Carbon mandates with cost-based vs. emission-based innovation

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Abstract

In this paper we compare two carbon mandate policies in the fuel producing context. With the first policy, a mandate requires the fuel producers to use a minimum percentage of biofuel in their fuel blend. With the second policy, the mandate is a carbon emission standard that defines the maximum GHG emission level per unit of fuel blend. The comparison is made with a partial equilibrium model where an innovator can licence the innovation to a fuel industry.

We show that the two policies have the same effect on the incentive to innovate for decreasing the cost for producing biofuel. However the two policies differ when considering innovation that leads to a reduction of the emission of biofuel. More precisely, there is no incentive to innovate with quantity mandates while carbon emission standard can create incentives for such innovation.

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1 Introduction

Using biofuel as a substitute to fossil fuel is one lever to reduce greenhouse gas emission. Indeed, biofuel comes from biomass which production uses carbon dioxin. As a consequence, the carbon footprint of biofuel is generally lower compared to fossil fuel. However, the production cost of biofuel is higher compared to fossil fuel, leading to a lack of incentive to use this more environmental friendly source of fuel. Different public policies have been implemented in Europe and Northern America during the last decades to correct such market failure.

In this paper we compare the impact of two main biofuel related public policies on the promotion of innovations in the biofuel sector. This issue is addressed in several recent papers (Clancy and Moschini, 2018, 2016). Yet, these papers all focus on innovations enabling a decrease in the biofuel marginal production cost. Our paper departs from this literature by considering innovations that lower either the marginal production cost or the GHG emission of the biofuel.

One exemple of such innovation is Nitrogen Use Efficiency (NUE) in the rapeseed production[1]. Rapeseed is a major input for biofuel in France. Improving Nitrogen Use Efficiency leads to a cost reduction because it enables farmer to use less Nitrogen per ton of rapeseed. The production of nitrogen fertilizer is also known for being a major source of GHG emission because it requires large amount of energy. Hence, reducing the use of Nitrogen enables also to reduce the carbon footpring of biofuel production. Several research programs, such as the french project named RAPSODYN[2], aim to promote NUE.

We compare two main public policies : a mandate that requires the fuel industry to blend a minimum percentage of biofuel in their fuel, and a carbon emission standard that defines the maximum GHG emission level of the final fuel blend. The analysis takes place in a partial equilibrium framework where an innovator can licence the innovation to a fuel industry that is imperfectly competitive. This model is in line with those that have been developed in the agricultural economics literature on public policies related to biofuel.

We first show that the two policies are equivalent with cost decreasing innovation: whatever

[1]see Charbonnier *et al.* (2019) for more details on this example).

[2]This project gathers a large consortium of public research units as well as private seed companies from 2013 to 2020. It received a public subsidy of 7M€.

the objective of one of the policies, the same objective can be reached with the other one. This property no longer holds with an emission-based innovation. We show that, whatever the level of competition, a minimum mandate discourages the fuel industry to adopt this type of innovation. Conversely, a carbon emission standard can create such incentive for this type of innovation.

The literature and our contribution to this literature are presented in the next section. The model and its properties in the benchmark case with no regulation are presented in section 3. We then compare the two policies with a cost decreasing innovation in the section 4 and with an emission-based innovation in section 5.

2 Literature

Our paper first contributes to the theoretical literature on the promotion of environmental innovation by carbon policies. This literature models a closed economy using the partial equilibrium concept. It considers an R&D sector providing an innovation to a competitive fuel industry. The innovation diminishes the marginal cost of a renewable input. The fuel industry decides whether to buy the innovation and blends renewable inputs with conventional inputs to produce fuel.

In such setting, Clancy and Moschini (2018) studies the innovation incentive of a policy mandate that obliges the fuel industry to blend a minimal quantity of renewable input. It shows that such a mandate creates poor incentive for breakthrough innovation but strong incentive for incremental innovation. In a similar setting, Clancy and Moschini (2016) shows that innovator entries in the R&D sector depends on carbon policies. It finds that R&D subsidies provide more variation in the number of entries than a carbon tax.

In real life, the fuel industry sets a margin on fuel sales and we aim to explore the effect of such a margin on the equilibrium outcomes. We thus follow the partial equilibrium methodology but extend it to imperfect competition on the fuel industry side. In addition, we extend the scope of innovation by adding the possibility of an emission-based innovation, that is an innovation which only diminishes the carbon emissions of renewable inputs.

Our paper also relates to the literature on the efficiency of carbon intensity standards. Carbon intensity standards restrict the amount of carbon emission released by a fuel. This second strand of literature joins the above literature in the use of the partial equilibrium concept to assess the policy effect.

Holland *et al.* (2009) shows that such a policy cannot be efficient. This essentially occurs because the policy does decrease the production of high carbon fuel but increases the production of low carbon fuel which possibly raise carbon emissions. Interestingly, Lade and Lawell (2018) finds that a cost containment mechanism - over compliance cost - increases the efficiency of the policy.

We contribute to this literature by bringing a new insight. Such carbon intensive policy may promote a new type of innovation that is not profitable under the largely spread minimum mandate policies.

3 The benchmark situation: an unregulated industry

3.1 The model

We assume a λ-competitive industry C that produces fuel (e.g., diesel) in quantity q. The parameter $\lambda \in [0, 1]$ encompasses the industry competitiveness. When $\lambda = 0$, we model a perfectly competitive industry while a $\lambda = 1$ means that the industry acts as if it were a monopolist. Fuel is a costless blend of two inputs: a conventional input and a renewable input. The two inputs are perfect substitutes. We denote the quantity of the conventional input by q_c and the quantity of the renewable input by q_r. We assume the fuel production function is $q = q_c + q_r$. Note that although renewable fuel often delivers less energy than the conventional fuel, it is possible to reason in energy-equivalent quantities. The industry serves a representative consumer with inverse demand for fuel given by $P(q) = 1 - q$. Assume each input is associated with an emission factor and that the emission factor of the renewable input ϕ_r is lower than the one of conventional input $\phi_c = 1$, then the total emission of the produced fuel is $q_c + \phi_r q_r$. Total emission enters negatively into total welfare.

