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. 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 develop a model to address this question, and consider two contexts: first, where the regulatory policy is fixed at an initial policy that achieves static efficiency, and second, where the regulatory policy is adjusted to achieve static efficiency when a lower-carbon technology is invented. If each policy would remain fixed despite the lower emissions rate, emissions taxes create better incentives to innovate than the equivalent carbon cap. On the other hand, if each policy would be adjusted for static efficiency at the lower emissions rate, the incentive to innovate would be reduced in the tax regime, but increased in the cap-and-trade regime.

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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.

I compare these policies in a different model than previous authors have used. In the previous models, the innovation problem is to reduce the marginal cost of abating pollution. See, in particular, Milliman and Prince (1989), Jung, Krutilla and Boyd (1996), Parry (1995,2003) and Fischer, Parry and Pizer (2003). My model does not focus on abatement, but rather on developing lower-carbon technologies to replace the old technologies. For example, affordable hydrogen power might eventually replace gasoline-powered automobiles, or affordable solar power might eventually replace coal-fired power plants. That does not require retrofitting or "abating," but instead requires that producers switch technologies. Before they can do that, someone must develop the lower-carbon alternatives.

The conclusion from the previous 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. See Fischer, Parry and Pizer (2003). The same conclusion emerges in my own model, and for the same reason. 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 model below) or to license a technology that reduces the cost of abatement (in the previous 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] I show how this conclusion emerges in my own model, and add other conclusions as well, in particular, 2, 3 and 4 below.

Regardless of which type of regulation is chosen, the policy must perform two tasks. One task is to encourage innovation. The other task is to ensure static efficiency in the energy sector, by which I mean the efficient balance of energy consumption and carbon emissions,

[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.

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 cost. Productive efficiency 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. By consumption efficiency, I mean that the energy sector achieves the right *level* of production, or more particularly, the right balance of energy consumption and carbon emissions, assuming that production is efficient. For consumption efficiency, the cap or tax must be chosen to get the price of energy right. Because productive efficiency is trivial in this paper – it is achieved by switching to the lower-carbon technology – I use the term "static efficiency" to mean consumption efficiency, or getting the price of energy right.

I first consider a tax policy and a cap-and-trade policy that achieve static efficiency in the initial situation. Even though the policies are equivalent in achieving static efficiency, they are not equivalent for innovation. In particular,

1 The emissions tax leads to more licensing revenue for the proprietor of a lower-carbon technology than the equivalent carbon cap.

2 The two policies deliver different social benefits from the innovation. With the emissions tax, energy production stays fixed, while carbon emissions are reduced. With the carbon cap, carbon emissions stay fixed, while energy production is increased.

The second conclusion implies that, even if the tax or carbon policy is efficient before the lower-carbon technology is introduced, it will not be efficient afterwards. Once the lower-emissions technology is available, static efficiency requires more energy production at a lower price, and less carbon emissions. Neither policy has this effect. This raises the question of how incentives are changed if the policy is adjusted to achieve static efficiency *ex post* with the lower-carbon technology.

In the case of an emissions tax, the adjustment is complicated by the fact that the new technology is proprietary. With public domain technologies, the optimal tax is equal to the social cost of emissions. However, Parry (1995) pointed out that, when energy producers pay a royalty in addition to the tax, the optimal tax is lower than the social cost of emissions. That is also true here. I characterize the optimal adjustment for each type of policy, an emissions tax or carbon cap, and then characterize how the adjustment affects licensing revenue, or equivalently, the incentive to innovate. The main conclusions are that

3 If both the emissions tax and the carbon cap are adjusted for static efficiency after the lower-carbon technology is invented, then the tax policy and cap-and-trade policy generate equal licensing revenue.

4 If regulation is with an emissions tax, an efficiency adjustment reduces the proprietor's licensing revenue. If regulation is with a carbon cap, an efficiency adjustment increases the proprietor's licensing revenue.

Fischer, Parry and Pizer argue informally that point 3 also applies in their abatement model. It is shown explicitly below.

