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Incentives for innovation and adoption of new technology under emissions trading

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Abstract

A common claim in both the public and academic debate is that a tradable emission permits scheme does not provide sufficient incentives for R&D investments. The present paper addresses R&D investments and penetration rates of new technology focusing on the specific characteristics of a tradable permits market. It is showed that a complex dependency between the emissions cap, the market price for emission permits, the price for technology once it is developed and the R&D investment decision add an additional layer to the 'traditional' market failures associated with R&D. Even though the cap and how it is calibrated in response to the introduction of new technology is shown to be of importance both for the level of R&D investment and the technology's penetration rate, we argue that the policy maker's ability to use the cap to counter market failures in the R&D stage is limited. This is due to a dynamic inconsistency problem where the policy maker is unable to credibly commit to a future policy that is more stringent than motivated by efficiency concerns given the then existing technology. Such a policy may not be stringent enough to cover the necessary R&D investments.

JEL classifications; *L51, O31, Q55, Q58*

Key words: *Tradable permits, Innovation, R&D, Policy, Dynamic inconsistency*

1. Introduction

The use of economic instruments to regulate emissions has gained widespread acceptance and popularity over the last decades. They have been subject to extensive discussions both in the academic and public debate, not least in the wake of climate change having evolved into a major policy issue. A claim in the debate is that there is a great need for technological change if the climate targets are to be reached, see *e.g.*, Barret (2009). Another claim is that even if a cap-and-trade approach will establish a price for emissions and thereby creates incentives for technological change, this will not be enough. That is, there is a need for additional policy instruments in order to spur the required research and development (R&D). The second claim, which will be addressed in this paper, is in a way obvious. Conventional wisdom suggests that usually more than one policy instrument is needed to remedy a situation characterized by more than one market failure. In the climate policy case the cap-and-trade regime primarily targets the externality of greenhouse gas emissions. That the market generally provides less than the socially desirable amount of R&D follows from other market failures typically associated with knowledge having public goods characteristics so the full benefit of the R&D is not appropriable to the innovating party. This is often referred to as spill-over.

Spill-over is a feature of basically all R&D, not just in that targeting markets regulated by a tradable permit scheme. However, a cap-and-trade regime in some sense creates an artificial market that differs from 'normal' markets as the demand for emission permits directly depends on political decisions. The question addressed in the paper is thus; does a cap-and-trade regime introduce additional problems from a technological change perspective as compared to a 'normal' market?

There is a vast literature on endogenous technological change (ETC) in general and induced technological change (ITC) in particular, *i.e.*, technological change following from, in this case, policies aimed at mitigating global warming. We will not review this literature here as there are several studies containing comprehensive surveys, *e.g.*, Gillingham et.al. (2008), Fisher and Newell (2007), Wing (2006), Gerlagh and Wise (2005), Jaffe et.al. (2005), Löschel (2002), and Weynant and Olavson (1999). To a large extent this literature deals with how to introduce ETC and/or ITC into simulation models in an appropriate way. Major obstacles to overcome include how to model the spill-over effects and, in particular, effects associated with learning-by-doing and learning-by-using. These effects are generic to most R&D, and therefore will not be in the focus of the present paper. To some extent the work above builds on an older literature that examines the impact on technological change from different policy instruments, *e.g.*, Milliam and Prince (1989), McHugh (1985), Magat (1979), and Orr (1976).

A more recent study which has gained attention in this field is Montgomery and Smith (2007), who paint a somewhat grim picture on the possibilities of achieving technological change through emission taxes or a cap-and-trade regime. They claim the problem lies in a dynamic inconsistency following from the government being unable to commit to a stringent future policy. In order to spur research activities the (future) price of emissions must be high, since this creates a demand for new technology capable of reducing emissions. The government must therefore declare a high tax level to be valid in the future, *i.e.*, when the new technology is available, in order to stimulate research. However, once the innovation is implemented, the government has an incentive to set the tax to a level below that declared. The reason is that the government, to minimize deadweight losses, would strive to set the tax such that the marginal cost of abatement equals the marginal benefit from abatement. That tax rate is typically too low to recover the development costs, which at this stage has already been sunk. This situation is likely to be anticipated by the developer who, knowing that there is a risk of not being able to recover R&D-costs, will not invest in R&D (or invest less than socially desirable). A similar problem is analyzed by Kremer (2000) for the case of research on vaccines for malaria, HIV and tuberculosis. A plausible analogous behaviour in the cap-and-trade case would entail the government setting a stringent cap to provide research incentives but, once the research has resulted in new technology, the cap will be relaxed, see Alfsen and Eskeland (2007).