The industry bears increasing and convex production cost to produce the inputs that we denote $C_c(q_c)$ and $C_r(q_r)$ respectively for conventional and renewable. For simplification and in line with Clancy & Moschini (AJAE, 2017), we assume $\frac{dC_c}{dq_c}(q_c) = c_c \geq 0$ and $\frac{dC_r}{dq_r}(q_r) = c_r - \theta + r + q_r \geq 0$

where θ measures an innovation efficiency brought by an external innovator, r is the royalty paid by the industry to this innovator for the use of its innovation, c_c is a constant parameter and the same applies to c_r. We assume that at best θ makes the marginal cost of the first unit nil $\theta \leq c_r$. In addition, we assume that ex ante innovation the renewable marginal cost is always higher than the conventional marginal cost $c_c < c_r$ but ex post innovation the renewable marginal cost may intersect the conventional marginal cost. That is innovation brings sufficient cost efficiency $\theta \geq c_r - c_c$ so that $c_c \geq c_r - \theta + r$ for some $r \geq 0$.[3] The monopolist innovator M can propose two types of innovations: *Cost-based innovation* (CBI) which only decreases marginal renewable cost by θ and a *Emission-based innovation* (EBI) that decreases the emissions of the renewable input from ϕ_r to 0.

Timing of the game. The timing of the game is as follows. The innovator decides whether to innovate and if so then sets the level of the royalty r. The competitive industry observes the innovation type and the associated royalty. It then decides whether to use the innovation and produces fuel for the representative consumer given the market price. Finally, the representative consumer buys the fuel from the competitive industry.

Profit functions. Given the final outcomes, and in particular the market price P, the profit functions of the competitive industry denoted π_C and the innovator denoted π_M are:

$$\pi_C = P.(q_c + q_r) - c_c.q_c - (c_r + \mathbb{1}_a.(r - \theta) + \frac{1}{2}q_r)q_r \tag{1}$$

$$\pi_M = \mathbb{1}_a.r.q_r \tag{2}$$

where $\mathbb{1}_a$ equals 1 if the competitive industry accepts to buy the innovation from the innovator, and equals 0 otherwise.

3.2 The equilibrium outcomes

We solve for the Subgame Perfect Nash equilibrium in pure strategy (SPNE) using backward induction. At the last stage, the industry chooses q_c and q_r so as to maximize its profits π_C

[3] EU market approval mechanism

given market price P. The first order conditions give $\frac{\partial \pi_C}{\partial q_c} = \lambda P' + P - c_c = 0$ and $\frac{\partial \pi_C}{\partial q_r} = \lambda P' + P - c_r - \mathbb{1}_a(r-\theta) - q_r = 0$. Remind that the parameter $\lambda \in [0,1]$ encompasses the industry competitiveness. When $\lambda = 0$, we model a perfectly competitive industry while a $\lambda = 1$ means that the industry acts as if it were a monopolist. At market equilibrium the market price equals the inverse demand $P = 1 - q$ and we easily find the continuation equilibrium quantity of final fuel and market price:

$$q^* = \frac{1-c_c}{1+\lambda} \quad \& \quad P^* = \frac{\lambda + c_c}{1+\lambda} \tag{3}$$

Whatever the final blend is, the final price always equals the conventional input marginal cost. The final quantity of fuel q^* is thus at the intersection of the inverse demand and the marginal cost of the conventional input. Note that if the industry does not buy the innovation the marginal cost to produce the renewable input remains strictly higher than the marginal cost of conventional input. In this case, the industry uses only conventional input into the final blend and sells the latter at the conventional marginal cost level. At the opposite, if the industry buys the innovation the marginal cost of renewable input may intersect the marginal cost of conventional input for some pair (θ, r). In that case, the industry may use both conventional and renewable inputs into the final blend and sells the latter at the conventional marginal cost level. The industry this time makes positive profits. Besides, in that case, a natural constraint arises: the total quantity of fuel must be higher than the quantity of renewable input. We find the following continuation equilibrium quantities of renewable inputs and conventional inputs:

$$q_r^U(\mathbb{1}_a) = \text{Max}\{\text{Min}\{1 - c_c\,; c_c - (c_r + \mathbb{1}_a(r-\theta))\}; 0\} \tag{4}$$

$$q_c^U(\mathbb{1}_a) = \frac{1-c_c}{1+\lambda} - \text{Max}\{\text{Min}\{1 - c_c\,; c_c - (c_r + \mathbb{1}_a(r-\theta))\}; 0\} \tag{5}$$

If the industry does not buy the innovation, the industry uses only conventional input into the final blend and makes zero profits $\pi(\mathbb{1}_a = 0) = 0$. At the opposite, if the industry buys the innovation then it may use both conventional and renewable inputs into the final blend. It is easy to see that the industry makes the following profits for some pair (θ, r)

$$\pi_C(\mathbb{1}_a) = \frac{[q_r^*(\mathbb{1}_a)]^2}{2} + \lambda \left(\frac{1-c_c}{1+\lambda}\right)^2$$

Therefore, the industry prefers to buy the innovation whenever its profit from buying is higher than its profit from not buying $\pi_C(\mathbb{1}_a = 1) \geq \pi_C(\mathbb{1}_a = 0)$. This is equivalent to $q_r^*(\mathbb{1}_a = 1) \geq q_r^*(\mathbb{1}_a = 0)$ and it then obvious that this inequality holds as long as $r \leq c_c - c_r + \theta$.

The innovator correctly anticipates this behaviour and sets its royalty rate r so as to maximize its expected profits under the constraint that the industry prefers to buy the innovation:

$$\underset{r\in[0,\theta]}{\text{Max}} \quad \pi_M = \mathbb{1}_a.r.q_r^*(\mathbb{1}_a)$$

$$s.t. \quad \pi_C(\mathbb{1}_a = 1) \geq \pi_C(\mathbb{1}_a = 0)$$

The first order condition gives $\frac{d\pi_M}{dr} = c_c - c_r + \theta - r - r = 0$ and the optimal royalty rate is:

$$r^U = \text{Min}\{\frac{c_c - c_r + \theta}{2} \; ; \; 0\} \tag{6}$$

That royalty rate is strictly lower than the maximum royalty rate accepted by the industry and the industry therefore buys the innovation. In other words, the buying constraint does not bind and the industry strictly benefits from the innovation.

