity of output demand in equilibrium, both with and without innovation. Thus, by fixing S the regulator determines the change in total revenue for each firm. This is also true in the following subsection.

3.2 Innovation FEE

For an innovation equilibrium to arise the cost of implementation must be lower than the possible increase in total revenues due to innovation, *i.e.* $F \leq F_2(q_2^*)$. Figure 4 shows the difference in output revenues when a firm is innovating as everybody else (red dashed curve) *versus* the costs when being the only one not-innovating (increasing green dotted curve).

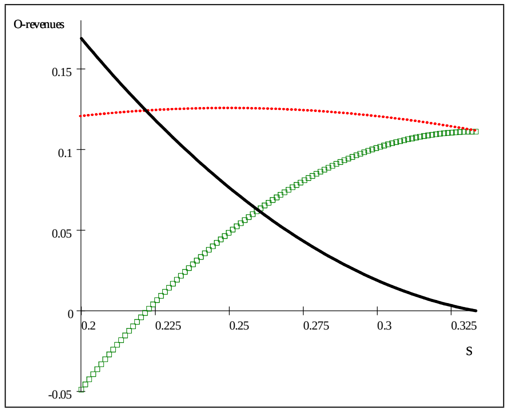

Figure 4: Output revenues

The threshold $F_2(q_2^*)$ is not a monotonic function of S, in fact, it presents a maximum at $S = \frac{(2K-1)}{3K^2}$. This is due to the effect of output demand elasticity. The threshold $S = \frac{(2K-1)}{3K^2}$ measures the effect of innovation on the elasticity of demand at the FEE equilibrium after innovation. Clearly, the incentives to innovate depend on the change of output demand elasticity before and after innovation. More precisely,

Proposition 3 *When output demand is elastic firms have incentives to use the increased efficiency achieved by innovation therefore incentives to innovate are positive and increasing, allowing firms to cover a higher implementation cost F. Instead, when demand is quite elastic firms still have positive incentives to innovate but incentives are decreasing as elasticity of output demand decreases.*

Pollution control policy covers many sectors (power, steel, aluminium, cement) with very different market configurations. While the power sector is well-known for facing an inelastic demand, other sectors like cement or steel are subject to international competition and therefore they may face a more elastic demand. Therefore, industries with different output markets characteristics will certainly differ in their innovation reaction to a pollution control policy.

4 Concluding Remarks

Previous literature finds that, when the fixed cost of implementation is sufficiently low, innovation is always undertaken because it produces a decrease in the unit cost of production (price of permits)[11]. Sanin and Zanaj (2011) show that, when firms are subject to a cap and trade regulation, innovation may produce an *increase* in permits' price that leads to a higher cost of output production. Herein we have shown that, under these conditions,

[11] See, for example, Belleflamme and Vergari (2011).

innovation incentives can be negative, even for low fixed implementation costs. In particular, we characterize the way firms' strength in the output market (symmetric *versus* asymmetric Cournot) interacts with firms' position in the permits market (buyer or seller) to determine innovation incentives.

From the policy perspective, the allocation of permits between firms determines whether a certain firm is a buyer or a seller of permits and therefore the incentives that each firm has in the permits market. Most importantly, the cap on emissions determines both the incentives in the output market (through its influence on the availability of input) and on the permits market (through its influence on permits' price).

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Appendix A: Positivity of profits

Herein we show that in the set $KS \in \left\{\frac{K-1}{2K-1}; \frac{2}{3}\right\}$, firms' profits are positive. To do this we substitute the equilibrium values of permits prices in each the profit functions (6). It is straightforward to see that profits corresponding to symmetric outcomes are positive when the condition of positivity of permits price $KS \leq \frac{2}{3}$ is satisfied. Whereas, as far as concerns profits of asymmetric Cournot FEE we have

$$\pi_i(1, K, q_1) \geq 0 \text{ iff} \qquad \alpha \geq \frac{1}{2}\frac{\left(-K + 2K^2S - KS + 1\right)^2}{KS\left(-K + K^2 + 1\right)\left(-K + 3KS - 1\right)} \tag{13}$$

This condition always holds because

$$\frac{1}{2}\frac{\left(-K + 2K^2S - KS + 1\right)^2}{KS\left(-K + K^2 + 1\right)\left(-K + 3KS - 1\right)} \leq 0 \tag{14}$$

since $((3S-1)K-1) \leq 0$ due to positivity of permits prices.