The present paper focuses on the specific influence from a cap-and-trade regime on R&D investment using a similar set-up as Montgomery and Smith (2007). In particular, we study a case with distinct *ex ante* (before the R&D investment decision) and *ex post* (after the investment has resulted in new technology) stages. Certain attention is paid to the penetration rate of the new technology. In the present paper, emitters differ with respect to the costs associated with switching from old to new technology. It is then not necessarily the case that all emitting firms should adopt a new technology even from a social welfare perspective. We will show that the penetration rate depends on the cap-and-trade regime and how it is expected to be calibrated in response to new technology becoming available. The approach has similarities to Barret (2006), which also addresses penetration rates but in the form of the number of countries choosing to adopt a technology treaty.

The remaining paper is structured as follows. Section 2 presents the model and discusses both the market outcome and a social planner benchmark. Section 3 contains a discussion about policy recommendations following from the model. Finally, concluding remarks are given in section 4.

2. The model

The model contains several sequential steps as illustrated in Figure 1. First, the policy maker decides on a cap after which a developer decides on whether to invest in research, which will (deterministically) result in an innovation that reduces the costs of abatements. If the investment is made, the developer determines a price for the new product. We assume that the product is protected by a patent (or similar) such that the developer has monopoly power. Given the price, the emitters in the economy choose whether or not to buy the innovation. If they do, their abatement costs will decrease and, thus, they will emit less given that they are regulated by a cap-and-trade regime. If some emitters reduce their emissions there will be (1) a reallocation of abatements between emitters in the economy and (2) a reduction in the market price for emission permits. As the model is deterministic and all agents are rational, the impact of the introduction of the innovation, and how it is priced, on the market for emission permits will be taken into account both by the emitters in their choice whether to invest in the innovation and by the developer when deciding on whether to invest in research.

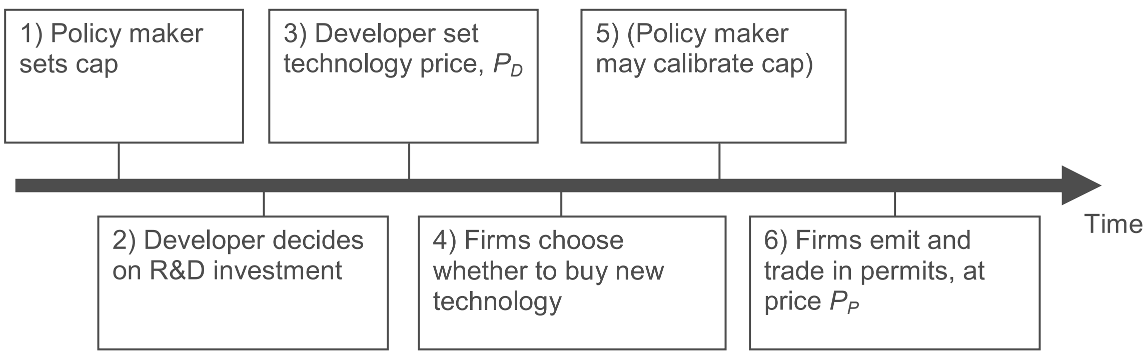

Figure 1, *Illustration of the sequential steps of the model*

The two stages in Figure 1 that regard the policy maker's behaviour, stage 1) and 5), will be addressed in a later section. Here we derive a model in which the government is passive in the sense that it decides on a cap in the *ex ante* stage, *i.e.*, before the research decision is made, that will be valid also for the *ex post* stage.

We start by solving the last stage of the game, labelled 6) in Figure 1, in which the firms trade in emission permits. Assume total abatement costs to be quadratic in abatements. Given that a firm i uses the old technology its marginal abatement cost is given by

$$MAC_O = g - b\,E_i \qquad \forall i \textit{ using the old technology} \tag{1}$$

Where MAC_O is the marginal abatement cost (O for 'old'), E_i is the amount of emissions by firm i, and g and b are positive parameters. If the new technology is used it will reduce the cost of abatement. A simple way to capture this, which also results in a readily interpretable model, is to let the new technology shift the marginal abatement cost function (MAC) to a lower level. Thus, if the innovation is installed by firm j this results in a MAC_D-function (D for 'developed') as

$$MAC_D = d - b\,E_j \qquad \forall j \textit{ using the new technology} \tag{2}$$

Where d is a positive parameter. As the new technology reduces abatement costs, $d < g$.

