Climate Change and Carbon Tax Expectations

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Abstract

If governments cannot commit to future carbon tax rates, investments in greenhouse gas mitigation will be based on uncertain and/or wrong predictions about these tax rates. Predictions about future carbon tax rates are also important for decisions made by owners of non-renewable carbon resources. The effects of the size of expected future carbon taxes on near-term emissions and investments in substitutes for carbon energy depend significantly on how rapidly extraction costs increase with increasing total extraction. In addition, the time profile of the returns to investments in non-carbon substitutes is important for the effects on emissions and investments.

JEL-Code: H23, Q30, Q42, Q54.

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1 Introduction

It is widely recognized among economists that a price on carbon emissions, henceforth called a carbon tax[1], is the most important policy instrument to reduce such emissions. Standard economic reasoning also implies that in the absence of other market failures, an appropriately set carbon price is the *only* instrument needed to achieve an efficient climate policy. However, it is widely believed that in the real world there are many market failures associated with energy markets and other climate related markets, suggesting that there is a role for policy instruments in addition to a correct price on carbon emissions. Market failures associated with knowledge creation are certainly important in this respect, as it is difficult to imagine a significant reduction in carbon emissions during the coming decades without major technological changes.

Even ignoring market failures other than those directly associated with carbon emissions, one may question the conventional wisdom that an carbon tax will give an efficient mitigation of carbon emissions. The conventional wisdom is based on the ability of governments to commit to a future tax path. In reality, this is not possible. Without commitment, market agents who make investment decisions must base their decisions on what they expect about future climate policies. In a hypothetical world without any uncertainty related to technology, preferences, etc. in the future, future carbon taxes could be correctly predicted even in the absence of commitment. In the real world these conditions obviously do not hold. As discussed in more detail in section 6, non-commitment can therefore lead to uncertain and/or wrong predictions about the future carbon tax.

In policy debates, it is often argued that lack of commitment may lead to inefficiently low emission reducing investments, and that emissions therefore will be higher than they would be with commitment. For instance, Stern (2007, p. 399) argues that "lack of certainty over the future pricing of the

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[1] The price on carbon emissions could also be the price of carbon quotas; none of the results in the paper depend on whether taxes or quotas are used as the policy instrument.

carbon externality will reduce the incentive to innovate". This reasoning implicitly argues that the carbon price uncertainty due to lack of commitment has a similar effect on investments and emissions as the future carbon tax being "too low"; a point that is explicitly made by Ulph and Ulph (2009).

Much of the discussion on the importance of expected future carbon taxes on investments and hence on emissions ignores the fact that most CO_2 emissions are due to combustion of fossil fuels, which are scarce exhaustible resources. For such resources, Sinclair (1992) pointed out that "the key decision of those lucky enough to own oil-wells is not so much how much to produce as when to extract it." More recently, this issue has received considerable attention, often with reference to the so-called "green paradox"[2]. This term stems from Sinn (2008a,b), who argues that some designs of climate policy, intended to mitigate carbon emissions, might actually increase carbon emissions, at least in the short run. The reason for this possibility is closely related to the insights given by Sinclair. Sinn's point is that if e.g. a carbon tax rises sufficiently rapidly, profit maximizing resource owners will bring forward the extraction of their resources. Hence, in the absence of carbon capture and storage (CCS), near-term carbon emissions increase.

If lack of commitment has similar consequences as the future expected carbon tax being lower than under commitment, owners of the non-renewable carbon resources will postpone extraction compared with the extraction path they would have chosen had the policy makers been able to commit to the optimal price path. This argument suggests that it is not obvious whether near term emissions will increase or decline as a consequence of lack of commitment: If lack of commitment has similar consequences as the future carbon tax being lower than a government would like to set if it could commit, there

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[2] Contributions to this literature include Strand (2007), Grafton et al. (2010), Gerlagh (2010), Eichner and Pethig (2009), van der Ploeg and Withagen (2010), Hoel (2008, 2010). Earlier contributions making the link between climate policy and markets for non-renewable resources include Ulph and Ulph (1994), Withagen (1994), Hoel and Kverndokk (1996), Tahvonen (1997), Chakravorty et al. (2006, 2008).

are two effects working in opposite direction: Low investments in emission reducing capital tends to increase emissions, while postponed extraction works in the opposite direction. Notice also that these two effects interact: Owners of carbon resources are not only concerned about future carbon taxes, but also about how large is the future demand for energy and the supply of competing energy[3]. Similarly, firms investing in energy saving technologies or renewable energy care about what the future carbon tax will be, but also about what the supply of fossil energy will be.

