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Climate policy without commitment*

Rolf Golombek[†], Mads Greaker[‡] and Michael Hoel[§]

Abstract

Climate mitigation policy should be imposed over a long period, and spur development of new technologies in order to make stabilization of green house gas concentrations economically feasible. The government may announce current and future policy packages that stimulate current R&D in climate-friendly technologies. However, once climate-friendly technologies have been developed, the government may have no incentive to implement the pre-announced future policies, that is, there may be a time inconsistency problem. We show that if the government can optimally subsidize R&D today, there is no time inconsistency problem. Thus, lack of commitment is not an argument for higher current R&D subsidies. If the offered R&D subsidy is lower than the optimal subsidy, the current (sub-game perfect) climate tax should exceed the first-best climate tax.

Keywords: Time consistency, carbon tax, climate policy, R&D, endogenous technological change

JEL classification: H21, O30, Q2, Q28, Q42

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1 Introduction

Global warming represents man's biggest environmental challenge. In spite of the fact that current concentration in the atmosphere of greenhouse gases (GHGs) is approaching critical levels, global emissions are steadily increasing. Economic growth in developing countries and proposed stabilization targets for GHG concentrations in the atmosphere simply do not match easily. Reaching both goals would for instance require more than twice as much carbon free power by mid-century than we now derive from fossil fuels (Hoffert et al. 2002). This is a major technological challenge, and governments in industrialized countries are currently announcing daunting future emission targets, hoping this will trigger the right kind of innovations.

If a government announces climate policies, for example, carbon taxes, to be implemented in the future, firms may increase their R&D in green technologies today, expecting a reward on their R&D investment in the future. However, once climate friendly technologies have been developed, the government may have no incentive to implement the pre-announced policies. Moreover, if firms have rational expectations, and the government cannot commit to future carbon taxes, firms understand that the announced policies will never be implemented, and hence present R&D in climate friendly technologies will not change.

This paper examines the optimal design of carbon taxes. In our study, present and future climate taxes increase demand for climate friendly technologies, and thereby spur present technology development. Because of a number of externalities in the R&D markets, we show that implementation of the *first-best* outcome requires a subsidy that internalizes the net effect of these externalities. Depending on the strength of the (positive and negative) externalities, this subsidy may be positive or negative. Moreover, carbon taxes should be imposed, but these should equal the Pigovian taxes only if there is competitive supply of abatement technologies.

We show that if the available technology subsidy is the first-best one, then both under commitment (open-loop equilibrium) and under no commitment (subgame perfect equilibrium) the first-best outcome will be reached. However, for a number of reasons (see Section 4) the available technology subsidy may differ from the first-best one. Under such an assumption we explore how carbon taxes will be determined under commitment and under no commitment. In particular, we compare equilibrium carbon taxes under commitment and under no commitment. We show that if the available subsidy to the government is lower than the first-best subsidy, then the future carbon tax under no commitment is lower than the future carbon tax under commitment. Hence, under no commitment the government cannot (credibly) announce a "high" future carbon tax, that is, a carbon tax at the same level as the tax rate under commitment. In order to compensate for the lack of a high future carbon tax, we show that under no commitment the present carbon tax is increased. This is in line with the informal story above.

There is a strand of literature analyzing the optimal time path of a carbon tax. In the seminal paper by Wigley et al. (1996), future costs are discounted and a fraction of the carbon emitted today is removed from the atmosphere by natural processes as time passes. This suggests to postpone expensive carbon abatement, that is, carbon taxes should increase over time. However, in the early literature technological progress was exogenous, and critics claimed that if technological change were made endogenous results would change.

Goulder and Mathai (2000) was one of the first contributions which analyzed the implications of endogenous technological change for the optimal carbon tax path. Rather surprisingly, they found that if the government could affect technological change through a carbon tax, the government should set lower carbon taxes today, and consequently, also less carbon abatement would be carried out today. The intuition is simply that the prospect of technological development made it even more advantageous to postpone carbon abatement.

In Goulder and Mathai (2000) the government directly decides both the amount of carbon abatement and the rate of new knowledge accumulation, and it is assumed that all market failures of knowledge creation are taken care of by other policies than climate policy. Assuming that the government cannot control the rate of knowledge creation directly by, for instance, an R&D subsidy, both Gerlagh et al. (2009) and Greaker and Pade (2009) found that governments should set a *higher* carbon tax today if patent protection is imperfect and/or if there is a positive externality from present R&D to future R&D. In the present paper, where there are other types of externalities than imperfect patent protection and knowledge spillovers, we show that the first-best taxes are declining over time. If the available technology subsidy differs from the first-best one, the path of subgame perfect carbon taxes, as well as the ranking of subgame-perfect carbon taxes relative to first-best carbon taxes, depends on whether the available technology subsidy exceeds the first-best subsidy (which may be positive or negative).

