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 show how tax regulation can do a better job of encouraging innovation and of ensuring that all energy producers use the cleaner technology. Under both tax regulation and carbon regulation, the royalty controls the price of energy. However, in the case of carbon regulation, the proprietor must expand energy supply in order to earn revenues. This may reduce gross profits in the energy sector and lead to lower rewards than under tax regulation. Making it worse, the proprietor might avoid price erosion by diffusing the clean technology only partially, so that the dirty technology stays in use.

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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 (Laffont and Tirole (1996), Denicolo (1999), Montero (2010)). 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 somewhat 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 in other contexts.

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.

The conclusion from the literature that I regard as most important for the policy debate is that 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.

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 by licensees (gross of taxes or payments for allowances). If the innovation is fully diffused, the gross profit earned by licensees is the gross profit in the energy market. The results alluded to above can therefore be explained by explaining what happens to gross profits in the energy market.

With tax regulation, a proprietor of a clean technology can diffuse the technology to all producers and earn royalties from it without expanding energy supply, and without reducing the price of energy from its previous regulated value. In contrast, a proprietor under cap-and-trade regulation must expand energy supply in order to have any licensees. If he tries to license without expanding energy supply, there will be an excess supply of allowances. That is not an equilibrium. The expansion in energy supply can reduce gross

[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.

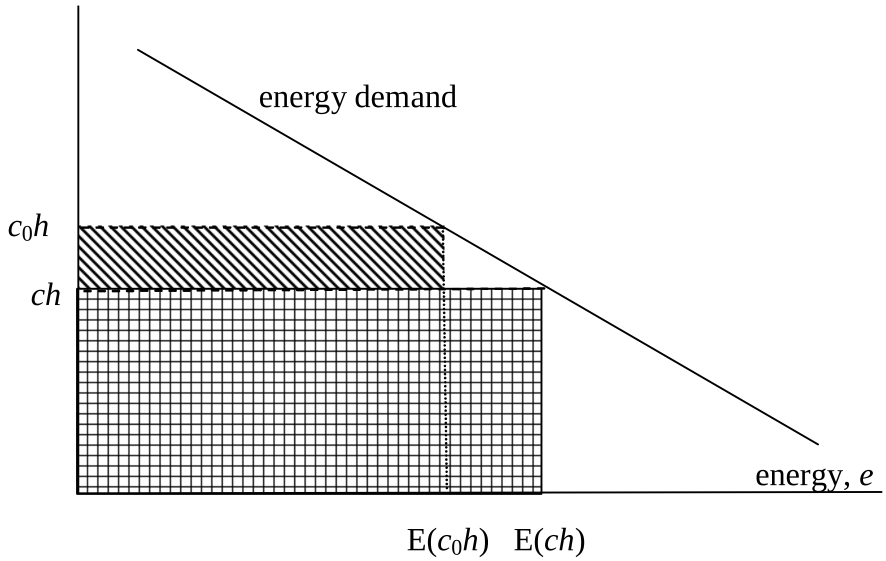

Figure 1: The efficient adjustment in energy supply and emissions when the emissions rate falls

profits in the energy market, and reduce the profitability of licensing. This is the essential revenue avantage that tax regulation has over cap-and-trade regulation.

However, to make this precise, the policies being compared must be benchmarked in some way. After laying out the basics in section 2, I compare the two policies, assuming in section 4 that they are initially equivalent, assuming in section 5 that they are equivalent ex post, and assuming in section 7 that they achieve the same carbon emissions after innovation has occurred. In section 3, I illuminate the diffusion problem that arises under cap-and-trade regulation, but not under tax regulation. If the clean technology is diffused widely, gross profits in the energy market fall, and thus the proprietor's share of the profits is smaller. He might avoid this by not licensing some of the producers, so that the full benefits of the clean technology are not realized. In section 6 I illustrate these ideas with an example.

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, shown in figure 1. I will refer to its inverse as $\mathrm{P}(\cdot)$, and will refer to gross profit in the energy market as $\mathrm{G}(E) \equiv E\mathrm{P}(E)$.

For simplicity, suppose the social cost of releasing carbon is the same for every carbon ton, say h. In the figures below, I will assume that the marginal cost of producing energy is zero, even though that is unrealistic. This allows us to isolate the effect of regulation on prices without cluttering the diagrams with marginal cost curves. Thus, in the absence of regulation, the competitive price of energy is zero.

The arguments below will be different depending on whether energy production is in the elastic or inelastic part of the demand curve, that is, whether the price of energy is relatively high (higher than the monopoly price in the energy market) or relatively low (lower than the monopoly price in the energy market).

An emissions tax should be levied on emissions, not on the energy that is produced. This encourages energy producers to avoid emissions by making good decisions about technologies and abatement, and about investing in cleaner technologies. The emissions tax should be equal to the social cost of emitting each carbon ton, which I will call h. In a competitive market where producers make zero profit, the equilibrium price of energy would then be ch, which achieves the efficient balance of energy production and emissions.

When a lower-emissions technology is introduced, the benefits can be taken either as higher energy supply, for example, keeping total emissions fixed, or as a reduction in emissions, for example, keeping the energy supply fixed. Which of these happens, or in what combination, depends on the regulatory policy. Figure 1 shows that it is optimal to adjust both energy supply and the level of emissions.

