# Cost-based or emission-based innovations in biofuel markets

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**Abstract**

Since the last decades, Europe and Northern America have applied various biofuel mandates with the indirect aim of promoting innovations in the biofuel sector. The economic literature generally assumes green innovations diminish the production cost of an environmentally friendly product (*cost-based innovations*, henceforth CBI). We extend this paradigm to green innovations that do not affect cost but still reduce a product emission factor (*emission-based innovations*, henceforth EBI). We assume an innovator tries to monetize one of the two types of innovation to a competitive fuel industry. We find that if a regulator specifies a minimum biofuel mandate, it only promotes a CBI. In contrast, if the regulator sets an emission carbon standard, it additively promotes the EBI on some conditions. Besides, even though the innovator prefers to sell a CBI, the EBI offers a profitable and welfare-enhancing option when the CBI is not feasible.

**Keywords:** R&D incentive; innovation; renewable energy.

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# 1 Introduction

Since the last decades, Europe and Northern America have used various biofuel mandates (e.g., Renewable Energy Directive in 2009, Renewable Fuel Standard in 2007) to oblige the industries to blend more biofuel directly. Substituting fossil fuel with biofuel would reduce greenhouse gas emissions as biofuel is more environmentally friendly. However, there is a lack of private incentive to operate this substitution as biofuel is also more costly to produce. Importantly, the mandates also consider the lever of environmental innovations to encourage firms to use biofuel. They promote the latter by creating profit opportunities for private innovators. For example, the Renewable Energy Directive (2009) stipulates that 'the main purpose of mandatory national targets is to provide certainty for investors and to encourage continuous development of technologies [...]'.[1]

Economists often model environmental innovations as innovations that diminish the production cost of an environmentally friendly product (see, for example, Clancy and Moschini (2018, 2016)). Yet, environmental innovations could make the product more environmentally friendly without modifying its cost. For example, suppose a cleaner substitute but as costly substitute to nitrogen is found, then rapeseed production becomes cleaner, which triggers a cleaner biodiesel (Cf. RAPSODYN project for nitrogen use efficiency[2] in the rapeseed sector). We denote the former cost-based innovations and the latter emission-based innovations. Our paper investigates on what conditions biofuel policies theoretically promote these innovations and compares the outcomes.

To this aim, we focus on two policies: a renewable share mandate, that directly obliges the fuel industry to blend a minimum share of biofuel in their fuel, and a carbon emission standard, that specifies the maximum GHG emission level of the final fuel blend and thus only indirectly obliges to blend a share of biofuel. The most prominent examples of such policies lie in the United States. We observe minimum share mandates at the federal level. The US Renewable Fuel Standard gives a total biofuel target (36 billion gallons by 2022), and the US Environmental Protection Agency deduces the blending share obligations (the 'standards'). In 2012, these standards required a total

[1] Cf. DIRECTIVE 2009/28/EC (14).

[2] Rapeseed is a major input for biofuel in France, and its production essentially uses nitrogen fertilizer which is reputed for being a major pollutant. The RAPSODYN project aims to reduce the use of nitrogen in rapeseed production. This project gathers a large consortium of public research units and private seed companies from 2013 to 2020. It received a public subsidy of 7M€.

blending ratio of 9.23% for total renewable fuel Schnepf and Yacobucci (2012). This percentage is then used to determine the individual Renewable Volume Obligations that pertain to fuel blenders.[3] On the other hand, we observe carbon emission standard in California. The present Low Carbon Fuel Standard has required a 10% reduction in the average carbon intensity of fuels sold in the state by 2020.[4]

We find that the two policies promote a cost-based innovation, provided it is sufficiently efficient. However, only the carbon emission standard additionally promotes an emission-based innovation on the conditions that (i) the policy is initially sufficiently restrictive, and (ii) the emission-based innovation is not too efficient. In practice, this innovation is likely not to be very efficient because biofuel is often already very environmentally friendly. On the other hand, our result claims that the presence of a blend wall (technological constraint - e.g., cars engines) which impedes setting very restrictive policies, prevents the innovator from monetizing an emission-based innovation. Our paper thus shows that policies must first eliminate the blend wall and become more stringent if they aim to promote emission-based innovation. That last finding supports the recommendation by European Technology and Innovation Platform Bioenergy which claims that 'GHG emission quotas for fuels [...] are a good instrument but should be set to ambitious reduction targets'.[5]

Provided the above conditions are satisfied, then the emission-based innovation is feasible under a carbon emission standard. We still find that the innovator prefers to sell a cost-based innovation than an emission-based innovation when the former is feasible. Nevertheless, the emission-based innovation offers a profitable option when the cost-based innovation is not feasible. Therefore, a carbon emission standard offers a wider range of profitable innovations than a renewable share mandate. Finally, we find that the emission-based innovation is welfare-enhancing with respect to the absence of innovation (say with RSM – and no cost-based innovation) and can also be welfare improving with respect to a cost-based innovation provided the latter is sufficiently weak.

[3] Another prominent example of this kind of policy is given by renewable portfolio standards, which mandate that suppliers of an electricity source a set percentage of electricity from renewable sources such as solar, wind, biomass, and hydroelectric providers (Holland, 2012)

[4] British Columbia and Oregon have similar policies in place, and Washington and the European Union have proposed instituting low carbon fuel standards (British Columbia Ministry of Energy and Mines, 2014; Oregon Department of Environmental Quality, 2016; Pont et al., 2014; European Commission, 2014).

[5] (Strategic research and innovation agenda, 2018)

Our paper contributes to two strands of the literature. First, it contributes to the theoretical literature on the promotion of environmental innovation by carbon policies. This literature assumes a closed economy using the partial equilibrium concept with an R&D sector providing an innovation to a competitive fuel industry. The innovation is cost-based. In such a 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 a poor incentive for breakthrough innovation but a strong incentive for incremental innovation. In a similar setting, Clancy and Moschini (2016) shows that innovator entries in the R&D sector depend on carbon policies. It finds that R&D subsidies provide more variation in the number of entries than a carbon tax. We contribute to this literature by studying other biofuel policies. We elaborate on minimum proportion mandates instead of quotas, and our findings nuance the previous results with quotas. We also extend the scope of innovation by adding the possibility of an emission-based innovation.

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 using the partial equilibrium concept to assess the policy effect. Holland *et al.* (2009) shows that such a policy cannot be efficient. It essentially occurs because the policy decreases the production of high carbon fuel but increases the production of low carbon fuel, which possibly raises carbon emissions. Interestingly, Lade and Lawell (2018) finds that a cost-containment mechanism - over compliance cost - increases the policy's efficiency. We contribute to this literature by bringing an innovative sector and finding a new insight: such a carbon-intensive policy may promote a new type of innovation, an emission-based innovation, that is not profitable under the largely spread minimum mandate policies.

The remainder of the paper is as follows. Section 2 presents the model. Section 3 derives the equilibria under cost-based innovation (the benchmark innovation type). Then, section 4 derives the equilibria with an emission-based innovation. Section 5 compares the equilibria and provides our main results, which are re-discussed in section 5 where we extend the model to imperfect competition. Finally, section 7 concludes. Proofs are relegated to the appendix.

## 2 The model

**The industry.** We suppose a competitive fuel industry, denoted C, which produces fuel, in quantity $q \in [0,1]$, by blending conventional inputs, denoted $q_c \in [0,1]$, and renewable inputs, denoted $q_r \in [0,1]$ given blending technology $q = q_c + q_r$. The two inputs are thus perfect substitutes. Even though renewable fuel often delivers less energy than the conventional fuel, it is possible to reason in energy-equivalent quantities. The industry bears increasing and convex production costs to produce the conventional and renewable inputs which denote respectively $C_c(q_c)$ and $C_r(q_r)$, and faces inverse demand $P(q) = 1 - q$. The industry's profit is:

$$\pi_C(q, q_c, q_r) = P(q)q - C_c(q_c) - C_r(q_r) \tag{1}$$

We further assume a per-unit of input emission factor such that the emission factor of the renewable input $\phi_r \in [0,1]$ is lower than the one of conventional input, normalized to one $\phi_c = 1$. The total emission of the produced fuel is $q_c + \phi_r q_r$. Total emission creates a damage for the welfare of all agents with marginal damage $\kappa \in [0,1]$. More formally, the damage function $\kappa.(q_c + \phi_r q_r)$ enters negatively into total welfare.

**The innovator.** A monopolist innovator M proposes the following two types of green innovations on the renewable input in exchange of a per-unit royalty $r \in \Re^+$:

- a *cost-based innovation* (CBI) which decreases the renewable marginal cost by $\theta$, or ;
- an *emission-based innovation* (EBI) that decreases the emissions of the renewable input by $\Psi$.

To have a neat parametrization of the cost-based innovation, we specify the cost functions such that $C_c(q_c) = c_c q_c$ and $C_r(q_r) = (c_r - \theta + r)q_r + (1/2)(q_r)^2$ where $c_c \in [0, \frac{1}{2}]$ and $c_r \in [0, \frac{1}{2}]$ are constant parameters. This gives the following marginal cost functions $dC_c(q_c)/dq_c = c_c$ and $dC_r(q_r)/dq_r = c_r - \theta + r + q_r$. We further assume that $c_c < c_r$ so that without such innovation the renewable marginal cost remains greater than the conventional marginal cost.