A key issue in the present paper is whether the carbon taxes differ between the commitment case and the no commitment case. Neither Gerlagh et al. (2009) nor Greaker and Pade (2009) examine the no commitment case (subgame-perfect equilibrium). Several decades ago, Kydland and Prescott (1977) drew attention to inefficiency caused by dynamic inconsistency. This insight has proven essential for several policy areas. It is, however, easy to check that the optimal controls are time consistent in the model of Goulder and Mathai because the maximization problem is time invariant and the two state variables follow smooth paths, see Greaker and Pade (2009). However, with decentralized decisions by private agents - like in the present paper - time consistency could be a problem.

The time consistency problem is not new to environmental economics. For example, Downing and White (1986) examine the ratchet effect; if a polluting firm discovers a less polluting process, the government may tighten the regulation of the firm. Consequently, the innovating polluting firm may not reap the (naively) expected benefits from their innovation, and R&D investments may not be profitable. Downing and White (1986) conclude that for all other environmental policy instruments than emission taxes, the ratchet effect may lead to too little innovation.

Unlike Downing and White, Requate (2005) distinguishes between the regulated polluting sector, which employs new abatement technology, and the R&D sector, which develops new abatement technology. According to Requate, empirical work shows that more than 90 percent of environmental innovations reducing air and water pollution are invented by non-polluting firms marketing their technology to polluting firms. This tends to change the incentive structure as the ratchet effect often implies a larger market for the innovation.

Our paper differs from Downing and White (1986) and Requate (2005) in several respects. While in these contributions there is only one government making one decision, that is, either before or after the innovation activity has taken place, we include two governments making decision at different points in time. We thereby aim to model a central feature of the ongoing negotiations over a Kyoto II treaty: a climate treaty can commit nations to a climate policy only until some future year. Later, new governments are not committed.

Unlike Requate (2005) we focus on characterizing the optimal tax path under different policy and commitment alternatives. As stated above, the optimal tax path depends on whether the available technology subsidy is higher or lower than the first-best subsidy. Note that like Requate (2005) we assume that innovations take place in an R&D sector, not in the polluting firms.[1]

[1] Requate (2005) finds that an emission tax welfare dominates a tradeable quota system for most commitment alternatives. In the present paper, we only analyze an emission tax. However, an emission tax is equivalent to a tradeable quota system in our model because the mark-up in the R&D sector is given. In Requate (2005), endogenous mark-up is a key driving force.

Both Alfsen and Eskeland (2007) and Montgomery and Smith (2007) argue that because a government cannot commit to future tax rates, the government must increase its support of climate friendly R&D today. We show that if the government can offer the first-best technology subsidy to the R&D firms, then the first-best outcome is reached both under commitment and under no commitment. Hence, if feasible, the government should use the first-best subsidy, and it is not welfare improving to increase the subsidy above the first-best level even if the government cannot commit to future taxes. Thus, lack of commitment is not an argument for R&D subsidies above the first-best level. However, if the government for various reasons cannot use the first-best technology subsidy, it should instead adjust the carbon taxes. The adjustment, relative to the first-best carbon taxes, depends on whether the offered technology subsidy exceeds the first-best subsidy.

Karp and Tsur (2008) offers another perspective on time inconsistency. In their paper, time inconsistency is driven by hyperbolic discounting, not innovations. The optimal level of current abatement under commitment is compared with the optimal level under limited commitment. They find that present carbon abatement should be highest in the limited commitment case. This result has some resemblance with our result when subsidies to R&D are insufficient; the present carbon tax, and therefore also present abatement, should be higher under no commitment than under commitment if the applied technology subsidy falls short of the first-best subsidy.

The paper is laid out as follows: In Section 2 we present our model, and in Section 3 we examine the first-best solution. In Section 4 we assume that the R&D subsidy cannot be set optimally, and derive the second best solution. We distinguish between the case in which the government can commit to future carbon taxes, and the no commitment case. Lastly, Section 5 sums up and conclude.

2 The model

We use a model with two sectors and two periods. In the R&D sector, each firm develops *one* abatement technology. First, the firm develops an idea - a basic technology concept - at a fixed cost. This idea can then be advanced to a marketable product, which is rented to the carbon emission sector. The latter sector has a Business-as-Usual (BaU) amount of emissions related to its production activities, but by renting abatement equipment from the R&D sector emissions will be reduced. Abatement technologies are imperfect substitutes, and it is optimal to rent a mix of all abatement technologies. Remaining carbon emissions are subject to carbon tax payment to the government.