The treatment in this paper is "long run" in that once a lower-carbon technology has been invented, all producers have an opportunity to switch to it. The time scale must be long enough so that existing energy facilities depreciate and can be replaced with new facilities that use the lower-carbon technology.

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.

2 Static Efficiency: Balancing emissions and energy

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 $K(\cdot)$. It is natural to think of $K(\cdot)$ as an increasing convex function such that $K(0) = 0$. Then $K'(\cdot)$ 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, $e^m = \arg\max e\mathrm{P}(e)$.

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

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

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

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 less emissions and more energy production] *Suppose that* $c < c_0$. *Then* $\hat{E}(c) > \hat{E}(c_0)$ *and if* $\hat{E}(c_0) > e^m$, *then* $c\hat{E}(c) < c_0\hat{E}(c_0)$

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

Because $\hat{E}(c_0)$ is assumed larger than the monopoly supply of energy, and using $\hat{E}(c) > \hat{E}(c_0)$, it holds that $\hat{E}(c_0)\mathrm{P}\left(\hat{E}(c_0)\right) > \hat{E}(c)\mathrm{P}\left(\hat{E}(c)\right)$. Multiplying (1) by $\hat{E}(c_0)$ at c_0 and $\hat{E}(c)$ at c, and using the assumptions on K, it follows that

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

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

This shows that if a carbon-reducing technology becomes available royalty-free to producers, some of the benefit should be taken as more energy, and some as lower carbon emissions.

3 Incentives when the regulatory policy is stationary

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. I assume the new technology will be proprietary, in the sense that it can be licensed for a royalty. The energy producers are willing to pay for licenses

because the new technology lowers their emissions taxes or reduces the carbon allowances that they must buy.

My objective is to show how the proprietor's license 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. In comparing the profitability of the two regulatory regimes, I suppose that the regulatory policy is efficient in the static sense that it achieves the energy production and carbon emissions described by Proposition 2.1.

But Proposition 2.1 implies that energy production and carbon emissions should change after a carbon-reducing technology is introduced. In particular, energy consumption should rise and carbon emissions should fall. I show in section 4 that if the policy is adjusted to achieve static efficiency with the carbon-reducing technology, the incentives to invest are reduced if regulation is with an emissions tax, but enhanced if regulation is cap-and-trade.

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. This cannot be revenue-maximizing for the proprietor.

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 total revenue.

The 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.

Proposition 3.1 (The revenue-maximizing royalty 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 satisfies $\tau c_0 < p^m$, the rrevenue-maximizing royalty satisfies*

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

(b) If the emissions tax τ satisfies $\tau c_0 > p^m$, 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 $\tau c_0 < p^m$, the energy produced with the proprietary technology is $\hat{E}(c_0)$, and the innovator's per-period revenue is $\tau (c_0 - c) \hat{E}(c_0)$.

Proof: (a) Suppose to the contrary that $\gamma < \tau (c_0 - c)$ and $\tau c + \gamma < \tau c_0 < p^m$. Because the function defined by $p\mathrm{E}(p)$ is concave, the maximand in (2) is a concave function of γ. Then

$$\begin{aligned} \frac{d}{d\gamma}\gamma \mathrm{E}(\tau c + \gamma) &= \gamma \mathrm{E}'(\tau c + \gamma) + \mathrm{E}(\tau c + \gamma) > \\ \frac{d}{dp}p\mathrm{E}(p)|_{p=(\tau c+\gamma)} &\geq \frac{d}{dp}p\mathrm{E}(p)|_{p=\tau c_0} \geq \frac{d}{dp}p\mathrm{E}(p)|_{p=p^m} = 0 \end{aligned} \tag{5}$$

Thus, the proprietor can profit by increasing γ.

(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 from (a) and (b), given that the proprietor licenses all the producers. ■

Depending on the tax rate, the price of energy can be higher or lower than the revenue-maximizing price of energy, p^m. I have not yet discussed the optimal emissions tax, but either hypothesis in Proposition 3.1 can be consistent with optimality, depending on the social cost of emissions.

When the tax is not too high, the proprietor collects the shaded horizontal area in figure 1 for the duration of the property right. In figure 1, I have assumed that 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, $\tau = K'$.