The present paper uses a simple two-period model of an aggregate economy to analyze how the expected future carbon tax may affect both emissions and investments in substitutes for the carbon resource. Carbon capture and storage is ignored, implying that emissions are identical to carbon extraction.[4] Period 1 in the model may be interpreted as the near future where one has reasonable confidence about the size of the carbon tax, with period 2 being the remaining future. In terms of the number of years, 5-15 years might be a crude estimate of the length of period 1.

In period 1 the government first sets the carbon tax in period 1 and announces its intended carbon tax for period 2. Once the tax is set, carbon resource owners and investors in mitigation capital simultaneously make their choices of period 1 extraction and investment, respectively. Given the outcome of period 1, the government sets the carbon tax for period 2, after which the carbon resource owners decide how much to extract in this period. There is no further investment in mitigation capital in period 2.

The rest of the paper is organized as follows. Sections 2-5 describe the market equilibrium for exogenous carbon taxes in the two periods, and derives the consequences of a change in the period 2 carbon tax rate. The formal

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[3] This is studied in detail by Strand (2007), Gerlagh (2010), and van der Ploegh and Withagen (2010)

[4] Discussions of climate policy when there is a possibility of CCS and when the carbon resource scarcity is taken into considereation have been given by Amigues et al. (2010), Le Kama et al. (2010) and Hoel and Jensen (2010).

analysis in these sections is valid independently of whether the period 2 carbon tax rate is an actual tax rate that the government has committed to or it is the tax rate that market agents expect will be implemented in period 2.

The results in section 5 depend on how sensitive extraction costs are to total carbon extraction. If there is no physical scarcity of the resource and extraction costs only rise weakly with accumulated extraction, a higher future carbon tax implies lower near-term emissions and higher investments in the non-carbon substitute. On the other hand, near-term emissions will be higher the higher is the future carbon tax rate if extraction costs rise rapidly with accumulated extraction. Whether investments in the substitute are increasing or declining in the future carbon tax rate will in this case depend on the time profile of the returns to the investment. If most of the returns to the investments come in the near future, investments are declining in the expected future carbon tax, while the opposite is true if most of the returns to the investments come in the more distant future.

Section 6 introduces the government's preferences related to climate change, and derives the optimal tax rates for the two periods for the case of commitments. This section also gives a discussion of why lack of commitment will make the future tax rate be uncertain, with an expected value that might differ from the optimal tax rate under commitment.

The actual carbon tax rate for period 2 is set in period 2. This tax rate will depend on decisions made in period 1, which in turn depends on what tax rate market agents expected for period 2 when they made their decisions in period 1. Climate costs are assumed to depend on resource extraction in both periods, and in section 7 it is shown that equilibrium climate costs will depend on the expectations about the period 2 tax rate that market agents had in period 1. Climate costs may be increasing or declining in this expected tax rate, depending of key parameters in the model.

As mentioned above, it is often argued that lack of commitment may give lower investments in energy efficient technologies or renewable energy than one would get with commitment. This may be an argument for an investment subsidy, as suggested by Ulph and Ulph (2009). With this motivation, section 8 studies the consequences of an investment subsidy. It is shown that an investment subsidy always increases investments, while the effect on near-term emissions is ambiguous. Equilibrium climate costs will decline as a response to the subsidy, unless most of the returns to the investments come in period 1 and early emissions are considerable more harmful to the climate than later emissions.

Section 9 concludes.

2 The market for the general purpose good

Carbon is used as an input in production of a general purpose good in both periods. The output is increasing in the carbon input and also in a capital good that is a substitute for carbon energy. An obvious interpretation is that there is a substitute that has high capital costs and low operating costs (such as hydro, wind, and solar energy). Once the investment in capacity of such a substitute is made, it will be operated at full capacity. Alternatively, one could think of the substitute as knowledge capital, i.e. an improved technology that is available at a low cost once it has been developed.

Output in the two periods is $\tilde{f}(x, I)$ and $\tilde{F}(X, I)$, where x is carbon extracted and used in period 1 and X is carbon extracted and used in period 2. The variable I is the investment in the carbon substitute, which takes place only in period 1. This investment is assumed to affect output in both periods, with either $\tilde{f}_I$ or $\tilde{F}_I$ being zero as special cases. The functions $\tilde{f}$ and $\tilde{F}$ are assumed to be concave and increasing in both arguments, and it is also assumed that the cross derivatives $\tilde{f}_{xI}$ and $\tilde{F}_{XI}$ are negative, so that the marginal productivity of using the carbon resource is lower the higher is the capital good I.