In each period there is one government. The objective of a government is to minimize total social costs. We first examine the case where the government has enough instruments to implement the first-best social optimum. In general, this requires the use of carbon taxes as well as an R&D subsidy. We then consider two cases where each government only can set the carbon tax optimally.

All development of new ideas takes place in the first period. Thus, one way to think of the model is that technologies used to combat climate change will be developed over the next decades (Period 1 in the model). Later (period 2 in the model), these concepts will be applied to reduce carbon emissions. Such an interpretation suggests that the two periods are of unequal length. It is not difficult to implement periods of unequal length in the model, however, since it would not change our main results, we have chosen to keep the two periods equally long.

2.1 The R&D sector

Each firm in the R&D sector develops a unique type of abatement technology in period 1. First, an R&D firm develops one idea at the fixed development cost $F(n)$ where n is the number of ideas being developed and $F'(n) > 0$, $F''(n) > 0$. The average cost of developing an idea is increasing in the number of ideas, for example, because costs of developing an idea differ across ideas and the least expensive ideas are assumed to be developed first - firms are "fishing out" the best ideas. Hence, the fixed cost of firms is increasing in the number of firms, and therefore the average fixed cost of firms is also increasing in the number of ideas being developed in a period. Of course, in the R&D sector there is a chance for duplication, but this would just strengthen our argument because the probability of duplication is increasing in the number of R&D firms - with more firms there will be more duplication. A firm discovering that a competitor has already invented the idea the firm is working on has to start from scratch, and therefore the average effort required for each firm to develop a unique technology concept is increasing in the number of firms. Notice that duplication may be accidental (companies simultaneously discovering the same type of improvement), or intentional, as for example in patent races (see Jones and Williams, 2000).

Once a new idea is developed, there is a constant cost b per period of producing and marketing one standardized unit of technology, and this cost is assumed to be identical for all firms in the R&D sector. The new abatement technology can be rented to the emission sector in both periods. Supply of abatement equipment services are monopolistic competitive, and each firm charges a price $p_t = mb$, $t = 1, 2$, where the markup $m > 1$ is assumed to be identical across firms. Under our assumptions, the amount of technology rented to the emission sector in period t will be the same across firms, and denoted u_t.

Let S be a (positive or negative) subsidy received by each firm in the R&D sector that develops an idea. The present value of the profits of a firm in the R&D sector is $S + (m-1)bu_1 + \beta(m-1)bu_2 - F(n)$, where $\beta < 1$ is the discount factor. We assume that firms enter until profit is driven down to zero, that is, the number of R&D firms is determined from

$$S + (m-1)b(u_1 + \beta u_2) - F(n) = 0. \tag{1}$$

Relation (1) defines n as a function of S and $u_1 + \beta u_2$:

$$n = F^{-1}(S + (m-1)b(u_1 + \beta u_2)) \equiv n(S + (m-1)b(u_1 + \beta u_2)), \tag{2}$$

implying that $\frac{\partial n}{\partial S} = n' = \frac{1}{F'} > 0$, $\frac{\partial n}{\partial u_1} = (m-1)bn' > 0$, and $\frac{\partial n}{\partial u_2} = (m-1)b\beta n' > 0$. Notice in particular that an increase in the future use of abatement technologies (increased u_2) increases the number of new ideas developed today.

2.2 The emission sector

Emissions in each period are given by $\varepsilon^0 - na(u_t)$, where ε^0 is the BaU emission level in the emission sector, and $a(u_t)$ measures the decline in emissions from using u_t units of one abatement technology. We assume that $a(u_t)$ is increasing in u_t and strictly concave. Hence, there are decreasing returns to each type of abatement equipment. On the other hand, this effect can be circumvented by employing more abatement technologies instead of steadily increasing the use of one particular type.

In each period the emission sector minimizes the sum of emission tax payment and carbon abatement cost. For Period t we have:

$$\min_{u_t} \left\{ \tau_t(\varepsilon^0 - na(u_t)) + np_t u_t \right\}, \tag{3}$$

where τ_t is the carbon tax rate in period t. Because $\varepsilon^0 - na(u_t)$ is actual emissions in period t, the first term in (3) is the carbon tax payment. The second term in (3) is the rental cost of abatement equipment. Using the equilibrium condition $p_t = mb$ this minimization gives

$$\tau_t a'(u_t) = mb. \tag{4}$$

which defines u_t as a function of τ_t. Relation (4), together with the pricing rule of the R&D sector ($p_t = mb$), gives the demand for abatement equipment as $u_t = u(\tau_t)$ where $u'(\tau) = \frac{a'(u)}{-\tau a''(u)} > 0$. Hence, a higher carbon tax in period t will increase the use of each abatement technology in this period, which will lead to more abatement technologies being developed due to $\frac{\partial n}{\partial u_t} > 0$. Hence, the number of ideas is increasing in both tax rates.