We also assume $\theta$ belongs to the interval $[c_r - c_c, c_r]$. The cost-based innovation makes the marginal cost of the first unit at best nil, that is $c_r - \theta \geq 0$ while it brings sufficient cost efficiency so that the marginal costs functions may intersect after innovation $c_c \geq c_r - \theta + r$ for some $r \in \Re^+$.

In practice, the EU market approval mechanism enables to select efficient innovations. On the other hand, we assume $\Psi$ belongs to the interval $[0, \phi_r]$. The emission-based innovation is at least nil but cannot reduce more than the renewable emission factor initial level.

Note that the industry pays the royalty upon accepting to buy the innovation. We denote the industry's acceptance decision under innovation type by $a = \{1, 0\}$ where $a = 1$ means the industry buys the innovation while $a = 0$ means the industry does not buy it. Such notation enables the following neat notations given acceptance decision $a$. Under cost-based innovation, we now have $r(a) = a.r$ and $c_r(a) = a(c_r - \theta) + (1 - a)c_r$. Under emission-based innovation, we now have $r(a) = a.r$ and $\phi_r(a) = a(\phi_r - \Psi) + (1 - a)\phi_r$. The innovator's profit is:

$$\pi_M(r) = r(a).q_r \tag{2}$$

**The regulator.** We suppose a regulator chooses between two mandate policies to reduce the negative impact of fuel emission. Our focus on mandates follows what is observed in practice: authorities often prefer mandates over taxes because the latter are much less welcome by fuel consumers (refer to the yellow vest protest about carbon tax in France). The regulator can use:

- a *Renewable share mandate (RSM)*, denoted $\gamma \in [0, 1]$, which specifies a minimum share of renewable input to blend into the final fuel: $q_r \geq \gamma q$, or ;
- a *Low carbon emission standard (LCES)*, denoted $\sigma \in [\phi_r, 1]$, which specifies a threshold that fuel emissions must satisfy: $\frac{q_c + \phi_r q_r}{q_c + q_r} \leq \sigma$.[6]

Interestingly, we can rewrite the LCES policy so as to get a ratio of renewable input over total fuel that we denote $\gamma_\sigma$. In other words, it is possible to set a LCES policy that specifies a ratio of renewable input $\gamma_\sigma$. Formally, we have $\frac{q_c + \phi_r q_r}{q_c + q_r} \leq \sigma$ is equivalent to $q_r \geq \gamma_\sigma(\phi_r, \sigma).q$ with $\gamma_\sigma(\phi_r, \sigma) = \frac{1-\sigma}{1-\phi_r}$. Therefore, it is also possible to set a LCES policy to get the same ratio as under a RSM policy that specify a ratio $\gamma$. For the latter to occur, it is sufficient to set $\sigma$ such that

[6]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 $\sigma$ belongs to the interval $[\phi_r, 1]$.

$\gamma(\sigma) = \gamma$. In the end, we find there is a $\sigma-$LCES equivalent ratio for any $\gamma$-RSM policy:

$$\text{[RSM]} \qquad q_r \geq \gamma q \tag{3}$$

$$\text{[LCES-equivalent]} \qquad q_r \geq \gamma_\sigma(\phi_r, \sigma).q \tag{4}$$

where $\sigma$ is such that $\gamma = \gamma_\sigma(\phi_r, \sigma)$ and $\gamma_\sigma(\phi_r, \sigma) \in [0, 1]$. We see that the LCES-equivalent ratio depends on the renewable input emission factor, which implies the following property.

**Property 1.** *Suppose the two policies specify the same constraining fuel ratios without innovation $\gamma = \gamma_\sigma$. Then, the LCES policy's targeted ratio of renewable input $\gamma_\sigma$ is affected by an emission-based innovation but not by a cost-based innovation. In contrast, the RSM policy's targeted ratio of renewable input $\gamma$ is not affected by neither innovations.*

**The game.** Given a regulator's decision to regulate or not, the timing of the game is as follows.

1. The innovator decides whether to innovate and if so then sets the level of the royalty $r$.

2. The industry observes the innovation type and the associated royalty. It then decides whether to use the innovation, and produces the final blend for the representative consumer.

3. The representative consumer buys the blend from the industry.

We use the Sub-game Perfect Nash Equilibrium (SPNE) concept to solve this game.

# 3 Equilibria with the cost-based innovation (CBI)

## 3.1 No regulation

In this section, we suppose the regulator does not regulate the fuel industry. We use backward induction to find the SPNE. We also skip most of the computations because the methodology under cost-based innovation is the same as in Clancy and Moschini (2018). We nevertheless provide the intuitions.

At the last stage, the competitive industry is price taker. Given price $P$, and irrespective of the innovation, the industry sets $q_c$ and $q_r$ so as to maximize its profit function (Equation 1). The first order conditions give the equilibrium price $P^U = c_c$. Since at equilibrium, the market price equals the inverse demand, $P^U = 1 - q^U$, we find $q^U = 1 - c_c$. Intuitively, the final quantity of fuel $q^U$ lies at the intersection of the inverse demand and the equilibrium price which equals the marginal cost of the conventional input (see Figure 5 in Appendix).

If the industry does not buy the innovation, then it uses only conventional input because the renewable input marginal cost remains strictly higher than the conventional input marginal cost. Consequently, the industry makes no profits since the price equals the conventional input marginal cost. By contrast, if the industry buys the innovation, then it may mix the two inputs because the renewable input marginal cost may intersect the conventional input marginal cost. In that case, the expected profit is positive because there is a surplus provided by the production of renewable inputs ($\pi_C(c_r(a), r(a)) = \frac{[q_r^U(c_r(a), r(a))]^2}{2}$). It becomes clear that the industry buys the innovation whenever it can mix some renewable inputs given the proposed royalty, which implies that it cannot set a royalty above the following threshold $r^U_{sup}$:

$$r \leq \theta - (c_r - c_c) \equiv r^U_{sup} \tag{5}$$

At the first stage, the innovator sets its royalty rate $r$ so as to maximize its expected profits (Equation 2), under the constraint that the industry buys the innovation. We find:

$$r^U = \frac{c_c - c_r + \theta}{2} \leq r^U_{sup} \tag{6}$$

Note that royalty rate is lower than the maximum royalty rate accepted by the industry, so the buying constraint does not bind and the industry benefits from using the innovation. We find the following equilibrium quantities which are in line with Clancy and Moschini (2018).

**Result 1.** *In the absence of regulation, the industry buys the cost-based innovation,* $a^U = 1$*, and the equilibrium quantities are*

$$q^U = 1 - c_c \ , \quad q^U_r = \frac{c_c - c_r + \theta}{2} \ , \quad q^U_c = q^U - q^U_r$$

### 3.2 Regulation

**Bindingness.** Using Result 1, the unregulated ratio of renewable inputs over total fuel, under cost-based innovation, is:

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

It is positive (it even increases with the cost-based technology) so the mandates may not bind.[7] To simplify the analyses of next sections, and as in practice, we suppose the regulator aims to diminish pollution by encouraging the use of biofuel through a mandate that specify a higher proportion of biofuel than without regulation. Formally, it means the regulator specify $\gamma$ or $\sigma$ such that $\gamma = \gamma_\sigma \geq \bar{\gamma}^{CBI}(\theta)$, for any state of technology $\theta$.

According to Property 1, the cost-based innovation affects neither policy ratios. Therefore, RSM and LCES are equivalent in this setting, and we only compute the SPNE under a RSM policy.

**The industry choice.** At the stage of the competitive industry choice, the industry maximizes the profit (Equation 1) with respect to $q_c$ and $q_r$ given the regulator's policy $q_r \geq \gamma q$. Since $\gamma > \bar{\gamma}^{CBI}(\theta)$, the mandate binds which means $q_r = \gamma q$ and $q_c = (1 - \gamma)q$. We then obtain a simplified objective profit function $\pi_C = P(q).(q) - C_c((1 - \gamma)q) - C_r(\gamma q)$ which only depends on $q$. The associated First Order Condition leads to the following optimal equality:

$$[FOC_q] \quad P - (1 - \gamma)C_r'((1 - \gamma)q) - \gamma C_r'(\gamma q) = 0 \tag{8}$$

Note that we recover the usual property that a competitive price equals the average marginal cost. Given cost functions, we have $C_c'((1-\gamma)q) = c_c$ and $C_r'(\gamma q) = c_r(a)+r(a)+\gamma q$. At market equilibrium, total offer equals total demand $P = 1-q$ and we find the following continuation equilibrium quantity $q^{CBI}(c_r(a), r(a)) = \frac{1-c_c-\gamma(c_r(a)-c_c+r(a))}{1+\gamma^2}$. The continuation equilibrium input quantities follow: $q_r^{CBI}(c_r(a), r(a)) = \gamma q^{CBI}(c_r(a), r(a))$ and $q_c^{CBI}(c_r(a), r(a)) = (1 - \gamma)q^{CBI}(c_r(a), r(a))$.

[7] Note that the maximal value of this unregulated blend is $\bar{\gamma}^{CBI}(\theta = c_r) = \frac{c_c(1+\lambda)}{2(1-c_c)}$ is positive and lower than one. Remind that Assumption $c_c < c_r < 1/2$ is sufficient so that $q_R \leq q$ but it also sufficient so that $\theta$ belongs to the interval $[c_r - c_c; c_r]$ and the unregulated blend lies in its interval $[0; 1]$.

