Cap-and-Trade, Emissions Taxes, and Innovation*

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Abstract

Emissions taxes and carbon caps can both lead to efficient production of energy, in the sense of controlling carbon emissions to the extent that is efficient with existing technologies. However, the regulatory policy has a second objective, which is to create incentives to develop lower-carbon technologies. With both objectives in mind, does one policy dominate the other? I address this question in a model of technology switching. I show (under mild conditions) that, for both policies, the innovator's licensing revenue is a given fraction of gross profit in the energy market, where the fraction is the innovator's reduction in the emissions rate. This implies that the emissions tax is more lucrative for the innovator than a carbon cap when the regulatory policies are fixed and initially equivalent, that an adjustment for efficiency increases licensing revenue in the cap-and-trade regime, but reduces licensing revenue in the taxation regime, and that the two regulatory policies are equally lucrative when they would be adjusted after the innovation for static efficiency.

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1 Introduction

Carbon emissions are an important byproduct of producing energy, and it is widely accepted that they contribute to global warming. Managing this problem will require carbon-reducing technologies that are not yet available. This raises the question of how regulation can best create incentives to innovate.

Any regulatory mechanism that makes it expensive to emit carbon will encourage the development of lower-carbon technologies. Tradeable carbon allowances have that effect, as do emissions taxes. However, these regulatory instruments are not equivalent, and environmental economists have long been interested in the question of which is superior.

Two types of innovation have been addressed in the economics literature. One concerns abatement technologies (Milliman and Prince (1989), Jung, Krutilla and Boyd (1996), Parry (1995,2003) and Fischer, Parry and Pizer (2003)), and the other concerns replacement technologies (Denicolo (1999)). For example, gasoline-powered automobiles might eventually be replaced by those with affordable hydrogen combustion. Electricity might eventually be produced with solar power rather than coal. These improvements do not require retrofitting or "abating," but instead require that producers switch to the lower-carbon technology.

I will discuss replacement technologies, since those seem most germane to the problem of global warming. My objective is to synthesize what is known from the two literatures, adding modestly to the conclusions, and giving a different lens through which to interpret them.

Regardless of which type of regulation is chosen, an emissions tax or a carbon cap, the policy must perform two tasks. One task is to encourage innovation. The other task is to ensure "static efficiency", given the best technology available.

Static efficiency has two aspects, which we might call "productive" efficiency and "consumption" efficiency. Productive efficiency means that energy is produced at the cheapest social and private cost. It requires that the social and private cost of producing energy is the same at the margin for each producer, possibly accounting for efficient abatement measures. When a cleaner replacement technology becomes available, productive efficiency requires that eventually every producer switches to it.

Supposing that production efficiency is achieved, consumption efficiency requires that the price of energy is equal to the marginal cost of producing it. Marginal cost must include the social cost of emissions. Unless the replacement technology achieves zero emissions, energy supply should still be lower than the supply where price equals the private marginal cost of producing it. One of the main questions is whether consumption efficiency and incentives to innovate are in conflict, as they are for other innovations.

Because a carbon-reducing innovation reduces the social cost of emissions, it is intuitive that the new technology should lead to an expansion in energy consumption. But what should happen to total emissions? An expansion in energy production can increase emissions even though the emissions rate is lower. I show below that a decrease in emissions is optimal if energy production is in the elastic portion of the demand curve, but not necessarily otherwise.

Because the production of energy and emissions should adjust when a new technology is available, the regulatory policy should be adjusted. Denicolo (1999) focusses on such adjustments, and shows that if innovators anticipate an efficiency adjustment of either type, the incentives to innovate are the same under both policies. The argument is reprised below. Fischer, Parry and Pizer (2003) argue that this is also true for abatement technologies.

However, there are many reasons that the regulatory policy might not adjust. Parry (1995) argues (and Denicolo agrees) that the emissions tax must fall if the new technology is proprietary. Otherwise, the emissions tax and royalty together will cause the price of energy to be inefficiently high. The argument is persuasive, but it could be hard to implement. The regulator would have to anticipate the royalty when choosing the emissions tax. That would require complicated legislation. As to carbon caps, they are probably easier to adjust upwards than downwards. Because either adjustment might be required, it is again not clear how the underlying legislation should be drafted.

I reprise these arguments below, but, like Fischer et al (2003), I mostly focus on policies that are efficient to start with, and then consider the incentives to innovate when innovators do not anticipate a policy adjustment.

The conclusion from the literature that I regard as most important for the policy debate is that, if patents are perfectly enforceable, an emissions tax is more conducive to innovation than a carbon cap. With either a carbon cap or an emissions tax, energy producers must pay to emit pollutants. This is why producers are willing to license a technology that reduces emissions (in the replacement model) or reduces the cost of abatement (in the abatement model). But when the lower-emissions technology is widely diffused, the allowance price falls, while an emissions tax would stay fixed. The fall in the allowance price reduces the producers' willingness to pay for the license. It thus erodes licensing revenues, and erodes the incentive to innovate, as compared to the emissions tax.[1] This is explicit in the discussion of Fischer, Parry and Pizer (2003), and implicit in Denicolo's analysis. I show it explicitly below using the replacement model, but interpret the result through a different lens.

[1] Jung, Krutilla and Boyd (1996) agree with this analysis to the extent that they assume that the allowance price falls when the cost of abatement is reduced. But they come to an opposite conclusion, that (auctioned) permits are better than emissions taxes for innovation. This is because they assume that the reduction in the allowance price becomes part of the reward to innovation, instead of a drag on innovation. In the model here, the reduced allowance price reduces the price of energy, so the benefit accrues largely to energy consumers.

In particular, I show that the innovator's licensing revenue can be characterized under both regulatory regimes as the size of the improvement (defined as the percentage reduction in emissions per kilowatt hour) times the gross profit earned in the energy market (gross of taxes or payments for allowances). The results alluded to above can therefore be explained by explaining what happens to gross profits in the energy market.

First consider an emissions tax and carbon cap that are optimal for the old technology, and are not adjusted to account for the new technology. Initially they support the same level of energy production and the same gross profit in the energy market. However, this equivalence is broken once the new technology emerges. The two regulatory policies deliver different social benefits from the innovation, which also has implications for profit. With the emissions tax, energy production stays fixed, while carbon emissions fall. With the carbon cap, carbon emissions stay fixed, while energy production increases. Thus, gross profit in the energy market stays fixed under the emissions tax, but (typically) decreases under the carbon cap. According to the above characterization, the innovator's licensing revenue is smaller under the carbon cap than under the emissions tax.

Second, if each policy would be adjusted for static efficiency, then both policies support the same energy production with the new technology (the efficient level), and the same gross profit in the energy market, leading to the same licensing revenues for the innovator.

The thrust of these arguments is that, unless there will be a quick and seamless adjustment to the regulatory policy after the cleaner technology is available, regulation through a carbon cap is less lucrative for innovators than regulation through an emissions tax. I add further to the defects of cap-and-trade regulation by showing that an innovator might not diffuse his innovation fully to the energy producers. The innovator has no incentive to invest in a larger improvement than he will use.