Note also that providing that the innovation is not too drastic then the quantity of renewable input never exceeds the final quantity of fuel. A simple way too limit this innovation is to focus on a sub-case where the original marginal cost of renewable input is also not too high.

Assumption 1. The marginal cost of the fist quantity of renewable input is not too high, $c_r < 1/2$.

We will see in the next sections that this assumption simplifies greatly the analysis without loosing its interest and we provide insights in the appendices on what happens when we relax this assumption. Under Assumption 1, we obtain the following equilibrium outcomes summarized in the following lemma.

Lemma 1. *In the absence of regulation, the equilibrium price, quantities and profits are*

$$P^U = \frac{\lambda + c_c}{1+\lambda}\ , \quad q^U = \frac{1-c_c}{1+\lambda}\ , \quad q_r^U = \frac{c_c - c_r + \theta}{2}\ , \quad q_c^U = \frac{1-c_c}{1+\lambda} - \frac{c_c - c_r + \theta}{2}$$
$$\pi_C^U = \frac{(c_c - c_r + \theta)^2}{8} + \lambda \left(\frac{1-c_c}{1+\lambda}\right)^2 \ \textit{and} \quad \pi_M^U = \left(\frac{c_c - c_r + \theta}{2}\right)^2.$$

Intuitively, the innovator leaves some rent to the industry because the industry can credibly commit not to produce any quantity of renewable input if the royalty rate is too high.

It is obvious that the emission-based innovation has no bite into the unregulated benchmark essentially because it does not procure any monetized benefit to the industry.

3.3 The unregulated equilibrium blend

Lemma 2. *Under Assumption 1, the unregulated blend gives a benchmark ratio between renewable inputs and total fuel that we write:*

$$\bar{\gamma}(\theta) = \frac{c_c - c_r + \theta}{2(1-c_c)}(1+\lambda) \tag{7}$$

The unregulated blend depends on the technology (state of the world). It is especially increasing with respect to the technology cost efficiency. Indeed, the more renewable input is efficient in production, the more the competitive industry uses renewable input into the final blend. Formally, we have: $\frac{\partial \bar{\gamma}}{\partial \theta} = \frac{1+\lambda}{2(1-c_c)} \geq 0$ and $\frac{\partial^2 \bar{\gamma}}{\partial \theta^2} = 0$. Remind that Assumption 1 is sufficient so that $q_R \leq q$ but it also sufficient so that θ belongs to the interval $[c_r - c_c; c_r]$ and the unregulated blend lies in its interval $[0; 1]$. The maximal value of this unregulated blend is $\bar{\gamma}(\theta = c_r) = \frac{c_c(1+\lambda)}{2(1-c_c)}$ is positive and lower than one given A1.

Figure 1 illustrates our findings. Obviously, for any state of technology θ, a policy imposing a ratio lower than the unregulated blend constrains the competitive industry. We shall see in the next sections that the innovator can exploit this constraint to increase its margin, henceforth the royalty rate.

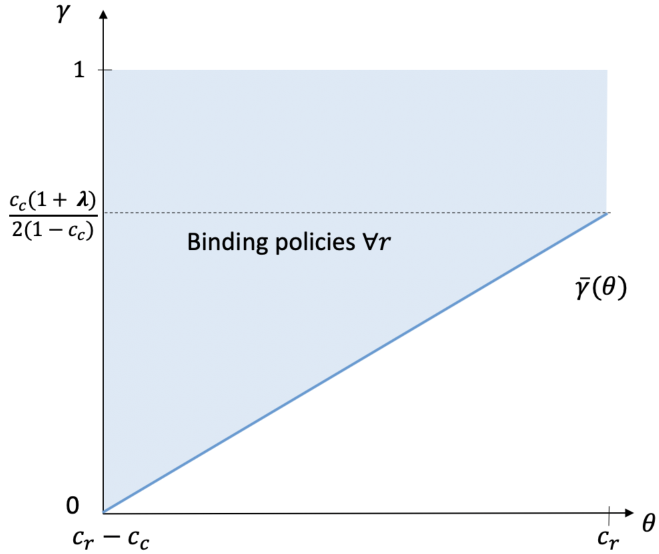

Figure 1: Unregulated ratio

4 Regulated industry and cost-based innovation

In this section, a regulator tries to promote environmental innovation thanks to a unique environmental policy.

4.1 The available emission policies

We focus our analysis on two main emission policies:

· *Renewable share mandate (RSM)* specifies the minimum share of renewable input to blend into the final fuel. Denote such a mandate by γ, we formally get $q_r \geq \gamma q$. The RSM is a priori useful at least if it specifies a positive share of renewable input into the blend $\gamma \geq 0$ while it is simply not feasible if it specifies a share so that renewable inputs become higher than the final quantity $\gamma \leq 1$. We therefore assume that γ belongs to the interval $[0, 1]$.

$$\text{RSM} \; : \; q_r \geq \gamma q \tag{8}$$

· *Low carbon emission standard (LCES)* specifies a threshold that fuel emissions must satisfy. Denote such standard σ, then we formally get $\frac{\phi_c q_c + \phi_r q_r}{q_c + q_r} \leq \sigma$. The LCES is a priori useful at least if it specifies lower emission amount than the maximal rate of emission $\sigma \leq \phi_c = 1$ while it is simply not feasible if the standard is lower than the minimal emission rate $\sigma \geq \phi_r$. We therefore assume that σ belongs to the interval $[\phi_r, 1]$ and rewrite the standard so as to get a ratio of renewable input over total quantity that we denote γ_σ, meaning this is the $\sigma-$LCES equivalent of $\gamma-$RSM policy.

$$\text{LCES} \;:\; q_r \geq \frac{1-\sigma}{1-\phi_r} q \equiv \gamma_\sigma(\phi_r).q \tag{9}$$

Observe that $\frac{\partial \gamma_\sigma}{\partial \sigma} = -\frac{1}{1-\phi_r} \leq 0$ so that γ_σ is decreasing in σ. In addition, we can already notice that γ does not change following an innovation whereas γ_σ does if the innovation is Emission-based. This is going to be essential for the innovation incentive as we shall see in the next sections.