A firm's emissions will be such that the marginal abatement cost equals the permit price, P_p. Thus, a firm that utilizes the old technology will emit $E_O = (g - P_p) / b$ units of emissions while a firm that has adopted the new technology will emit $E_D = (d - P_p) / b$ units. Normalizing the number of firms to one and denoting the share of emitters who adopts the new technology by n, so $1 - n$ emitters use the old technology, total emissions are given by

$$E_{tot} = n\frac{d - P_p}{b} + (1-n)\frac{g - P_p}{b} \tag{3}$$

Under a cap-and-trade regime total emissions are given by the number of permits issued. Denote this cap $\overline{E}_{tot}$. The implementation of new technology, if the cap is not changed, will influence the permit price rather than $\overline{E}_{tot}$. To capture this, we rearrange (3) as

$$P_p = nd + (1-n)g - b\overline{E}_{tot} \tag{4}$$

Simple inspection of (4) yields the expected characteristics that the price decreases in the number of emission permits allocated to the market. It is also affected by d, g and b; the lower (through d and g) and/or steeper (through b) the marginal abatement cost functions are, the lower the permit price. The permit price decreases in the share of emitters adopting the new technology as this corresponds to a higher value of n which will put more weight on d relative to g.

We now turn to stage 4) where the firms decide on whether or not to adopt the new technology, and thus leave the government's choice in stage 5) until later. We start by noting that a firm's total cost from the cap-and-trade regime comprises two parts. Firstly, the cost of permits for emissions made. For firm i, this is given by $P_p E_i$. Secondly, the cost of conducting the abatements, which, under the assumptions used, amounts to $(BAU_i - E_i) P_p / 2$, where BAU_i denotes firm i's business as usual emissions level, *i.e.*, the level chosen in the absence of any price on emissions. Given the use of the old technology, total costs amount to

$$TC_O = \frac{(2g - P_p)P_p}{2b} \tag{5}$$

This is the cost a firm will incur from being subject to the cap-and-trade regime given that it behaves optimally when choosing its emissions/abatement level and given that it does not adopt the new technology. A similar expression (only differing by containing d rather than g) may be derived for a firm that has adopted the new technology.

Switching technology is costly. Firstly, purchasing the technology is associated with a (positive) price. Assuming that the developer cannot price discriminate, all firms face the same price for purchasing the technology, denoted P_D. Secondly, there may be costs associated with switching from the old technology to the new and these may differ between firms. To capture this we use an approach similar to the famous Hotelling's (1929) linear city. Let the firms be uniformly distributed on a line ranging from zero to one. Let a particular firm i be located on point i on the line. By assuming that the switching cost is zero for a firm in point zero, and increasing in a linear fashion the further away from zero a firm is located, we may capture the switching cost by $t\,i$. Where t is a non-negative scaling parameter. Adding these components together yields the total cost for a firm that chooses to switch to the new technology as

$$TC_{D,i} = \frac{(2g - P_p)P_p}{2b} + P_D + ti \tag{6}$$

Firm i will switch technology iff $TC_{D,i} \leq TC_O$. If it is optimal for a firm in location i to switch technology, this must also be the case for all firms at $j < i$, since the switching cost increases in i.

Let us now turn to stage 3) in the model to examine the developer's pricing strategy. The developer will, given that it has developed the new technology, sell it in a profit maximizing manner. Without major influence on generality, we assume that the cost for the developer of selling a unit of the technology, given that it already has been developed, is zero. For the developer to decide on how many units to provide, which in this setting corresponds to setting n, he needs to know at what price the share of firms switching amounts to n. This requires finding the firm that is indifferent between switching and keeping the old technology, *i.e.*, the firm for which $TC_O = TC_{D,i}$. Setting (5) equal to (6) and solving for P_D yield

$$P_D = \frac{(g-d)P_p}{b} - nt \tag{7}$$

P_D is thus the highest price at which a share of the emitters equal to n will buy the new technology. The expression in (7) makes intuitive sense; given n, the price that may be charged is higher the better the new technology is relative to the old one, *i.e.*, the larger the difference between g and d, and the less rapid is the growth in switching cost over distance from zero, *i.e.*, the smaller the t is. The price also decreases in b, which follows from that a high value of b, given d and g, yields a low business as usual level and hence less abatements are needed to reach a given cap.

An important observation from (7) is that, given n, the optimal price to charge for the technology will decrease in the permit price. We know that the more firms that adopt the new technology, the lower will the permit price be as these firms will emit less and thus the total demand for permits will decrease. Consequently, there is a crucial feed-back effect from the adoption of new technology on P_D working through the permit market. That is, we must take into consideration that the permit price depends on n by substituting P_p in (7) by (4). This yields

$$P_D = \frac{(g-d)\left(nd + (1-n)g - b\overline{E}_{tot}\right)}{b} - nt \tag{8}$$

Comparing (8) to (7) we still have the impact from how the switching cost develops, through the last term, and that the relative merits of the new technology influences the price, through $g - d$. From (8) we also see that P_D decreases in n not only due to the switching cost but also through its impact on the permit price, as $nd + (1 - n)g$ decreases in n. Furthermore, P_D decreases in the total amount of emissions allowed, which also seems intuitively correct.