Although emissions taxes and carbon caps are two ways of making the benefits of a carbon-reducing technology appropriable, there are many aspects of intellectual property law that may work against appropriability. Fischer, Parry and Pizer stress spillover benefits to unlicensed energy producers. Not only does the proprietor lose the licensing revenue, but the spillover increases rivalry in the market. I do not address spillovers, because they merge into a complex set of questions about optimal enforcement and optimal patent breadth (see chapters 4 and 6 of Scotchmer(2004).) Suffice to say that appropriability has many challenges, including the finite length of intellectual property rights, unlicensed spillovers, limited patent breadth, and under a cap-and-trade system, the endogeneity of the allowance price.

Economists have a long history of studying price-versus-quantity regulation, although not with a focus on innovation. The focus has been on which instrument deals best with asymmetric information, rather than which instrument gives best incentives for innovation (see Kaplow and Shavell (2002) for a synopsis and critique). So far as I know, it is only in the context of energy that the comparison has focussed on innovation.

In sections 2, 3 and 4, I review and recast what is known about the relative virtues of carbon caps and emissions taxes when innovation is taken into account. In section 5, I show that the discrepancy in incentives can be substantial when the regulatory policy does not adjust. In section 6, I show that carbon caps have an additional defect. An innovation that could provide a large reduction in emissions will not be fully diffused. The innovator will limit the expansion in energy supply in order to support the price of energy and the price of allowances, and overall profit in the energy market. This implies that energy production will be divided between the clean and dirty technologies, so that carbon emissions are higher than necessary, conditional on the supply of energy. Further, the innovator's incentive to reduce emissions is truncated. The innovator has no incentive to improve the technology beyond the level that would be fully licensed.

2 Static Efficiency: Balancing emissions and energy

Following Denicolo (1999), I identify a technology with its emissions rate, and suppose that producing e kilowatt hours of energy emits ce units of carbon. That is, c is the carbon *emissions rate*.

Let $\mathrm{E}(\cdot)$ be the demand for energy, such that $\mathrm{E}' < 0$, and let $\mathrm{P}(\cdot)$ be its inverse, the willingness to pay for energy. I assume that the revenue functions defined by $p\mathrm{E}(p)$ and $e\mathrm{P}(e)$ are concave. For simplicity (and without loss of insight), I assume that the private cost of producing energy is zero, but that there is a social cost to releasing carbon, which I describe by a function $\mathrm{K}(\cdot)$. It is natural to think of $\mathrm{K}(\cdot)$ as an increasing convex function such that $\mathrm{K}(0) = 0$. Then $\mathrm{K}'(\cdot)$ is the marginal social cost of releasing carbon.

In the absence of regulation, the competitive price of energy would be zero, since the marginal cost of production is zero. Denote the revenue-maximizing price by $p^m = \mathrm{P}(e^m)$ where e^m is the revenue-maximizing supply, $e^m = \arg\max e\mathrm{P}(e)$. Below, I say that aggregate supply, say e, is in the *elastic part of the demand curve* when $e > e^m$. Analogously, I say that a price, say p, is in the *elastic part of the demand curve* when $p < p^m$.

The social value of producing electricity is the consumers' surplus it provides, net of the social cost of emissions, namely $S(E) - \mathrm{K}(cE)$, where $S(E) = \int_0^E \mathrm{P}(e)\, de$. I assume that $S(E) - \mathrm{K}(cE)$ is a concave function of E.

For each c, let $\hat{E}(c)$ be the optimizer of $S(E) - \mathrm{K}(cE)$, that is, the efficient supply of energy. The optimizer satisfies (1), and describes both the *optimal supply of energy*, which I will call $\hat{E}(c)$, and the *optimal emissions*, $c\hat{E}(c)$.

$$\mathrm{P}\left(\hat{E}(c)\right) = c\mathrm{K}'\left(c\hat{E}(c)\right) \tag{1}$$

There is clearly a tradeoff between energy and carbon emissions. I use the term *static* *efficiency* for the optimal balance described by (1).

Proposition 2.1 [Static Efficiency: A lower emissions rate should optimally lead to more energy production. Whether emissions should decrease depends on whether demand for energy is elastic at the optimal supply.] *Suppose that $c < c_0$. Then $\hat{E}(c) > \hat{E}(c_0)$ If $\hat{E}(c_0)$ is in the elastic part of the demand curve, then $c\hat{E}(c) < c_0\hat{E}(c_0)$. If $\hat{E}(c)$ is in the inelastic part of the demand curve, then $c\hat{E}(c) > c_0\hat{E}(c_0)$.*

Proof: Condition (1) is the first order condition describing the maximum of $S(E) - \mathrm{K}(cE)$. The implicit function theorem together with the second order condition imply that $\hat{E}'(c) < 0$.

Multiplying (1) by $\hat{E}(c_0)$ at c_0 and $\hat{E}(c)$ at c, it follows that if $\hat{E}(c_0)$ is in the elastic part of the demand curve,

$$c_0\hat{E}(c_0)\,\mathrm{K}'\left(c_0\hat{E}(c_0)\right) = \hat{E}(c_0)\,\mathrm{P}\left(\hat{E}(c_0)\right) > \hat{E}(c)\,\mathrm{P}\left(\hat{E}(c)\right) = c\hat{E}(c)\,\mathrm{K}'\left(c\hat{E}(c)\right)$$

Since $x \to x\mathrm{K}'(x)$ is increasing with x, this shows that $c_0\hat{E}(c_0) > c\hat{E}(c)$.

If $\hat{E}(c)$ is in the inelastic part of the demand curve,

$$c_0\hat{E}(c_0)\,\mathrm{K}'\left(c_0\hat{E}(c_0)\right) = \hat{E}(c_0)\,\mathrm{P}\left(\hat{E}(c_0)\right) < \hat{E}(c)\,\mathrm{P}\left(\hat{E}(c)\right) = c\hat{E}(c)\,\mathrm{K}'\left(c\hat{E}(c)\right)$$

Again because $x \to x\mathrm{K}'(x)$ is increasing with x, this shows that $c_0\hat{E}(c_0) < c\hat{E}(c)$. ■

Thus, if a carbon-reducing technology becomes available royalty-free to producers, some of the benefit should be taken as more energy, and if demand is elastic at the optimal supply, some of the benefit should be taken as lower carbon emissions.

3 Incentives when the regulatory policy is fixed

In the remainder of the paper I assume there is a public domain technology for producing energy, which has emissions rate c_0. I consider the incentive to introduce a new technology with a lower emissions rate, say c. It is useful to define the percentage reduction $\frac{c_0 - c}{c_0}$ as *the size of the improvement.*

I assume the new technology will be proprietary, in the sense that it can be licensed for a royalty. I show that, whether the regulation is by an emissions tax or a carbon cap, the innovator's revenue is equal to the size of the improvement times the gross profit earned in the energy market, at least when the innovation is fully diffused, and energy production is in the elastic part of the demand curve.

My objective is to show how the proprietor's revenue depends on the regulatory policy, and to ascertain which policies create more revenue for innovators. Higher revenue means more incentive to invest. In this section I assume that the regulatory policy, either an emissions tax or a carbon cap, is fixed.

3.1 Emissions Taxes

Let the emissions tax, τ, be given, and suppose a proprietary technology reduces the emissions rate from c_0 to c.