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 $\hat{E}(c)$,

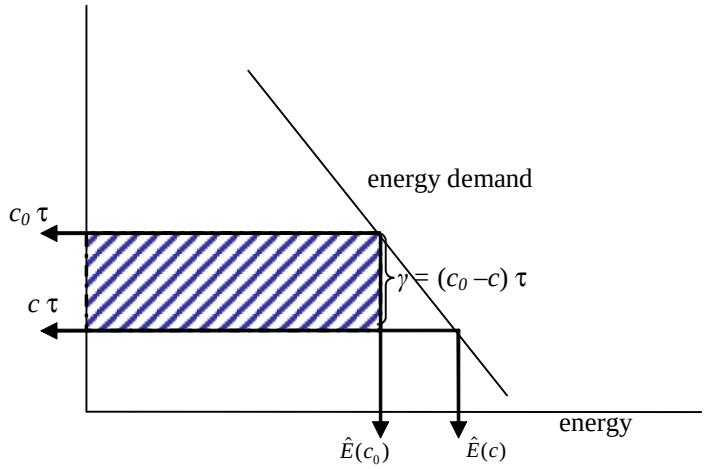


Figure 1: Licensing revenue with a fixed emissions tax

but that does not happen because of the royalty. For the duration of the intellectual property right, the proprietor collects as revenue the saved social costs of emissions, namely $(c_0 - c)\,\tau \hat{E}\,(c_0)$, which is the shaded area.

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 $\mathbb{C}/c$. 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.

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

$$E\,(e; c) = \frac{\mathbb{C}}{c_0} + \left(\frac{c_0 - c}{c_0}\right) e \tag{6}$$

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

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.

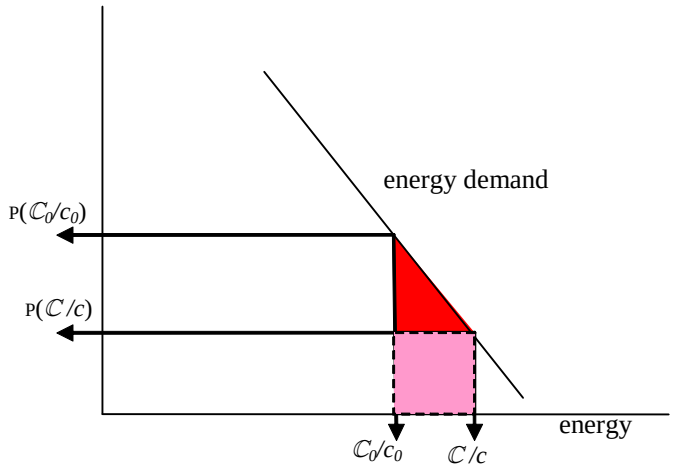


Figure 2: Licensing revenue with a fixed carbon cap

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

and

$$\begin{aligned} &\mathrm{P}\left(E\left(\hat{e}\left(\gamma\right);c\right)\right)-c_0q\left(\gamma\right)\leq 0 \\ &\left[\mathrm{P}\left(E\left(\hat{e}\left(\gamma\right);c\right)\right)-c_0q\left(\gamma\right)\right]\left[\tfrac{\mathbb{C}}{c}-\hat{e}\left(\gamma\right)\right]=0 \end{aligned} \tag{8}$$

I showed in my companion paper (2009) that, if the size of the advance, $\frac{c_0-c}{c_0}$, is very large, the proprietor might choose a royalty γ such that the new technology is not fully diffused, that is, $\hat{e}\left(\gamma\right)<\mathbb{C}/c$. For my purposes here, I will avoid that complication and simply assume that the revenue-maximizing royalty γ leads to full diffusion. We can therefore write the equilibrium conditions as

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

$$\mathrm{P}\left(\frac{\mathbb{C}}{c}\right)-c_0q\left(\gamma\right)=0 \tag{10}$$

The lefthand sides of (9) and (10) cannot be positive because energy producers would expand production in response to positive profit. The equality (9) 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 (10) could conceivably be negative.