When the emissions rate falls from c_0 to c, the social cost of emissions per kilowatt hour (equivalently, the optimal price of energy) falls from c_0h to ch. In figure 1, the optimal supply of energy increases from $\mathrm{E}(c_0h)$ to $\mathrm{E}(ch)$. Total emissions go from $c_0\mathrm{E}(c_0h)$ to $c\mathrm{E}(ch)$. If the efficient price c_0h is in the inelastic part of the demand curve (c_0h is smaller than the revenue-maximizing price of energy), then the gross profits in the energy market satisfy $c_0h\mathrm{E}(c_0h) > ch\mathrm{E}(ch)$. Dividing by h, this implies that total emissions should optimally decrease. More surprisingly, if the efficient price ch is in the elastic part of the demand curve (ch larger than the revenue-maximizing price of energy), then $c_0h\mathrm{E}(c_0h) < ch\mathrm{E}(ch)$, which implies that emissions should optimally increase rather than decrease. That is, when the emissions rate goes down, the supply of energy should increase so much that emissions also go up. In that area of the demand curve, the willingness to pay for energy is high relative to the social harm from emissions.

- When a lower emissions technology becomes available, it is optimal to take the benefits of that technology as an increase in energy production and a decrease (respectively, increase) in carbon emissions when the energy production is in the inelastic (respectively, elastic) part of the demand curve.

3 The problem of diffusion

With regulation in place, to what extent will the private market step up to develop cleaner technologies? Ultimately, the incentives depend on intellectual property protection, and on the benefits to producers of licensing a cost-reducing innovation. In the case of tax regulation, the license allows the producer to pay less in emissions taxes. In the case of a carbon cap, the license allows the producer to buy fewer emissions allowances. Thus, the willingness to pay for licenses depends either on the tax rate or on the allowance price. The profitability of a cleaner technology depends on the stringency of the regulation.

In order to compare the incentive effects of the two regulatory policies, we must first ask whether an innovation, once it is achieved, will be diffused fully to the producers of electricity. By full diffusion, I mean that no energy is produced with the old technology. I show that there will be full diffusion with tax regulation, but not necessarily with a cap-and-trade policy. This is the first sense in which tax regulation may be the superior instrument.

I assume there is an initial technology with emissions rate c_0, which is nonproprietary. I then suppose that a proprietor has introduced a new technology with a lower emissions rate, say $c < c_0$. I will refer to the percentage reduction in emissions rate, $\left(\frac{c_0 - c}{c_0}\right)$, as the size of the improvement.

I assume throughout that the energy sector is competitive and that the marginal resource cost of producing energy is zero. This means that under a tax policy, the competitive price of energy is equal to the taxes paid plus the royalty. Under a carbon policy, the competitive price of energy is equal to the allowances purchased plus the royalty.

First consider tax regulation. The royalty, say γ, is levied on kilowatt hours of energy produced with the new technology. It must satisfy $\gamma \leq \tau (c_0 - c)$, where τ is the tax on emissions. Otherwise producers prefer the old technology. The price of energy is $\min \{c_0 \tau, c\tau + \gamma\}$. The government and the proprietor divide the price of energy between them, and if the maximum royalty is used, the proprietor's share is the fraction $\left(\frac{c_0 - c}{c_0}\right)$, namely, the size of the improvement. With the maximum royalty, energy production and the price of energy are the same as with the old technology, namely, $c_0 \tau$. However, as we will see below, the proprietor might want to charge a smaller royalty in order to expand the number of licensees.

In contrast, it might be profitable under a carbon cap to let some of the producers use the old technology. It might be profitable to restrict energy supply below its maximum $\mathbb{C}/c$, and this can only be done by letting some producers use the old technology. If all producers use the new technology but energy supply is less than $\mathbb{C}/c$, there must be an excess supply of allowances. This cannot be an equilibrium, as the excess allowances will find their way into use. Thus, in the case of carbon regulation, I will use the term "full diffusion" to mean that energy supply is at its maximum under the cap, $\mathbb{C}/c$.

Under carbon regulation, the royalty rate γ and the allowance price, say q, satisfy the following two conditions, which say that producers make zero profit using either technology. If producers strictly prefer the new technology (that is, if $c_0 q > cq+\gamma$), the proprietor could raise the royalty a bit without losing licensees, which would be profitable.

$$\begin{aligned} \mathrm{P}(E) &= c_0 q \\ \mathrm{P}(E) &= cq + \gamma \end{aligned} \tag{1}$$

Here, E is the total supply of energy produced using the old and new technologies. These expressions again assume that producers are competitive, so that the price of energy is the sum of the royalty γ and payments to the owners of allowances, either $c_0 q$ or cq, depending on which technology is used.

Solving the two equations,

$$\gamma = \left(\frac{c_0 - c}{c_0}\right) \mathrm{P}\left(E\right) \tag{2}$$

The proprietor thus receives a fraction $\left(\frac{c_0-c}{c_0}\right)$ of the energy price from the licensees, and the rest is paid to the owners of allowances. For kilowatt hours supplied with the old technology, the entire price is paid to owners of allowances.

In figure 2, the carbon cap is $\mathbb{C}$, and an improvement $\left(\frac{c_0-c}{c_0}\right)$ can allow energy supply to expand from $\mathbb{C}/c_0$ to $\mathbb{C}/c$. However, full diffusion might not be the most profitable choice. The expressions (1) show that a higher royalty γ leads to a higher allowance price q, a higher price of energy, and implicitly, fewer licensees. If less energy is demanded, a larger share of it must be supplied by high-carbon producers. Otherwise there would be an excess supply of allowances, which cannot be an equilibrium.

Figure 2 shows a situation where the optimal royalty rate leads to energy supply $E = \mathbb{C}/c_d < \mathbb{C}/c$, that is, incomplete diffusion. A lower royalty would allow energy production to expand to its maximum, $\mathbb{C}/c$, but that reduces the proprietor's revenue. The shaded areas show the proprietor's licensing revenue with limited diffusion and with full diffusion. In each situation, the proprietor earns a share $\left(\frac{c_0-c}{c_0}\right)$ of the energy price. Full diffusion to $\mathbb{C}/c$ is not optimal because the price of energy falls too much. Even though the proprietor gets a fixed share of the licensees' profit, and even though there are more licensees with full diffusion than with partial diffusion, the licensees make less gross profit.