The proprietor licenses the lower-emissions technology at a royalty γ per kilowatt hour of energy. With the tax and royalty (τ, γ) in place, the cost of producing a kilowatt hour of energy is $\tau c + \gamma$, and in a competitive market, this will be the price of energy. The proprietor will choose the royalty γ to solve

$$\max_{\gamma} \gamma \mathrm{E}\left(\tau c + \gamma\right) \tag{2}$$

$$\text{subject to } \gamma \leq \tau\left(c_0 - c\right) \tag{3}$$

If the constraint (3) were not satisfied, the royalty would not attract energy producers. They would prefer the public domain technology with emissions rate c_0.

Proposition 3.1(a) below says that when the emissions tax is "not too high," the royalty on the lower-emissions technology will be chosen as the highest royalty that attracts the energy producers. This is where (3) holds as an equality. The supply of energy stays the same as before the innovation.

I regard Proposition 3.1(a) as the main case of interest, but the other case is also possible, so I include it for completeness. Proposition 3.1(b) says that, if the emissions tax is "high," and the reduction in emissions "substantial," the proprietor might set a royalty lower than the maximum that would still attract all the producers. A lower royalty can be profitable if the energy price would otherwise end up higher than the revenue-maximizing price p^m. A lower royalty lowers the energy price and increases gross profit in the energy market.

Proposition 3.1(c) says that, when the efficient energy supply is in the elastic part of the demand curve, the proprietor's licensing revenue is a fraction $\frac{c_0 - c}{c_0}$ of gross profit in the energy market.

An important consequence of the following proposition is that, unless the emissions tax is quite high, an emissions-reducing innovation will not increase the supply of energy. The benefits of the new technology are taken entirely as a reduction in emissions.

A second important implication is that, when energy supply is in the elastic portion of the demand curve, the innovator's license revenue is equal to the size of the improvement times the gross profit in the energy market (gross of the tax).

Proposition 3.1 (The maximum licensing revenue with tax regulation) *Given an emissions tax τ, suppose that a proprietor achieves a lower-emissions technology, with $c < c_0$.*
(a) If the emissions tax τ is such that τc_0 is in the elastic part of the demand curve, the revenue-maximizing royalty satisfies

$$\gamma = \tau (c_0 - c) \tag{4}$$

(b) If the emissions tax τ is such that τc_0 is in the inelastic part of the demand curve, and if c is sufficiently small, then the revenue-maximizing royalty satisfies

$$\gamma < \tau (c_0 - c)$$

(c) If the emissions tax τ is such that τc_0 is in the elastic part of the demand curve, the maximum licensing revenue available to the proprietor is

$$\left(\frac{c_0 - c}{c_0}\right) p\mathrm{E}(p) \;\; \textit{where } p = \tau c_0$$

Proof: (a) Suppose to the contrary that $\gamma < \tau (c_0 - c)$ and $\tau c + \gamma < \tau c_0 < p^m$. Let $\hat{\gamma} > \gamma$ satisfy $\tau c + \hat{\gamma} = \tau c_0$. Then we can show that $\hat{\gamma}$ is more profitable than γ. Because the function $p \to p\mathrm{E}(p)$ is concave,

$$(\tau c_0)\, \mathrm{E}(\tau c_0) = (\tau c + \hat{\gamma})\, \mathrm{E}(\tau c + \hat{\gamma}) > (\tau c + \gamma)\, \mathrm{E}(\tau c + \gamma)$$

Since $(\tau c)\mathrm{E}(\tau c + \hat{\gamma}) < (\tau c)\mathrm{E}(\tau c + \gamma)$, it holds that $\hat{\gamma}\mathrm{E}(\tau c + \hat{\gamma}) > \gamma \mathrm{E}(\tau c + \gamma)$.

(b) Suppose that $\tau c_0 > p^m$. If (3) holds as an equality and $c = 0$, then $\gamma = \tau c_0$ and

$$\gamma \mathrm{E}'(\gamma) + \mathrm{E}(\gamma) = (\tau c_0)\, \mathrm{E}'(\tau c_0) + \mathrm{E}(\tau c_0) < p^m \mathrm{E}'(p^m) + e^m = 0$$

Revenue can therefore be increased by reducing γ. By continuity, this is also true for c close to zero.

(c) follows because, when the royalty is $\tau (c_0 - c)$, the price is τc_0, so total revenue is

$$\tau (c_0 - c)\, \mathrm{E}(\tau c_0) = \left(\frac{c_0 - c}{c_0}\right) \tau c_0 \mathrm{E}(\tau c_0) \qquad \blacksquare$$

In figure 1, I have assumed that the tax τ is optimal, and that K' is constant, so that $c_0 \tau = \mathrm{P}\left(\hat{E}(c_0)\right)$ and $c\tau = \mathrm{P}\left(\hat{E}(c)\right)$. Implicitly, $\tau = \mathrm{K}'$. Figure 1 shows the the case described in Proposition 3.1(a), where the optimal supply of energy is in the elastic part of the demand curve. The proprietor collects the shaded horizontal area in figure 1 for the duration of the property right. This area is a fraction $\frac{c_0 - c}{c_0}$ of gross profit in the energy market.

Figure 1 shows that the supply of energy stays the same after the emissions rate is lowered, while total emissions decline. The supply of energy should optimally rise to $\hat{E}(c)$, but that does not happen because of the royalty.

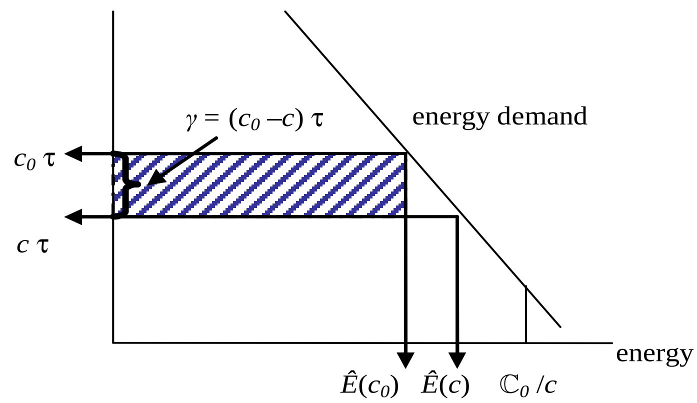

Figure 1: Licensing revenue with a fixed emissions tax

3.2 Cap and Trade

Let $\mathbb{C}$ be an arbitrary carbon cap. This is the number of allowances that are allocated to owners, who are assumed to be widely dispersed and to behave as price takers. When the emissions rate falls from c_0 to c, the energy supply that is feasible under the cap increases from $\mathbb{C}/c_0$ to $\mathbb{C}/c$. If the innovation is fully diffused, the price of energy falls from from $\text{P}(\mathbb{C}/c_0)$ to $\text{P}(\mathbb{C}/c)$.

The carbon cap $\mathbb{C}$ cannot be optimal for both the original emissions rate c_0 and the lower emissions rate c. If $\mathbb{C}$ is optimal for c_0, then by Proposition 2.1, the optimal carbon cap for c is smaller, provided that demand is elastic at that level of production.