However, the proprietor's revenue-maximizing choice of γ will force an equality in (10). 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 $(\gamma + \varepsilon)(\mathbb{C}/c)$ instead of $\gamma(\mathbb{C}/c)$. The increase in γ will be balanced by a reduction in the allowance price $q(\gamma)$, such that the equality (9) holds at the energy price $\text{P}(\mathbb{C}/c)$. The price of energy cannot rise (fall) because there would be an over- (under-) supply of allowances.

The equilibrium conditions (9) and (10) determine the proprietor's optimal royalty for the cap-and-trade policy, as it depends on $\mathbb{C}$.

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

The following proposition summarizes the implications of this equilibrium:

Proposition 3.2 (The revenue-maximizing royalty with a carbon cap) *Suppose that the carbon cap $\mathbb{C}$ satisfies $\mathbb{C}/c_0 > e^m$, and suppose the public domain technology has emissions rate c_0. Then if a proprietary technology reduces the emissions rate to $c < c_0$, and energy producers are fully licensed, the optimal license satisfies (11), energy production expands to $\mathbb{C}/c$, and the optimal license yields per-period revenue in amount*

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

Proof: The proprietor's revenue is $\gamma\frac{\mathbb{C}}{c}$. Using (11),

$$\gamma\frac{\mathbb{C}}{c} = \text{P}\left(\frac{\mathbb{C}}{c}\right)\left(\frac{\mathbb{C}}{c} - \frac{\mathbb{C}}{c_0}\right) \qquad \blacksquare \tag{12}$$

The innovator's revenue is shown as the lightly shaded rectangle in figure 2. The innovator's per-period revenue is less than the consumers' surplus provided by the expansion in energy supply.

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 reduction in carbon emissions.

In Proposition 3.2, I made no assumption about the carbon cap except that it is fixed. I will now assume that it is fixed at an optimal level for the emissions rate c_0. My objective is to compare the incentives to innovate under a carbon cap, as compared to an emissions tax, assuming that each policy was chosen to achieve static efficiency (1) with the initial emissions rate c_0. First I give expressions for the efficient emissions tax and the efficient carbon cap.

Given an emissions rate c, the tax τ_c is *efficient for emissions rate* c if it satisfies (13), where $\hat{E}(c)$ is the optimal energy supply described by (1).

$$\tau_c = K'\left(c\hat{E}(c)\right) \tag{13}$$

Given an emissions rate c, the carbon cap $\mathbb{C}_c$ is *efficient for emissions rate* c if it satisfies (14), where $\hat{E}(c)$ is the optimal energy supply described by (1).

$$\mathbb{C}_c = c\hat{E}(c) \tag{14}$$

The tax described by (13) is only optimal if the producers can use the technology without paying a royalty. Thus, (13) is more appropriately described as the royalty-free efficient tax.

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 $\hat{E}(c_0) > e^m$, the proprietor earns more revenue when producers are subject to the efficient emissions tax than when they trade allowances under the efficient carbon cap.*

Proof: The first equality below uses the optimality of the tax rate, (13). The second equality uses the fact that the carbon cap is optimal for c_0, as described by (1). The third equality is a rearrangement, and the inequality follows because $\text{P}\left(\frac{\mathbb{C}_0}{c_0}\right) > \text{P}\left(\frac{\mathbb{C}_0}{c}\right)$.

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

This proves the result. ■

4 Adjustments for Static Efficiency

In the previous section, I showed under mild conditions that, if producers face a fixed emissions tax, optimal licensing leads to a reduction in carbon emissions but no expansion in energy consumption. If the producers face a carbon cap, optimal licensing leads to an expansion in energy consumption but no reduction in emissions. Thus, even if the initial emissions tax and the initial carbon cap would both achieve static efficiency, neither achieves static efficiency after the carbon-reducing technology becomes available. As a consequence, there will be pressure to adjust the policy. I now characterize the adjustments required to achieve static efficiency with the lower-carbon technology, and ask how the licensing revenue changes.