Note that most policies do not reach a ratio implementing as much as renewable as conventional inputs (B7 in diesel, E10 in fuel). In addition, policies face the constraint of vehicle motors ("blend wall"). The recent technology inside most car models does not permit to process a lot more renewable fuel than the policies encourage. In France, there exist some alternative technologies that aim to enhance the processing of renewable fuel by vehicle motors but this is still not well spread in the market. This is explained by a high cost of its deployment joint with its marketing strategy and the alternative of electric cars.

4.2 The new timing and equilibrium outcomes

The timing of the game is as follows. The regulator first chooses which emissions policy to implement γ or σ. Then the innovator decides whether to innovate and if so then sets the level of the royalty r. The competitive industry observes the policy and the innovation. It also decides whether to use the innovation and produces fuel for the representative consumer given the market price. Finally, the representative consumer buys the fuel from the competitive industry. We use backward induction to find the SPNE of this game.

- The industry choice

At the stage of the competitive industry choice, the mandate can either bind or not. When it does not bind we obtain the continuation equilibrium choices derived in the previous section (see

Equation (5)). In what follows, we derive the continuation choices of the competitive industry under a binding mandate. We remind that the competitive industry is price taker so the the competitive industry's profit maximization problem is

$$\begin{aligned} \underset{q_r, q_c}{\text{Max}} \quad & \pi_C = P.(q_c + q_r) - c_c.q_c - (c_r + \mathbb{1}_a.(r - \theta) + \frac{1}{2}q_r)q_r \\ s.t. \quad & q_r \geq \gamma q \end{aligned}$$

Assuming the policy binds irrespective of the royalty rate then we can rewrite the whole profit as function of the total quantoty q. We then obtain a First Order Condition giving that we can rewrite to obtain the equilibrium price:

$$\lambda P' q + P = (1-\gamma)c_c + \gamma(c_r + \mathbb{1}_a.(r - \theta) + \gamma q)$$

We recover the usual property than a competitive price ($\lambda = 0$) equals the average marginal cost. At market equilibrium, total offer equals total demand so that $P = 1 - q$. Simple computations lead to the following continuation equilibrium quantity:

$$q^{\gamma}(\mathbb{1}_a) = \frac{1 - (1-\gamma)c_c - \gamma(c_r + \mathbb{1}_a)}{1 + \lambda + \gamma^2}$$

The continuation equilibrium input quantities hence write as follows: $q_r^{\gamma}(\mathbb{1}_a) = \gamma q^{\gamma}(\mathbb{1}_a)$ and $q_c^{\gamma}(\mathbb{1}_a) = (1-\gamma) q^{\gamma}(\mathbb{1}_a)$. Note that, taking the royalty as given at the stage, any cost-innovation innovation increases the equilibrium quantities of renewable inputs ($\frac{\partial q_r^{\gamma}}{\partial \theta} = \frac{\gamma^2}{1+\lambda+\gamma^2} > 0$). It contrasts Clancy & Moschini (AJAE, 2017) where innovation does not impact the quantity of renewable input due to the framing of the mandate which is a minimum quantity in their framework. Formally, the authors consider a minimum quota mandate such that $q_r \geq \bar{q}$.

Since we assumed $q_r = \gamma q$, the profit re-writes $\pi_c(\mathbb{1}_a) = (P - [(1-\gamma)c_c + \gamma(c_r + \mathbb{1}_a + \gamma q)])\, q + \frac{1}{2}(\gamma q)^2 = \frac{[q_r^{\gamma}(\mathbb{1}_a)]^2}{2} - \lambda P'(q)^2$. At the continuation equilibrium we obtain:

$$\pi_c^{\gamma}(\mathbb{1}_a) = \left(\frac{1}{2} + \frac{\lambda}{\gamma^2}\right)[q_r^{\gamma}(\mathbb{1}_a)]^2$$

- The innovator choice

The innovator's choice affects the regulation bindingness. We focus on policies that aim to implement a higher ratio of renewable input over total fuel with respect to the unregulated one, given a technological state θ. Figure 2 illustrates this assumption. That is the regulator is not satisfied with the unregulated ratio even in the event where the industry buys the innovation. In an extension, we explore what might happen in case the regulator makes a mistake of interpretation of the technological state θ so that the policy may allow the innovator to choose whether it binds or not.

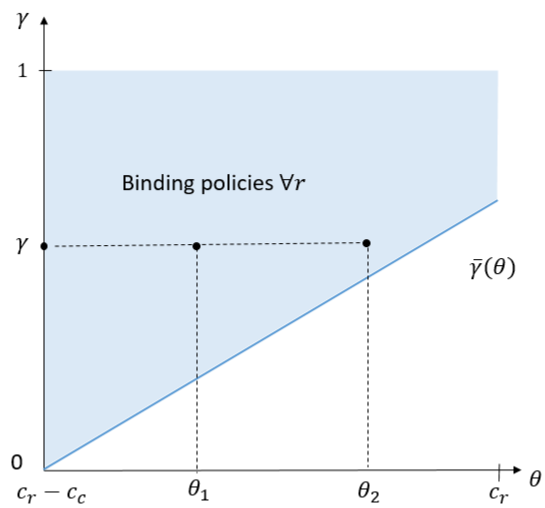

Figure 2: Regulated ratio: cost-based innovation

If the industry does not buy the innovation the marginal cost to produce the renewable input remains strictly higher than the marginal cost of conventional input. In contrast to the unregulated case, the industry is now obliged to use both the conventional and renewable inputs into the final blend and sells the latter at a higher price. The industry makes the following profit $\pi(\mathbb{1}_a = 0) = \left(\frac{1}{2} + \frac{\lambda}{\gamma^2}\right)[q_r^\gamma(\mathbb{1}_a = 0)]^2$ which is now positive. On the other hand, if the industry buys the innovation then the marginal cost of renewable input may intersect the marginal cost of conventional input for some pair (θ, r). The industry uses both conventional and renewable inputs into the final blend. Nevertheless, due to a binding regulation, it blends more renewable input than without regulation. The industry makes the following profit for some pair (θ, r): $\pi_C(\mathbb{1}_a = 1) = \left(\frac{1}{2} + \frac{\lambda}{\gamma^2}\right)[q_r^\gamma(\mathbb{1}_a = 1)]^2$.