If the proprietor licenses energy production in amount $e > 0$, the total supply of energy under the carbon cap $\mathbb{C}$ is given by $E(e;c)$, defined as

$$E(e;c) = \frac{\mathbb{C}}{c_0} + \left(\frac{c_0 - c}{c_0}\right) e \tag{5}$$

To be in compliance with the carbon cap, $0 \le e \le \frac{\mathbb{C}}{c}$, which implies that $\frac{\mathbb{C}}{c_0} \le E(e;c) \le \frac{\mathbb{C}}{c}$.

Given a royalty rate γ, let $\hat{e}(\gamma) \in \left[0, \frac{\mathbb{C}}{c}\right]$ represent the demand for licenses, measured in kilowatt hours, and let $q(\gamma)$ be the allowance price per ton of released carbon. The demand for energy and the allowance price satisfy the following in equilibrium.

$$\begin{aligned} &\text{P}(E(\hat{e}(\gamma);c)) - cq(\gamma) - \gamma \le 0 \\ &[\text{P}(E(\hat{e}(\gamma);c)) - cq(\gamma) - \gamma]\,\hat{e}(\gamma) = 0 \end{aligned} \tag{6}$$

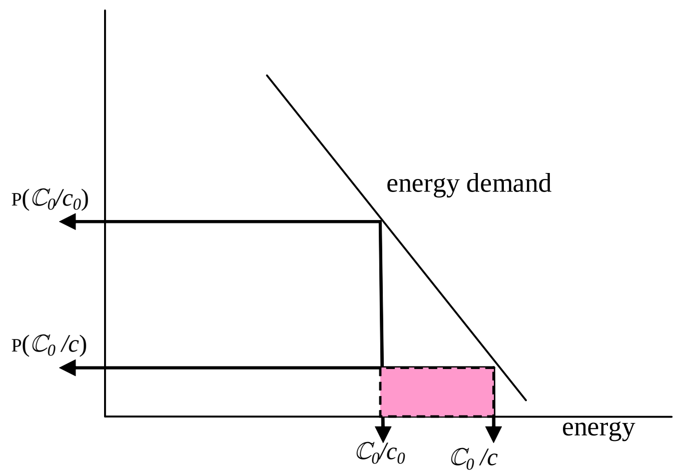

Figure 2: Licensing revenue with a fixed carbon cap

and

$$\begin{aligned} &\mathrm{P}\left(E\left(\hat{e}\left(\gamma\right);c\right)\right)-c_0 q\left(\gamma\right)\leq 0 \\ &\left[\mathrm{P}\left(E\left(\hat{e}\left(\gamma\right);c\right)\right)-c_0 q\left(\gamma\right)\right]\left[\tfrac{\mathbb{C}}{c}-\hat{e}\left(\gamma\right)\right]=0 \end{aligned} \tag{7}$$

If the revenue-maximizing royalty γ leads to full diffusion, $\hat{e}\left(\gamma\right)=\frac{\mathbb{C}}{c}$, we can write these equilibrium conditions as

$$\mathrm{P}\left(\frac{\mathbb{C}}{c}\right)-cq\left(\gamma\right)-\gamma=0 \tag{8}$$

$$\mathrm{P}\left(\frac{\mathbb{C}}{c}\right)-c_0 q\left(\gamma\right)=0 \tag{9}$$

The lefthand sides of (8) and (9) cannot be positive because energy producers would expand production in response to positive profit. The equality (8) holds because the proprietor has positive market share; hence profit cannot be negative.

No producers are using the old technology, so the lefthand side of (9) could conceivably be negative. However, the proprietor's revenue-maximizing choice of γ will force an equality in (9). If the profitability of the old technology is negative, the profitability remains negative even if the proprietor raises γ a bit, say to $\gamma+\varepsilon$. The proprietor's revenue is then $\left(\gamma+\varepsilon\right)\left(\mathbb{C}/c\right)$ instead of $\gamma\left(\mathbb{C}/c\right)$. The increase in γ will be balanced by a reduction in the allowance price $q\left(\gamma\right)$, such that the equality (8) holds at the energy price $\mathrm{P}(\mathbb{C}/c)$. The price of energy cannot rise (fall) because there would be an over- (under-) supply of allowances.

The equilibrium conditions (8) and (9) determine the proprietor's optimal royalty for the cap-and-trade policy, assuming full diffusion ($\hat{e}(\gamma) = \frac{\mathbb{C}}{c}$):

$$\gamma = \mathrm{P}\left(\frac{\mathbb{C}}{c}\right)\left(\frac{c_0 - c}{c_0}\right) \tag{10}$$

The following proposition summarizes the implications of this equilibrium, and in particular, says that the licensing revenue is again a fraction of gross profit in in the energy market (before paying for allowances). The fraction is again the size of the improvement, $\frac{c_0 - c}{c_0}$.

Proposition 3.2 (Maximum revenue with a carbon cap) *Suppose that the public domain technology has emissions rate c_0, and that $\mathbb{C}/c_0$ is in the elastic part of the demand curve. Then if a proprietary technology reduces the emissions rate to $c < c_0$, and if all producers are licensed, the optimal royalty satisfies* (*10*). *Energy production is $\mathbb{C}/c$, and the proprietor's per-period revenue is*

$$\left(\frac{c_0 - c}{c_0}\right) e\mathrm{P}(e) \;\; \textit{where } e = \frac{\mathbb{C}}{c}$$

Proof: The proprietor's revenue is $\gamma\frac{\mathbb{C}}{c}$. Using (10),

$$\gamma\frac{\mathbb{C}}{c} = \mathrm{P}\left(\frac{\mathbb{C}}{c}\right)\left(\frac{\mathbb{C}}{c} - \frac{\mathbb{C}}{c_0}\right) = \mathrm{P}\left(\frac{\mathbb{C}}{c}\right)\frac{\mathbb{C}}{c}\left(\frac{c_0 - c}{c_0}\right) \qquad \blacksquare \tag{11}$$

The innovator's revenue is shown as the lightly shaded rectangle in figure 2, which is a fraction $\frac{c_0 - c}{c_0}$ of the gross profit in the energy market.

Thus, the social benefits of a proprietary emissions-reducing innovation will be taken differently under the two regulatory systems. With an emissions tax, the benefits will be taken at least partly (and maybe completely) as a reduction in carbon emissions. With a cap-and-trade system, the benefits will be taken as more energy, but carbon emissions are fixed by the cap. Neither outcome is optimal. As shown in Proposition 2.1, it is efficient to realize the benefits of a carbon-reducing technology as both an increase in energy production and a decrease (increase) in carbon emissions, according to whether production is in the elastic (inelastic) part of the demand curve.

So far I have made no assumption about the regulatory policies except that they are fixed. I will now describe efficient regulatory policies, and consider how the incentives to innovate are different if the policies are optimal for the public-domain technology.

Given an emissions rate c, say that the tax τ_c is *efficient for emissions rate* c if it satisfies (12), where $\hat{E}(c)$ is the optimal energy supply described by (1).

$$\tau_c = \mathrm{K}'\left(c\hat{E}(c)\right) \tag{12}$$

Given an emissions rate c, say that the carbon cap $\mathbb{C}_c$ is *efficient for emissions rate* c if it satisfies (13), where $\hat{E}(c)$ is the optimal energy supply described by (1).

$$\mathbb{C}_c = c\hat{E}(c) \tag{13}$$

The tax described by (12) is only optimal if the producers can use the technology without paying a royalty. Thus, (12) is more appropriately described as the royalty-free efficient tax.