Suppose that the public domain technology has emissions rate c_0, and that a new, proprietary technology has a lower emissions rate c. The following proposition says that, under a cap-and-trade system, the carbon cap should fall when the emissions rate falls, and under an emissions tax system, the royalty-free emissions tax should either stay the same or fall.

Proposition 4.1 [Changing the policy to achieve static efficiency] *Suppose that* $\hat{E}(c_0) > e^m$. *If the emissions rate falls from* c_0 *to* c, *and the technology is made available without royalties, then the carbon cap that is efficient for* c *is smaller than the carbon cap that is efficient for* c_0, *and the (royalty-free) tax that is efficient for* c *is no greater than the tax that is efficient for* c_0.
(a) $\mathbb{C}_c < \mathbb{C}_0$.
(b) $\tau_c \leq \tau_0$

Proof: (a) follows from Proposition 2.1, since $\mathbb{C}_c = c\hat{E}(c) < c_0\hat{E}(c_0) = \mathbb{C}_0$. (b) follows because $\tau_c = K'\left(c\hat{E}(c)\right) \leq K'\left(c_0\hat{E}(c_0)\right) = \tau_0$. ■

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 (13) is only optimal if there is no royalty. I now argue that if the new technology is proprietary, the tax should be lower than if the technology is in the public domain.[2] This is because energy producers pay a royalty in addition to the tax. The royalty chosen by the proprietor will depend on the emissions rate of the public-domain technology as well as on the emissions rate of the proprietary technology, and also on the emissions tax. The optimal tax must take this into account.

Let t be the emissions tax when the new technology is proprietary.

To achieve the optimal production of energy, the tax and the royalty together must equal the marginal social cost of carbon emissions:

$$tc + \gamma = cK'\left(c\hat{E}(c)\right) \tag{15}$$

I now show that the following is the optimal emissions tax when the user must also pay the royalty that maximizes the proprietor's licensing revenue.

$$t_{c,c_0} = \frac{c}{c_0}K'\left(c\hat{E}(c)\right) \tag{16}$$

Lemma 4.1 (When producers must pay a royalty, the optimal emissions tax is smaller than with no royalty and satisfies (16).) *Let* c_0 *be the emissions rate of a public-domain*

[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.

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 (16). Suppose that $c_0\tau_0 < p^m$.
(a) The proprietor's most profitable royalty γ satisfies

$$\gamma = (c_0 - c)\, t_{c,c_0} \tag{17}$$

(b) If γ satisfies (17), energy production is efficient, namely $\hat{E}(c)$ defined by (1);
(c) The optimal emissions tax is smaller if there is a royalty than if not: $t_{c,c_0} < \tau_c$.

Proof: (a) Using (16), $c_0 t_{c,c_0} = cK'\left(c\hat{E}(c)\right) < c_0 K'\left(c_0\hat{E}(c_0)\right) = c_0\tau_0 < p^m$. The hypothesis of Proposition 3.1 is satisfied for t_{c,c_0}, hence the result follows from Proposition 3.1. (b) With the optimal royalty in place, the price of energy is equal to

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

Hence (1) is satisfied. Part (c) follows from (16) and (13). ■

The next proposition says that the proprietor makes less revenue if the emissions tax is reduced to achieve static efficiency than if not. The adjustment for static efficiency therefore has a harmful effect on the incentive to innovate.

Whatever the tax rate, the proprietor will choose a royalty equal to the saved emissions taxes, namely $(c_0 - c)$ times the tax rate. If the tax rate is reduced, the proprietor's revenue is reduced, even though there are more licensees at the lower tax rate. (This is where the hypothesis $cK'\left(c\hat{E}(c)\right) < p^m$ is used.)

Proposition 4.2 (Adjusting the emissions tax to achieve static efficiency decreases the proprietor's licensing 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. Let the tax τ_0 be efficient for c_0, and let t_{c,c_0} satisfy (16). Suppose that $c_0\tau_0 < p^m$. Then*
(a) (Static Efficiency) *When the proprietary technology is not available and the tax is τ_0, the equilibrium consumption of energy is $\hat{E}(c_0)$. When the proprietary technology becomes available and the tax is t_{c,c_0}, the equilibrium consumption of energy is $\hat{E}(c)$.*
(b) The proprietor makes less licensing revenue when the emissions tax is t_{c,c_0} than when it is τ_0.