3 First-best social optimum

We assume that the marginal social values of emission reductions in period 1 and 2 are d_1 and d_2, respectively. These marginal social values of emission reductions are based on some underlying economic costs of climate change, which depend on emissions in both periods.[2] The assumption that d_1 and d_2 are constant seems a reasonable simplification for the range of emission changes that our analysis covers.

The social surplus from emission mitigation is the value of the abatement minus the abatement costs and the R&D costs. Denoting the social surplus by Π we thus have

$$\Pi = n\left[\phi(u_1, u_2) - F(n)\right], \tag{5}$$

where

$$\phi(u_1, u_1) = \left[d_1 a(u_1) - bu_1\right] + \beta\left[d_2 a(u_2) - bu_2\right] \tag{6}$$

is the social value of abatement for each type of abatement equipment minus the cost of using this equipment.

The first-best optimum is found from maximizing the social surplus with respect to the number of technologies being developed (n) and the use of abatement technologies in each period (u_1, u_2). From (5) and (6) this gives:

$$\phi_1 = d_1 a'(u_1) - b = 0, \tag{7}$$

$$\beta^{-1}\phi_2 = d_2 a'(u_2) - b = 0, \tag{8}$$

$$(\phi - F) - nF' = \left[d_1 a(u_1) + \beta d_2 a(u_2) - b(u_1 + \beta u_2)\right] - \left[F(n) + nF'(n)\right] = 0. \tag{9}$$

[2] A simple "standard" assumption is that climate costs are given by $D(A_t)$ in period t, where A_t is the carbon in the atmosphere in the end of period t. If a fraction γ of emissions in period 1 remains in the atmosphere in period 2, we have $d_1 = D'(A_1) + \beta\gamma D'(A_2)$ and $d_2 = D'(A_2)$. Notice that d_t constant is strictly true only if $D'' = 0$. For the special case in which we only care about the carbon in the atmosphere in the end of period 2 we have $d_2 = (\beta\gamma)^{-1} d_1 > d_1$. More generally, the sign of $d_2 - d_1$ is ambiguous.

According to (7) and (8), marginal benefit of increased use of an abatement technology, which is $d_1 a'(u_1)$ in period 1 and $d_2 a'(u_2)$ in period 2, should equal the corresponding marginal cost b. Further, according to (9) the net social benefit of the last idea being developed should be zero. In other words, the value of lower emissions reflecting that one more technology is used to abate in both periods, $d_1 a(u_1) + \beta d_2 a(u_2)$, less the cost of using this technology, $b(u_1 + \beta u_2)$, should equal the total cost of developing this technology. This amounts to one more R&D firm paying the fixed cost of developing a new idea, $F(n)$, and this additional firm increases the fixed cost of all R&D firms by $nF'(n)$.

In the subsequent discussion we let $(u_2^{FB}, u_2^{FB}, n^{FB})$ denote the first-best optimum given by the above conditions. The government can implement the first-best solution as follows: First, combining (4) with (7) and (8) we see that the first-best emission taxes are given by:

$$\tau_1^{FB} = md_1, \tag{10}$$

$$\tau_2^{FB} = md_2. \tag{11}$$

Relations (10) and (11) reflect that with a constant mark-up m one instrument is sufficient (in each period) to correct for both market power and the negative environmental externality[3]. The emissions taxes are higher the higher is the mark-up m: a high mark-up implies a high emission tax, which gives an incentive to rent out more units of the abatement equipment, thereby correcting the disincentive for a monopolist who charges a price in excess of marginal cost. Note that in the special case where (in the limit) $m = 1$, that is, the competitive case, the Pigovian taxes should be imposed.

Relation (9) determines the optimal number of ideas, n^{FB}, when $u_t = u_t^{FB}$. Using (1) we see that in order to implement the first-best solution, the following subsidy should be offered to each R&D firm;

$$S^{FB} = F(n^{FB}) - (m-1)b(u_1^{FB} + \beta u_2^{FB}). \tag{12}$$

Relation (12) does not give any guidelines with respect to the sign of S^{FB}. To this end we combine (9) and (12) to obtain:

$$d_1 a(u_1^{FB}) + \beta d_2 a(u_2^{FB}) - mb(u_1^{FB} + \beta u_2^{FB}) = n^{FB} F'(n^{FB}) + S^{FB}. \tag{13}$$

The left hand side of (13) shows the social value of reducing emissions by the optimal use of abatement equipment in the two periods,

[3] A similar result was first derived by Buchanan (1969).