The following proposition says that proprietor earns more licensing revenue with an efficient emissions tax than with the efficient carbon cap. This follows from two facts that I previously established: (1) With both forms of regulation, the proprietor's licensing revenue is the size of the improvement, $\frac{c_0-c}{c_0}$, times the gross profit collected in the energy market. (2) The gross profit collected in the energy market is lower with a carbon cap than with the emissions tax, because the supply of energy expands under the carbon cap, and because (by assumption) production is in the elastic portion of the demand curve.

Proposition 3.3 (The incentive to innovate is greater under a fixed, efficient emissions tax than under a fixed, efficient carbon cap.) *Let c_0 be the emissions rate of a public-domain technology, and let c be the lower emissions rate of a proprietary technology. Let the tax τ_0 and the carbon cap $\mathbb{C}_0$ be efficient for emissions rate c_0. Then provided $\hat{E}(c_0)$ is in the elastic part of the demand curve, the proprietor earns more revenue when producers are regulated with the emissions tax τ_0 than when they are regulated by the carbon cap $\mathbb{C}_0$.*

Proof: The first two equalities below use the optimality of the tax rate and the carbon cap. The inequality follows from the fact that $E(c_0)$ is in the elastic portion of the demand curve, which implies $\mathrm{P}\left(\frac{\mathbb{C}_0}{c_0}\right)\frac{\mathbb{C}_0}{c_0} > \mathrm{P}\left(\frac{\mathbb{C}_0}{c}\right)\frac{\mathbb{C}_0}{c}$.

$$\begin{aligned}
\tau_0(c_0-c)\frac{\mathbb{C}_0}{c_0} &= c_0\mathrm{K}'(\mathbb{C}_0)\frac{\mathbb{C}_0}{c_0}\left(\frac{c_0-c}{c_0}\right) = \mathrm{P}\left(\frac{\mathbb{C}_0}{c_0}\right)\frac{\mathbb{C}_0}{c_0}\left(\frac{c_0-c}{c_0}\right) \\
&> \mathrm{P}\left(\frac{\mathbb{C}_0}{c}\right)\frac{\mathbb{C}_0}{c}\left(\frac{c_0-c}{c_0}\right) = \mathrm{P}\left(\frac{\mathbb{C}_0}{c}\right)\left(\frac{\mathbb{C}_0}{c} - \frac{\mathbb{C}_0}{c_0}\right)
\end{aligned}$$

This proves the result. ■

4 Adjustments for Static Efficiency

Because the proprietor's revenue is a given fraction of the gross profit earned in the energy market under both regulatory regimes, the proprietor's revenue in the two regimes can be compared by comparing the gross profit earned in the energy market. In the previous section, this led us to the conclusion that an emissions tax is more lucrative for the innovator than a carbon cap, provided both support the same production of energy before the innovation.

By the same reasoning, an efficient tightening of the carbon cap should increase the proprietor's licensing revenue, whereas an efficient reduction in the emissions tax should decrease the proprietor's licensing revenue. This assumes that tightening the cap increases gross profit, while reducing the tax increases supply and increases gross profit in the energy market. I now show this.

With an emissions tax, one of the complications is that the initial technology is assumed nonproprietary, while the new technology is proprietary. The tax τ_c defined by (12) is only optimal if there is no royalty. If the new technology is proprietary, the tax should be lower than if the technology is in the public domain, because energy producers pay a royalty in addition to the tax.[2] If the tax were equal to the social cost of emissions, the tax plus royalty would be inefficiently high, and energy consumption would be inefficiently low. To achieve the optimal production of energy, the tax t and the royalty together must equal the marginal social cost of carbon emissions:

$$tc + \gamma = c\mathrm{K}'\left(c\hat{E}\left(c\right)\right) \tag{14}$$

I now show that the following, also derived by Denicolo (1999), is the optimal emissions tax when producers also pay a royalty.

$$t_{c,c_0} = \frac{c}{c_0}\mathrm{K}'\left(c\hat{E}\left(c\right)\right) \tag{15}$$

Lemma 4.1 (When producers must pay a royalty, the optimal emissions tax is smaller than with no royalty.) *Let c_0 be the emissions rate of a public-domain technology, and let c be the lower emissions rate of a proprietary technology. Let the tax τ_0 be efficient for c_0, and let t_{c,c_0} satisfy (15). Suppose that $c_0\tau_0$ is in the elastic part of the demand curve. Then (a) The proprietor's most profitable royalty γ satisfies*

$$\gamma = \left(c_0 - c\right)t_{c,c_0} \tag{16}$$

(b) If γ satisfies (16), energy production is efficient, namely $\hat{E}\left(c\right)$ defined by (1).

Proof: (a) Using (15), $c_0 t_{c,c_0} = c\mathrm{K}'\left(c\hat{E}\left(c\right)\right) < c_0\mathrm{K}'\left(c_0\hat{E}\left(c_0\right)\right) = c_0\tau_0 < p^m$. The result follows from Proposition 3.1(a).

(b) With the optimal royalty in place, the price of energy is equal to

$$\gamma + ct_{c,c_0} = t_{c,c_0}\left(c_0 - c\right) + ct_{c,c_0} = c_0 t_{c,c_0} = c\mathrm{K}'\left(c\hat{E}\left(c\right)\right)$$

Hence (1) is satisfied. ■

The next proposition says that the proprietor makes less revenue if the emissions tax is reduced to achieve static efficiency.

[2] Parry (1995) makes the same argument. Barnett (1980) made a similar argument for the case that the emissions tax regulates a monopolist. Since the monopolist already has an incentive to cut supply, the tax should be lower than if the market were competitive.

Proposition 4.1 (Adjusting the emissions tax to achieve static efficiency decreases the proprietor's licensing revenue, whereas adjusting the carbon cap to achieve static efficiency increases the proprietor's revenue) *Let c_0 be the emissions rate of a public-domain technology, and let c be the lower emissions rate of a proprietary technology. Suppose that $\hat{E}(c_0)$ is in the elastic part of the demand curve.*
(a) Let the tax τ_0 be efficient for c_0, and let t_{c,c_0} satisfy (15). The proprietor makes less licensing revenue when the emissions tax is t_{c,c_0} than when it is τ_0.
(b) Let $\mathbb{C}_c$ be the efficient cap for c, and let $\mathbb{C}_0$ be the efficient cap for c_0. Then licensing revenue is higher under the cap $\mathbb{C}_c$ than under the cap $\mathbb{C}_0$.