Proof: (a) If $c_0 K'\left(c_0\hat{E}(c_0)\right) < p^m$, then $c_0\tau_0 < p^m$ and $cK'\left(c\hat{E}(c)\right) < p^m$. Using Proposition 3.1(a) and Lemma 4.1(a), the revenue-maximizing royalty with tax rate τ_0 satisfies $\gamma_0 = (c_0 - c)\,\tau_0$ and with tax rate t_{c,c_0} satisfies $\gamma_c = (c_0 - c)\, t_{c,c_0}$. Then

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

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

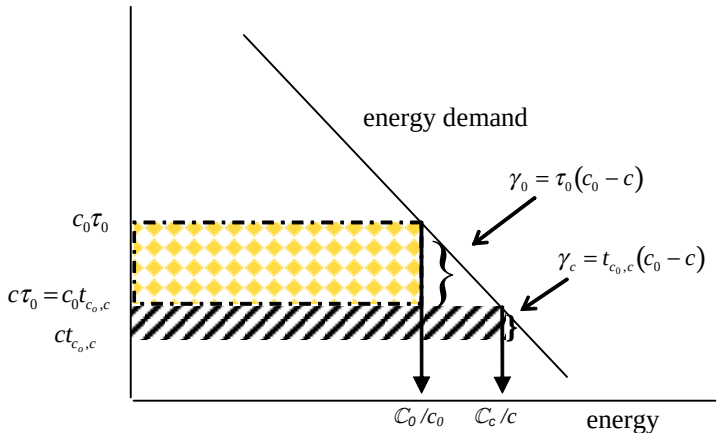


Figure 3: Licensing revenue is lower if the emissions tax is reduced for static efficiency

In each case, the equilibrium consumption of energy satisfies (2.1) and is efficient.

(b) The licensing revenue at emissions rate c_0 is $\gamma_0 \hat{E}(c_0)$ and at emissions rate c is $\gamma_c \hat{E}(c)$. Use the fact that $xK'(x)$ is increasing with x, and recall from Proposition 2.1 that $c\hat{E}(c) < c_0\hat{E}(c_0)$. Then

$$\begin{aligned}\gamma_c \hat{E}(c) &= \hat{E}(c)\, t_{c,c_0}(c_0 - c) = \left(\frac{c_0 - c}{c_0}\right)\left(c\hat{E}(c)\right) K'\left(c\hat{E}(c)\right) \\ &< \left(\frac{c_0 - c}{c_0}\right)\left(c_0\hat{E}(c_0)\right) K'\left(c_0\hat{E}(c_0)\right) = (c_0 - c)\,\tau_0\hat{E}(c_0) = \gamma_0\hat{E}(c_0)\end{aligned}$$

■

Proposition 4.2 is illustrated in figure 3 using the assumption that K' is constant. This implies that $\tau_0 = K'$ 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 with dotted lines around it, and the licensing revenue after the adjustment is the lower shaded rectangle, which is smaller. If the emissions tax is reduced to achieve static efficiency ex post, licensing revenue is reduced, hence, the incentive to innovate is reduced.

In contrast, an adjustment for static efficiency has the effect of increasing revenue in the cap-and-trade system, rather than reducing it. The licensing revenues 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 $\mathbb{C}_c/c$.

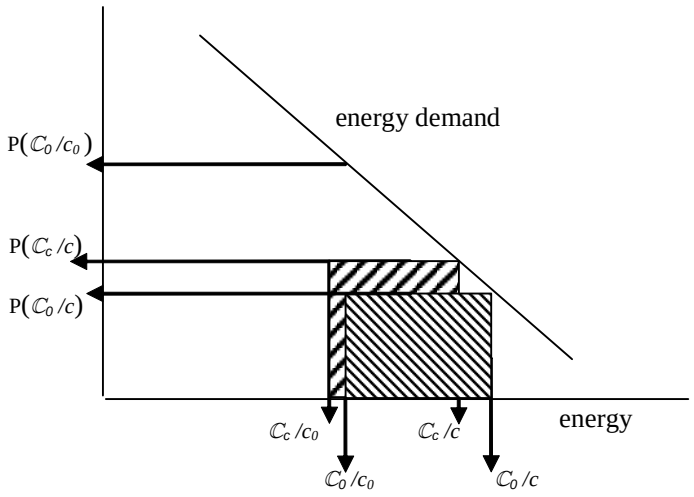


Figure 4: Licensing revenue is higher if the carbon cap is reduced for static efficiency