Still given that the new technology has been developed, and that it then is associated with zero costs to provide, the developer strives to maximize its revenue given by $n\,P_D$. Thus, after multiplying the expression in (8) by n to get an expression for the revenue, we may derive the following first order condition for the optimal n

$$n_D^* = \frac{(g-d)(g-b\overline{E}_{tot})}{2\left((d-g)^2+bt\right)} \tag{9}$$

Where subindex D denotes that the n is optimal from the developer's, but not necessarily the society's, perspective. By substituting for (9) in (8), we achieve an expression for the price the developer will charge as

$$P_D^* = \frac{(g-d)(g-b\overline{E}_{tot})}{2b} \tag{10}$$

Multiplying (9) and (10) yields the (maximized) revenue

$$R_D^* = \frac{(g-d)^2(g-b\overline{E}_{tot})^2}{4b\left((g-d)^2+bt\right)} \tag{11}$$

The first thing to note in (9), (10) and (11) is that $g - b\overline{E}_{tot}$ is the permit price if all firms use the old technology. Both this and $g - d$ is always positive (since the new technology is assumed to be better than the old), so all three expressions are positive. It is also noteworthy that n_D^* decreases in t, while P_D^* does not. That is, a sharper increase in switching cost results in that fewer firms switch technology, which seems intuitively correct. However, the price charged by the developer is not affected by the switching cost. Consequently, and seen from (11), the developer's revenue is strictly decreasing in t.

Leaving the decision about the initial cap until the next section, let us briefly address stage 2) of the model in which the developer chooses how much to invest in R&D. The relative merit of the new technology as compared to the old one affects (9), (10) and (11). The merit is captured by the magnitude of the shift in *MAC*-function, *i.e.*, $g - d$. For clarity, let $a \equiv g - d$. A larger a thus implies a larger improvement in technology relative to the old one. From the developer's perspective, g is exogenously given – but the developer can, subject to the R&D investment, choose d, and thereby influence a. Substituting for a in (11) and differentiating with respect to a yield

$$\partial R^* / \partial a = at\left(g - b\overline{E}_{tot}\right) / \left(2\left(a^2 + bt\right)^2\right) \tag{12}$$

Thus, the revenue is strictly increasing in a in optimum[1]. Let I denote the lowest research investment needed to achieve a technology which is, roughly speaking, a units better than the existing one. For simplicity, assume that I is convex function of a, *i.e.*, $I'(a) > 0$ and $I''(a) \geq 0$. This implies that the research investment needed to improve on the existing technology increases in the improvement at an increasing rate. To maximize profit, the developer aims for an a such that $I'(a) = \partial R / \partial a$ and $I''(a) > \partial^2 R / \partial a^2$. From (12) we may derive the second derivative as $\partial^2 R / \partial a^2 = t\left(bt - 3a^2\right)\left(g - b\overline{E}_{tot}\right)^2 / \left(2\left(a^2 + bt\right)^3\right)$, which is positive when $a < \sqrt{bt}/3$ and negative for a larger than that. Thus, the solution, if any, typically contains two roots out of which the one associated with the higher a is a maximum. As reducing $\overline{E}_{tot}$ increases $\partial R / \partial a$ for any given a, we conclude that, given $I(a)$, a more stringent cap results in that the maximising root appears at a higher a. That is, a lower $\overline{E}_{tot}$ (applicable once the technology has been developed) implies that the developer will invest more in R&D.

The socially optimal penetration rate, given the cap and technology

Above we have studied the incentives for innovation and the developer's strategy under a cap-and-trade regime given that the developer has monopoly power. We should expect that the new technology may be underprovided in this scenario, since the developer will apply a mark-up on the price for the technology. Thus, there is most probably an efficiency loss present. As

[1] From (9) and (10), the optimal price increases in a, but the situation is more complex for the optimal n. For low values of a, increasing a will result in that the developer would like more firms to switch technology. For larger values of a, the opposite applies. The a at which the derivative changes sign depends on how rapidly the switching costs increase and how steep the *MAC*-functions are.

a benchmark we will now examine the optimal penetration rate of the technology from a social planner's perspective, given that the research investment has been made and that the cap is not changed due to this. That is, we seek the optimal *n* from the social planner's perspective, denoted n_S^*, given *d* and $\overline{E}_{tot}$. This is such that the total costs of reaching $\overline{E}_{tot}$ are minimized. These costs consist of two parts; the total abatement costs in the economy and the switching costs for all firms that adopt the new technology.[2] The former is, by design, always decreasing in *n*, *i.e.*, if switching costs are zero all firms should change technology. However, this is not necessarily the case if $t > 0$.