Proof: (a) Using Proposition 3.1(a), the prices of energy without a tax adjustment and with a tax adjustment are, respectively,

$$\text{P}\left(\hat{E}(c_0)\right) = \gamma_0 + c\tau_0 = c_0\tau_0 = c_0\text{K}'\left(c_0\hat{E}(c_0)\right)$$

$$\text{P}\left(\hat{E}(c)\right) = \gamma_c + ct_{c,c_0} = c_0 t_{c,c_0} = c\text{K}'\left(c\hat{E}(c)\right)$$

Using Proposition 3.1(c), and the fact that $\hat{E}(c_0) < \hat{E}(c)$, the result follows because

$$\left(\frac{c_0 - c}{c_0}\right)\hat{E}(c_0)\,\text{P}\left(\hat{E}(c_0)\right) > \left(\frac{c_0 - c}{c_0}\right)\hat{E}(c)\,\text{P}\left(\hat{E}(c)\right)$$

(b) Because $\frac{\mathbb{C}_c}{c} > \frac{\mathbb{C}_0}{c_0}$ and both are in the elastic part of the demand curve,

$$\frac{\mathbb{C}_c}{c}\text{P}\left(\frac{\mathbb{C}_c}{c}\right)\left(\frac{c_0 - c}{c_0}\right) > \frac{\mathbb{C}_0}{c}\text{P}\left(\frac{\mathbb{C}_0}{c}\right)\left(\frac{c_0 - c}{c_0}\right)$$

Using Proposition 3.2, the result follows. ■

Proposition 4.1 is illustrated in figure 3 and 4, using the assumption that K' is constant. This implies that $\tau_0 = \text{K}'$ is the optimal royalty-free emissions tax before and after the reduction in emissions. The price of energy that supports optimal consumption is $\tau_0 c_0$ when only the public domain technology is available, and is $\tau_0 c$ when the lower-carbon technology is available. The licensing revenue with a fixed emissions tax is the higher rectangle in figure 3 with dotted lines around it, and the licensing revenue after the adjustment is the lower shaded rectangle, which is smaller. Both areas are a fraction $\frac{c_0 - c}{c_0}$ of gross profit in the energy market. Because energy supply increases with the cleaner technology and lower tax, gross profit in the energy market is reduced, hence licensing revenue is reduced.

The licensing revenues under the cap-and-trade regime are shown in figure 4. Licensing revenue with the fixed cap is the lower shaded rectangle, with energy supply $\mathbb{C}_0/c$. If the cap is reduced to $\mathbb{C}_c$, as is efficient, licensing revenue is the larger rectangle slightly to the left and above, with the efficient energy supply $\mathbb{C}_c/c$. Again, both areas are a fraction $\frac{c_0 - c}{c_0}$ of gross profit in the energy market.

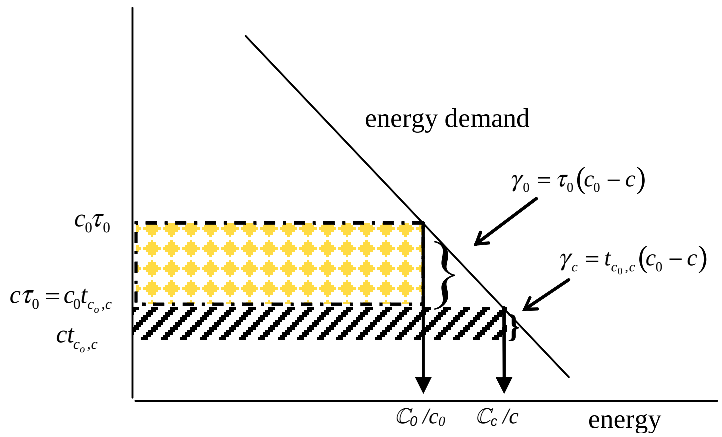

Figure 3: Licensing revenue is lower if the emissions tax is reduced for static efficiency

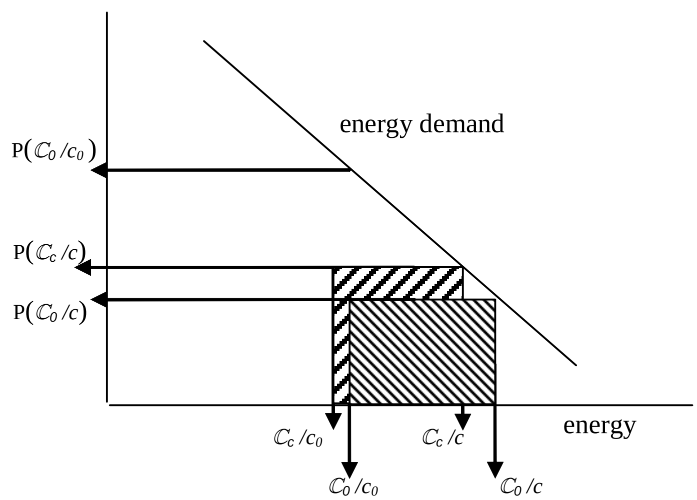

Figure 4: Licensing revenue is higher if the carbon cap is reduced for static efficiency

Finally, the following proposition, which is proved by Denicolo (1999), follows immediately from my characterization of the innovator's licensing revenue as a fixed fraction of gross profit in the energy market. The efficiency adjustments ensure that the gross profit earned in the energy market is the same under both regimes, because both support the same energy output.

Proposition 4.2 (If there will be an optimal dynamic adjustment in the regulatory policy, emissions taxes and carbon caps create the same incentives to innovate.) *Let c_0 be the emissions rate of a public-domain technology, and let c be the lower emissions rate of a proprietary technology. Let t_{c,c_0} satisfy (15), and let the carbon cap $\mathbb{C}_c$ be efficient for emissions rate c. Suppose that $\hat{E}(c)$ is in the elastic part of the demand curve. Then the proprietor's licensing revenue is the same with the emissions tax t_{c,c_0} as with the carbon cap $\mathbb{C}_c$, namely, $\left(\frac{c_0-c}{c_0}\right)\mathrm{P}\left(\frac{\mathbb{C}_c}{c}\right)\frac{\mathbb{C}_c}{c}$.*

5 Comparing Incentives

Assuming linear demand, I now show that the divergence in licensing revenues can be significant.

Suppose that the marginal social cost of emissions is $\mathrm{K}' = 1$, and that demand for energy is given by $\mathrm{P}(e) = 2 - e$. Then for each emissions rate c, the optimal emissions tax is c, the optimal energy production is $\hat{E}(c) = 2 - c$, and the optimal carbon cap is $\mathbb{C}_c = c(2 - c)$. Let the initial emissions rate be $c_0 = 1$, hence $\mathbb{C}_0 = 1$.

Suppose that a proprietor achieves a new technology with emissions rate $c < c_0$. Using (4), when energy producers must pay the tax $\tau_0 = 1$, the proprietor's most profitable royalty satisfies $\gamma^{EM} = (c_0 - c) = 1 - c$.

With the tax $\tau_0 = 1$ and royalty γ^{EM}, the price of energy is the same as before the innovation, $\mathrm{P}\left(\frac{\mathbb{C}_0}{c_0}\right) = \gamma^{EM} + c\tau_0 = c_0 = 1$, so gross profit in the energy market is 1. Using Proposition 3.1(c), the proprietor's licensing revenue is $\left(\frac{c_0-c}{c_0}\right)$ times 1. The proprietor's revenue in the tax regime is graphed as the top line in figure 5, as a function of c/c_0. Large improvements (small c) are on the left side of figure 5.