The price of the general purpose good is normalized to 1, while the price of the carbon resource that the producers of the general purpose good must pay in the two periods is $p+q$ and $P+Q$, respectively. Here p and P are the prices that the producers of the carbon resource receive in the two periods, while q and Q are the carbon taxes in the two periods. Investment in the carbon substitute uses the general purpose good, and the cost of one unit of I is $c(I)$.[5] Finally, the exogenous discount factor is β (equal to $(1+r)^{-1}$, where r is the exogenous discount rate).

Producers of the general purpose good take the resource price in period 1 and 2 as given ($p+q$ and $P+Q$, respectively) and maximize

$$\tilde{f}(x,I) - (p+q)x - cI + \beta\left[\tilde{F}(X,I) - (P+Q)X\right]$$

The maximization gives

$$\begin{aligned} \tilde{f}_x(x,I) - (p+q) &= 0 \qquad (1)\\ \tilde{F}_X(X,I) - (P+Q) &= 0 \qquad (2)\\ \tilde{f}_I(x,I) + \beta\tilde{F}_I(X,I) - c'(I) &= 0 \qquad (3) \end{aligned}$$

3 The market for the carbon resource

To extract the carbon resource one needs to use the all purpose good as an input. The input needed per ton of the resource extracted is assumed to be independent of the extraction rate, but increases with accumulated extraction. A special case of this is the case of a constant unit cost of extraction combined with an absolute upper limit $\bar{A}$ on accumulated extraction $x+X$. The general specification is frequently used in the resource literature, see e.g. Heal (1976) and Hanson (1980). Formally, let each unit of the resource be indexed by a continuos variable z, and let $g(z)$ be the cost of of extracting unit z, with

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[5] With the interpretation of I as investment in the capacity to produce a substitute, $c(I)$ includes the present value of the operating costs of the substitute at full capacity.

$g' \geq 0$. In the two-period model x is extraction in period 1, and X is extraction in period 2. The cost of extracting x is thus given by $G(x) = \int_0^x g(z)dz$, and the cost of extracting X is $\int_x^{x+X} g(z)dz = \int_0^{x+X} g(z)dz - \int_0^x g(z)dz = G(x+X) - G(x)$. Notice that these relationships imply that $G'(x) = g(x)$ and $G'(x+X) = g(x+X)$. The limiting case of a constant unit cost g of extraction up to an exogenous limit $\bar{A}$ would imply that $G(x) = gx$ and $G(x+X) - G(x) = gX$ (with X having an upper limit of $\bar{A} - x$). In the subsequent analysis it is assumed that $g'(z) = 0$ for $z \leq \tilde{z}$ and $g'(z) > 0$ for $z > \tilde{z}$, and that $x < \tilde{z} < x + X$ for all relevant values of x and X.[6] This implies that $g'(x) = 0$, while $G'(x+X) = g(x+X) > g(x)$ and $G''(x+X) = g'(x+X) > 0$; $g'(x+X)$ is henceforth denoted g'.

Producers of the carbon resource maximize

$$px - G(x) + \beta \left[PX - (G(x+X) - G(x)) \right]$$

This gives (using $G'(x) = g(x)$ and $G'(x+X) = g(x+X)$)

$$p - g(x) = \beta \left[P - g(x) \right] \tag{4}$$

and

$$P = g(x+X) \tag{5}$$

Using $\beta = (1+r)^{-1}$, this equation implies that

$$P - p = r(p - g(x))$$

This is simply the Hotelling rule, which formulated this way also holds for the extraction cost assumption we are using.

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[6] This simplifying assumption is not important for the results.

4 The market equilibrium

Equations (1)-(5) are 5 equations determining the 5 variables p, P, x, X, I as functions of the exogenous tax rates q and Q. Eliminating p and P, the market equilibrium (1)-(5) may be rewritten as

$$\begin{aligned} \tilde{f}_x - (1-\beta)g(x) - \beta g(x+X) - q &= 0 \qquad (6) \\ \tilde{F}_X - g(x+X) - Q &= 0 \qquad (7) \\ \tilde{f}_I + \beta \tilde{F}_I - c' &= 0 \qquad (8) \end{aligned}$$

These equations are of course also the first order conditions to the problem of maximizing the total private sector profits given by

$$\begin{aligned} \Pi(x, X, I, q, Q) = & \left[\tilde{f}(x, I) - G(x) - c(I) - qx\right] \qquad (9) \\ & + \beta\left[\tilde{F}(X, I) - (G(x+X) - G(x)) - QX\right] \end{aligned}$$

which is concave in (x, X, I) since $\tilde{f}$, $\tilde{F}$, $-G(x+X)$ and $-(1-\beta)G(x)$ are concave.