Given $FOC_q$, the profit simplifies to $\pi_c^{CBI}(c_r(a), r(a)) = \frac{[\gamma q^{CBI}(c_r(a),r(a))]^2}{2}$. This continuation profit function is similar to the one without regulation except that it is now always strictly positive due to the policy which enforces strictly positive renewable inputs: $\gamma q^{CBI}(c_r(a), r(a)) > 0$. In particular, 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 but the industry is now obliged to mix the two inputs and actually passes this burden to the consumer through a higher price. The industry buys the innovation whenever $\pi_C^{CBI}(c_r - \theta, r) \geq \pi_C^{CBI}(c_r, 0) \Leftrightarrow q^{CBI}(c_r - \theta, r) \geq q^{CBI}(c_r, 0) > 0$ which boils down to

$$r \leq \theta \equiv r_{sup}^{CBI} \tag{9}$$

**The innovator choice.** The innovator anticipates the behaviour of the competitive industry and sets $r$ so as to maximize its profits, $\pi_M = r.q_r^{CBI}(c_r - \theta, r)$, under the constraint that the industry buys the innovation, $\pi_C^{CBI}(c_r - \theta, r) \geq \pi_C^{CBI}(c_r, 0)$. Appendix shows that the constraint binds and therefore the innovator sets

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

Note that the mandate enables the industry to make positive profit even when the royalty is at its maximum willingness to pay. It contrasts the benchmark situation where the profit turned to be nil in this case which incited the innovator to lower its royalty offer.

**The equilibrium.** The following result summarizes the equilibrium outcomes.

**Result 2.** *With cost-based innovation and binding policy $\gamma > \bar{\gamma}(\theta)$, the industry buys the innovation, $a^{CBI} = 1$. The equilibrium fuel quantity is*

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

We find that total quantity diminishes ($q^{CBI} < q^U$). Since the equilibrium price follows the reverse pattern ($P^* = 1 - q^*$), it follows that the price increases ($P^{CBI} > P^U$). The industry passes the burden of the regulation to the consumers. The consumers are thus worse off by the higher price.

In the meantime, the decrease in quantities diminishes the total emission. In addition, the higher ratio of renewable inputs diverts the use of inputs with high emission factors (conventional) to inputs with lower emission factors (renewable) which also decreases the total emission. Proposition 1 summarizes these results.

**Proposition 1.** *Compared with the unregulated benchmark, a carbon policy $\gamma > \bar{\gamma}(\theta)$ with cost-based innovation decreases the negative externalities due to total emission but harms consumers.*

Proposition 1 extends the result by Clancy and Moschini (2018) where the regulation takes the form of a minimum quota of renewable input instead of a minimum proportion or maximum emission rate. This is interesting because it occurs while regulation potentially diminishes the quantity of renewable inputs, in contrast to Clancy and Moschini (2018). Precisely, the regulation has two opposite effects on the quantity of renewable input. The industry first adapts to the regulator's decision given the current fuel quantity produced: the *ratio effect* (short run). But this is not sustainable and the industry thus then modifies its production of fuel: the *quantity effect* (long run).[8] Equation 11 displays these two effects. Figure 1 illustrates them.

$$q_r^{CBI} - q_r^U = \underbrace{\gamma(q^{CBI} - q^U)}_{\text{quantity effect} < 0} + \underbrace{(\gamma - \bar{\gamma})q^U}_{\text{ratio effect} \geq 0} \tag{11}$$

**Lemma 1.** *Ex post regulation, the quantity of renewable input increases whenever the positive ratio effect ($(\gamma - \bar{\gamma})q^U \geq 0$) overcomes the negative quantity effect ($\gamma(q^{CBI} - q^U) \leq 0$). This happens when the regulation is above a threshold $\gamma > \ddot{\gamma}(\theta) \in [\bar{\gamma}, 1]$ with $d\ddot{\gamma}/d\theta \geq 0$.*

Lemma 1 claims that minimum proportion or maximum emission rate policies increase renewable inputs, as with quotas, when the renewable input proportion they specify is sufficiently high.

Also, we see that the royalty rate increases, $r^{CBI} > r^U$, and, in particular, it now equals the industry's maximal willingness to pay, $r^{CBI} = r_{sup}^{CBI}$ while $r^U < r_{sup}^U$. This means that the innovator now captures all the industry's rent from the innovation. It happens because the regulation constrains the industry to produce some renewable input and the industry therefore cannot threaten

[8] Note that the innovator also adapts its royalty rate in consequence and because this choice also affects the final quantity we embed this into the quantity effect.

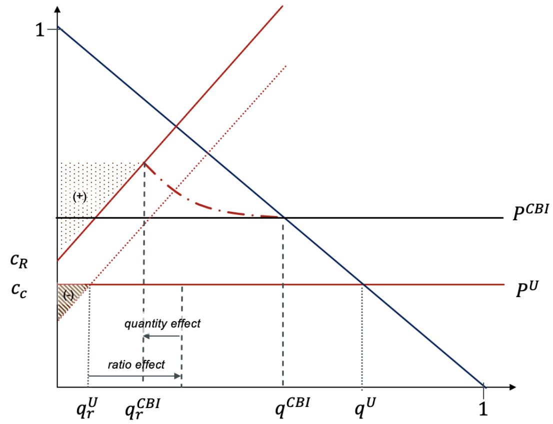



Figure 1: Unregulated and regulated blends with cost-based innovation

the innovator not to use any. Appendix shows that the increase of the royalty rate overcomes the possible decrease of renewable quantities, so the innovator benefits from regulation.

Last, we observe that the variation of the industry's profit depends on the variation of renewable inputs. Intuitively, a rise of the quantity of renewable inputs enlarges the cost surplus while a decrease shrinks such surplus.

**Proposition 2.** *Provided $\gamma > \bar{\gamma}(\theta)$, the variation of industry's profit is the same as the one of renewable quantities: it increases when the regulation is above a threshold $\gamma > \ddot{\gamma}(\theta) \in [\bar{\gamma}, 1]$ with $d\ddot{\gamma}/d\theta \geq 0$, and decreases otherwise. In contrast, the innovator's profit always increases.*

# 4 Equilibria with the emission-based innovation (EBI)

## 4.1 No regulation

In this section, we suppose the regulator does not regulate the fuel industry. We use backward induction to find the SPNE.

Intuitively, the emission-based innovation, does not affect the marginal costs. Therefore, the industry never uses renewable inputs and the absence of renewable input impedes the innovator to monetize its innovation.

**Result 3.** *In the absence of regulation, the industry does not buy the emission-based innovation,*

*$a^U = 0$, and the equilibrium quantities are*

$$q^U = 1 - c_c \ , \quad q_r^U = 0 \ , \quad q_c^U = q^U$$

## 4.2 Regulation

**Lemma 2.** *The emission-based innovation modifies the LCES ratio from $\gamma_\sigma(\phi_r, \sigma)$ to $\gamma_\sigma(\phi_r - \Psi, \sigma)$, such that $\gamma_\sigma(\phi_r - \Psi, \sigma) = \frac{1}{\delta(\Psi)} \gamma_\sigma(\phi_r, \sigma)$ where $\delta(\Psi) = \frac{1-(\phi_r - \Psi)}{1-\phi_r} \in [1, \frac{1}{1-\phi_r}]$ proxies its efficiency.*

Lemma 2 extends the property mentioned in Section 2. It also reminds that the emission-based innovation relaxes the LCES-equivalent ratio, and suggests that the innovator may monetize this type of innovation with such a policy.

**RSM policy.** Lemma 2 also underlines that an emission-based innovation only affects the constraint associated with an LCES policy. Therefore, if we consider an RSM, Lemma 2 implies that the industry does not benefit from any emission-based innovation and thus does not buy any. In the end, we find the same equilibrium outcomes as with cost-based innovation except for the innovator's profit. Intuitively, we previously had an equilibrium at $r^* = \theta$ which means the marginal cost of renewable input remains at $c_r + q_r$ which is equivalent to have no innovation on the renewable input.

**Result 4.** *In the presence of emission-based innovation and binding RSM policy $\gamma$, the equilibrium quantity is the same as in Result 2. However, the industry does not buy the innovation, $a^{EBI} = 0$, and the innovator makes no profits.*

**LCES policy.** In contrast, with an LCES policy, the emission-based innovation can relax a binding constraint, $q_r = \gamma_\sigma q$, in the industry's program. In what follows, we omit to write $\sigma$ to alleviate notations.