As above, the abatement cost for firm *i* is given by $(BAU_i - E_i)\, P_p / 2$. Substituting for BAU_i and E_i yields firm *i*'s abatement cost to be $P_p^2 / 2b$ disregarding whether it uses the old or the new technology, which is due to the assumption that the technology shifts the *MAC*-function while leaving the slope unaffected. The introduction of new technology will nevertheless decrease the abatement cost as it decreases P_p. Thus, the total costs for the firms are given by:

$$TC_{firms} = \frac{\left(dn + (1-n)g - b\overline{E}_{tot}\right)^2}{2b} + \int_0^n ti\, di \tag{13}$$

where the integral captures the switching costs. Differentiating (13) with respect to *n* yields

$$\frac{\partial TC_{firms}}{\partial n} = nt - \frac{(g-d)}{b}\left(nd + (1-n)g - b\overline{E}_{tot}\right) \tag{14}$$

which clearly illustrates the opposing effects from the impact on switching cost (the first term) and permit price (the last term). From (14) we may derive the socially optimal *n* as

$$n_S^* = \frac{(g-d)(g - b\overline{E}_{tot})}{(d-g)^2 + bt} \tag{15}$$

Comparing (15) with (9) shows that $n_S^* = 2\; n_D^*$. That is, the socially desirable number of firms to switch technology is exactly twice as large as what the number would be in the market solution. As we have assumed the marginal cost of providing the technology once it is

[2] Costs associated with firms having to surrender allowances to cover their emissions are of no concern here as they only constitute a transfer between parties.

developed to be constant (at zero) and the maximum price that may be charged is linear in n, this is not a very surprising outcome given that the developer is a monopolist.

One reaches the exact same expression as in (15) simply by looking at what the optimal n would be if the technology is provided at marginal cost, in this case zero. Consequently, the distortion – in that the outcome under the market solution differs from the social optimal one – follows from the mark-up in price by the monopolist only, given that the cap is not calibrated due to the introduction of new technology. Even if the assumption regarding zero marginal cost is specific, this outcome clearly illustrates the problem as a zero price does not yield any incentives for R&D.

Calibration of the cap and consequences thereof

As discussed in the introduction, Montgomery and Smith (2007) argue there is a lack of incentives for innovation under emissions taxes due to the policy maker's inability to credibly commit to future policies. To examine the corresponding problem in a cap-and-trade setting, we need an expression for the abatement benefits as these affect the optimal cap. Assuming total abatement benefits to be quadratic in abatements and that the emissions are fully mixed we may write the marginal abatement benefits (MAB) as

$$MAB = \alpha + \beta E_{tot} \tag{16}$$

where α and β are positive parameters. We may think of three different levels of commitment, which will influence the level of the cap. In the one extreme, the policy maker may commit to a future cap before the research decision is made, *i.e.*, there is no dynamic inconsistency present. In the other extreme, the policy maker cannot commit to any future policy. There is also an intermediate level where the policy maker can commit to a future cap before the firms chose whether or not to buy the new technology, but after the R&D investment has been made.

When the policy maker cannot commit, the cap will be calibrated after the firms have chosen whether to purchase the new technology, *i.e.*, in stage 5 in Figure 1. Then both d and n are given and a policy maker striving to maximize the difference between total abatement benefits and total abatement costs would set the cap such that $MAC = MAB$. The same approach as used to derive (4) yields a MAC-function given by $nd + (1 - n)g - bE_{tot}$. Using this, the optimal cap is given by

$$\overline{E}_{tot}^{*} = \frac{nd + (1-n)g - \alpha}{b + \beta} \tag{17}$$

From (17) it is seen that the optimal cap increases in both d and g, which is intuitively correct as this implies higher marginal abatement costs. The optimal cap decreases in α and β, since higher α and β imply a higher and steeper marginal abatement benefit function respectively. That the optimal cap decreases in b follows from that the business as usual level decreases in b and, hence, so does the amount of abatements required to reach the cap.

The most important observation to be drawn from (17) is that the optimal cap decreases in n since a high n puts more weight on d. That is, if new technology is introduced and implemented, the optimal response from the policy maker is to calibrate the cap downwards and thereby making it more stringent, *i.e.*, the exact opposite to the behaviour under the emissions tax discussed above. We should however be clear on the difference between the tax and the cap-and-trade case. The government may 'promise' a high tax in the future but the developer knows this is not a credible commitment and, thus, will not act on it. In the cap-and-trade case, as we have seen, the developer has no reason to believe that the cap will be increased due to new technology, but nevertheless knows that the technology will have a negative impact on permit prices[3]. There is thus a parallel between the two systems in that both will result in a lower price per emissions after the innovation is implemented, but for different reasons. A more direct analogy, also discussed in Montgomery and Smith (2007), lies in that the government faces incentives to abolish the patent protection once the new technology is in place. This would open up for competition, which would drive prices down to marginal cost and, hence, the market solution would coincide with the (*ex post*) social desirable one. Of course, if the developer would anticipate such behaviour, very little would be invested in R&D. However, this is a generic problem for all innovations, not only those driven by emission regulations and there seems to be no reason to believe that problems would be larger in an emission regulation setting than elsewhere.