If the government could commit to a tax rate Q in the future, both tax rates q and Q would be known when decisions are made for the first period. In the first period the variables x and I are decided upon, while X has the status of a planned variable for the resource owners, and an expected variable for the other agents. However, as long as the future tax rate Q and other exogenous variables are not changed when period 2 arrives, the planned extraction in period 2 will be the extraction that actually will occur.

Without commitment about the future tax rate, Q is the tax rate that agents expect in period 2. When period 2 arrives, x, I and p are all historically determined, while P and X will be determined by (2) and (5). If Q

turns out to be different from what agents expected in period 1, P will also be different from what agents expected, and X will be different from what agents planned.

The next section discusses how the equilibrium depends on the tax rate Q. The formal analysis is valid independently of whether Q is set already in period 1 or Q is what agents expect the future tax rate to be. However, in section 6 it is argued that governments in practise cannot commit to tax rates far into the future, implying that Q should be interpreted as the tax rate that agents expect in period 2. In section 6 it is also argued that there may be good reasons for private agents to expect a future tax rate that differs from the tax rate that the present government plans to set.

5 The effects of a change in the expected future carbon tax

This section describes how changes in Q affect x and I. Derivations using the general functions $\tilde{f}(x, I)$ and $\tilde{F}(X, I)$ give ambiguous results that are not easy to interpret. In particular, the results will depend on how close a substitute I is for x and X, i.e. on the size of $\tilde{f}_{Ix}$ and $\tilde{F}_{IX}$, which are assumed negative. One limiting case is $\tilde{f}_{xI} = \tilde{F}_{XI} = 0$. In this case the market for I (described by (8)) is completely independent of the market for the resource (described by (6) and (7)). For this case all results are trivial, and not considered any more in the present paper.

A second limiting case, which the proceeding formal analysis focuses on, is the case in which the capital good I is a perfect substitute for the resource. If I is a perfect substitute for x and X, x and I must enter linearly in $\tilde{f}$, so that $\tilde{f}(x, I) = f(x + aI)$, and similarly for X and I, so that $\tilde{F}(X, I) = F(X + bI)$. By a suitable choice in the units I is measured in, we can set $a + b = 1$, so the functions become

$$\begin{aligned}\tilde{f}(x, I) &= f(x + aI) \\ \tilde{F}(X, I) &= F(X + (1 - a)I)\end{aligned}$$

The parameter a tells us what share of the total returns to investment are obtained already during period 1. It is perhaps easiest to interpret a by considering the limiting cases of $a = 0$ and $a = 1$. If $a = 0$ the investment gives no payoff in period 1. This could be interpreted as the time lag from the investment decision till the investment is completed and contributes to production being at least as long as the time period for which commitment to a specific carbon tax rate is assumed. The opposite limiting case of $a = 1$ could be interpreted as the case of an investment in a capital good that depreciates rapidly, so that it only contributes to production for the time period for which commitment to a specific carbon tax rate is assumed. The more general cases of $a \in (0, 1)$ are intermediate between the two limiting cases. Notice that the size of a will not only depend on properties of the capital good: The longer one assumes the period is for which the government can commit to a specific tax rate, the larger will a be.

The assumption that a is an exogenous parameter that does not depend on carbon taxes and other economic variables reflects a limitation of the present analysis I will return to in section 9: The analysis is limited to how total investment in a substitute may depend on carbon taxes and carbon tax expectations, and not on how the composition of such investments may be affected.

With the specification above the market equilibrium (1)-(5) may be rewritten as

$$
\begin{aligned}
f'(x+aI)-(1-\beta)g(x)-\beta g(x+X)-q &= 0 && (10)\\
F'(X^e+(1-a)I)-g(x+X)-Q &= 0 && (11)\\
af'(x+aI)+\beta(1-a)F'(X+(1-a)I)-c' &= 0 && (12)
\end{aligned}
$$

This gives three equations to determine the three variables x, X and I as functions of q and Q. Just as in the general case, these equations are also the first order conditions to the problem of maximizing the total private sector profits given by

$$
\begin{aligned}
\Pi(x,X,I,q,Q) &= [f(x+aI)-G(x)-I-qx] && (13)\\
&\quad +\beta\,[F(X+(1-a)I)-(G(x+X)-G(x))-QX]
\end{aligned}
$$

which is concave in (x,X,I) since f, F, $-G(x+X)$ and $-(1-\beta)G(x)$ are concave.