**The industry's choice.** The constraint binds before and after the emission-based innovation, the industry's optimization program is thus very similar to the one in the previous section in both cases. The only differences are the following. On the one hand, after emission-based innovation we have $\frac{1}{\delta}\gamma$ if the industry buys the innovation at royalty rate $r$, while $\gamma$ remains unchanged when the industry does not buy the innovation. On the other hand, the marginal cost of the renewable input is not affected by the emission-based innovation and therefore stays at $c_r + q_r$. Therefore, by denoting $\gamma(a) = a\frac{1}{\delta}\gamma + (1-a)\gamma$, the First Order Condition follows the same pattern as with cost-based innovation:

$$[FOC_q'] \quad P - (1-\gamma(a))C_r'((1-\gamma(a))q) - \gamma(a)C_r'(\gamma(a)q) = 0 \tag{12}$$

It follows that $q^{EBI}(\gamma(a), r(a)) = 1 - c_c - \gamma(a)(c_r - c_c + r(a))$ and leads to $\pi_c^{EBI}(\gamma(a), r(a)) = \frac{[\gamma(a)q^{CBI}(\gamma(a),r(a))]^2}{2}$ which is again strictly positive. The industry is willing to pay for the innovation whenever its profit with the innovation is higher than its profit without innovation, $\pi_C^{EBI}(\frac{1}{\delta}\gamma, r) \geq \pi_C^{EBI}(\gamma, 0)$. Denote $\Delta q_r^{EBI}(\gamma(a), r(a)) = \frac{1}{\delta}\gamma q^{EBI}(\frac{1}{\delta}\gamma, r) - \gamma q^{EBI}(\gamma, 0)$, this happens whenever $\Delta q_r^{EBI}(\gamma(a), r(a)) \geq 0$. The competitive industry is thus willing to buy the innovation whenever the latter raises the renewable inputs. We saw that the variation of renewable quantities generally depends on the balance between a ratio (or short term) effect and a quantity (long term) effect. In the present case, they write as follow:

$$\Delta q_r^{EBI}(\gamma(a), r(a)) = \underbrace{\frac{1}{\delta}\gamma(q^{EBI}(\frac{1}{\delta}\gamma, r) - q^{EBI}(\gamma, 0))}_{\text{quantity effect} > 0} + \underbrace{(\frac{1}{\delta}\gamma - \gamma)q^{EBI}(\gamma, 0)}_{\text{ratio effect} < 0} \tag{13}$$

The ratio effect is negative: the innovation diminishes the ratio which reduces renewable inputs. At the opposite, the quantity effect is positive: because the industry passes the policy burdens to the consumers, a relaxed ratio enables to increase the total quantity of fuel released on the market, which pushes the industry to use renewable inputs. Lemma 3 below displays the conditions triggering a rise of renewable inputs.

**Lemma 3.** *Under perfect competition, the industry is willing to buy an emission-based innovation whenever the latter does not relax too much the constraint, $\delta \leq \ddot{\delta}(\gamma)$, and provided the initial regulation is sufficiently restrictive, $\gamma \geq \dot{\gamma}$.*

Imagine the current technology does not enable to produce energy from a blend with proportion of renewable above a certain threshold, what is called the "blend wall", then policies will not oblige the industry to blend fuel with a proportion of renewable higher than this threshold.[9] Now suppose this threshold is above $\bar{\gamma}(\theta)$ but below $\dot{\gamma}$, then the industry will not buy any emission-based innovation and will only buy a cost-based innovation. The following propositions follows.

**Proposition 3.** *The existence of a blend wall of level $\gamma^{wall}$, such that $\gamma^{wall} < \dot{\gamma}$, discourages the industry to buy any emission-based innovation.*

**Proposition 4.** *An emission factor of renewable input sufficiently low, $\phi_r \in [0, \bar{\phi}_r]$ such that $\delta \leq \frac{1}{1-\bar{\phi}_r} \leq \dot{\delta}(\gamma)$, incites the industry to buy an emission-based innovation.*[10]

In what follows, we suppose that such a blend wall is not constraining, the regulation in place is sufficiently restrictive, $\gamma \geq \dot{\gamma}$, and the innovation does not relax too much the latter, $\delta \leq \ddot{\delta}(\gamma)$. The industry is thus willing to pay $r^{EBI}_{sup}$ such that Eq. (13) binds.

**The innovator choice.** The innovator anticipates the behaviour of the competitive industry and sets $r$ so as to maximize its profits, $\pi_M = r.q^{EBI}_r(\frac{1}{\delta}\gamma, r)$, under the constraint that the industry buys the innovation, $\pi^{EBI}_C(\frac{1}{\delta}\gamma, r) \geq \pi^{EBI}_C(\gamma, 0)$. Appendix shows that the constraint binds and that the innovator sets

$$r^{EBI} = \frac{(1-\delta)(\gamma c_c(\gamma+\delta+1) - c_c\delta - \gamma(\gamma + c_r\delta + c_r) + \delta)}{\gamma^3+\gamma} = r^{EBI}_{sup} \tag{14}$$

**The equilibrium.** The following result summarizes the equilibrium outcomes.

**Result 5.** *With emission-based innovation, provided the LCES-equivalent policy $\gamma$ is restrictive $\gamma > \dot{\gamma}$ and the innovation does not relax the latter too much $\delta \leq \ddot{\delta}(\gamma)$, the industry buys the innovation and the equilibrium quantity is*

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

[9] 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.

[10] Remind range of $\delta$ is $[1, \frac{1}{1-\phi_r}]$

We can distinguish the effects of the regulation and the innovation on the equilibrium quantity by rewritting the quantity such that $q^{EBI}(\delta,\gamma) = \frac{1-c_c-\frac{1}{\delta}\gamma(c_r-c_c)}{1+(\frac{1}{\delta}\gamma)^2} - \delta\frac{\Delta q^{EBI}(\gamma(a),0)}{\gamma}$. First, the regulation constrains the firm to use some renewable and the firm passes on this constraint to the consumers which decreases the fuel quantities. The innovation relaxes this constraint and the industry produces more fuel. But the industry must pay for this innovation which then decreases the fuel quantity. Because $r^{EBI}_{sup}$ makes the industry's constraint, $\Delta q^{EBI}_r(\gamma(a), r(a)) \geq 0$, binds we find, at equilibrium: $q^{EBI}(\frac{1}{\delta}\gamma, r^{EBI}_{sup}) = \delta q^{EBI}(\gamma, 0)$.

**Proposition 5.** *Compared with the unregulated benchmark, a LCES-equivalent policy $\gamma > \bar{\gamma}(\theta)$ with emission-based innovation decreases the negative externalities due to total emission but harms consumers. The regulation benefits both the innovator and the industry.*

# 5 Comparison

## 5.1 No regulation

Compared with the EBI, the CBI affects the industry cost function which induces a potential monetization by the innovator. The innovator is better off since the industry can threaten not to use renewable inputs, the innovator leaves some rent to the latter. The industry gets some rent, and does not transmit the cost-reduction to the consumers. It is therefore also better off. The consumers are not affected by the innovation. In the end, the industry blends more renewable inputs into the final blend which decreases total emission.

**Proposition 6.** *Without regulation, the innovator only monetizes a cost-based innovation. Cost-based innovation makes the industry earn greater profits and does not affect the consumer surplus. Negative externalities decrease and welfare increases.*

Next subsection studies whether regulation could modify this result.

## 5.2 Regulation

In this section, we compare the two equilibria under regulation. That is to say, for a given initial regulation $\gamma$, we compare the equilibrium outcomes under a cost-based innovation with the ones under an emission-based innovation.

### 5.2.1 The innovative incentive

We first study the innovative incentive of the innovator. It earns $r^{CBI}.q_r^{CBI}$ upon creating a cost-based innovation while $r^{EBI}.q_r^{EBI}$ upon creating an emission-based innovation. We have seen that $r^{EBI}$ is such that $q_r^{CBI} = q_r^{EBI}$. It implies that the innovator prefers to search for a cost-based innovation whenever $r^{CBI} > r^{EBI}$, and an emission based-innovation otherwise. But the two royalty rates are not always comparable because not always feasible depending on the parameters' values. Figure 2 illustrates the innovator's incentive for the case where $c_r = 0.5$, $c_c = 0.2$ and the initial regulation is sufficiently stringent $\gamma = 85\%$ (e.g. the real-life blend E85).

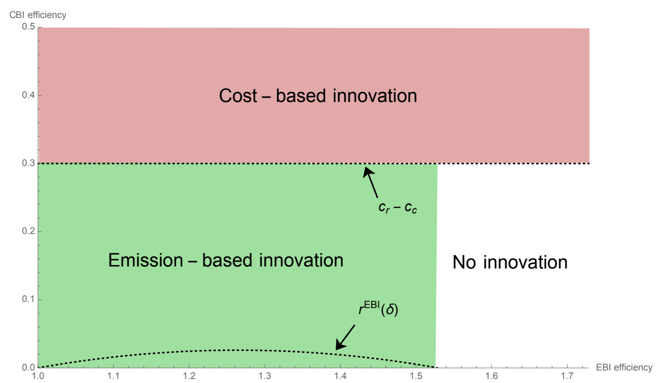



Figure 2: Partition of cost-based and emission-based innovation

Note: $c_r = 0.5$, $c_c = 0.2$ and $\gamma = 85\%$ (e.g. E85).