We can conclude from this that there is a maximum expansion in energy supply, in particular to $\mathbb{C}/c_d$, that the proprietor will facilitate. If the improvement is small, such that $\mathbb{C}/c < \mathbb{C}/c_d$, the proprietor will diffuse the innovation fully, and the innovator gets a share $\left(\frac{c_0-c}{c_0}\right)$ of the price on every kilowatt hour sold in the market. If the improvement is large,

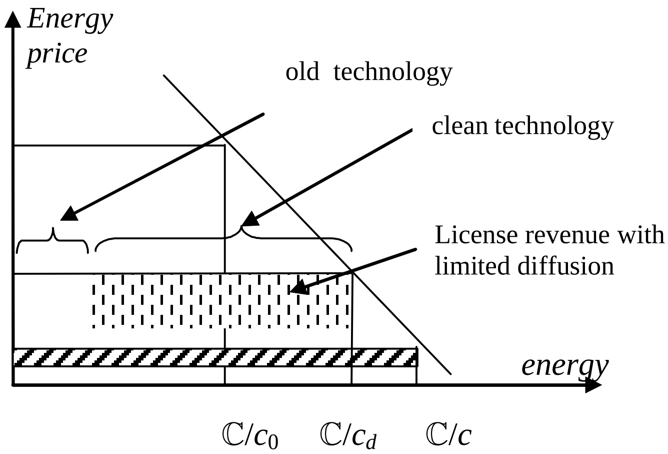

Figure 2: Limited diffusion of large improvements in the cap-and-trade regime

such that $\mathbb{C}/c_d < \mathbb{C}/c$, the proprietor will limit diffusion. He still earns a share $\left(\frac{c_0-c}{c_0}\right)$ of the energy price on each kilowatt hour supplied under license, but there are a smaller number of kilowatt hours at a higher price than with full diffusion.

Of course, as I have already mentioned, it is not necessary that the proprietor literally witholds his offer from some of the producers. He can achieve the desired outcome by charging a higher royalty. Given a royalty γ, producers will enter until the competitive supply, say $\mathbb{C}/c_d$, satisfies $\gamma = \left(\frac{c_0-c}{c_0}\right)\mathrm{P}\left(\frac{\mathbb{C}}{c_d}\right)$. This royalty is larger than the royalty that would yield full diffusion, namely, $\gamma = \left(\frac{c_0-c}{c_0}\right)\mathrm{P}\left(\frac{\mathbb{C}}{c}\right)$.

The problem of diffusion feeds back into the problem of innovation. Under tax regulation, an innovator's licensing revenue increases with the size of the improvement. This is not true under a carbon cap for improvements larger than $\left(\frac{c_0-c_d}{c_0}\right)$. Although this is not obvious from figure 2, it is an easy calculation. Suppose that the supply produced under license, say $\hat{e}$, leads to total energy supply $\mathbb{C}/c_d$. Then $\hat{e}\left(\frac{c_0-c}{c_0}\right) = (\mathbb{C}/c_d) - (\mathbb{C}/c_0)$. For an improvement c and licensing $\hat{e}$, the innovator's licensing revenue is given by the left side of (3). The innovator's profit when the improvement c_d has been achieved is the right side.

$$\left(\frac{c_0-c}{c_0}\right)\hat{e}\mathrm{P}\left(\frac{\mathbb{C}}{c_d}\right) = \left(\frac{\mathbb{C}}{c_d} - \frac{\mathbb{C}}{c_0}\right)\mathrm{P}\left(\mathbb{C}/c_d\right) = \frac{\mathbb{C}}{c_d}\left(\frac{c_0-c_d}{c_0}\right)\mathrm{P}\left(\frac{\mathbb{C}}{c_d}\right) \quad (3)$$

As discussed by Fischer et al (2003), an intuitive explanation for why the proprietor limits diffusion is that licensing causes the price of allowances to fall. Since the producers' willingness to pay for licenses depends on the avoided payments for allowances, the fall in the allowance price reduces the producers' willingness to pay, and cuts into licensing revenue.

The conclusions of this section are

- A proprietary clean technology will be fully diffused under tax regulation, but not necessarily under a carbon cap.
- Under cap-and-trade regulation, an innovator cannot increase licensing revenue by investing in a larger improvement than would be fully diffused.
- If both the original price of energy and its price under full diffusion are in the elastic part of the demand curve, innovations will be fully diffused.

The last point follows because, due to demand elasticity, an increase in aggregate supply increases gross profit in the energy sector. An expansion in licensing increases both the gross profit in the energy market and the share of gross profit earned by licensees. Hence the innovator benefits from an expansion.

4 Incentives when the regulatory policy is fixed

In order to compare the incentives for innovation under the two regulatory policies, the policies must be benchmarked in some way. In this section, I compare the two regulatory policies that are equivalent *before* the innovation, in the sense that they support the same energy supply and the same carbon emissions, such as the efficient ones. In section 5, I compare the two regulatory policies that are equivalent *after* the innovation, in the sense that they support the same energy supply and carbon emissions afterwards. Policies that are equivalent before the innovation will not be equivalent afterwards, even with the same size innovation.

Incentives in both regulatory environments depend on whether the regulated energy price is in the elastic or inelastic part of the demand curve. I first consider the elastic part of the demand curve, where the regulated price of energy is initially higher than the monopoly price.

4.1 Taxes and caps when demand is elastic at the regulated supply

Suppose that demand is elastic at the regulated price of energy, that is, the regulated price is above the monopoly price.

First consider tax regulation, where τ is the tax on emissions and $c_0\tau$ is the initial regulated price of energy. When the proprietor introduces the clean technology, he will charge a royalty γ on kilowatt hours, such that $\gamma \leq (c_0 - c)\,\tau$.