With the initially optimal carbon cap, $\mathbb{C}_0 = 1$, the proprietor's most profitable royalty γ^C for the lower emissions technology satisifes (10). This royalty determines the equilibrium price of energy and the equilibrium allowance price as $\mathrm{P}\left(\frac{\mathbb{C}_0}{c}\right) = 2 - \frac{\mathbb{C}_0}{c}$, $q = \frac{1}{c_0}\mathrm{P}\left(\frac{\mathbb{C}_0}{c}\right)$, and $\gamma^C = \frac{(c_0-c)}{c_0}\mathrm{P}\left(\frac{\mathbb{C}_0}{c}\right)$. Energy supply expands from $\frac{\mathbb{C}_0}{c_0}$ to $\frac{\mathbb{C}_0}{c}$. Using Proposition 3.2, the proprietor's licensing revenue is $\frac{(c_0-c)}{c_0}$ times the gross revenue in the energy market, $\frac{\mathbb{C}_0}{c}\mathrm{P}\left(\frac{\mathbb{C}_0}{c}\right)$. The proprietor's revenue in the cap-and-trade regime is graphed as the bottom line in figure 5. From the expression $q = \frac{1}{c_0}\mathrm{P}\left(\frac{\mathbb{C}_0}{c}\right) < q = \frac{1}{c_0}\mathrm{P}\left(\frac{\mathbb{C}_0}{c_0}\right)$, a reduction in the

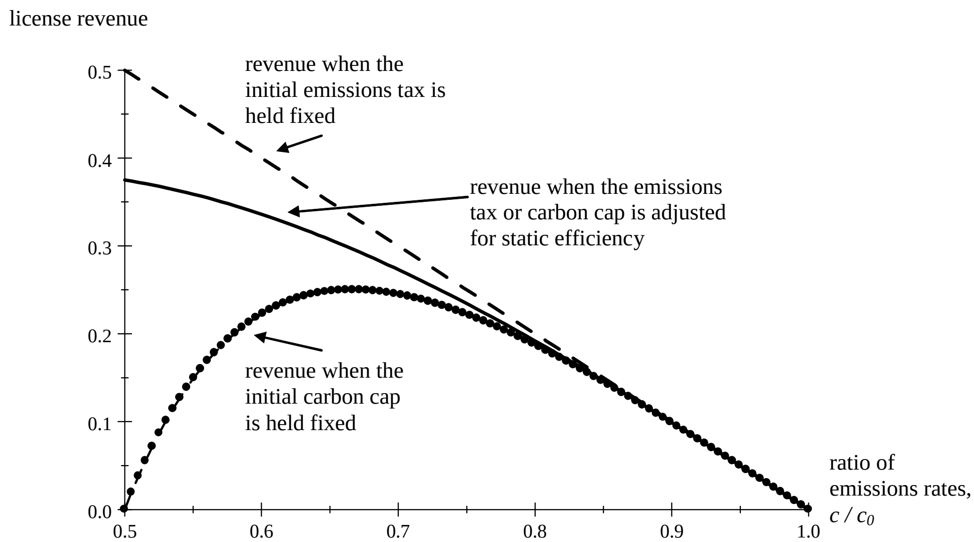

Figure 5: Comparison of licensing revenues with fixed emissions tax and carbon cap

carbon emissions rate from c_0 to c reduces the price of energy and reduces the price of allowances.

The middle line in figure 5 graphs the proprietor's licensing revenue if the policy (either the tax or the carbon cap) is adjusted for static efficiency using the new technology. This is where the tax rate falls to (c/c_0) and the carbon cap is increased to $\mathbb{C}_c = c\,(2-c)$. The two regimes produce the same gross profit in the energy market, by Proposition 4.2.

Figure 5 shows that the licensing revenue can be much lower with the carbon cap than with an emissions tax when the carbon reduction is large (the left side of the graph). For smaller improvements (toward the right), the discrepancy vanishes. It also shows that, in the tax regime, the proprietor's revenue falls if the emissions tax is adjusted for static efficiency, but in the cap-and-trade regime, the proprietor's revenue rises with the analogous adjustment.

6 The Diffusion Problem

The analysis above assumes that the clean technology will be fully diffused to energy producers. The assumption is valid in the case of an emissions tax, but I show here that it might not be valid in the case of a carbon cap. If the improvement is large, the innovator will limit diffusion in order to mitigate price erosion in the energy market and in the market for allowances. Some of the market will be supplied by the old higher-emissions technology. This is the type of exclusion on use that we usually expect from proprietary pricing. Here it has two important implications. First, electricity production is smaller than it could be, conditional on the carbon emissions, and second, it undermines the incentive to invest in large carbon reductions.

The following lemma describes a restriction on the royalty rates that could possibly be optimal for the proprietor.

Lemma 6.1 *(a) The innovator's most profitable royalty satisfies*

$$\mathrm{P}\left(\frac{\mathbb{C}}{c}\right)\left(\frac{c_0-c}{c_0}\right)\leq\gamma\leq\mathrm{P}\left(\frac{\mathbb{C}}{c_0}\right)\left(\frac{c_0-c}{c_0}\right) \tag{17}$$

(b) If γ is in the domain (17), the demand for licenses $\hat{e}(\gamma)$ satisfies

$$\gamma\leq\mathrm{P}\left(E\left(\hat{e}\left(\gamma\right);c\right)\right)\left(\frac{c_0-c}{c_0}\right)\ \textit{with equality if}\ \hat{e}\left(\gamma\right)<\frac{\mathbb{C}}{c} \tag{18}$$

Proof: (a) If the royalty γ is smaller than the lower bound, then, using (6) and (7), $\mathrm{P}(\mathbb{C}/c)-c\hat{q}\left(\gamma\right)-\gamma>(c/c_0)\left(\mathrm{P}\left(\mathbb{C}/c\right)-c_0\hat{q}\left(\gamma\right)\right)$. All producers use the lower-emissions technology and make zero profit, but they would make strictly negative profit using the old technology. Then the proprietor can increase its royalty γ without losing market share. This cannot be an equilibrium.

If the royalty γ is larger than the upper bound, then $\mathrm{P}(\mathbb{C}/c_0)-c\hat{q}\left(\gamma\right)-\gamma<(c/c_0)$ $\left(\mathrm{P}\left(\mathbb{C}/c_0\right)-c_0\hat{q}\left(\gamma\right)\right)$. All producers use the old technology, and the proprietor has no licensees. The proprietor can increase profit by reducing γ so that the new technology is competitive with the old technology.

(b) There are two cases, that $\hat{e}\left(\gamma\right)=\mathbb{C}/c$ and $\hat{e}\left(\gamma\right)<\mathbb{C}/c$. In the first case, $0=\mathrm{P}(\mathbb{C}/c)-c\hat{q}\left(\gamma\right)-\gamma\geq\mathrm{P}(\mathbb{C}/c)-c_0\hat{q}\left(\gamma\right)$, which implies the inequality (18). In the second case, $0=\mathrm{P}(\mathbb{C}/c)-c\hat{q}\left(\gamma\right)-\gamma=\mathrm{P}(\mathbb{C}/c)-c_0\hat{q}\left(\gamma\right)$, which implies equality. ■

For royalty rates in the interior of (17), the condition (18) holds as an equality, and establishes a one-to-one relationship between γ and the demand for electricity, $\hat{e}\left(\gamma\right)$. For royalty rates in the interior of (17), there is a monotonic relationship between the royalty rate γ, the number of kilowatt hours produced under license, $\hat{e}\left(\gamma\right)$, the total supply of electricity, $E\left(\hat{e}\left(\gamma\right);c\right)$, and the innovator's contribution to it, which I shall call s. The proprietor's optimization problem can be phrased in terms of any of these four variables.