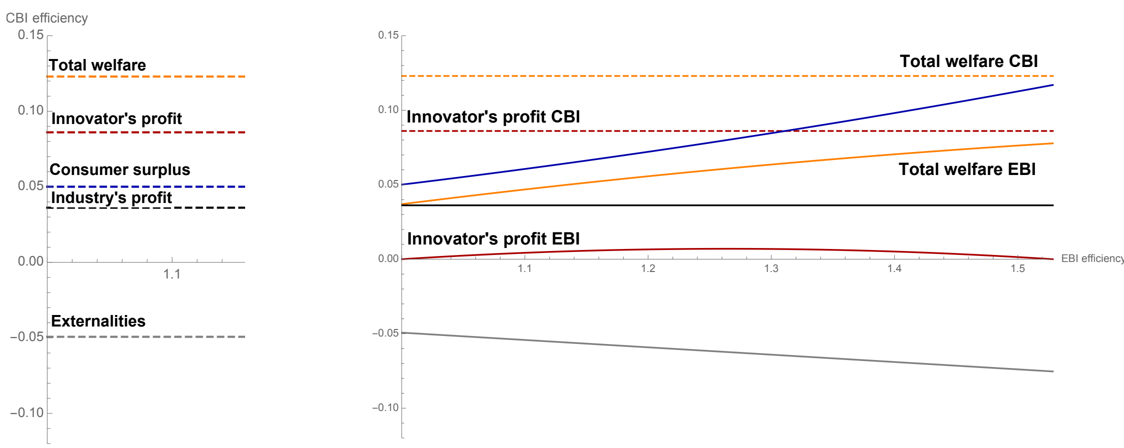
Figure 2 displays three areas. They build on the feasibility condition of the cost-based innovation $\theta > c_r - c_c$, and the feasibility of the willingness to pay $r^{EBI}(\delta) > 0$. In the red area, we have $r^{CBI} = \theta > c_r - c_c$. Because $c_r - c_c > r^{EBI}$, the innovator selects a cost-based innovation. Indeed, the cost-based innovation can be monetized and is more profitable than the emission-based innovation so the innovator selects a cost-based innovation. In the green area, we have $r^{CBI} = \theta < c_r - c_c$ so the cost-based innovation cannot be monetized. However, the emission-based innovation can be monetized as long as $r^{EBI}(\delta) > 0$. Therefore, the emission-based innovation is profitable while the cost-based innovation is not, so the innovator selects the emission-based innovation. Actually, the inequality $c_r - c_c > r^{EBI}(\delta)$ remains true for all $c_r$ and $c_c$ in the assumed ranges. Last, in the white area, the two feasibility constraints are not satisfied so no innovation can be monetized.

**Proposition 7.** *Upon feasibility, a cost-based innovation is more profitable than an emission-based innovation. Nevertheless, an emission-based innovation - not too efficient - is profitable when the cost-based innovation is not profitable.*

### 5.2.2 Welfare analysis

This section compares the different surplus obtained at equilibrium when the two types of innovations are feasible. Figure 3 provides an illustration of these surplus where $c_r = 0.5$, $c_c = 0.2$, $\gamma = 85\%$ (e.g. E85), $\theta = 0.32$, and $\kappa = 0.5$.

Let us first consider the surplus with the cost-based innovation (Figure 3a). Obviously, the different surplus do not depend on the EBI efficiency, hence the constant dashed lines. The innovator and the industry earn profits represented respectively by the red and black lines. The consumer surplus is represented by the blue line while the negative externalities are in grey. Remind that a rise of the cost-based innovation efficiency only benefits the innovator. Therefore, a rise of the cost-based innovation only increases total welfare because the innovator earns more.




(a) Cost-based innovation

(b) Emission-based innovation

Figure 3: Surplus comparison (illustration)

Note: $c_r = 0.5$, $c_c = 0.2$, $\gamma = 85\%$ (e.g. E85), $\theta = 0.32$, and $\kappa = 0.5$.

Let us now consider the surplus with the emission-based innovation. The surplus follow the same color pattern. Interestingly, the industry's profit remains the same. It happens because it comes from the quantity of renewable inputs which does not change from one innovation to another. On the other hand, the innovator's profit, this time, increases and then decreases with respect to the EBI efficiency. The consumer surplus and the negative externalities (in absolute value) increase. This happens because the EBI efficiency relaxes the industry's constraint and so increases the quantity of fuel produced (i.e. it decreases the final price).

Overall, the innovator always make greater profits with a CBI (red and dashed line) than an EBI (red line). This result holds as long as the CBI is feasible, that is $\theta \geq c_r - c_c$. By contrast, the consumers are better off under EBI (blue line). In terms of total welfare, the figure illustrates the case where total welfare under CBI remains higher than that under EBI. Yet, the opposite can occur, henceforth the proposition below.

**Proposition 8.** *Total welfare under cost-based innovation is generally greater than total welfare under emission-based innovation. Nevertheless, total welfare under emission-based innovation can intersect total welfare under cost-based innovation when the latter is sufficiently weak and for some* $\kappa$ *(*$\theta < \theta^w := \frac{(\delta-1)\left(\frac{(\delta+1)((\gamma-1)c_c-\gamma c_r+1)}{\gamma^2+1}+\frac{2\kappa(\gamma-2\gamma c_c+\gamma c_r+c_r-1)}{\gamma(c_c-1)+c_c-c_r}\right)}{2\gamma}$*).*

# 6 Imperfect competition

In this section, we acknowledge the role of the biofuel industry's degree of competitiveness. In practice, we observe different market structures depending on the biofuel we focus on. For example, ethanol production is mostly dominated by large companies that were already major players in the agri-food sector such as Archer Daniels Midland (ADM), Bunge, Cargill and Louis Dreyfus. By contrast, the European Diesel Board lists more than 20 separate producing members (and another 20 "associate members") for the biofuel production. The latter represent multinational agri-food giants (e.g., ADM, Bunge [Novaol] and Cargill), chemical companies (Dow), and specialist biodiesel producers (e.g., D1 Oils).

## 6.1 The new model with many firms

We now suppose the fuel industry is composed by $n \in \mathbb{N}^*$ symmetric firms. Each firm $i \in \{1, ..., n\}$ produces fuel, in quantity $q_i \in [0,1]$, by blending conventional inputs, denoted $q_{i,c} \in [0,1]$, and renewable inputs, denoted $q_{i,r} \in [0,1]$ given blending technology $q_i = q_{i,c} + q_{i,r}$. The two inputs are still perfect substitutes. Each firm bears increasing and convex production costs to produce the conventional and renewable inputs which denote respectively $C_c(q_{i,c})$ and $C_r(q_{i,r})$, and faces inverse demand $P_i(q_i, q_{-i}) = 1 - q_i - q_{-i}$ where $q_{-i}$ is the vector of the rival firms' quantities. Firm $i$'s profit is:

$$\pi_i(q_i, q_{i,c}, q_{i,r}) = P(q_i, q_{-i})q_i - C_c(q_{i,c}) - C_r(q_{i,r}) \tag{15}$$

Since firms are symmetric, at the aggregate level, the total quantity of fuel in the market is $q = nq_i$ and the total amounts of conventional inputs and renewable inputs are respectively $q_c = nq_{i,c}$ and $q_r = nq_{i,r}$. The aggregate production function is $q = q_c + q_r$ and aggregate costs are $C_c(q_c) = C_c(nq_{i,c})$ and $C_r(q_r) = C_r(nq_{i,r})$. It also means that the industry still serves a representative consumer with inverse demand for fuel given by $P(q) = 1 - q$.

## 6.2 Degree of competitiveness ($\lambda$)

We now detail how we implement and measure the degree of competitiveness. We take the no regulation equilibrium computations as an example to detail the method. The method is the same for the other cases.

Let us consider the game in the absence of regulation and with a cost-based innovation. At the last stage, irrespective of the innovation, the profit of firm $i \in \{1, ..., n\}$ is $\pi_i(q_i, q_{-i}) = P_i(q_i, q_{-i})q_i - C_c(q_{i,c}) - C_r(q_{i,r})$. The firm chooses $q_{i,c}$ and $q_{i,r}$ so as to maximize its profits $\pi_i$. The first order conditions for firm $i$ are $\partial\pi_i/\partial q_{i,c} = P'q_i + P - C'_c(q_{i,c}) = 0$ and $\partial\pi_i/\partial q_{i,r} = P'q_i + P - C'_r(q_{i,r}) = 0$. Because firms are symmetric $q_i = q/n$, and these FOCs rewrite $P'q(1/n) + P - C'_c(q_{i,c}) = 0$ and $P'q(1/n) + P - C'_r(q_{i,r}) = 0$. Furthermore, we have $C'_c(q_{i,c}) = C'_c(q_c)$ and $C'_r(q_{i,r}) = C'_r(q_r)$.

Assuming $\lambda = (1/n)$, we find:

$$[FOC_{q_c}] \qquad P'q\lambda + P - C_c'(q_c) = 0 \tag{16}$$

$$[FOC_{q_r}] \qquad P'q\lambda + P - C_r'(q_r) = 0 \tag{17}$$

We observe that $\lambda$ proxies the industry's level of competitiveness. When $n = 1$, $\lambda = 1$ and the industry acts as a monopolist. In contrast, when $n$ tends towards infinity, then $\lambda = 0$ and the industry is perfectly competitive. In the intermediate case, when $1 < n < +\infty$ then $0 < \lambda < 1$ and the industry is imperfectly competitive.

### 6.3 Some distinct effects of mark-up on our previous results

**Proposition 9.** ***No regulation.*** *A less competitive industry decreases the final fuel quantity and harms consumers, irrespective of the innovation considered. Under cost-based innovation, a less competitive industry improves the ratio of renewable inputs over conventional ones.*

A less competitive industry puts a higher mark-up on fuel sales which increases the price and diminishes the final fuel quantity. This is true irrespective the innovation. However, the quantity of renewable inputs does not depend on the industry's competitiveness. With a cost-based innovation, a less competitive industry therefore diminishes the final fuel quantity without reducing the renewable inputs used in the process: the ratio increases. This does not happen with emission-based innovation as no renewable input is used (the ratio remains nil).