Similarly,

$$\pi_j(1, K, q_1) \geq 0 \text{ if} \qquad \alpha \leq \frac{\left(\left(K^2 - 2K + 1\right)K + \left(\left(\left(-5K^2 + 2K - 2\right)S + 6K - 4\right)K + 2\right)S\right)}{-2S\left(-K + K^2 + 1\right)\left(-K + 3KS - 1\right)} \tag{15}$$

This condition always holds because

$$\frac{\left(K^3 - 5K^3S^2 + 2K^2S^2 + 6K^2S - 2K^2 - 2KS^2 - 4KS + K + 2S\right)}{-2S\left(-K + K^2 + 1\right)\left(-K + 3KS - 1\right)} \geq 1 \tag{16}$$

and by definition of $\alpha \leq 1$.

Appendix B: Non existence of FEE

Herein we discuss Cournot equilibria that are not FEE. Depending on the expectations of the firms about the permit price q^e, these equilibria can be symmetric or asymmetric. Cournot equilibria that are not FEE arise in the set $F \in \{F_2(q_2^*); F_2(q_1^*)\} \cup \{F_0(q_1^*); F_0(q_0^*)\}$, which is not empty since the inequality

$$F_2(q_2^*) < F_2(q_1^*) < F_0(q_1^*) < F_0(q_0^*). \tag{17}$$

holds.

Let us consider different expectations of firms to see what equilibria may arise in the set $\{F_2(q_2^*); F_2(q_1^*)\}$. For instance, assume that firm i expects $q^e = q_2^*$, whereas firm j expects $q^e = q_1^*$.Then, firm i has no incentive to innovate if

$$\begin{aligned} \Pi_i(K_i, K_j, q_2^*) - \Pi_i(1, K_j, q_2^*) &< F \\ F_2(q_2^*) &< F \end{aligned}$$

while firm j has incentive to innovate in this same interval. Firm j innovates if she believes that $q^e = q_1^*$ and

$$\begin{aligned} \Pi_j\left(1, K_j, q_1^*\right) - \Pi_j\left(1, 1, q_1^*\right) &> F \\ F_2(q_1^*) &> F \end{aligned}$$

Hence, in the set $F \in \{F_2(q_2^*); F_2(q_1^*)\}$ the Cournot equilibrium of the game is an asymmetric Cournot with firm j innovating and firm i not innovating, but this Cournot equilibrium is not a FEE.

Similarly, if firm i believes that $q^e = q_0^*$ she has incentive to innovate because

$$\begin{aligned} \Pi_i(K_i, 1, q_0^*) - \Pi_i(1, 1, q_0^*) &> F \\ F(q_0^*) &> F \end{aligned}$$

while, if at the same time firm j expects $q^e = q_1^*$, she has no incentive to innovate because

$$\begin{aligned} \Pi_j(K_i, 1, q_1^*) - \Pi_j(1, 1, q_1^*) &< F \\ F_2(q_1) &< F \end{aligned}$$

Then, in the set $F \in \{F_0(q_1^*); F_0(q_0^*)\}$, an asymmetric Cournot that is not a FEE prevails.

Nevertheless, in the same set of parameters, *i.e.* for $F \in \{F_2(q_2^*); F_2(q_1^*)\}$, it is also possible that a non-innovation equilibrium arises. This equilibrium takes place if both firms expect $q^e = q_2^*$, but none has incentive to innovate and then

$$\begin{aligned} \Pi_i(K_i, K_j, q_2^*) - \Pi_i(1, K_j, q_2^*) &< F \\ F_2(q_2^*) &< F \end{aligned}$$

$$\begin{aligned} \Pi_j\left(K_i, K_j, q_2^*\right) - \Pi_j\left(1, K_j, q_2^*\right) &< F \\ F_2(q_2^*) &< F \end{aligned}$$

A non innovation symmetric Cournot equilibrium that is not a FEE arises.