If the proprietor charges the maximum royalty, he receives a share $\left(\frac{c_0 - c}{c_0}\right)$ of gross profit in the energy market; otherwise his share is lower. If the improvement is modest, he will charge the maximum, and energy production will not expand, but for a large improvement, he may charge a royalty $\gamma < (c_0 - c)\,\tau$ in order to add licensees. With a larger improvement, each licensee pays a larger royalty, so adding licensees becomes more lucrative, even if each one pays a slightly smaller royalty. However, the royalty will never be reduced to the point that the price of energy drops below the monopoly price. In the extreme case that $c = 0$, the royalty will be the monopoly price, and for positive emissions rates will be higher.

Now consider the equivalent carbon cap, $\mathbb{C} = c_0 \mathrm{E}(c_0 \tau)$. In contrast to the emissions tax, a carbon cap will always cause the supply of energy to expand. The higher the energy supply, the larger fraction is supplied by producers under license.

Under cap-and-trade regulation, the proprietor always earns a fixed fraction, $\left(\frac{c_0 - c}{c_0}\right)$, of the licensees' gross profit. From this we can conclude that the proprietor will always want to expand production beyond the monopoly supply if that is possible under the cap. When production is in the elastic part of the demand curve, an expansion in supply increases gross profit, and at the same time, increases the share of gross profit earned by the licensees. Thus, the expansion is good for the proprietor.

We conclude

- if demand is elastic at the initial regulated price, tax regulation leads to an energy price that is higher than the monopoly price, regardless of the size of the innovation;
- if demand is elastic at the initial regulated price, carbon regulation leads to an energy price that is lower than the monopoly price if that is feasible under the carbon cap.

These conclusions can be seen in figure 3. The dark lines bracket the prices that the proprietor can support with his royalty under tax regulation. The vertically shaded area shows the proprietor's profit, which is close to the monopoly profit in the energy market if c is small. The horizontally shaded area shows the proprietor's profit under cap-and-trade regulation, and shows that the price will be smaller than the monopoly price, even if full diffusion is not optimal.

The theme in the two bullet points and in figure 3 will recur throughout this analysis: Under tax regulation, the royalty controls the price of energy and total energy supply, but the clean technology is fully diffused in the sense that no producers of energy use the old technology. Under a carbon cap, the royalty controls not only the price, but also the fraction of the market that is served by the proprietor's licensees. The clean technology might not be fully diffused. Under cap-and-trade regulation, the proprietor faces a tradeoff between the fraction of the producers who take licenses and the royalty he charges.

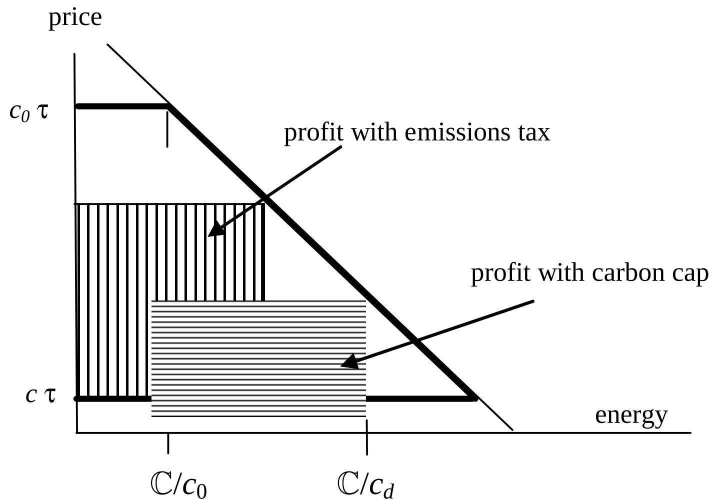

Figure 3: Licensing under an emissions tax and a carbon cap when the improvement is large and the regulated price was initially high.

4.2 Taxes and caps when demand is inelastic at the regulated supply

When the regulated price is lower than the monopoly price, the proprietor's licensing revenue can be characterized under both regulatory policies as the size of the improvement times the gross profit earned by the licensees. Under tax regulation, the proprietor cannot increase profit by choosing a royalty lower than its maximum, $\gamma = \tau\,(c_0 - c)$. Lowering the royalty would decrease both the gross profit earned in the energy market and the gross profit earned by licensees, which are the same. This cannot be profitable. Hence, the proprietor charges the maximum royalty and earns a share $\left(\frac{c_0 - c}{c_0}\right)$ of gross revenue in the energy market. This is shown in figure 4.

Under the carbon cap, the proprietor also earns the share $\left(\frac{c_0 - c}{c_0}\right)$ of licensees' profit. To have any licensees at all, he must expand supply, which reduces gross profit. Whether the innovation is fully diffused or not, gross profit in the energy market, and therefore the licensees' gross profit, is smaller than under tax regulation. Hence, the proprietor earns less under a carbon cap than under tax regulation.

With full diffusion (and using the expression (3) with $\frac{\mathbb{C}}{c_d} = \frac{\mathbb{C}}{c}$), the proprietor's profit under a carbon cap is

$$\left(\frac{\mathbb{C}}{c_0} - \frac{\mathbb{C}}{c}\right) \mathrm{P}\left(\frac{\mathbb{C}}{c}\right) = \left(\frac{c_0 - c}{c_0}\right) \left[\frac{\mathbb{C}}{c} \mathrm{P}\left(\frac{\mathbb{C}}{c}\right)\right]$$