Proposition 4.3 (Adjusting the carbon cap to achieve static efficiency increases the proprietor's licensing 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 $\hat{E}(c) > e^m$. Let the cap $\mathbb{C}_c$ be efficient for c, and the cap $\mathbb{C}_0$ be efficient for c_0. The proprietor's licensing revenue is larger under the cap $\mathbb{C}_c$ than under the cap $\mathbb{C}_0$.*

Proof: I showed in Proposition 3.2 for an arbitrary cap $\mathbb{C}$ that the proprietor's revenue is $\mathrm{P}\left(\frac{\mathbb{C}}{c}\right)\left(\frac{\mathbb{C}}{c} - \frac{\mathbb{C}}{c_0}\right)$, provided $\frac{\mathbb{C}}{c_0} > e^m$. Using Proposition 2.1, $\mathbb{C}_0 = c_0\hat{E}(c_0) > c\hat{E}(c) = \mathbb{C}_c$ and $\mathbb{C}_0/c > \mathbb{C}/c$. Because $e\mathrm{P}(e)$ is decreasing for $e > e^m$, it holds that

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

which can be rewritten

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

This proves the result. ■

Finally, the following proposition compares the two policies. If the policies are adjusted ex post for static efficiency, the licensing revenues are the same with an emissions tax and with a cap-and-trade policy.

Proposition 4.4 (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 (16), and let the carbon cap $\mathbb{C}_c$ be efficient for emissions rate c. Suppose that $\hat{E}(c) > e^m$. 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, $\mathrm{P}\left(\frac{\mathbb{C}_c}{c}\right)\left(\frac{\mathbb{C}_c}{c} - \frac{\mathbb{C}_c}{c_0}\right)$.

Proof: From the efficiency condition (1),

$$cK'(\mathbb{C}_c) = \mathrm{P}\left(\frac{\mathbb{C}_c}{c}\right)$$

Multiply each side by $\left(\frac{c_0 - c}{c_0}\right)(\mathbb{C}_c/c)$. Then

$$\begin{aligned} cK'(\mathbb{C}_c)\left(\frac{c_0 - c}{c_0}\right)\frac{\mathbb{C}_c}{c} &= \left[\frac{c}{c_0}K'(\mathbb{C}_c)(c_0 - c)\right]\frac{\mathbb{C}_c}{c} \\ &= \mathrm{P}\left(\frac{\mathbb{C}_c}{c}\right)\left(\frac{\mathbb{C}_c}{c} - \frac{\mathbb{C}_c}{c_0}\right) \end{aligned}$$

where the term in square brackets is the optimal royalty, using Lemma 4.1(a). Thus, the lefthand side is the revenue under the dynamically adjusted emissions-tax policy. Using Proposition 3.2 with the cap $\mathbb{C}_c$, the righthand side is the revenue under the cap-and-trade policy. This proves the result. ■

5 Comparing Incentives

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

Suppose that the social cost of emissions is linear in emissions with marginal social cost equal to $K' = 1$, 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 $c_0 = 1$.

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

$$\gamma^{EM} = (c_0 - c)$$

With the tax $\tau_0 = 1$ and royalty γ^{EM}, the price of energy is the same as before the innovation, $\mathrm{P}\left(\frac{\mathbb{C}_0}{c_0}\right) = \gamma^{EM} + c\tau_0 = c_0 = 1$. The supply of energy does not expand. Using Proposition 3.1(c), the proprietor's licensing revenue is $(c_0 - c)(2 - c_0)$. The proprietor's revenue in the tax regime is graphed as the top line in figure 5, as a function of c/c_0, which measures the size of the improvement. Large improvements (small c) are on the left side of figure 5.