[3] To see this, enter (17) into (4), the permit price equation, and differentiate with respect to n. This yields $\frac{\partial P_p}{\partial n} = \left(1 - \frac{b}{b+\beta}\right)(d-g)$, which is negative.

From (9) and (15) we see that whether the government will act optimally, *i.e.*, by decreasing the cap as predicted by (17), or not will influence the number of firms that switch technology. Table 1 summarizes four different cases by looking at the market outcome versus the social outcome both in a situation where the cap is calibrated in accordance with (17) and when it is kept at the level that is optimal without the new technology[4], denoted Optimal Cap and Old Cap respectively.

Table 1, *optimal share of switching firms in different scenarios*

	Market outcome	Socially desirable outcome
Optimal Cap	$n^*_{D,Opt} = \dfrac{(g-d)(b\alpha + g\beta)}{2\left(\beta(d-g)^2 + bt(b+\beta) + \frac{b}{2}(d-g)^2\right)}$	$n^*_{S,Opt} = \dfrac{(g-d)(b\alpha + g\beta)}{\beta(d-g)^2 + bt(b+\beta)}$
Old Cap	$n^*_{D,Old} = \dfrac{(g-d)(b\alpha + g\beta)}{2\left(\beta(d-g)^2 + bt(b+\beta) + b(d-g)^2\right)}$	$n^*_{S,Old} = \dfrac{(g-d)(b\alpha + g\beta)}{\beta(d-g)^2 + bt(b+\beta) + b(d-g)^2}$

The first thing to note in Table 1 is that $n^*_{S,Old} = 2n^*_{D,Old}$, which is expected as we above showed this to be the case for any given value of the cap, not only the (*ex ante*) optimal one. Comparing $n^*_{S,Old}$ to $n^*_{S,Opt}$ shows that the denominator is $b(d - g)^2$ larger in the former case. The difference in penetration rate under the calibrated and the non-calibrated cap thus increases in the slope of the *MAC*-function and, exponentially, in the relative merits of the new technology. There is a similar relationship between $n^*_{D,Old}$ and $n^*_{D,Opt}$ in the market outcome. However, in that case the term $b(d - g)^2$ is present also in the optimal cap case, but its impact is less than under the non-calibrated cap. That is, the number of firms that switches technology is larger under the calibrated cap both in the market solution and in the social optimum, as in both cases the denominator is larger under the old cap. However, the difference is smaller in the market solution.

[4] The Old Cap is thus $(g - \alpha)/(b + \beta)$ which follows from (17) given n=0, *i.e.*, the new technology is not used.

As a consequence, the relative difference between the market and the socially desirable outcome when the cap is optimally calibrated is even larger than when it is not, *i.e.*, $n^*_{S,Opt} > 2n^*_{D,Opt}$. This is due to the interconnectivity between the number of firms switching technology and the optimal cap. That *n* is higher in the social than in the market solution implies the cap to be more stringent in the former case, which, in turn, calls for an even higher *n* in the social optimum. Thus, the reason for an even higher discrepancy between the social and the market optimum is that the optimal cap is no longer the same in the two cases.

This points towards a second source of efficiency loss which, in contrast to the one due to the monopolist's mark-up discussed above, is specific for the cap-and-trade setting. This follows from how the policy maker calibrates the cap. We have shown, in (17), that the more firms that switch technology, the more stringent should the new cap be. However, there is also a causality working in the opposite direction in that the more stringent the cap is, the more firms should switch technology. The share of the firms that should switch depends on the marginal impact on abatement cost and the marginal switching cost, as seen in (14). Taking into account that the cap optimally should be made more stringent, this will increase the permit price and, thus, allow for higher abatement costs in optimum. This implies that more firms optimally should switch technology when allowing for cap calibration than otherwise, as seen in Table 1.

The same story applies for the market outcome. In particular, the share of switching firms should be larger when allowing for calibrations of the cap. The mark-up of the price for the technology applied by the monopolistic developer however results in a less than socially desirable penetration rate. As a consequence, the increase in permit prices caused by changing the cap is less than it should be in a social optimum and, thus, the feed-back from higher permit prices into more firms switching firms becomes inefficiently weak.