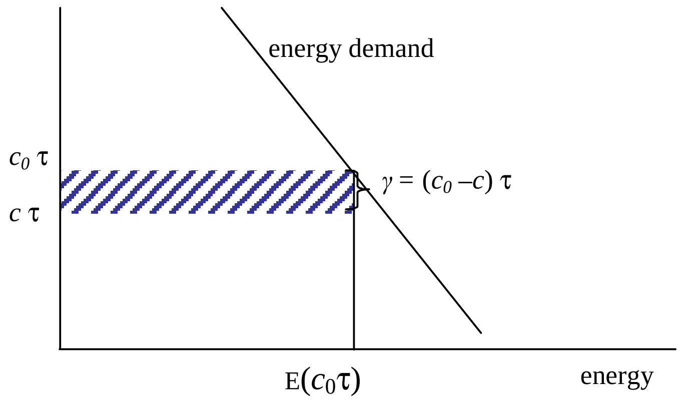

Figure 4: Licensing revenue with a fixed emissions tax, leading to price in the inelastic part of the demand curve

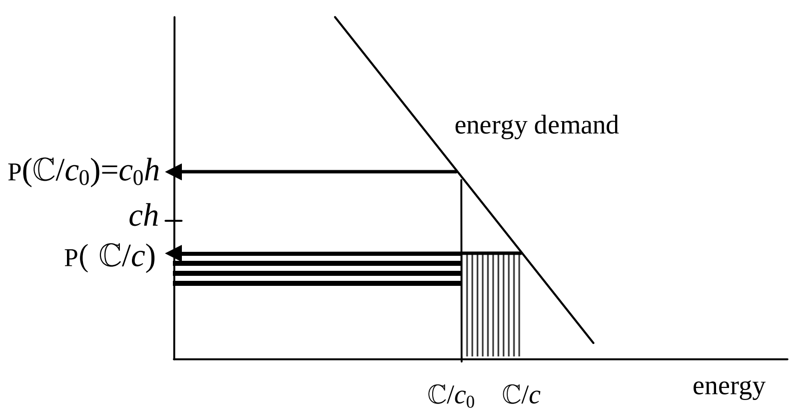

Figure 5: Licensing revenue with a fixed carbon cap and full diffusion of the cleaner technology

Figure 5 shows these two representations of profit, which are equal.

It is also instructive to consider how the licensing revenue matches up to the social value of the innovation. Suppose, in particular, that the regulatory policy is the efficient one, where the emissions tax is equal to the social cost of carbon emissions, $\tau = h$. With the efficient tax in place, figure 4 shows that the proprietor's per-period licensing revenue is equal to the social value of the reduced carbon emissions, namely, $(c_0 - c)\, h$ times energy production. This suggests that the regulatory tax is a good incentive scheme, since the innovator receives a reward that is commensurate with the social value he provides. At the same time, however, the adjustment in the market is *not* efficient. The entire benefit of the cleaner technology is taken as a reduction in emissions, with no expansion in energy supply. As argued above, this is not the efficient way to use the new technology.

The equivalent (efficient) carbon cap is $\mathbb{C} = c_0 \mathrm{E}(c_0 \tau)$. With this cap in place, the price of carbon allowances before the innovation is $c_0 \tau$, just as with the tax $\tau = h$. This is shown in figure 5. However, the carbon emissions and energy supply are inefficiently high at the new emissions rate. As argued in section 2, when the regulated price is in the inelastic part of the demand curve, it would be efficient to reduce energy production in order to reduce total carbon emissions. If $\mathbb{C}/c_0$ is the efficient energy supply at the original emissions rate c_0, then the efficient energy supply at the smaller emissions rate c is smaller than $\mathbb{C}/c$, the efficient carbon emissions are smaller than $\mathbb{C} = c\mathrm{E}(c_0 h)$, and the new price of energy, $\mathrm{P}(\mathbb{C}/c)$ is smaller than the efficient price of energy, ch.

Figure 5 shows that the proprietor's per-period licensing revenue is smaller than the social value he provides. The social value is not the benefit of reduced carbon, as with the emissions tax, because the carbon emissions stay fixed. The social value is the consumers' surplus from expanded energy consumption. The proprietor does not collect the entire increase in consumers' surplus as profit.

I summarize these conclusions as follows.

- Suppose that the emissions tax and carbon cap support equal energy production and carbon emissions using the old technology (for example, the efficient level). If energy production is in the inelastic part of the demand curve,
  - after the innovation, cap-and-trade leads to larger energy production than an emissions tax, and to less licensing revenue for the proprietor;
  - if all production is under license, the proprietor earns the same fraction of the gross profit in the energy market under both policies, but gross profit is smaller under cap-and-trade regulation than under tax regulation;
  - the social benefits of the improvement are taken as increased energy production under the carbon cap, but as a reduction in carbon emissions under the emissions tax.

5 Efficency Adjustments

Whether regulation is by an emissions tax or a carbon cap, the policy will generally not be efficient ex post, even if it was efficient ex ange, and there will be pressure to change the policy after the cleaner technology is introduced. It is the anticipated policy that matters for incentives, rather than the policy initially in effect.

A difficulty under carbon regulation is that it might be impossible to implement the efficient energy supply and carbon emissions. Suppose that the initial emissions rate c_0 is high, and the proprietary emissions rate c is very low. Suppose the carbon cap is such that $\mathbb{C}/c$ is the efficient energy supply. As discussed in section 3, the proprietor might set a high royalty that excludes some producers and achieves a smaller supply of energy with a higher price. If so, there is no ex post carbon cap that will achieve static efficiency. Partial diffusion is never efficient.

On the other hand, we showed that the proprietor gets no additional revenue from an improvement larger than the maximum that would be licensed. Therefore, if he anticipates the efficiency adjustment, he will never invest in an improvement that would only be diffused partially. Although this relieves the problem of incomplete diffusion, it highlights that there is generally less incentive to innovate under a carbon cap than under a tax.

The problem of incomplete diffusion does not arise with a tax. The cleaner technology will be fully diffused under tax regulation, and for a given target energy supply, there is always an emissions tax that achieves it. A higher tax leads to a higher royalty because the higher tax makes the license more valuable. Both lead to a higher price of energy and lower production.