The industry prefers to buy the innovation if $\pi_C(\mathbb{1}_a = 1) \geq \pi_C(\mathbb{1}_a = 0)$ which boils down to $r \leq \theta$, irrespective of λ.

The innovator anticipates the behaviour of the competitive industry and sets r so as to maximize its profits under the constraint that the industry buys the innovation, that is

$$\underset{r\in[0,\theta]}{\text{Max}} \quad \pi_M = \mathbb{1}_a.r.q_r^\gamma(\mathbb{1}_a)$$
$$s.t. \quad \pi_C^\gamma(\mathbb{1}_a = 1) \geq \pi_C^\gamma(\mathbb{1}_a = 0)$$

Appendix shows that the constraint binds under Assumption 1 and therefore the innovator sets

$$r^{CBI} = \theta \tag{10}$$

Note that at ($\mathbb{1}_a = 1$ & $r = \theta$) or ($\mathbb{1}_a = 0$), the quantity of renewable input is positive because the mandate still obliges the industry to blend some renewable input. This burden is in the end paid by the consumer through a higher market price. It enables the industry to make positive profit even when the royalty is at its maximum willingness to pay or when it rejects the innovation. It contrasts the benchmark situation where the profit turned to be nil, in those cases. In our model, this new "outside option" does not affect the bargaining process essentially because the innovator remains a monopolist and still holds full bargaining power. We shall see in an extension what happens if we relax such assumption on bargaining power.

The following lemma sumarizes the findings under a cost-based innovation.

Lemma 3. *In the presence of cost-based innovation, the equilibrium price, quantities and profits, given a binding policy γ, are*

$$P^{CBI} = \lambda q^{CBI} + \gamma c_c + (1-\gamma)(c_r + \gamma q^{CBI}) \ , \quad q^{CBI} = \frac{1 - c_c + \gamma(c_c - c_r)}{1 + \lambda + \gamma^2},$$
$$q_r^{CBI} = \gamma q^{CBI} \ , \quad q_c^{CBI} = (1-\gamma)q^{CBI} \ , \quad \pi_C^{CBI} = \left(\frac{\gamma^2}{2} + \lambda\right)[q^{CBI}]^2 \ and \quad \pi_I^{CBI} = \theta\gamma q^{CBI}.$$

These values hold irrespective of the type of policy (γ or γ_σ).

It is obvious that $P^{CBI} > P^U$ and $q^{CBI} < q^U$. Also, the innovator is now able to capture all the industry rent from the innovation because the industry is now obliged to produce some renewable input and cannot threaten the innovator not to produce any. This explains why $r^{CBI} > r^U$. Note that this holds true irrespective of the policy but as we shall see in next section policies are no more equivalent with an emission-based innovation.

4.3 Profit comparative statics

Figure 3 shows the effect of variation of the policy level on the industry profit. Note that the direction of change of the industry profit under perfect competition is the same as the direction of change of the innovator profit (see eq (11) & (12)). Indeed, in that case, both profits vary as function of the sign of the derivative of the renewable inputs. However, this correlation breaks down under imperfect competition due to the presence of the extra terms linked to the industry margin (see eq (12)).

$$\frac{\partial \pi_I}{\partial \gamma} = \theta \frac{\partial q_r}{\partial \gamma} \tag{11}$$

$$\frac{\partial \pi_C}{\partial \gamma} = 2q_r \frac{\partial q_r}{\partial \gamma}\left(\frac{1}{2} + \frac{\lambda}{\gamma^2}\right) - \frac{2\lambda}{\gamma^3}(q_r)^2 \tag{12}$$

Lemma 4. *The industry equilibrium profit and the innovator equilibrium profit vary in the same direction under perfect competition ($\lambda = 0$) but in potentially different directions under imperfect competition ($\lambda > 0$).*

Lemma 5. *The industry equilibrium profit is increasing with respect to the policy mandate between thresholds policy level that we denote $\tilde{\gamma}_1$ and $\tilde{\gamma}_2$ when competition is sufficiently fierce. Beyond those levels or when competition is sufficiently soft, the profits are decreasing with respect to the policy mandate.*

Proof. see appendix □

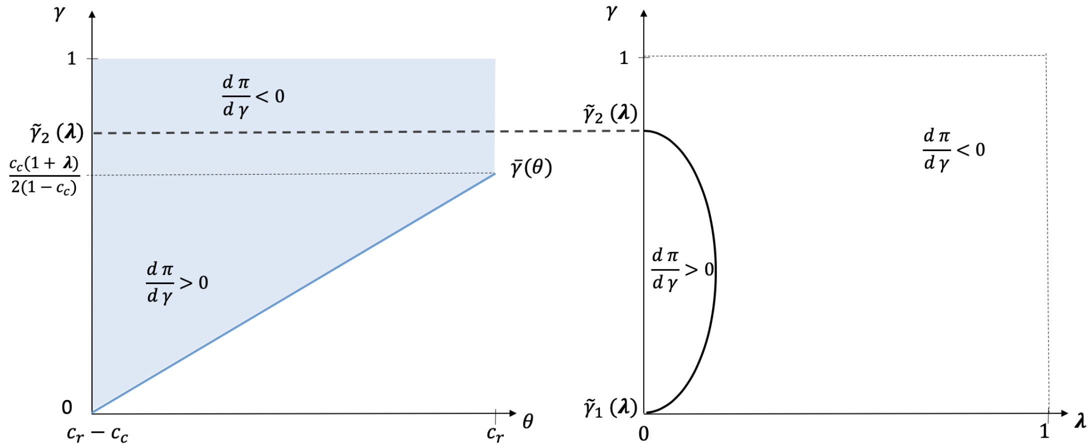

Figure 3: Policy impact wrt λ-competitiveness, starting at perfect competition ($\lambda = 0$)