It is worth noting that both sources of efficiency loss in the market outcome ultimately are due to the monopolistic pricing of the developer. However, one is the standard textbook efficiency loss directly associated with monopolistic behaviour while the other is associated with the policy maker's choice of optimal cap being distorted by the mark-up in technology price.

Let us now address the cap, which unlike *n* may be directly targeted by the policy maker. The optimal cap valid for a given *n* follows from (17). The penetration rate that will emerge on the market follows from the developer's pricing decision, which in turn depends on the expected cap as specified in (9). Entering (9) into (17) and solving for the cap yields the optimal cap if it is to be calibrated after the firms have chosen whether or not to adopt the new technology as

$$\overline{E}^{*}_{tot,After\ n} = \frac{g\left((d-g)^2 + 2bt\right) - 2\alpha\left((d-g)^2 + bt\right)}{b\left((d-g)^2 + 2bt\right) + 2\beta\left((d-g)^2 + bt\right)} \tag{18}$$

In a situation where the policy maker may calibrate the cap before the firms make their investment choices but after the new technology is available, things are different. The policy maker may then take into consideration that the (actual, not expected) cap will influence the resulting penetration rate. The policy maker aims to solve

$$\max_{E_{tot}}\left(\int_{E_{tot}}^{BAU_{NEW}} (MAB - MAC) + \int_{BAU_{NEW}}^{BAU_{OLD}} MAB + \int_0^n ti\ di\right) \tag{19}$$

Where BAU_{NEW} denotes the business as usual level given the resulting penetration rate and BAU_{OLD} the level with no new technology. The first two integrals capture the efficiency gain from moving from a total emissions volume equal to BAU_{OLD} to E_{tot}.[5] The last integral captures the switching cost involved with adopting the new technology. Note that the R&D investment is sunk and therefore does not appear in (19). Solving the maximization, taking account for that the penetration rate is given by (9), yields

$$\overline{E}^{*}_{tot,Before\ n} = \frac{g\left((d-g)^2 + 4bt\right) - 4\alpha\left((d-g)^2 + bt\right)}{b\left((d-g)^2 + 4bt\right) + 4\beta\left((d-g)^2 + bt\right)} \tag{20}$$

Comparing (18) to (20) reveals that $\overline{E}^{*}_{tot,After\ n} > \overline{E}^{*}_{tot,Before\ n}$. That is, the policy is less stringent if the policy maker takes the new aggregated *MAC*–function as given, which is the case if both the technology and its penetration rate are decided before the cap is calibrated, than otherwise. This is an intuitively appealing result as it implies that the policy will be more stringent when it does not only influence the abatements directly, but also the penetration rate.

Finally, as discussed above, the developer will invest in R&D up to the point where the additional investment for a marginal improvement in technology equals the increase in

[5] The first integral in (19) captures the gain from the cap-and-trade system's impact on emissions, given the new technology. The second integral captures the efficiency gain from the new technology reducing the business as usual level.

revenue from the improvement. We have shown that the marginal revenue increases the more stringent the policy is, *i.e.*, for lower $\overline{E}_{tot}$. From this we may conclude that, *if* the policy maker would be able to commit at the *ex ante* stage on an *ex post* policy, the optimal policy would likely be more stringent than when he cannot commit since this would increase the R&D investment.

3. Discussion; policy implications – what could be done?

The primary aim of the present paper is to add to the understanding of the link between innovation incentives, technology penetration and the cap-and-trade regulation. Even so, the model provides some conclusions regarding policy design. We may start by noting that several model parameters arguably are outside the policy maker's control, *e.g.*, the original *MAC*-function, *i.e.*, *g* and *b*, and the *MAB*-function, *i.e.*, α and β. Others may not be directly influenced, but may – for instance through subsidies – be indirectly targeted by public policy, *e.g.*, the R&D investment and the switching cost. Finally, there is the cap which is the only variable in the model directly decided upon by the policy maker.

Regarding the cap, two questions are of particular interest. First, is it feasible for the policy maker to commit to a stringent *ex post* cap to incentivise more research? Second, has the *ex ante* cap got any impact on innovation incentives?

The first question is important since the model tells us that both the penetration rate and the research investment increase in the permit price, which in turn is higher the more stringent is the cap. We have argued that *if* the policy maker could in a credible (costless) way commit *ex ante* to a stringent policy *ex post*, it would be optimal to do so. The reason why this will not work is the time inconsistency problem noted by Montgomery and Smith (2007) discussed in the introduction. That is, a promise about a future cap which is more stringent than the optimal one is not credible and, hence, will not influence the developer's research decision.

The second question regards potential gains from setting a stringent cap already at the stage where the research investment decision is made (*ex ante*). This would increase the permit price, which potentially could provide a signal to the developer to invest in research. However, only the (expected) permit price when the new technology has been implemented affects the research decision – and a high *ex ante* permit price will not make a commitment to a high *ex post* price any more credible.