The natural objective for an ex post adjustment is efficiency in the sense of section 2, describing the optimal tradeoff between energy production and carbon emissions. If the clean technology were in the public domain, this would be achieved by setting the tax equal to the social cost of emissions, $\tau = h$. However, when the clean technology is proprietary, the emissions tax must be lower. Otherwise, the price of energy would be inefficiently high when the proprietor's royalty is added to the tax. Denicolo (1999) points out that when the optimal royalty is set as $\gamma = \tau (c_0 - c)$, the emissions tax should be chosen as $\tau = (c/c_0) h$ instead of $\tau = h$. If the innovation is such that the proprietor would set $\gamma < \tau (c_0 - c)$, then the tax rate that implements the intended energy price must be higher than $(c/c_0) h$, but not as high as h.

When the royalty is $\gamma = \tau (c_0 - c)$, the proprietor earns the fraction $\left(\frac{c_0 - c}{c_0}\right)$ of gross profit in the energy sector. The proprietor also earns the fraction $\left(\frac{c_0 - c}{c_0}\right)$ under the optimal carbon cap, although this is a share of licensees' profit, which may be less than the gross profit in the energy sector if some producers are excluded.

The conclusions are

- When the clean technology is proprietary, an emissions tax should be smaller than the social cost of emissions.
- For an arbitrary proprietary improvement, there might not be a carbon policy that implements the efficient supply of energy and emissions ex post. There is always an emissions tax that does so.
- When the initial regulated price of energy is in the inelastic part of the demand curve, a policy adjustment for ex post efficiency will increase the innovator's licensing revenue under cap-and-trade regulation, but will reduce it under tax regulation.
- When the initial regulated price of energy is in the inelastic part of the demand curve, and with a policy adjustment for ex post efficiency, the proprietor earns the same licensing revenue under both regimes if the innovation is fully diffused under both regimes.

The last two points follow from my characterization of licensing revenue as a fraction of gross profits in the energy market. In the inelastic part of the demand curve, the optimal adjustment to the carbon cap is to tighten it up. As compared to no adjustment, this increases the price of energy and increases gross profits in the energy market. The optimal adjustment of the emissions tax is to reduce it, which reduces the price of energy and reduces gross profits in the energy market. But if the two policies are equivalent ex post, they generate the same gross profit for licensees in the energy market, which leads to the same licensing revenue for the innovator.

6 Comparing Incentives

It is instructive to work out an example, showing how the profits compare. In this example, all the action takes place in the inelastic part of the demand curve (the regulated price of energy is lower than monopoly price).

Suppose that the marginal social cost of emissions is $h = 1$, 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 $2 - c$, and the optimal carbon output is $c\,(2 - c)$. Let the initial emissions rate be $c_0 = 1$, which means that the initial regulated price of energy is the monopoly price in the energy market. Improvements will be at prices in the inelastic part of the demand curve.

Suppose that a proprietor achieves a new technology with emissions rate $c < c_0$.

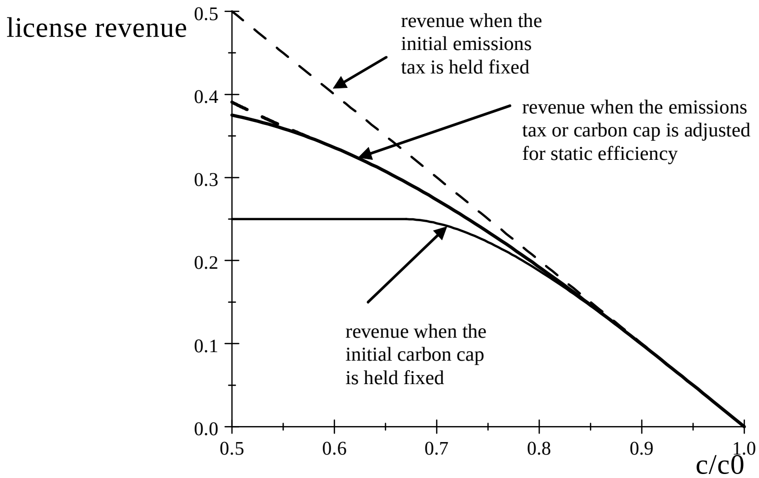

Figure 6: Comparison of licensing revenues with fixed emissions tax and carbon cap

First consider the emissions tax. When energy producers must pay the efficient tax $\tau = 1$ on emissions, the proprietor's most profitable royalty satisfies $\gamma = 1 - c$. Then the price of energy is the same as before the innovation, namely 1. In addition, gross profit in the energy market is 1, and 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 dashed line in figure 6, as a function of c/c_0. Large improvements (small c) are on the left side of figure 6.

Now consider a carbon cap. To be optimal, the carbon cap must initially be $\mathbb{C} = 1$. The proprietor's revenue is the fraction $\left(\frac{c_0 - c}{c_0}\right)$ of licensees' profit. This is shown by the solid bottom line in figure 6, as a function of the new emissions rate. The left side represents large improvements (small c), for which the proprietor will restrict the supply of licenses as discussed in section 3. This is why profit is constant for small c. For lesser improvements (toward the right side of the diagram), the proprietor diffuses fully, and the royalty satisfies $\gamma = \left(\frac{c_0 - c}{c_0}\right) \mathrm{P}\left(\frac{\mathbb{C}}{c}\right)$. For each c, energy supply expands from $\frac{\mathbb{C}}{c_0}$ to $\frac{\mathbb{C}}{c}$.

On the right side of the diagram, where the proprietor diffuses fully in both regulatory regimes, profit is greater in the tax regime because the supply of energy is smaller, and gross profit is larger.

The middle line in figure 6 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 $c\,(2 - c)$. The two regimes produce the same gross profit in the energy market, and with full diffusion, this is why the proprietor's licensing revenues are the same. At the extreme left of the diagram, there is a "spur" lying above the solid line, which reflects the fact that for low values of

c (large improvements), the proprietor will not provide full diffusion in the cap-and-trade regime, and his profit is larger when he excludes some producers.