If regulation is with a carbon cap instead, the initially optimal carbon cap is $\mathbb{C}_0 = 1$. The proprietor's most profitable royalty, γ^{CT}, satisfies (11), and will determine the equilibrium price of energy and the equilibrium allowance price. These satisfy

$$\begin{aligned} \text{P}\left(\frac{\mathbb{C}_0}{c}\right) &= 2 - \frac{\mathbb{C}_0}{c} = 2 - (1/c) \\ q &= \frac{1}{c_0}\left(2 - \frac{1}{c}\right) \\ \gamma^{CT} &= \frac{(c_0 - c)}{c_0}\left(2 - \frac{1}{c}\right) \end{aligned} \tag{18}$$

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 $\frac{(c_0-c)}{c_0}\left(2 - \frac{1}{c}\right)\frac{\mathbb{C}_0}{c}$. The proprietor's revenue in the cap-and-trade regime is graphed as the bottom line in figure 5.

The equations (18) show that when the carbon cap is fixed, a reduction in carbon emissions reduces the price of energy and reduces the price of allowances. The price of allowances and the price of energy both increase like $1/c^2$ (thus, decrease when the emissions rate falls).

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. These are the same, by Proposition 4.4. The graph 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. The graph 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 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, it is not obvious whether they are equivalent from the point of view of encouraging innovation.

For static efficiency, each policy – an emissions tax or the carbon cap – must adjust when a technology with lower emissions becomes available. I have shown, however, that the adjustment changes the incentives to innovate. For the tax policy, the incentive is reduced, while for the cap-and-trade policy, the incentive is increased. (See figure 5.) On the other hand, adjustments for static efficiency restore the equivalence of the two policies. If an innovator anticipates an adjustment for static efficiency, then the licensing revenue

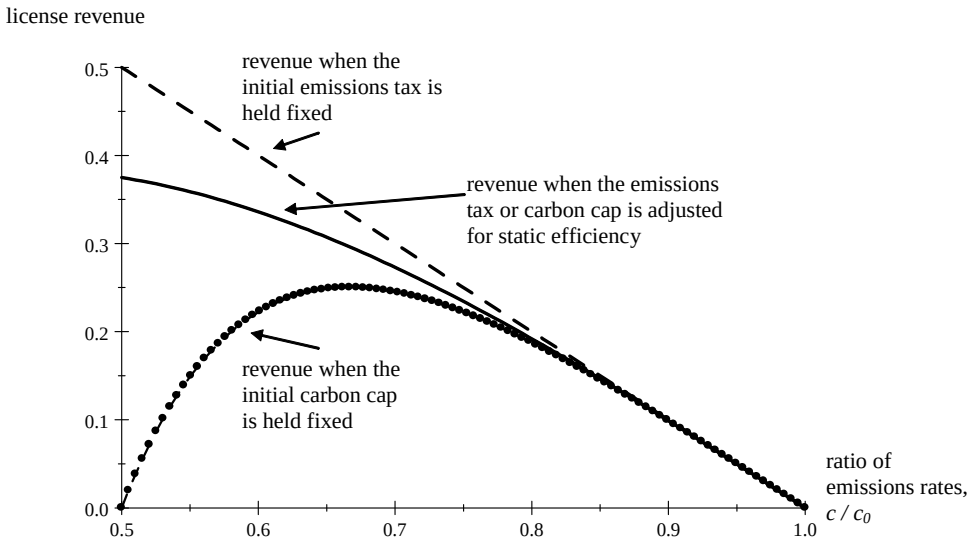


Figure 5: Comparison of licensing revenues with emissions tax and carbon cap

produced by a carbon-reducing innovation is the same under the efficient tax policy and the efficient carbon cap. If no adjustment will be made, a tax on emissions is more lucrative for the innovator than a cap-and-trade policy.

The revenue advantages of the emissions tax are linked to the endogeneity of the allowance price when there is a carbon cap. 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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