$d_1 a(u_1^{FB}) + \beta d_2 a(u_2^{FB})$, less gross revenue in the R&D sector of renting out these amounts, $mb(u_1^{FB} + \beta u_2^{FB})$. As long as this difference is positive, only a part of the social value of using the abatement equipment accrues to an R&D firm, and hence, too few ideas will be invented.[4] This effect, which is often termed the *appropriation effect*, see, for example, Tirole (1997, ch. 10), suggests to offer a subsidy to R&D firms in order to reach the optimal number of new abatement technologies. On the other hand, free entry into the R&D sector drives up R&D costs ($F'(n) > 0$), and all R&D firms suffer from this externality, $n^{FB}F'(n^{FB})$. Jones and Williams (2000) coin this the "*stepping on toes*" effect. This negative cost externality tends to yield too much entry from a welfare point of view, that is, too much technology development, which suggests to impose a tax on R&D firms. To sum up, in order to implement the first-best outcome the government should offer a subsidy to R&D firms if and only if the appropriation effect exceeds the stepping on toes effect.

The discussion above gives us the following proposition:

Proposition 1 *The first-best outcome can be implemented by the environmental taxes* $\tau_1^{FB} = md_1$ *and* $\tau_2^{FB} = md_2$ *combined with a subsidy* $S^{FB} = (m-1)b(u_1^{FB} + \beta u_2^{FB}) - F(n^{FB})$. *This subsidy should be positive if the appropriation effect exceeds the stepping on toes effect, but negative if the stepping on toes effect exceeds the appropriation effect.*

If the stepping on toes effect is larger than the appropriation effect, the government should tax each idea. This may sound odd, but remember that in our model there are no knowledge spillover between R&D firms, which would have provided an additional argument for an R&D subsidy.

4 Second-best social optimum

In this section we examine the case in which governments cannot set an optimal subsidy to R&D firms. First, it may be difficult for the governments to identify good ideas worthy of support and deny bad ideas support, see, for example, Cohen and Noll (1991). Second, once there is a subsidy innovators may spend time chasing for government funds. Whereas this may be rational and beneficial for an agent, it is a loss for society. Third, subsidy programs require funding, and public spending may have a higher opportunity cost than private spending.

[4] Whereas $d_1 a(u_1^{FB}) + \beta d_2 a(u_2^{FB})$ is independent of the mark-up m, the term $mb(u_1^{FB} + \beta u_2^{FB})$ is increasing in m. Hence, for a large enough m the appropriation effect is negative. Note that for the limiting case of $m = 1$ we know from the first-order condition for optimal number of abatement technologies, see (9), that the appropriation effect is positive.

In the commitment case (Section 4.1), the government in period 1 can force the government in period 2 to set a certain tax rate in the second period, that is, the government in period 1 determines the carbon taxes in both periods (The open-loop solution). However, this type of commitment is seldom possible, and hence in Section 4.2 we also discuss the sub-game perfect equilibrium in the two stage game between the governments.

4.1 Open-loop solution

From (4) we know that finding the optimal taxes is equivalent to finding the optimal use of abatement equipment of each type in the two periods, i.e. finding u_1 and u_2. As before, social surplus is given by (5). However, in the present case the subsidy S is not determined by optimization, but given exogenously by S^0 (which may be equal to zero). When choosing u_1 and u_2 we must therefore take into consideration that the number of ideas (i.e. n) depends on this choice, see (2). The optimal values of u_1 and u_2 must therefore satisfy

$$n\phi_t + [\phi - F - nF'] \frac{\partial n}{\partial u_t} = 0 \qquad t = 1, 2 \tag{14}$$

Can the first-best values (u_2^{FB}, u_2^{FB}), and thus the first-best taxes $(\tau_1^{FB}, \tau_2^{FB})$, be the solution of (14)? The first-best values imply that the first terms in (14) are zero, see (7) and (8). Thus, the first-best optimum can only be the solution to (14) when the term in square brackets is zero (remembering that $\frac{\partial n}{\partial u_t} > 0$). This in turn requires that the exogenously given subsidy equals the first-best subsidy, see (9). Consequently, if the term in square brackets differs from zero the first-best taxes cannot be the solution. In the Appendix we prove the following proposition (under a weak regularity assumption):