Figure 6 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.

7 The commitment problem: Who moves first?

I have shown that, for a given improvement $\left(\frac{c_0-c}{c_0}\right)$, the proprietor earns the same licensing revenue in both regimes, provided both regimes support the same energy supply and carbon emissions with the new technology in place. In particular, the policy may be adjusted to achieve efficiency ex post as described in section 4.

However, even if the two policies are equivalent, they might not be very lucrative. Suppose, for example, that an innovator makes a very large improvement, so that the new emissions rate is very low, even zero. An efficient regulatory adjustment of either type would increase energy supply substantially, reducing the price of energy and reducing gross profits in the energy sector. This makes the innovator's reward low, even if the innovator gets almost all the profit. Anticipating the low reward, the innovator might not invest, at least in a large improvement.

But how would regulators achieve the outcome in any case? The efficient emissions tax is still $\tau = h$, which means that production with the old technology must be at a high price. The proprietor of the zero-emissions technology will license for a royalty that supports either the price $c_0\tau$ or the monopoly price in the energy sector if that is lower. The full benefits of efficient energy production will not be realized, but this outcome mimics what generally happens with intellectual property protection. The innovation is diffused, although at a high price, and the innovator is rewarded with a monopoly position in the market.

However, the carbon cap presents a more serious challenge as to what regulators should do. The efficient carbon cap is zero, which will obviously not support innovation. To avoid this ex post "expropriation of benefits," the regulator might want to commit in advance to a more stringent tax or carbon cap (Laffont and Tirole, 1996, Montero, 2010). I now ask how the ability to commit affects this regulatory environment.

By commitment, I mean that the regulator moves first, and guarantees either an emissions tax or a carbon cap that will be in effect after the innovation takes place. The regulator binds himself not to erode the innovator's profit, even if that would be efficient.

While this solves the problem of getting the innovators to trust the regulatory environment, it introduces another problem: The policy cannot be tailored to the size of the innovation.

Suppose, in particular, that the regulator commits to achieve a given level of emissions $\mathbb{C}$. In the cap-and-trade regime, he sets $\mathbb{C}$ as a carbon cap directly. Innovators respond to this commitment by investing in improvements as they find profitable. Both the emissions rate c that emerges is endogenous, and so is the supply of energy $\mathbb{C}/c$. There is no guarantee that the supply of energy $\mathbb{C}/c$, together with the carbon emissions $\mathbb{C}$, will be efficient for the emissions rate c, as described in section 2.

Now suppose the regulator uses tax regulation τ instead of a cap. If an innovator achieves the emissions rate c, the price of energy will be $c\tau$. Energy will be supplied in amount $\text{E}(c\tau)$. This achieves the carbon cap $\mathbb{C}$ if the new emissions rate c and the tax τ satisfy $c\text{E}(\tau c) = \mathbb{C}$. Again, there is no guarantee that the carbon cap $\mathbb{C}$, together with the energy supply $\text{E}(c\tau)$, are efficient for the endogenous emissions rate c. Further, there is no reason to believe that innovators will undertake the same size improvement in both regimes.

Like the arguments above, it can be shown in this setup that the emissions tax is more conducive to innovation than a carbon cap. However, it is phrased a little differently. In section 4 I argued that, if the two policies are equivalent in the sense of achieving the same energy supply and carbon emissions with the old technology, and if the energy supply is in the inelastic part of the demand curve, then any given improvement is more lucrative for the innovator under the emissions tax than under the equivalent carbon cap. The argument was benchmarked to policies that are equivalent before the innovation. Here I make a similar argument that is benchmarked differently, but still has the conclusion that emissions taxes are more conducive to innovation when energy supply is in the inelastic part of the demand curve.

In particular, suppose that a regulator commits to an emissions tax τ, which leads to an improvement $\left(\frac{c_0-c}{c_0}\right)$ and to an emissions level $c\text{E}(\tau c) = \mathbb{C}$. As in Denicolo (1999), I compare this with a carbon policy that sets the cap $\mathbb{C}$ directly. The idea is that the regulator targets a given level of emissions, whether he does it with the emissions tax or a carbon cap.

Suppose that the proprietor chooses his maximum royalty under tax regulation and chooses full diffusion under carbon regulation. Then with tax regulation, the proprietor's licensing revenue is $\left(\frac{c_0-c}{c_0}\right)\text{G}(E)$ where $E = \mathbb{C}/c$, and the marginal profit available from a marginal reduction in c is $\frac{d}{dc}\left(\frac{c_0-c}{c_0}\right)\text{G}(E)$. With cap-and-trade regulation, and $\mathbb{C}$ as a carbon cap, the proprietor's licensing revenue is $\left(\frac{c_0-c}{c_0}\right)\text{G}\left(\frac{\mathbb{C}}{c}\right)$. The marginal profit available from a marginal reduction in c is $\frac{d}{dc}\left(\frac{c_0-c}{c_0}\right)\mathrm{G}\left(\frac{\mathbb{C}}{c}\right)$. Then

$$\begin{aligned}\frac{d}{dc}\left(\frac{c_0-c}{c_0}\right)\mathrm{G}(E) &< \frac{d}{dc}\left(\frac{c_0-c}{c_0}\right)\mathrm{G}\left(\frac{\mathbb{C}}{c}\right) \\ \text{if } \frac{\mathbb{C}}{c} &= E \text{ and demand is inelastic at } E \\ \frac{d}{dc}\left(\frac{c_0-c}{c_0}\right)\mathrm{G}(E) &> \frac{d}{dc}\left(\frac{c_0-c}{c_0}\right)\mathrm{G}\left(\frac{\mathbb{C}}{c}\right) \\ \text{if } \frac{\mathbb{C}}{c} &= E \text{ and demand is elastic at } E\end{aligned}$$

Since an improvement is achieved with a reduction $dc < 0$, a smaller derivative means a larger incentive to invest in an improvement. Because an incremental reduction in the emissions rate increases energy supply under carbon regulation but not under tax regulation, the marginal reduction is more (less) lucrative under tax regulation than under carbon regulation if energy supply is in the inelastic (elastic) part of the demand curve. It is the inelastic part of the demand curve that is mostly of interest, since the hypothesis of full diffusion might not be satisfied in the elastic part.