**Proposition 10.** ***Regulation and CBI.*** *Provided $\gamma > \bar{\gamma}(\theta)$, the variation of industry's profit is the same as the one of renewable quantities under perfect competition $\lambda = 0$, but depends on the balance between a cost effect and a mark-up effect otherwise.*

Formally, the variation of such profit becomes:

$$\pi^{CBI} - \pi^{U} = \underbrace{(\frac{1}{2})(q_r^{CBI})^2 - (\frac{1}{2})(q_r^{U})^2}_{\text{cost effect}} + \underbrace{\lambda(q^{CBI})^2 - \lambda(q^{U})^2}_{\text{mark-up effect} < 0} \tag{18}$$

The sign of the variation depends on the potential balance of two main effects. The *mark-up effect* is always negative because the regulation diminishes the total quantity of fuel. The *cost effect* depends on the variation of renewable inputs. A rise of the quantity of renewable inputs enlarges the cost surplus while a decrease shrinks such surplus.

**Proposition 11.** ***Regulation and EBI.*** *Imperfect competition enables the innovator to monetize its innovation - provided it is weak - for a wider range of policy level. At some point the blend wall does not impede such innovation anymore.*

Equation (19) displays the effect of an infinitesimal variation of the policy level on the industry profit. It mimics a situation where the emission-based innovation is very small and the royalty rate is almost nil. We observe that the direction of change of the industry profit under perfect competition is the same as before. However, this breaks down under imperfect competition due to the presence of the extra terms linked to the industry margin. Figure 4 illustrates our proposition.

$$\frac{\partial \pi_C}{\partial \gamma} = 2q_r \frac{\partial q_r}{\partial \gamma}\left(\frac{1}{2} + \frac{\lambda}{\gamma^2}\right) - \frac{2\lambda}{\gamma^3}(q_r)^2 \tag{19}$$

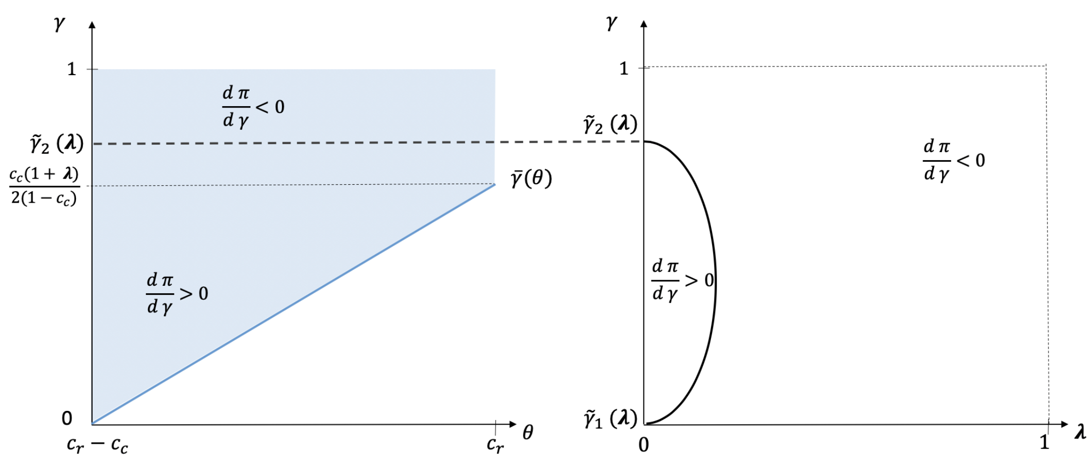



Figure 4: Policy impact wrt $\lambda$-competitiveness, starting at perfect competition ($\lambda = 0$)

## 7 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 perfectly 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-based 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 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 on certain circumstances. Specifically, the carbon emission standard enables the innovator to monetize an emission-based innovation when the policy is initially sufficiently restrictive and the innovation is not too efficient.

In practice, it is likely that the innovation is not very efficient because biofuel is often already very environmentally friendly. Nonetheless, our paper points out that the presence of a blend wall (technological blending constraint - e.g. cars' engines) that impede to set very restrictive policies could impede the innovator to monetize an emission-based innovation. This implies that in order to promote emission-based innovation, policies must first get rid off the blend wall and then be more restrictive. That last finding echoes the recommendation by European Technology and Innovation Platform Bioenergy which claims that 'GHG emission quotas for fuels [...] are a good instrument but should be set to ambitious reduction targets'(Strategic research and innovation agenda, 2018).

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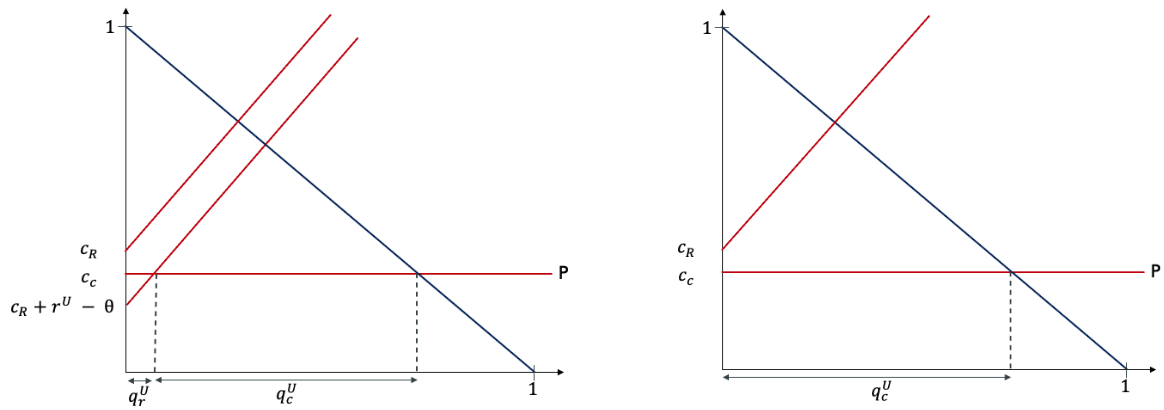
# A Figures




(a) Cost-based innovation

(b) Emission-based innovation

Figure 5: Benchmark blends under perfect competition

# B Proofs

**Proof of Equation 30**

Providing the competitive fringe buys the innovation, the innovator maximizes the following profit $\pi_M = q_r^{CBI}(c_r - \theta, r).r$. By replacing the values by the continuation equilibrium values we get:

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

The First Order Condition gives

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

$$r^{CBI}_{candidate} = \frac{c_c - c_r + \theta}{2} + \frac{1 - c_c}{2\gamma}$$

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 $r^{CBI}_{sup} = \theta$. Above this value the competitive fringe is better off producing without the innovation. 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:

$$\begin{aligned}
& r^{CBI}_{sup} > r^{CBI}_{candidate} \\
& \theta > \frac{c_c - c_r + \theta}{2} + \frac{1 - c_c}{2\gamma} \\
& \Leftrightarrow 2\gamma\theta > (c_c - c_r + \theta)\gamma + 1 - c_c \\
& \Leftrightarrow \gamma(\theta + c_r - c_c) > 1 - c_c \\
& \Leftrightarrow \gamma > \frac{1 - c_c}{\theta + c_r - c_c} \equiv \tilde{\tilde{\gamma}}(\theta)
\end{aligned}$$

It is obvious that $\tilde{\tilde{\gamma}}(\theta)$ is decreasing with respect to $\theta$ and $c_r$. Therefore, $\tilde{\tilde{\gamma}}(\theta)$ reaches is minimum value when $\theta$ is at its maximum i.e. $c_r$. Remind that $c_r$ 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 $r^{CBI} = r^{CBI}_{sup} = \theta$. □

**Proof Proposition 1.**

The difference of emission between the two settings is:

$$\kappa q^{CBI}(1 - \gamma(1 - \phi_r)) - \kappa q^{U}(1 - \bar{\gamma}(1 - \phi_r)) \tag{20}$$

Suppose $\epsilon \geq 0$ such that $1 \geq \gamma = \bar{\gamma} + \epsilon \geq \bar{\gamma}$ then the expression rewrites:

$$\kappa[(1 - \bar{\gamma}(1 - \phi_r))(q^{CBI} - q^{U}) - \epsilon(1 - \phi_r)q^{CBI}] \leq 0 \tag{21}$$

□

**Proof Lemma 1.**

We want to compute on what condition the quantity of renewable inputs under regulation is larger than that without regulation. The inequality writes $q_r^{CBI}(\gamma) \geq q_r^U$ and rewrites $\gamma q^{CBI}(\gamma) \geq q_r^U$ which leads to our condition:

$$\gamma \geq \frac{q_r^U}{q^{CBI}(\gamma)} \equiv \ddot{\gamma}(\gamma)$$

It is easy to check that $\ddot{\gamma}(\gamma) > \bar{\gamma}$ since $\ddot{\gamma}(\gamma) = \frac{q_r^U}{q^{CBI}(\gamma)} \geq \frac{q_r^U}{q^U} = \bar{\gamma}$ from $q^{CBI} \leq q^U$.