Proposition 2 *If the available technology subsidy S^0 is equal to the first-best subsidy S^{FB}, the open-loop carbon taxes coincide with the first-best carbon taxes, $\tau_t^{OL} = \tau_t^{FB}$. If $S^0 < S^{FB}$, then in each time period the open-loop carbon tax exceeds the first-best carbon tax, $\tau_t^{OL} > \tau_t^{FB}$. If $S^0 > S^{FB}$, then in each time period the first-best carbon tax exceeds the open-loop carbon tax, $\tau_t^{FB} > \tau_t^{OL}$.*

The intuition for our result is straight forward. A *positive first-best subsidy* stimulates the development of more abatement technologies. If the government cannot use this subsidy to the desired extent, for example, there is no subsidy ($S^0 = 0$), carbon taxes should be increased, relative to the first-best taxes, in order to spur more R&D. This intuition is correct irrespective of the sign of the first-best subsidy as long as the available subsidy is *lower* than the first-best subsidy. Correspondingly, if the offered subsidy *exceeds* the first-best subsidy, the subsidy tends to attract too many R&D firms. Carbon taxes should then be reduced - relative to the first-best taxes - in order to decrease profits in the R&D sector, thereby lowering the number of firms entering the R&D sector.

By departing from the first best tax rates, the government incurs a loss from too much, or too little, abatement, that is, marginal abatement cost will not equal marginal environmental damage. This loss is increasing in the tax rate, and hence, it is better to spread the loss over both periods by manipulating both tax rates.

4.2 Sub-game perfect equilibrium

We now examine the sub-game perfect equilibrium in the game between the current government and the future government. In period 2, the future government determines the carbon tax τ_2^{PE} that maximizes the social surplus in this period. Because there is no R&D in period 2, the number of abatement technologies, n, is predetermined. Also, the use of abatement technologies in period 1, u_1, is predetermined. Hence, the future government chooses u_2 to maximize (5), taking u_1 and n as given. Clearly, this implies that (8) must hold, i.e. $u_2^{PE} = u_2^{FB}$ and hence $\tau_2^{PE} = \tau_2^{FB}$.

The government in period 1 chooses u_1 to maximize social surplus, taking into account that $u_2 = u_2^{FB}$. As before, n depends on u_1, see (2). Maximizing (5) is this case therefore gives us (14) for $t = 1$. It follows that the fist-best optimum u_1^{FB} is a solution to our current problem only if the term in square brackets in (14) is zero for $t = 1$. This corresponds to the situation in which the exogenously given subsidy equals the first-best subsidy; $S^0 = S^{FB}$. The following proposition summarizes this finding:

Proposition 3 *If the offered R&D subsidy S^0 equals to first-best subsidy S^{FB}, the sub-game perfect carbon taxes are equal to the first-best carbon taxes, and thus there is no time inconsistency problem.*

If the available subsidy for some reason differs from the first-best subsidy, the first-best tax in period 1 implies that the term in square brackets in (14) differs from zero for $t = 1$, and hence this tax is not part of the solution of the game. In the Appendix we prove that the carbon tax path in the three cases - first best, open loop solution and sub-game perfect equilibrium - can be characterized as follows[5]:

[5] The formal proof in the Appendix does not cover the case where $S^0 - S^{FB}$ is positive and large. On the other hand, this case seems to be less likely.

Proposition 4 *If the first-best subsidy exceeds the offered subsidy,* $S^{FB} > S^0$*, then* $\tau_1^{PE} > \tau_1^{OL} > \tau_1^{FB}$ *and* $\tau_2^{OL} > \tau_2^{PE} = \tau_2^{FB}$*. In the opposite case,* $S^{FB} < S^0$*, then* $\tau_1^{FB} > \tau_1^{OL} > \tau_1^{PE}$ *and* $\tau_2^{FB} = \tau_2^{PE} > \tau_2^{OL}$*.*

If the first-best subsidy S^{FB} exceeds the exogenously given subsidy S^0, the government would like to announce that the carbon tax in period 2 will exceed the first-best carbon tax ($\tau_2 > \tau_2^{FB}$) in order to stimulate R&D. However, if the government in Period 1 cannot commit to this high (open loop) carbon tax, that is, if the agents know that once they are in Period 2 the carbon tax that will actually be imposed will be equal to the first-best carbon tax ($\tau_2^{PE} = \tau_2^{FB}$), the government will increase the $first\ period$ tax relative to the open-loop tax ($\tau_1^{PE} > \tau_1^{OL}$) to compensate for the lack of a high period 2 tax. Hence, because the government is "forced" to lower the carbon tax in period 2, it is optimal to increase the carbon tax in period 1 even further above the first-best carbon tax (than in the open-loop solution) in order to stimulate R&D. In the opposite case, that is, S^0 exceeds S^{FB}, the government cannot credibly commit to a carbon tax in period 2 below the first-best carbon tax. In order to compensate for the lack of a low carbon tax in period 2, the carbon tax in period 1 is reduced ($\tau_1^{FB} > \tau_1^{OL} > \tau_1^{PE}$).