Differentiating the three equations (10), (11) and (12) with respect to Q gives the following three linear equations (using $g'(x)=0$ and $g'(x+X)=g'$):

$$
M\cdot\begin{pmatrix}\frac{\partial x}{\partial Q}\\ \frac{\partial X}{\partial Q}\\ \frac{\partial I}{\partial Q}\end{pmatrix}=\begin{pmatrix}0\\1\\0\end{pmatrix}
$$

where

$$
\mathbf{M}=\begin{pmatrix} f''-\beta g' & -\beta g' & af'' \\ -g' & F''-g' & (1-a)F'' \\ af'' & \beta(1-a)F'' & a^2f''+\beta(1-a)^2F''-c'' \end{pmatrix} \qquad (14)
$$

Solving the equation system above gives (after some tedious calculations)

$$\frac{\partial x}{\partial Q}=\frac{\beta}{H}\left\{-a(1-a)f''F''-\left[a^2f''+\beta(1-a)^2F''-c''\right]g'\right\}\equiv\frac{\beta}{H}K_x \quad (15)$$

$$\frac{\partial I}{\partial Q}=\frac{\beta}{H}\left\{(1-a)f''F''+\left[af''-(1-a)\beta F''\right]g'\right\}\equiv\frac{\beta}{H}K_I \quad (16)$$

where $H=-|\mathbf{M}|>0$ due to the concavity of the function Π defined by (13).

It is easily verified that both these derivatives have ambiguous signs. In particular, the signs depend on the sizes of a and g'; in the Appendix the following result is shown:

Proposition 1 *The effects of a change in the future carbon tax rate on present decisions about resource extraction and investments in a substitute depend on* a *and* g' *in a way described by Figure 1, where* $a^*=\frac{\beta F''}{f'+\beta F''}$ *and the three regions A, B and C have the following properties:*

Region	$\frac{\partial x}{\partial Q}$	$\frac{\partial I}{\partial Q}$
A ("small g' ")	$-$	$+$
B ("intermediate g' or small a")	$+$	$+$
C ("large g' and large a")	$+$	$-$

Figure 1 about here

To interpret this result, it is useful first to consider regions B and C. In both of these cases we find the "standard" green paradox result that a higher future carbon tax shifts extraction from the future to the present. Investments where most of the returns come in period 1 (large a) therefore get a lower payoff due to increased extraction of the resource, implying lower investment (region C). On the other hand, investments where most of the returns come in period 2 (small a) get a higher payoff due to reduced extraction of the resource in period 2, implying higher investment (region B).

Region A is characterized by g' being small. This means that there is no strong relationship between extraction in the two periods. In particular, $g' = 0$ would imply that extraction decisions in period 1 were completely independent of extraction plans for period 2. As before, a higher carbon tax in the future tends to reduce future extraction. However, when g' is small the direct effect of this on period 1 extraction is small. Investments, on the other hand, become more profitable due to the reduced future extraction, as long as some of the returns to the investment accrue in period 2 ($a < 1$). But if these increased investments also reduce demand for the resource in period 1 ($a > 0$), this tends to reduce extraction in period 1.

6 The social optimum and the role of commitment

All of the analysis to now has considered arbitrarily given tax rates, and the effects of changing the (expected) future tax rate. In this section I discuss how the social optimum may be achieved by using appropriate carbon taxes in the two periods, and what role the possibility of commitment may have for achieving the social optimum. The analysis of the present section starts with a discussion of how the emissions in the two periods affect total climate costs.

Due to the time lag of the climate system, the effect of emissions in period 1 on the climate in period 1 is assumed to be negligible; this is certainly true if the length of period 1 is no longer than about 5-15 years. Climate costs are therefore assumed to depend on the temperature increase in period 2 (from some base level). The temperature increase will depend on emissions in both periods. According to Allen et al. (2009), the peak temperature increase due to greenhouse gas emissions is approximately independent of the timing of emissions. In the framework of the present model, peak temperature increase thus depends only on $x+X$. However, we would expect this peak temperature increase to occur earlier the more of the emissions occur at an early stage. It also seems reasonable to expect climate costs to be higher the more rapidly the temperature increases, for a given peak temperature increase. Hence, it seems reasonable to assume that climate costs are increasing in the two variables x and X, with x having a stronger marginal impact on climate costs than X. A simple way of capturing this it to assume that climate costs are given by a function $D(\gamma x + X)$, where $D' > 0$ and $\gamma > 1$.[7]

Given this climate cost function, the social optimum is found by maximizing

$$W = \tilde{f}(x, I) - G(x) - c(I) + \beta \left[\tilde{F}(X, I) - (G(x + X) - G(x)) \right] - \beta D(\gamma x + X) \tag{17}$$

The optimum conditions for the three variables x, X, I are

$$\begin{aligned} \tilde{f}_x - (1-\beta) g(x) - \beta g(x+X) - \beta\gamma D' &= 0 && (18) \\ \tilde{F}_X - g(x+X) - D' &= 0 && (19) \\ \tilde{f}_I + \beta \tilde{F}_I - c' &= 0 && (20) \end{aligned}$$

Comparing these equations with (6)-(8) it immediately follows that the market outcome coincides with the social optimum if

$$\begin{aligned} q &= \beta\gamma D'(\gamma x + X) && (21) \\ Q &= D'(\gamma x + X) && (22) \end{aligned}$$

Notice that this implies that

$$\frac{Q}{q} = \frac{1}{\beta\gamma}$$

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[7] A slightly more general function $\tilde{D}(x, x + X)$, increasing in both arguments, would make derivations slightly more complex without adding anything of substance.