These inequalities show that the relative incentives to invest are driven by how gross profit changes in the energy sector when a larger improvement is achieved. In both regulatory regimes, the innovator earns the same fraction of gross profit in the energy sector, namely, the size of the improvement. In both regimes, making a larger improvement increases the innovator's share of gross profit, but in the case of a carbon cap, there is a second effect. The gross profit changes as well. This is because the supply of energy increases and its price falls. The gross profit increases if the energy supply is in the elastic part of the demand curve, and decreases if energy supply is in the inelastic part of the demand curve.

How this matters for the innovative process depends on the nature of innovation. Denicolo (1999) and Montero (2010) give a classical analysis in which there is a production function for reducing the emissions rate, and the marginal cost of reducing c is increasing. The innovator's best response to the regulatory policy is to achieve the size of improvement such that the marginal licensing revenue is equal to the marginal cost of improving the emissions rate. On that reasoning, we can conclude the following.

- Consider tax and carbon policies that lead to the same carbon emissions with innovation, and suppose that the resulting energy supplies are in the inelastic part of the demand curve. Then the carbon emissions are achieved with a higher energy supply and more innovation under tax regulation than under carbon regulation.
- Consider tax and carbon policies that lead to the same carbon emissions, and suppose that the resulting energy supplies are in the elastic part of the demand curve. Then the carbon emissions are achieved with a lower energy supply and a smaller improvement under tax regulation than under carbon regulation.

8 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.

The thrust of the arguments summarized here is that tax regulation creates higher rewards for innovation than carbon caps, at least when energy production is in the inelastic part of the demand curve (when the price is lower than the monopoly price in the energy market). Otherwise that finding can be reversed.

In fact, I have illuminated two reasons that carbon emissions may be hard to control in cap-and-trade regime than in a tax regime:

- The cap-and-trade regime may generate less licensing revenue for innovators;
- In a cap-and-trade regime, innovations might not be fully diffused, whereas they will always be diffused fully in a tax regime.

However, the overriding problem is probably the conflict between static efficiency and innovation, where static efficiency means achieving the right balance of energy production and carbon emissions, conditional on the emissions rate. If the new technology is very clean, a low price of energy would be efficient ex post, whether achieved by tax regulation or carbon cap. Neither regime can support ex post efficiency (a low energy price) while also creating substantial rewards for the innovator. In the tax regime, the clean technology can be protected by maintaining the optimal emissions tax. The tax will not be paid, because all producers will use the clean technology. The role of the tax is to prevent entry and create market power for the proprietor. The proprietor will support a high price of energy with his royalty, leading to a large reward.

In the cap-and-trade regime, the regulator would have to choose a low carbon cap, which will support a high price of energy with a high price of allowances, as well as a royalty. As compared to the emissions tax, the policy creates a windfall for allowance holders, so the revenue that remains for the innovator is smaller.

In this latter solution, the regulator commits himself against adjusting the policy for ex post efficiency in order to support innovation (Laffont and Tirole, 1996, Montero, 2010). Too much of the benefit is taken as reduced emissions, and too little of the benefit is taken as an increase in energy consumption.

These problems surface immediately if one thinks about clean technologies like solar energy or wind power. The emissions rate for each of these technologies is essentially zero.

In countries where it is not subsidized on the demand side, solar power remains insignificant because of high capital costs (Borenstein, 2008). Wind power seems more cost-competitive for suitable sites, but there are few such sites (deCarolis and Keith, 2006). The unsuitability of sites lead to additional costs. Nevertheless, these technologies may eventually become competitive.

Another form of regulation is to set production standards directly. Although not focussing on innovation, Holland (2009) points out that standards can be better than either taxes or carbon caps, because standards have different price effects. Climate change is a global externality, and the solution must be global. Nevertheless, countries are not equally willing to control emissions. Regulation imposes costs on local industry. As a consequence, local production might be replaced by imports from non-regulating trading partners. This defeats the purpose of regulation and also creates a political obstacle. Although standards cut into profit, they might impose capital costs without imposing marginal costs, and will then have less effect on the price of energy. If producers have market power, they might be able to absorb the cost and stay in business, even if trading partners do not regulate.

The most direct solution is government subsidies for clean technologies. The obstacle here is international free-riding (Scotchmer, 2004b). Without an international treaty for joint development, the costs of the clean technology are paid by taxpayers in a single country. If the technologies are put in the public domain, other countries can use them without cost, which creates a positive externality for the subsidizer due to the global nature of externalities, but also relieves the the other countries of sharing the cost. The free-riding problem may be one reason that more and more government-sponsored innovation is only made available under a royalty arrangement (Scotchmer 2004a, chapter 8).

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 of Fischer et al (2003). I have characterized the licensing revenue of the innovator as the size of the innovator's improvement times the gross profit collected by licensees. 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 mostly 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. Because the allowance market must clear, energy supply must expand under the carbon cap when licensing occurs, but need not expand under tax regulation. At least when demand is inelastic, the expansion reduces gross profit in the energy market, which also reduces the proprietor's licensing revenue. Another way to express the revenue disadvantage of the carbon cap is through the endogeneity of the allowance price. I showed in section 6 that the price effect, and therefore the revenue discrepancy, can be significant.

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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