5 Discussion and conclusion

The purpose of this paper is to study and compare equilibrium carbon taxes under endogenous technology development of climate-friendly technologies. To simplify, we use a two-period model in which technology progress takes place in the first period and the new technology is used in both periods. There are positive and negative externalities in the R&D sector, and each developed abatement technology is unique and therefore supplied by *one* (monopolistic) agent. We show that the first-best outcome can be reached through a technology subsidy and carbon taxes. The sign of the subsidy depends on the strength of the externalities, and will be positive if the appropriation effect *exceeds* the stepping on toes effect. The first-best carbon taxes are decreasing over time. If the first-best subsidy is offered to the R&D firms, then the first-best outcome will be reached both under commitment (open-loop solution) and under no commitment (sub-game perfect equilibrium). In both cases, the first-best taxes will be implemented.

If the first-best subsidy is not offered to the R&D firms, the equilibrium under commitment will differ from the first-best outcome, and it will also be time inconsistent. Imposing time consistency through sub-game perfectness, we show that the ranking of the carbon taxes under first best, commitment and no commitment depends on whether the available subsidy is higher or lower than the first-best subsidy. If the first-best subsidy exceeds the offered subsidy, the government would ideally like to offer a high carbon tax in period 2 to spur present R&D. We have shown that in this case it is not time consistent to offer a high carbon tax in period 2, and therefore under no commitment the government will compensate the lack of a high carbon tax in period 2 through a high carbon tax in period 1. Hence, under no commitment the carbon tax in period 1 (2) is higher (lower) than the carbon tax under commitment. If the available technology subsidy exceeds the first-best subsidy, which may reflect successful lobbying from the R&D sector, the ranking is opposite.

In our analysis we have a number of simplifying assumptions. As pointed out in the paper, relaxing the assumptions of no decay parameter and periods of equal length would not change any of our propositions, just lead to more involved equations. Another simplifying assumption is no R&D in Period 2. As far as we can see, this does not influence the basic ranking of the carbon taxes between first-best, commitment and no commitment. With R&D in both periods, implementation of the first-best solution requires a technology subsidy in both periods. Suppose the available subsidies differ form the first-best ones. Yet, the basic mechanism in our model - seen from period 1 - that the future carbon tax affects current R&D - still applies. Also with R&D in period 2, the government in period 2 would - when setting the period 2 carbon tax - not take account of the R&D in period 1 simply because it is predetermined in period 2. Thus, under no commitment the government in period 1 adjusts the tax rate relative to the open-loop solution also when there is R&D in period 2. Of course, the adjustment will depend on the offered technology subsidies relative to the first-best subsidies.

In our model the mark-up is constant. This is clearly a simplification, and it is correct only under a constant elasticity of demand. On the other hand, an endogenous mark-up would not affect the basic message in the paper.

We have modelled only one cause for the appropriation effect; because of monopoly supply without price discrimination only a part of the social value of a new abatement equipment accrues to the R&D firm. In reality, there may be more reasons for an appropriation effect. First, patents may be copied and consequently the innovating firm loses its monopoly. Second, there may be positive knowledge spillovers from current R&D to future R&D. In a study which includes these appropriation effects, as well as the stepping on toes effect, Jones and Williams (2000) conclude that R&D is typically too small in a market economy without R&D subsidies. To the extent this holds also for R&D on climate-friendly technologies, the government should offer a positive technology subsidy. If this subsidy is below the first-best one, the government should rather go for high carbon taxes now than fall back on promising high carbon taxes in the future.

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Appendix: Proofs of Propositions 2 and 4

Proof of Proposition 2

Define the funcion $\pi(S)$ as the maximized social surplus for a given subsidy. From (5) we have

$$\pi(S) = \max_{u_1,u_2} n\left[\phi(u_1,u_2) - F(n)\right], \tag{15}$$

where n is given by (2). The function $\pi(S)$ gives the social surplus in the open-loop case for an exogenous S. In the first-best optimum, S is chosen so that $\pi(S)$ is maximized, giving $S = S^{FB}$.