Since $\gamma > 1$, the optimal carbon tax thus rises at a rate lower than the rate of interest ($= 1 + r = \beta^{-1}$).

If taxes for both periods were set already in period 1 according to (21) and (22), with the equilibrium values of x and X inserted from (6)-(8), the social optimum would be achieved. Moreover, if the government reoptimized in the beginning of period 2, i.e. maximized W taking x and I as given, there would be no change in the optimal tax in period 2. Whether or not it is possible to commit to a future tax rate is thus irrelevant in the present model as long as all kinds of uncertainties are ignored. Before turning to possible sources of uncertainties, it is useful briefly to see how relatively small changes in the present model would make the issue of commitment more important.

In the present model all market participants are price takers. If instead the firms investing in the substitute were so large that they realized that their investment decisions could influence the future tax rate in the case of no commitment, there would be a difference between the case of commitment and no commitment, see e.g. Ulph and Ulph (2009) for a further discussion.[8]

Any market failure (in addition to the climate externality) preventing the first-best social optimum from being achievable might also make the issue of commitment more important. Consider e.g. a market failure implying that investment in the substitute is lower than in the social optimum, even if carbon taxes are given by (21) and (22). In the case of commitment, the government might want to partly correct this market failure through choosing tax rates that deviate from (21) and (22). However, without commitment it would be optimal to set the second period tax according to (22) once period 2 arrived. If this were foreseen by market participants in period 1, there would thus be a difference in the outcome under commitment and no commitment. This issue is discussed in more detail by Golombek et al. (2010) for the case of investment in period 1 being R&D.

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[8] A similar point is made by Requate (2005) for R&D investments by an innovator that is so large than it may influence future tax rates.

Finally, a regulatory failure in period 1 implying that the tax in period 1 cannot be set as high as its optimal value would generally imply that if it were possible to commit, the optimal tax in period 2 would differ from the rate implied by (22). As in the reasoning above, reoptimization in period 2 would generally give a tax differing from the original tax rate. If this were foreseen by market participants in period 1, there would also in this case be a difference in the outcome under commitment and no commitment.

While all of the issues above are important in the real world, they are ignored in the present analysis. Instead, the focus is on various types of uncertainties, implying that market participants cannot predict future tax rates with certainty, given that the government cannot commit to a specific future tax rate. There are several sources of such uncertainties in the real world. Three sources that immediately come to mind in the context of the climate issue are uncertainties related to technological development, uncertainties related to the preferences of future governments, and uncertainties related to the development of international climate cooperation. Clearly, optimal future carbon taxes are going to depend on the development of all these factors.

Consider in particular the case of uncertain future political preferences, given by the climate cost function.[9] Let $D(\gamma x + X)$ be the preferences of the period 1 government, while the preferences of the period 2 government are given by $\theta D(\gamma x + X)$, where θ is uncertain in period 1.[10] A full treatment of the market equilibrium treating θ as a random variable is beyond the scope of the present analysis. What is important is that the expectations market participants have about θ will be an important factor determining what the agents believe about the future carbon tax, assumed to be given by an equation corresponding to (22), i.e. $Q = \theta D'(\gamma x + X)$. Notice in

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[9] Even if preferences regarding climate change were known with certainty, the function D decribing the relationship between emissions and climate costs could be uncertain due to uncertainty related to the climate effects of emissions.

[10] A similar specification is used by Ulph and Ulph (2009).

particular that even if agents have a subjective probability distribution over θ satisfying $E\theta = 1$, the expected future tax will, due to non-linearities, generally differ from what the expected price would have been with $\theta = 1$ for certain. Moreover, there is no reason why $E\theta = 1$. If the present government is considered to give climate issues high priority compared with potential other governments, $E\theta < 1$ would be more plausible. This may give an expected value of Q that is lower than what the present government considers as optimal.

The next section considers the situation from the perspective of the period 1 government with preferences $D(\gamma x + X)$. Given these preferences, it is of interest to see what the consequences are of Q differing from the optimal value given by (22), given that the present government will be in power also in period 2, and thus set the actual carbon tax according to (22).