5 Regulated industry with emission-based innovation

5.1 Properties of policies and profits with EBI

- EBI only affects γ_σ

It is rather obvious that the RSM policy does not change following a EBI. However, a LCES policy is affected by such an innovation. Following, a EBI the policy changes to $\gamma'_\sigma = 1 - \sigma$ which rewrites $\gamma'_\sigma = 1 - \sigma = \frac{1-\Phi_r}{1-\Phi_r}(1-\sigma) = \delta\gamma_\sigma$ so that we have the equality below:

$$\gamma'_\sigma = \gamma_\sigma \delta \qquad \text{where } \delta \in [0,1] \tag{13}$$

- New industry participation constraint

The industry is willing to pay for the innovation whenever its profit with the innovation is higher than its profit without innovation. The EBI does not affect the RSM policy and henceforth it is obvious that the industry never buys the innovation when the royalty is strictly positive. In the LCES case, note that the profit from a free innovation differs from the profit without innovation because the EBI directly affects the policy level. The industry buys the innovation whenever $\pi_C(\mathbb{1} = 1, \delta) \geq \pi_C(\mathbb{1} = 0)$ which boils down to (in what follows we omit to write σ to alleviate notations):

$$r \leq (1+\lambda+(\delta\gamma)^2)\frac{\sqrt{\frac{1}{2}+\frac{\lambda}{(\delta\gamma)^2}}\delta q[\delta\gamma,0]-\sqrt{\frac{1}{2}+\frac{\lambda}{(\gamma)^2}}q[\gamma,0]}{\sqrt{\frac{1}{2}+\frac{\lambda}{(\delta\gamma)^2}}\delta^2\gamma} \equiv MWTP(\delta) \tag{14}$$

Note that the maximum willingness to pay, denoted MWTP, depends on the innovation efficiency δ. In particular, the MWTP is positive as long as the innovation efficiency is above a certain level.

$$\delta \in \left[\frac{\sqrt{\frac{1}{2}+\frac{\lambda}{(\gamma)^2}}}{\sqrt{\frac{1}{2}+\frac{\lambda}{(\delta\gamma)^2}}}\frac{q(\gamma,0)}{q(\delta\gamma,0)},1\right] \tag{15}$$

5.2 The new equilibrium

The innovator anticipates correctly the participation constraint and optimises correspondingly.

Under RSM mandate, it can not sell the innovation because the industry is not interested in buying it for any strictly positive royalty.

Under LCES mandate, it sets the following equilibrium royalty:

$$r^{EBI} = \begin{cases} \frac{1-c_c+\delta\gamma(c_c-c_r)}{2\delta\gamma} & \text{if } \delta \in \left[2\frac{\sqrt{\frac{1}{2}+\frac{\lambda}{(\gamma)^2}}}{\sqrt{\frac{1}{2}+\frac{\lambda}{(\delta\gamma)^2}}}\frac{q(\gamma,0)}{q(\delta\gamma,0)},1\right] \\ MWTP(\delta) & \text{if } \delta \in \left[\frac{\sqrt{\frac{1}{2}+\frac{\lambda}{(\gamma)^2}}}{\sqrt{\frac{1}{2}+\frac{\lambda}{(\delta\gamma)^2}}}\frac{q(\gamma,0)}{q(\delta\gamma,0)}, 2\frac{\sqrt{\frac{1}{2}+\frac{\lambda}{(\gamma)^2}}}{\sqrt{\frac{1}{2}+\frac{\lambda}{(\delta\gamma)^2}}}\frac{q(\gamma,0)}{q(\delta\gamma,0)}\right] \\ 0 & \text{otherwise} \end{cases} \tag{16}$$

Proposition 1. *When the innovator offers an emission-based innovation, it can only make revenues under a carbon intense mandate* γ_σ.

Lemma 6. *In the presence of emission-based innovation, the equilibrium price, quantities and profits, given a binding policy* γ*, are*

- in case of RSM mandate γ*, the same as those given by Lemma 3*

- in case of LCES mandate γ_σ:

$$P^{EBI} = \lambda q^{EBI} + \delta\gamma c_c + (1-\delta\gamma)(c_r + \delta\gamma q^{EBI}) \ , \quad q^{EBI} = \frac{1 - c_c + \delta\gamma(c_c - c_r - r^{EBI})}{1 + \lambda + (\delta\gamma)^2},$$

$$q_r^{EBI} = \delta\gamma q^{EBI} \ , \quad q_c^{EBI} = (1-\delta\gamma) q^{EBI} \ , \quad \pi_C^{EBI} = \left(\frac{(\delta\gamma)^2}{2} + \lambda\right)[q^{EBI}]^2 \ \textit{and} \quad \pi_I^{EBI} = r^{EBI}\delta\gamma q^{EBI}.$$

when $\delta \in \left[\frac{\sqrt{\frac{1}{2}+\frac{\lambda}{(\gamma)^2}}}{\sqrt{\frac{1}{2}+\frac{\lambda}{(\delta\gamma)^2}}}\frac{q(\gamma,0)}{q(\delta\gamma,0)}, 1\right]$*. And the same as those in Lemma 3 otherwise.*

6 Conclusion

To sum up, we compare two main public policies : a mandate that requires the fuel industry to blend a minimum percentage of biofuel in their fuel, and a carbon emission standard that defines the maximum GHG emission level of the final fuel blend. The analysis takes place in a partial equilibrium framework where an innovator can licence the innovation to a fuel industry that is imperfectly competitive. This model is in line with those that have been developed in the agricultural economics literature on public policies related to biofuel (Clancy and Moschini, 2018, 2016).