To study when the inequality holds true, we use Result 1 & 2, and observe that $\ddot{\gamma}(\gamma)$ writes as follows: $\ddot{\gamma}(\gamma) = \frac{\theta-(c_r-c_c)}{1-c_c-\gamma(c_r-c_c)} . \frac{+\gamma^2}{2}$. Substituting into the inequality, the latter simplifies to the following polynomial expression:

$$-(\theta + c_r - c_c)\gamma^2 + 2(1 - c_c)\gamma - \theta + (c_r - c_c) \geq 0. \tag{$\mathcal{P}$}$$

We find that its associated determinant is $\Delta = 4[(1-c_c)^2-(\theta^2-(c_r-c_c)^2)]$. Given $c_c < c_r < 1/2$, this determinant is positive. This means that the polynomial expression has two roots. We find that one of root, say $\gamma_1$, is always lower than one, whereas the other, say $\gamma_2$, is always higher than one: $\gamma_1 \leq 1 \leq \gamma_2$. Because the coefficient of the second degree variable in ($\mathcal{P}$) is negative, we find that ($\mathcal{P}$) is positive between the roots. In other words, the inequality is verified when $\gamma \geq \gamma_1$. This threshold writes:

$$\gamma_1 = \frac{1 - c_c - \sqrt{(1-c_c)^2 - (\theta^2 - (c_r - c_c)^2)}}{\theta + c_r - c_c}$$

Finally, we find that

$$\frac{d\gamma_1}{d\theta} = \frac{\theta}{(-c_c + c_r + \theta)\sqrt{2c_r^2 - 2c_c(c_r+1) + c_r^2 - \theta^2 + 1}} + \frac{\sqrt{2c_c^2 - 2c_c(c_r+1) + c_r^2 - \theta^2 + 1} + c_c - 1}{(-c_c + c_r + \theta)^2} \geq 0$$

Rewritte for the sake of clarity $\gamma_1$ as $\ddot{\gamma}(\lambda)$ and we obtain the result of Lemma 1. □

**Proof Proposition 2.**

The profit of the innovator increases following a regulation if and only if $\pi_M^{CBI} \geq \pi_M^U$ which rewrites $r^{CBI}q_r^{CBI} \geq r^{UC}q_r^{UC}$. By Result 1, we have $r^{CBI} = \theta$ and $q_r^{CBI} = \gamma q^{CBI}$, while by Result 2 we have $r^U = q^U$. The inequality rewrites $\theta\gamma q^{CBI} \geq (q_r^U)^2$ and the inequality is satisfied as long as $\gamma \geq \frac{q_r^U q^U}{\theta q^{CBI}} \frac{q_r^U}{q^U} = \frac{q_r^U q^U}{\theta q^{CBI}} \bar{\gamma}$. Since by assumption $\gamma \geq \bar{\gamma}$, it is sufficient to show that $\frac{q_r^U q^U}{\theta q^{CBI}} \leq 1$ in order to prove the increase of the innovator's profit. In addition, note that $q^{CBI}$ is decreasing with $\gamma$ ($\frac{dq^{CBI}}{d\gamma} = \frac{-(c_r-c_c)(1+\gamma^2)-2\gamma(1-c_c-\gamma(c_r-c_c))}{(1+\gamma^2)^2} \leq 0$). This implies that the lowest $q^{CBI}$ is obtained at $\gamma = 1$. It is thus sufficient to prove $q^U q_r^U \leq \theta q^{CBI}(1)$. The following computations prove it.

One the one hand, $q^{CBI}(1) = \frac{1-c_c+1(c_c-c_r)}{1+1^2} = \frac{1-c_r}{2} = \frac{1-c_c}{2} - \frac{c_r-c_c}{2} = \frac{1}{2}q^U - \frac{c_r-c_c}{2}$. On the other hand, $q_r^U = \frac{\theta+c_c-c_r}{2} = \theta - \frac{\theta+c_r-c_c}{2}$. By replacing we have:

$$q_r^U q^U \leq \theta q^{CBI}(1) \tag{22}$$

$$\Leftrightarrow \left(\theta - \frac{\theta + c_r - c_c}{2}\right) q^U \leq \theta \left(\frac{1}{2}q^U - \frac{c_r - c_c}{2}\right) \tag{23}$$

$$\Leftrightarrow \theta\frac{c_r - c_c}{2} \leq q^U \left(\theta\frac{1}{2} - \theta + \frac{\theta + c_r - c_c}{2}\right) \tag{24}$$

$$\Leftrightarrow \theta(c_r - c_c) \leq q^U (c_r - c_c) \tag{25}$$

$$\Leftrightarrow \theta \leq q^U \tag{26}$$

$$\Leftrightarrow \theta \leq 1 - c_c \tag{27}$$

Because $c_c \leq c_r \leq 1/2$, we find $1 - c_c \geq 1/2 \geq c_r \geq \theta$ and the inequality is always satisfied. □

**Proof Lemma 3**

The methodology is roughly the same as with Lemma 1. We want to compute on what condition the quantity of renewable inputs under regulation is larger than that without regulation. The inequality writes $q_r^{EBI}(\delta\gamma, r) \geq q_r^{EBI}(\gamma, 0)$ and rewrites $\frac{1}{\delta}q^{EBI}(\frac{1}{\delta}\gamma, r) \geq q_r^{EBI}(\gamma, 0)$ which leads to our condition:

$$\frac{1}{\delta} \geq \frac{q_r^{EBI}(\gamma, 0)}{q^{EBI}(\frac{1}{\delta}\gamma, r)}$$

Remind that with emission-based innovation, any policy binds because without regulation, the industry prefers not to use any renewable inputs. We know that an increase of $r$ decreases the total quantity $q^{EBI}(\frac{1}{\delta}\gamma, r)$. This means that $r$ will reduce the potential industry's willingness to buy the innovation. Therefore, we evaluate on what conditions there exists such willingness, that on what conditions the inequality is true at $r = 0$.

To study when the inequality holds true, at $r = 0$, we use our result that $q^{EBI}(\gamma(a), 0) = \frac{1-c_c-\gamma(a)(c_r-c_c)}{1+\gamma(a)^2}$. The inequality simplifies to the following polynomial expression:

$$-\left(\gamma^2(1-c_c)+\gamma(c_r-c_c)\right)(\frac{1}{\delta})^2+(1-c_c)(1+\gamma^2)\frac{1}{\delta}-(1-c_c-\gamma(c_r-c_c)))\geq 0. \qquad (\mathcal{Q})$$

We find that its associated determinant is $\Delta = \left(-(1-c_c)+2\gamma(c_r-c_c)+\gamma^2(1-c_c)\right)^2$. This determinant is always positive. This means that the polynomial expression has two roots. We find that one of root, say $\frac{1}{\delta_1}$, is always lower than one, provided $\gamma$ is sufficiently restrictive, whereas the other root, say $\frac{1}{\delta_2}$, equals one. Formally, we have $\frac{1}{\delta_1} \leq \frac{1}{\delta_2} = 1$ provided $\gamma > \dot{\gamma} \equiv \sqrt{\frac{2(c_c)^2-2c_c(c_r+1)+(c_r)^2+1}{(c_c-1)^2}} + \frac{c_r-c_c}{c_c-1} \geq 0$, and $\frac{1}{\delta_1} \geq \frac{1}{\delta_2} = 1$, otherwise.

Because the coefficient of the second degree variable in $(\mathcal{Q})$ is negative, we find that $(\mathcal{Q})$ is positive between the roots. In other words, the inequality is verified when $\frac{1}{\delta} \geq \frac{1}{\delta_1}$ and provided $\gamma > \dot{\gamma}$. This threshold writes:

$$(\frac{1}{\delta_1}) = \frac{1-c_c-\gamma(c_r-c_c)}{\gamma((1-c_c)\gamma+c_r-c_c)}$$

Rewrite $\frac{1}{\delta_1}$ as $\frac{1}{\dot{\delta}(\lambda)}$ and we obtain the result of Lemma 3. □

**Proof Equation (14)**

Let us first compute the maximum willingness to pay of the industry $r_{sup}^{EBI}$. It is such that $\Delta q_r^{EBI}(\gamma(a), r(a)) = 0$, that is $\frac{1}{\delta}q^{EBI}(\frac{1}{\delta}\gamma, r) - q^{EBI}(\gamma, 0) = 0$. Remind that $q^{EBI}(\frac{1}{\delta}\gamma, r) = q^{EBI}(\frac{1}{\delta}\gamma, 0) + \frac{dq^{EBI}(\frac{1}{\delta}\gamma)}{dr}r$ where $\frac{dq^{EBI}(\frac{1}{\delta}\gamma)}{dr} < 0$. Denote We thus have $r_{sup}^{EBI} = -\frac{\Delta q_r^{EBI}(\gamma(a),0))}{\frac{1}{\delta}\gamma\frac{dq^{EBI}(\delta\gamma)}{dr}}$.