In terms of the royalty rate, the innovator's per-period revenue is $\gamma\hat{e}\left(\gamma\right)$. Using (18) as an equality, the revenue can be written as the following on the interior of (17).

$$\left(\frac{c_0-c}{c_0}\right)\hat{e}\left(\gamma\right)\mathrm{P}\left(E\left(\hat{e}\left(\gamma\right);c\right)\right) \tag{19}$$

Taking e as the choice variable instead of γ, the revenue can be written

$$\left(\frac{c_0-c}{c_0}\right)e\mathrm{P}\left(E\left(e;c\right)\right)=\left(\frac{c_0-c}{c_0}\right)e\mathrm{P}\left(\frac{\mathbb{C}}{c_0}+\left(\frac{c_0-c}{c_0}\right)e\right) \tag{20}$$

Using (5), the total supply of electricity can be written $\frac{C}{c_0} + s$ where $s = \left(\frac{c_0 - c}{c_0}\right) e$. Written as a function of the innovator's contribution, s, the revenue is

$$\hat{R}(s) = s\mathrm{P}\left(\frac{\mathbb{C}}{c_0} + s\right), \qquad 0 \le s \le \frac{\mathbb{C}}{c} - \frac{\mathbb{C}}{c_0} \tag{21}$$

Let $s^*(c)$ be the optimizer of $\hat{R}$:

$$s^*(c) = \arg \max_{s \le \frac{\mathbb{C}}{c} - \frac{\mathbb{C}}{c_0}} \hat{R}(s).$$

We have the following conclusion:

Proposition 6.1 [Limited Diffusion of Large Innovations] *Suppose that $\hat{R}$ is a concave function. Let c_0 be an initial emissions rate, available with a public domain technology. Let c be a lower emissions rate, available with a proprietary technology. There is a threshold emissions rate $\hat{c} < c_0$ such that full diffusion ($\hat{e}(\gamma) = \mathbb{C}/c$) is profit-maximizing if $c \in (\hat{c}, c_0]$, but not if $c \in [0, \hat{c}]$. If $c \in [0, \hat{c}]$, aggregate electricity supply does not depend on the emissions rate c. In particular, the aggregate electricity supply is $\mathbb{C}/\hat{c}$.*

Proof: Let $\hat{s} = \arg\max_{s \ge 0} \hat{R}(s)$. Then $\hat{s}$ does not depend on c. Let $\hat{c}$ be defined by $\hat{s} = \frac{\mathbb{C}}{\hat{c}} - \frac{\mathbb{C}}{c_0}$. For any c such that $\hat{s} < \frac{\mathbb{C}}{c} - \frac{\mathbb{C}}{c_0}$, it holds that $s^*(c) = \hat{s}$, and total energy supply is $\frac{\mathbb{C}}{\hat{c}} < \frac{\mathbb{C}}{c}$. For any c such that $\hat{s} \ge \frac{\mathbb{C}}{c} - \frac{\mathbb{C}}{c_0}$, then $s^*(c) = \frac{\mathbb{C}}{c} - \frac{\mathbb{C}}{c_0}$, and total energy supply is $\frac{\mathbb{C}}{c}$. The result follows. ■

Example: Suppose the demand price is given by a linear function, $\mathrm{P}(E) = a - bE$. Then

$$\begin{aligned} \hat{R}(s) &= \left(a - b\left(\frac{\mathbb{C}}{c_0} + s\right)\right) s \\ \hat{s} &= \frac{a}{2b} - \frac{\mathbb{C}}{2c_0} \\ \hat{c} &= \frac{2\mathbb{C}}{\frac{a}{b} + \frac{\mathbb{C}}{c_0}} \end{aligned}$$

The new technology is fully diffused if and only if

$$c > \hat{c} = \frac{2\mathbb{C}}{\frac{a}{b} + \frac{\mathbb{C}}{c_0}} \qquad ■$$

For a high enough royalty rate, (18) shows that electricity producers will not be fully licensed. Increasing the royalty rate will cause the price of electricity to rise. This is because the higher royalty rate reduces the number of licensees, which reduces electricity supply. At the same time, according to (7), the price of allowances rises. The higher price of allowances amplifies the producers' willingness to pay for licenses. It is largely due to this feedback effect that the innovator with a large improvement (low emissions rate c) will not license all producers. Instead he will find it valuable to license only some of the producers, in order to maintain a high price for allowances, and to maintain a high willingness to pay for his lower-emissions technology.

The innovator can avoid profit erosion either by witholding the new technology from some of the market, or by avoiding large advances in the first place. Proposition 6.1 says that, if an innovation entails a large reduction in emissions, the innovator will use the first strategy. He will license only part of the market. But then it would have been wasteful to invest in a large advance.

I interpret this as another reason that cap and trade is less conducive to innovation than an emissions tax.

7 Conclusion

Any regulatory policy that imposes financial burdens for emitting carbon will also create an incentive to invest in carbon-reducing technologies. Emissions taxes and carbon caps are two such policies. While these two policies can be made equivalent from the static point of view of managing the tradeoff between energy production and carbon emissions, they are not equivalent from the point of view of encouraging innovation.

Because a solution to global warming will likely require a change in technologies, I have focussed on the replacement model of Denicolo (1999) rather than on the abatement model. I have characterized the licensing revenue of the innovator as the size of the innovator's improvement times the gross profit collected in the energy market. (Of course, because the producers are assumed to be perfectly competitive, they will earn zero profit once they pay the emissions tax or the allowances price.)

This characterization of the innovator's licensing revenue holds whether the regulatory mechanism is an emissions tax or a carbon cap. It explains why the two policies are equivalent for innovation when the regulatory mechanism of either type would be adjusted ex post for efficiency, using the cleaner technology. Both regulatory policies would then lead to the same energy supply, to the same price of energy, and to the same gross profit in the energy market.

It also explains why the licensing revenues are higher with the emissions tax than with a carbon cap, when both policies are equivalent to begin with. Energy supply expands under the carbon cap, but not under the emissions tax, and this reduces gross profit in the energy market. Another way to express the revenue disadvantage of the carbon cap is through the endogeneity of the allowance price. I showed in section 5 that the price effect, and therefore the revenue discrepancy, can be significant.

One way to mitigate the price effect is to unify the markets for carbon emissions. If unified, the demand for carbon allowances comes from many sectors, not all of which use the new, proprietary technology. For this reason, there may be less reduction in the allowance price. This helps to restore the incentive to innovate, but also means that there is a smaller expansion in the consumption of energy, due to the fact that the price reduction in the energy market is also dampened.

The choice between emissions taxes and carbon caps has aspects not addressed in this paper. These are nicely laid out by Parry and Pizer (2007), pointing out, for example, how the policies compare in terms of the uncertainty they create for producers, their political viability, and the revenue consequences for the government.

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