We first show that the two policies are equivalent with cost decreasing innovation : whatever the objective of one of the policies, the same objective can be reached with the other one. This property no longer holds with an emission-based innovation. We show that, whatever the level of competition, a minimum mandate discourages the fuel industry to adopt this type of innovation. At the opposite, a carbon emission standard can create such incentive for this type of innovation.

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A Proofs

Proof of Equation 10

Providing the competitive fringe buys the innovation, the innovator maximizes the following profit $\pi_I = q_r.r$. By replacing the values by the continuation equilibrium values we get:

$$\pi_I = \gamma\frac{(1 - c_c + \gamma(c_c - c_r - r + \theta))}{1 + \lambda + \gamma^2}.r$$

The First Order Condition gives

$$\frac{d\pi_I}{dr} = 0 \Leftrightarrow -\gamma.r + 1 - c_c + \gamma(c_c - c_r - r + \theta) = 0$$
$$r = \frac{c_c - c_r + \theta}{2} + \frac{1 - c_c}{2\gamma}$$

This is the candidate equilibrium royalty providing the competitive fringe accepts the offer. Let's remind however that the maximum willingness to pay of the competitive fringe is $r = \theta$ - above this value the competitive fringe is better off producing without the innovation, i.e. $\pi_C(\mathbb{1}_a = 1) < \pi_C(\mathbb{1}_a = 0)$. Therefore, in order to have the candidate royalty to be an equilibrium royalty it must be lower than this maximum willingness to pay. That is:

$$\theta > \frac{c_c - c_r + \theta}{2} + \frac{1 - c_c}{2\gamma}$$
$$\Leftrightarrow 2\gamma\theta > (c_c - c_r + \theta)\gamma + 1 - c_c$$
$$\Leftrightarrow \gamma(\theta + c_r - c_c) > 1 - c_c$$
$$\Leftrightarrow \gamma > \frac{1 - c_c}{\theta + c_r - c_c} \equiv \tilde{\tilde{\gamma}}(\theta)$$

It is obvious that $\tilde{\tilde{\gamma}}(\theta)$ is decreasing wrt θ and c_r. Therefore, $\tilde{\tilde{\gamma}}(\theta)$ reaches is minimum value when θ is at its maximum i.e. c_r. Under Assumption 1, c_r is lower than $\frac{1}{2}$. In other words, the extreme minimal value of $\tilde{\tilde{\gamma}}(\theta)$ is reached at $\theta = c_r = \frac{1}{2}$ which gives $\tilde{\tilde{\gamma}}(\theta = c_r = 1/2) = 1$. Therefore $\tilde{\tilde{\gamma}}(\theta) \geq 1$ while $\gamma \leq 1$ and the candidate equilibrium royalty is not the equilibrium royalty. Since the innovator's profit function is increasing until the candidate equilibrium royalty then the equilibrium royalty is the maximum willingness to pay that is $r^{CBI} = \theta$. □

Proof of Lemma 5

******************* PERFECT COMPETITION ******************************

According to Eq. (12), the sign of the industry profit is the same as the one of the derivative of renewable input. Recall that the equilibrium quantity of renewable inputs denotes q_r^{CBI}. Let's also remind that under our binding policy γ, we also have $q_r^{CBI} = \gamma q^{CBI}$. Therefore, we have

$$\frac{dq_r^{CBI}}{d\gamma} = q^{CBI} + \gamma \frac{dq^{CBI}}{d\gamma}$$

It is easy to compute that $\frac{dq^{CBI}}{d\gamma} = -\frac{(c_r - c_c)(1-\gamma^2)+2\gamma(1-c_c)}{1+\gamma^2)^2} < 0$. It becomes then obvious that in order to have $\frac{dq_r^{CBI}}{d\gamma} > 0$ we need $\gamma < -\frac{q^{CBI}}{\frac{dq^{CBI}}{d\gamma}}$. Let us now compute this threshold. By replacing, the values in the above derivative we get the following second degree polynomial in γ : $-(1-c_c)\gamma^2 - 2(c_r - c_c)\gamma + 1 - c_c$. The second degree polynomial has a positive discriminant and thus has two roots. We find that one of the roots is negative and we therefore get rid of it - remind that $\gamma \in [0,1]$. The positive root, that we denote $\tilde{\gamma}$, simplifies to:

$$\tilde{\gamma} = \frac{1 - c_c}{\sqrt{(c_c - c_r)^2 + (1 - c_c)^2} + c_r - c_c}$$

It is easy to check that this root is positive. Also, we have $\sqrt{(c_c - c_r)^2 + (1 - c_c)^2} \leq \sqrt{(1 - c_c)^2} = 1 - c_c$ and hence $\sqrt{(c_c - c_r)^2 + (1 - c_c)^2} + c_r \geq 1 + c_r - c_c \geq 1$. So $\tilde{\gamma}$ belongs to $[0, 1]$. Furthermore, the coefficient of the term with the second-degree exponent is negative which means that the derivative is negative above $\tilde{\gamma}$ and positive below. Last, it is obvious from what we have seen that $ga\tilde{m}ma$ must intersect $\bar{\gamma}(\theta)$ for some θ. This happens for some $\theta > c_r$ henceforth the graph in figure 3. □

*******************IMPERFECT COMPETITION *******************

We can show that

$$\frac{\partial \pi_C}{\partial \gamma} = \frac{(1 - c_C - \gamma(c_R - c_C)) \cdot (1 - c_C) \cdot S}{(1 + \lambda + \gamma)^3}$$

with

$$S = -2T\lambda^2 - (2T + 3\gamma)\lambda + \gamma(1 - \gamma^2 - 2\gamma T)$$

and $T = (c_R - c_C)/(1 - c_C)$. Note that $T \in [0, 1]$ with $T = 0$ if c_R is minimum (equal to c_C) and $T = 1$ if c_R is maximum (equal to 1).