On the other hand, provided the industry buys the innovation the innovator maximizes $\pi_M(r) = r\frac{1}{\delta}\gamma q^{EBI}(\frac{1}{\delta}\gamma, r)$. The unconstrained royalty is given by the first order condition: $\frac{d\pi_M}{dr} = \frac{dq^{EBI}(\frac{1}{\delta}\gamma)}{dr}r + q^{EBI}(\frac{1}{\delta}\gamma, r)$. Using $q^{EBI}(\frac{1}{\delta}\gamma, r) = q^{EBI}(\frac{1}{\delta}\gamma, 0) + \frac{dq^{EBI}(\frac{1}{\delta}\gamma)}{dr}r$, the FOC rewrites $\frac{d\pi_M}{dr} = 2\frac{dq^{EBI}(\frac{1}{\delta}\gamma)}{dr}r +$

$q^{EBI}(\frac{1}{\delta}\gamma, 0)$ and therefore the unconstrained royalty is $r^{EBI}_{candidate} = -\frac{q^{EBI}(\frac{1}{\delta}\gamma,0)}{2\frac{dq^{EBI}(\frac{1}{\delta}\gamma)}{dr}}$.

Let us then show that $r^{EBI}_{candidate} > r^{EBI}_{sup}$. Given the above royalty values, the inequality simplifies to $q^{EBI}(\gamma, 0) - \Delta q^{EBI}(\gamma(a), 0) \geq 0$. It can be shown that the inequality holds for any value of $\delta < \dot{\delta}(\gamma)$. Intuitively, it is unlikely that the innovation, which must be not too efficient, increases the quantity more than the initial amount. Therefore $r^{EBI} = r^{EBI}_{sup}$. □

**Proof Proposition 6.**

Immediate by comparison of Result 1 and Result 3. □

**Proposition 7 and 8.**

If further info is needed, two Mathematica files (”graph partition EBI vs CBI” and ”general welfare”) are available upon request. □

**Results under imperfect competition**

- **No regulation**

The results come from the computations in the main text and are intuitive.

**Result 6.** *In the absence of regulation, the industry buys the cost-based innovation and the equilibrium price, quantities and profits are*

$$P^U = c_c + \frac{\lambda}{1+\lambda}(1-c_c)\,, \quad q^U = \frac{1-c_c}{1+\lambda}\,, \quad q^U_r = \frac{c_c - c_r + \theta}{2}\,, \quad q^U_c = \frac{1-c_c}{1+\lambda} - \frac{c_c - c_r + \theta}{2}$$
$$\pi^U_C = \frac{(c_c - c_r + \theta)^2}{8} + \lambda\left(\frac{1-c_c}{1+\lambda}\right)^2 \quad \textit{and} \quad \pi^U_M = \left(\frac{c_c - c_r + \theta}{2}\right)^2.$$

**Result 7.** *In the absence of regulation, the industry does not buy the emission-based innovation* *and the equilibrium price, quantities and profits are*

$$P^U = \frac{\lambda + c_c}{1+\lambda}\ , \quad q^U = \frac{1-c_c}{1+\lambda}\ , \quad q_r^U = 0\ , \quad q_c^U = q^U$$
$$\pi_C^U = \lambda\left(\frac{1-c_c}{1+\lambda}\right)^2 \ \textit{and} \quad \pi_M^U = 0.$$

- **Regulation and CBI**

We use backward induction to solve the game as with perfect competition.

**The industry choice.** At the stage of the competitive industry choice, the industry maximizes the profit $\pi_C = P(q_c+q_r).(q_c+q_r) - C_c(q_c) - C_r(q_r)$ with respect to $q_c$ and $q_r$ given the regulator's policy $q_r \geq \gamma q$. The mandate binds because of our assumption that the regulator specifies mandate $\gamma > \bar{\gamma}^{CBI}(\theta)$. This means $q_r = \gamma q$ and $q_c = (1-\gamma)q$. We then obtain a simplified objective profit function $\pi_C = P(q).(q) - C_c((1-\gamma)q) - C_r(\gamma q)$ which only depends on $q$. Given level of competitiveness $\lambda$, the associated First Order Condition leads to the following optimal equality:

$$[FOC_q] \quad \lambda P' q + P - (1-\gamma)C_r'((1-\gamma)q) - \gamma C_r'(\gamma q) = 0 \tag{28}$$

Note that we recover the usual property that a competitive price ($\lambda = 0$) equals the average marginal cost. When competition is imperfect, we observe that the market price again integrates a margin in addition to the average marginal cost.

Given cost functions, we have $C_c'((1-\gamma)q) = c_c$ and $C_r'(\gamma q) = c_r(a) + r(a) + \gamma q$. At market equilibrium, total offer equals total demand $P = 1-q$ and we find the following continuation equilibrium quantity $q^{CBI}(c_r(a), r(a)) = [1-c_c-\gamma(c_r(a)-c_c+r(a))]/[1+\lambda+\gamma^2]$. The continuation equilibrium input quantities follow and write $q_r^{CBI}(c_r(a), r(a)) = \gamma q^{CBI}(c_r(a), r(a))$ and $q_c^{CBI}(c_r(a), r(a)) = (1-\gamma)q^{CBI}(c_r(a), r(a))$. Furthermore, we can rewrite the profit as follows $\pi_c(c_r(a), r(a)) = P(q)q - c_c(1-\gamma)q - (c_r(a)+r(a)+(1/2)\gamma q)\gamma q = P(q)q - c_c(1-\gamma)q - (c_r(a)+r(a)+\gamma q)\gamma q + (1/2)(\gamma q)^2$ which given $FOC_q$ simplifies to $\pi_c^{CBI}(c_r(a), r(a)) = \frac{[\gamma q^{CBI}(c_r(a), r(a))]^2}{2} + \lambda[q^{CBI}(c_r(a), r(a))]^2$.

This continuation profit function is similar to the one without regulation except that it is now strictly positive under perfect competition due to the policy constraint which enforces strictly positive renewable inputs: $\gamma q^{CBI}(c_r(a), r(a)) > 0$. In particular, 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 $\pi(c_r, 0) = \left(\frac{1}{2} + \frac{\lambda}{\gamma^2}\right)[q_r^{CBI}(c_r, 0)]^2$ 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 $(\theta, r)$. 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 $(\theta, r)$: $\pi_C(c_r - \theta, r) = \left(\frac{1}{2} + \frac{\lambda}{\gamma^2}\right)[q_r^{CBI}(c_r - \theta, r)]^2$. The industry buys the innovation if $\pi_C^{CBI}(c_r - \theta, r) \geq \pi_C^{CBI}(c_r, 0) \Leftrightarrow q^{CBI}(c_r - \theta, r) \geq q^{CBI}(c_r, 0)$ which, irrespective of $\lambda$, boils down to

$$r \leq \theta \equiv r_{sup}^{CBI} \tag{29}$$

**The innovator choice.** The innovator anticipates the behaviour of the competitive industry and sets $r$ so as to maximize its profits, $\pi_M = r.q_r^{CBI}(c_r - \theta, r)$, under the constraint that the industry buys the innovation, $\pi_C^{CBI}(c_r - \theta, r) \geq \pi_C^{CBI}(c_r, 0)$. The constraint still binds and therefore the innovator sets

$$r^{CBI} = \theta = r_{sup}^{CBI} \tag{30}$$

*Proof.* The term $\lambda$ appears in the constant term of the innovator's profit. Imperfect competition does not affect the innovator's price strategy. □

**Result 8.** *With regulation, and binding policy $\gamma > \bar{\gamma}(\theta)$, the industry buys the cost-based innovation. The equilibrium price, quantities and profits are*

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

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

*These values hold irrespective of the type of policy ($\gamma$ or $\gamma_\sigma$).*

We then find 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 $\lambda$. The lowest root is negative and the higest root is:

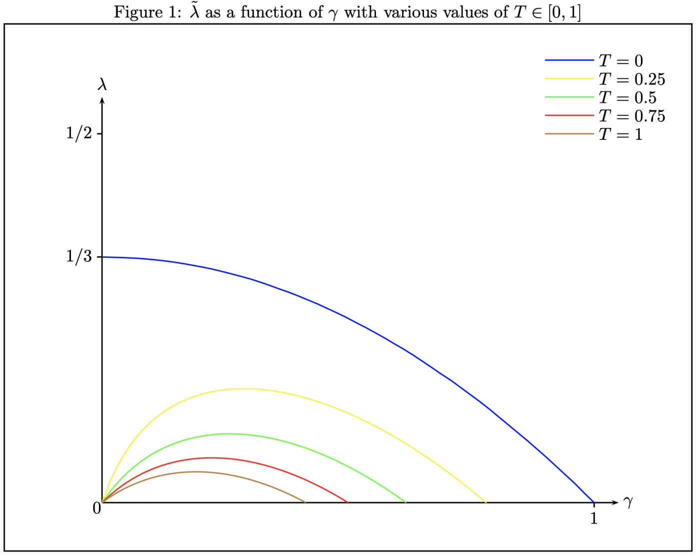
$$\tilde{\lambda} = \frac{(-2T + 3\gamma) + \sqrt{(2T + \gamma)(9\gamma + 2T(1 - 4\gamma^2))}}{4T}$$

It can be shown that we always have $9\gamma + 2T(1 - 4\gamma^2) > 0$ for $\gamma \in [0, 1]$ and $T \in [0, 1]$. [11]

The figure below gives the value of $\tilde{\lambda}$ as a function of $\gamma$ 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 $\gamma$ with various values of $T \in [0, 1]$




[11] $9\gamma + 2T(1 - 4\gamma^2) > 0$ 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 $\gamma \in [0.5, 1]$.