From the envelope theorem, we have

$$\pi'(S) = \left[\phi - F - nF'\right] n'(S). \tag{16}$$

We now make the following regularity assumption:

$$\begin{aligned} \pi'(S) &> 0 \qquad for \quad S < S^{FB} \\ \pi'(S) &< 0 \qquad for \quad S > S^{FB} \end{aligned}$$

By the definition of S^{FB}, this condition must hold for S close to S^{FB}. Our regularity assumption is that the condition holds for all relevant values of S.

Together with (16) and $n'(S) > 0$, our regularity assumption implies that

$$\begin{aligned} \left[\phi - F - nF'\right] &> 0 \qquad for \quad S < S^{FB} \\ \left[\phi - F - nF'\right] &< 0 \qquad for \quad S > S^{FB} \end{aligned} \tag{17}$$

The open-loop equilibrium was given by (14), i.e.,

$$\begin{aligned} nd_1\left[a'(u_1^{OL}) - b\right] &= -\left[\phi - F - nF'\right]\frac{\partial n}{\partial u_1}, \\ nd_2\left[a'(u_2^{OL}) - b\right] &= -\left[\phi - F - nF'\right]\frac{\partial n}{\partial u_2}, \end{aligned}$$

while the first-best values (u_1^{FB}, u_2^{FB}) where given by similar expressions but with zeros on the right hand sides. Since $a'' < 0$ and $\frac{\partial n}{\partial u_t} > 0$, it follows that $u_t^{OL} > u_t^{FB}$ if $[\phi - F - nF'] > 0$ and that $u_t^{OL} < u_t^{FB}$ if $[\phi - F - nF'] < 0$. Remembering that u_t is strictly increasing in τ_t, Proposition 2 follows from (17).

Proof of Proposition 4

The condition for the optimal value of u_1 in the sub-game perfect equilibrium is (14) for $t = 1$, which may be written as

$$\Phi(u_1, u_2) \equiv \phi_1(u_1, u_2) + T(u_1, u_2) = 0, \tag{18}$$

where

$$T(u_1, u_2) = [\phi(u_1, u_2) - F(n) - nF'(n)]\,(m-1)bn',$$

and where n depends on u_1 and u_2, see (2).

Equation (18) defines u_1 as a function of u_2, and implicit derivation of (18) gives

$$\frac{du_1}{du_2} = \frac{\Phi_2}{-\Phi_1},$$

where $\Phi_1 < 0$ from the second oreder conditions. The sign of $\frac{du_1}{du_2}$ is therefore equal to the sign of Φ_2. If $\Phi_2 < 0$, a change in u_2 from u_2^{OL} in the direction of u_2^{FB} will give a change in u_1 in the opposite direction, i.e., moving u_1 further away from u_1^{FB} (since $u_1^{OL} - u_1^{FB}$ from Proposition 2 has the same sign as $u_2^{OL} - u_2^{FB}$). Remembering that u_t is strictly increasing in τ_t, Proposition 4 must therefore hold if $\Phi_2 < 0$.

Using (6) and (18), we find

$$\Phi_2 = T_2 = (m-1)bn'\left\{\beta\left[d_2a'(u_2) - b\right] - \left[2F' + nF''\right]\frac{\partial n}{\partial u_2}\right\} + \frac{T}{n'}n''(m-1)b\beta.$$

Because $n' = \frac{1}{F'(n)}$, we have $n'' = \frac{-F''n'}{(F')^2}$, implying that $\frac{n''}{n'} = \frac{-F''}{(F')^2} = -F''(n')^2$. Moreover, $T = (m-1)b\pi'(S)$. The equation above may therefore be written as:

$$\Phi_2 = (m-1)bn'\left\{\beta\left[d_2a'(u_2) - b\right] - \left[2F' + nF''\right]\frac{\partial n}{\partial u_2} - \beta F''n'\pi'(S)\right\}.$$

We know that $-\left[2F' + nF''\right]\frac{\partial n}{\partial u_2} < 0$. A sufficient condition for $\Phi_2 < 0$ is therfore that the first and last term (including the minus sign) in curly brackets are both negative. This will for sure be the case if $S^0 < S^{FB}$, since in this case we have $\pi'(S) > 0$ and $d_2 a'(u_2) \leq b$. We have thus proved Proposition 4 for the case in which $S^0 < S^{FB}$ (and thus $u_2^{OL} > u_2^{FB}$ from Proposition 2).

The proof above implies that Proposition 4 is also valid for $S^0 > S^{FB}$ (and thus $u_2^{OL} < u_2^{FB}$) as long as S^0 is sufficiently close to S^{FB}, so that the positive terms $\beta \left[d_2 a'(u_2) - b \right]$ and $-\beta F'' n' \pi'(S)$ are small enough to be dominated by $\left[2F' + nF'' \right] \frac{\partial n}{\partial u_2}$.