S is quadratic and concave in λ. The lowest root is negative and the higest root is:

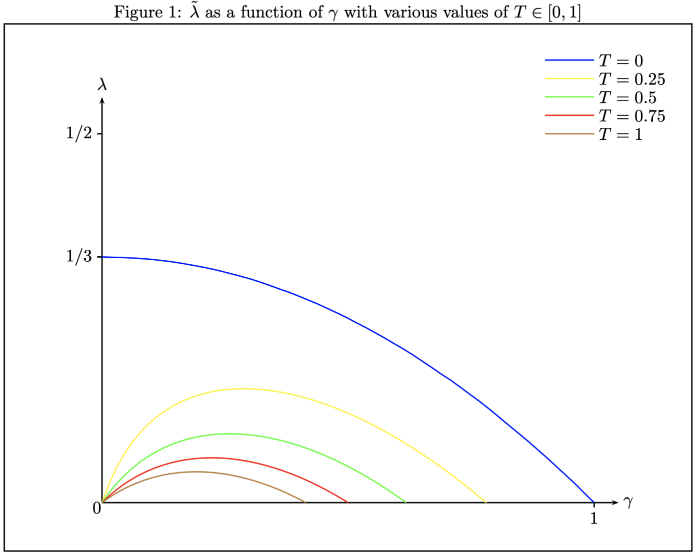
$$\tilde{\lambda} = \frac{(-2T + 3\gamma) + \sqrt{(2T + \gamma)(9\gamma + 2T(1 - 4\gamma^2))}}{4T}$$

It can be shown that we always have $9\gamma + 2T(1 - 4\gamma^2) > 0$ for $\gamma \in [0, 1]$ and $T \in [0, 1]$. [4]

The figure below gives the value of $\tilde{\lambda}$ as a function of γ with various values of T. It can, be shown that $\tilde{\lambda} > 0$ for between $0 < \gamma < \sqrt{1 + T^2} - T$ and that $\tilde{\lambda} < 0$ for $\sqrt{1 + T^2} - T < \gamma < 1$.

In summary, $\partial\pi_C/\partial\gamma > 0$ if $0 < \gamma < \sqrt{1 + T^2} - T$ and $\lambda \in [0, \tilde{\lambda}]$. Otherwise $\partial\pi_C/\partial\gamma < 0$. Note that $\tilde{\lambda} \leq 1/3$. Hence, if $\lambda > 1/3$, we always have $\partial\pi_C/\partial\gamma < 0$.

Figure 1: $\tilde{\lambda}$ as a function of γ with various values of $T \in [0, 1]$



[4] $9\gamma + 2T(1 - 4\gamma^2) > 0$ if $\gamma < 1/2$. If $\gamma > 1/2$, then $9\gamma + 2T(1 - 4\gamma^2) > 0$ of $T < 9\gamma/(2(1 - 4\gamma^2))$ which is always true because $9\gamma/(2(1 - 4\gamma^2)) > 1$ for $\gamma \in [0.5, 1]$.

Proof of Equation 14

The industry buys the innovation whenever $\pi_C(\mathbb{1}=1,\delta) \geq \pi_C(\mathbb{1}=0)$ which gives

$$\left(\frac{1}{2}+\frac{\lambda}{(\delta\gamma)^2}\right)\delta^2(q[\delta\gamma,r])^2 \geq \left(\frac{1}{2}+\frac{\lambda}{(\gamma)^2}\right)(q[\gamma,0])^2$$

$$\sqrt{\frac{1}{2}+\frac{\lambda}{(\delta\gamma)^2}}\delta\left(q[\delta\gamma,r]-\frac{\delta\gamma r}{1+\lambda+(\delta\gamma)^2}\right) \geq \sqrt{\frac{1}{2}+\frac{\lambda}{(\gamma)^2}}(q[\gamma,0])$$

$$r \leq (1+\lambda+(\delta\gamma)^2)\frac{\sqrt{\frac{1}{2}+\frac{\lambda}{(\delta\gamma)^2}}\delta q[\delta\gamma,0]-\sqrt{\frac{1}{2}+\frac{\lambda}{(\gamma)^2}}q[\gamma,0]}{\sqrt{\frac{1}{2}+\frac{\lambda}{(\delta\gamma)^2}}\delta^2\gamma} \equiv MWTP(\delta)$$

□

Proof of Equation 16

We first easily find that the royalty rate is nil when the innovation efficiency is lower than the minimum efficiency level. We thus only have to pin down on what conditions, the candidate royalty - obtained without the participation constraint - is the optimal royalty. This is the case whenever the participation constraint is satisfied at the royalty level. That is:

$$\left(\frac{1}{2}+\frac{\lambda}{(\delta\gamma)^2}\right)(\delta\gamma)^2\left(\frac{1}{2}\frac{1-c_c+\gamma\delta(c_c-c_r)}{1+\lambda(\delta\gamma)^2}\right)^2 \geq \left(\frac{1}{2}+\frac{\lambda}{(\gamma)^2}\right)\gamma^2\left(\frac{1-c_c+\gamma\delta(c_c-c_r)}{1+\lambda(\delta\gamma)^2}\right)^2$$

$$\left(\frac{1}{2}+\frac{\lambda}{(\delta\gamma)^2}\right)\left(\frac{\delta}{2}\right)^2(q[\delta\gamma,0])^2 \geq \left(\frac{1}{2}+\frac{\lambda}{(\gamma)^2}\right)(q[\gamma,0])^2$$

$$\sqrt{\frac{1}{2}+\frac{\lambda}{(\delta\gamma)^2}}\left(\frac{\delta}{2}\right)(q[\delta\gamma,0]) \geq \sqrt{\frac{1}{2}+\frac{\lambda}{(\gamma)^2}}(q[\gamma,0])$$

Henceforth, the optimal royalty rate is the candidate one when $\delta \in \left[2\frac{\sqrt{\frac{1}{2}+\frac{\lambda}{(\gamma)^2}}}{\sqrt{\frac{1}{2}+\frac{\lambda}{(\delta\gamma)^2}}}\frac{q(\gamma,0)}{q(\delta\gamma,0)},1\right]$ and the MWTP otherwise. Extending to the case where innovation efficiency can be lower to the minimum efficiency level, we obtain equation 16. □