Things may be different if we allow ourselves to divert from the simple setting where all agents are fully informed. Consider a case where the localisation of the *MAB*-function, α, is known by the policy maker only (or, at least, the policy maker is better informed about it). A stringent *ex ante* cap signals to the market participants, including the developer, that α is high. If α is high, the optimal policy in the *ex post* stage also includes a stringent cap and, thus, the signal will result in that the developer invests more in research than otherwise. This reasoning suggests that the policy maker may induce more research by setting an inefficiently stringent *ex ante* cap. However, the developer will probably understand the policy maker's incentives and not respond fully to the initial price. The model presented above is not suited to capture this, but it does not seem unlikely that the policy maker's ability to 'trick' the developer into conducting more research in this way results in an even worse outcome. However, we leave this question open for future research.

Thus far we have concluded that the (*ex post*) cap is important for the level of research and the penetration level of new technology, but also that the policy maker's ability to use the cap to incentivise innovations in a credible way is limited. Let us briefly discuss other instruments, in particular subsidies aimed either to decrease the research investment being carried by the developer or the switching cost carried by the firm.

R&D subsidies are associated with several problems, *e.g.*, related to rent seeking and moral hazard, not captured by the model above. Nevertheless, the model provides some valuable insights. We have argued that the developer will chose a research level such that $\partial I/\partial a = \partial R/\partial a$, *i.e.*, the additional investment required for a marginal improvement of the technology must equal the additional revenue raised from the marginal improvement. As discussed, the marginal revenue depends on the cap. Given a cap, a subsidy that decreases the developer's (marginal) investment cost, $\partial I / \partial a$, may thus result in a more efficient research level. One interesting outcome of the model is that such a subsidy will not decrease the price of the technology. Another observation is that, given that a subsidy has resulted in a larger a, there is still a discrepancy in penetration rate between the market solution and the social optimum – since in both cases a larger a should lead to a higher penetration rate.

Finally, the policy maker could subsidize the switching cost through paying part of the cost firms incur from adopting the new technology. From equations (12) to (14) we know that a subsidy designed to decrease t will increase the penetration rate. It will however not decrease the price charged by the developer who, consequently, will gain from increased revenues.

This will justify a larger investment in R&D and, once the new technology is implemented, this calls for a more stringent cap. As above, however, given the technology there will still be a discrepancy between the market outcome and the social optimum.

4. Concluding remarks

The present paper presents a model containing a developer who, if he develops a new technology, will be able to exercise monopoly power. As the developer then will charge a price above marginal cost, the share of firms adopting the new technology will be less than socially desirable. These effects are expected and typical consequences of a seller having market power. In the present context the situation is however further complicated due to the market ultimately being driven by a political decision regarding the cap, *i.e.*, the total emission volume allowed.

We have shown that there is a crucial feedback between the R&D investment, the market price for the new technology, the market price for emission permits and the potential calibration of the cap once new technology has been implemented. In short, the introduction of new technology that reduces the costs of abatements will decrease the market clearing permit price. As a lower permit price reduces the demand for the new technology, this is bad – but expected – news for the developer. However, reduced abatement costs will lead an efficiency concerned policy maker to calibrate the cap; making it more stringent. This increases permit prices and, in turn, demand, and hence the price, for the new technology.

There are differences between the cap-and-trade setting, as addressed here, and the emissions tax setting, as addressed in, *e.g.*, Montgomery and Smith (2007). In the latter case, the introduction of new technology results in the policy maker having incentives to relax the policy by reducing the tax level, while in the cap-and-trade setting the opposite applies as the policy maker should lower the cap, *i.e.*, implement a more stringent policy, as a response to new technology. However, the end results are similar; in both cases the price for emissions is reduced (even though the cap is lower) while total emissions are lower after the introduction of new technology. Another important difference between the analysis in the present paper and Montgomery and Smith lies in the monopoly power granted through the patent. This allows the developer to receive a greater surplus to recover the R&D investment, but also creates problems such as a low penetration rate.

Thus, the emissions cap and how it is calibrated in response to the introduction of new technology clearly influences the R&D decisions. This leads to the question whether the policy maker could use the cap to counter the problem of – from a social welfare perspective – low R&D investment and technology penetration. The conclusions we draw is that the possibility for this is very limited. This follows from the policy maker's inability to credibly commit to a future cap that is stringent enough to motivate an efficient level of R&D efforts. In the absence of some mechanism that resolves the dynamic inconsistency problem; additional policy instruments targeted towards R&D and/or adaptation of technologies that reduce abatement costs may be justified.

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