7 Climate costs and carbon tax expectations

Assume that the carbon policy is set optimally in period 2, no matter how x and I are determined in period 1. Letting as before Q denote the carbon tax in period 2 that was expected in period 1, the actual value of X follows from maximizing W (given by (17)) taking $x(Q)$ and $I(Q)$ as given. This gives

$$F'(X + (1-a)I(Q)) = g(x(Q) + X) + D'(\gamma x(Q) + X)$$

implying that

$$\frac{dX}{dQ} = J^{-1}\left\{-(g' + \gamma D'')\frac{\partial x}{\partial Q} + (1-a)F''\frac{\partial I}{\partial Q}\right\} \tag{23}$$

where $J = D'' + g' - F'' > 0$. Total climate costs depends on $\gamma x + X$, and it follows from (15), (16) and (23) that

$$\frac{dD(\gamma x + X)}{dQ} = \frac{\beta D'}{HJ}\left\{\left[(\gamma - 1)g' - \gamma F''\right)\right] K_x + (1-a)F'' K_I\right\} \tag{24}$$

where K_x and K_I are given by (15) and (16), respectively.

The term in front of K_x is positive (since $\gamma > 1$), while the term in front of K_I is negative. If K_x and K_I have opposite signs, $\frac{dD}{\partial Q}$ is therefore unambiguously signed. From Proposition 1 the following therefore follows:

Proposition 2 *The effects of a change in the expected future carbon tax rate on climate costs, given that the actual future carbon tax rate is set optimally, depend on* a *and* g' *in the way described by Figure 1, where* $a^* = \frac{\beta F''}{f'+\beta F''}$ *and the three regions A, B and C have the following properties:*

Region	$\frac{\partial x}{\partial Q}$	$\frac{\partial I}{\partial Q}$	$\frac{dD}{dQ}$
A ("small g' ")	$-$	$+$	$-$
B ("intermediate g' or small a")	$+$	$+$	?
C ("large g' and large a")	$+$	$-$	$+$

Going back to equation (24), we see that both the numerator and the denominator contain terms with $(g')^2$. For g' sufficiently high, these terms in the numerator will dominate other terms. The part of the numerator containing $(g')^2$ is $-(\gamma-1)\left[a^2 f'' + \beta(1-a)^2 F'' - c''\right](g')^2$. The term in square brackets is negative no matter what value a has, implying that the whole expression is positive since $\gamma > 1$. We therefore have the following proposition:

Proposition 3 *If the actual future carbon tax rate is set optimally, climate costs are increasing in the expected carbon tax for* g' *sufficiently large, no matter what value* a *has.*

Notice that this result follows immediately from $\gamma > 1$ for the limiting case of $x + X$ being exogenous, since $\frac{\partial x}{\partial Q} > 0$ in this case.

Intuitively, one might think that expectations about a high future carbon tax are good for the climate. This may be true, and Proposition 2 shows that it is certainly true for values of a and g' in Region A of Figure 1. However, if g' is sufficiently high we get the opposite result: Expectations about a high future carbon tax are *bad* for the climate.

8 The effects of subsidizing investments in the carbon substitute

In several countries, in particular in the EU, there are substantial subsidies offered to investments in renewable energy and energy saving capital. One reason that is often given for such subsidies is the assumed lack of confidence among private agents in a high future carbon tax (or quota price). An obvious question is whether a subsidy to the carbon substitute actually reduces climate costs. To investigate this, let private investment costs now be $c(I) - sI$, where s is an investment subsidy. Differentiating the three equations (10), (11) and (12) with respect to this subsidy gives

$$M \cdot \begin{pmatrix} \frac{\partial x}{\partial s} \\ \frac{\partial A^e}{\partial s} \\ \frac{\partial I}{\partial s} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ -1 \end{pmatrix}$$

where M as before is given by (14). Solving these equations we find that

$$\frac{\partial x}{\partial s} = \frac{1}{H} \left\{ -af''F'' + \left[af'' - \beta(1-a)F'' \right] g' \right\} \equiv \frac{1}{H} L_x \tag{25}$$

and

$$\frac{\partial x}{\partial s} = \frac{1}{H} \left\{ f''F'' - \left[f'' + \beta F'' \right] g' \right\} \equiv \frac{1}{H} L_I > 0 \tag{26}$$

While I for sure increases as a response to a subsidy, the effect of an investment subsidy on x is ambiguous. In particular, the sign of $\frac{\partial x}{\partial s}$ depend on the sizes of a and g'; in the Appendix the following result is shown:

Proposition 4 *An investment subsidy increases investment, while the effect on resource extraction in period 1 depends on* a *and* g' *in the way described by Figure 2, where* $a^* = \frac{\beta F''}{f'' + \beta F''}$ *and the two regions D and E have the following properties:*

Region	$\frac{\partial x}{\partial s}$	$\frac{\partial I}{\partial s}$
D ("large a")	$-$	$+$
E ("small a")	$+$	$+$

Figure 2 about here

The effect of an investment subsidy on climate costs, assuming the climate policy in period 2 is optimally designed, is given by a similar expression as (24):

$$\frac{dD(\gamma x + X)}{ds} = \frac{D'}{HJ}\left\{\left[(\gamma - 1)g' - \gamma F''\right)\right] L_x + (1-a)F'' L_I\right\} \tag{27}$$

where L_x and L_I are given by (25) and (26), respectively.

The term in front of L_x is positive (since $\gamma > 1$), while the sign in front of L_I is negative. If L_x and L_I have opposite signs, $\frac{dD}{\partial s}$ is therefore unambiguously signed. From Proposition 4 the following therefore follows that $\frac{dD}{ds} < 0$ in Region D of Figure 2. As for region E, the following is shown in the Appendix:

Proposition 5 *Given that the actual future carbon tax rate is set optimally, the effect of an investment subsidy on climate costs depend on* a, g' *and* γ *in a way described by Figure 2, where* $a^* = \frac{\beta F''}{f' + \beta F''}$ *and the two regions D and E have the following properties:*

Region	$\frac{\partial x}{\partial s}$	$\frac{\partial I}{\partial s}$	$\frac{dD}{ds}$
D ("large a ")	$-$	$+$	$-$
E ("small a ") and small γ	$+$	$+$	$-$
E ("small a ") and large γ	$+$	$+$	$+$

An investment subsidy is thus good for the climate if a is large or γ is small. However, it is bad for the environment if a is small and γ is large. The interpretation of this is that if a is small, encouraging investment will reduce demand for the resource in the future considerably more than in the present. Resource owners therefore speed up extraction. If climate costs are sufficiently strongly affected by shifting emissions from the future to the preset, climate costs therefore increase.

9 Concluding remarks

An obvious problem with implementing an optimal climate policy is that policy makers cannot commit to a high future carbon tax. In the policy debate on climate policies it is often argued that long-run investments in greenhouse gas mitigation may be smaller than desirable since investors fear that future carbon prices will be lower than currently announced by policy makers. The present paper shows that it is not obvious how expectations about future carbon taxes affect important variable such as investments in non-carbon energy and near-term emissions. .

The effects of expectations about future carbon taxes on near-term emissions and investments in substitutes for carbon energy depend significantly on how rapidly extraction costs increase with increasing total extraction. In addition, the time profile of the returns to the investment in the non-carbon substitute is important for the effects of expectations about future carbon taxes.

The analysis is based on an extremely simple model. Only two periods are considered, instead of a more general model with several periods or with continuous time. The assumption about commitment therefore was quite rigid: Market agents know the carbon tax with certainty in the first period, while they must guess on the tax in period 2. In reality, the degree of uncertainty about the carbon tax or any other price will typically be increasing gradually over time. Similarly, policy makers ability to commit is not an either or issue, but rather how strongly they can commit. It seems plausible that commitment is weaker the further into the future we look.

The model is highly aggregated. There is only one type of carbon resource in the model. In reality, there are quite large differences between coal, oil and natural gas. In particular, the degree of physical scarcity of the resource, captured by g' in the formal model, probably differs considerably between different types of fossil fuels. Similarly, there is only one type of investment in the model, with a given time profile of returns. In reality there are many types of emission reducing investments, differing along many dimensions, including the time profile of returns. We would therefore expect a change in the expectations about future tax rates to have different effects on different investment.

In spite of the shortcomings of the formal model, I believe the analysis gives an important insight: An key message is that in any analysis of dynamic effects of carbon taxes, investment subsidies and other mitigation policies, it is crucial to take the supply side of fossil fuel markets into consideration.

Appendix

Proof of Proposition 1

The signs of the derivatives (15) and (16) are equal to the signs of K_x and K_I, respectively.

Consider first K_x. This function is increasing in g' and quadratic in a. It is zero for $g' = a = 0$ and for $g' = 1 - a = 0$. The first term in the expression for K_x is negative (for $0 < a < 1$), while the second term (including the minus sign) is positive. The second term will dominate if g' is sufficiently large. However, for g' sufficiently small there will be a range of a-values giving $K_x < 0$. By setting $K_x = 0$ we can find the combinations of a and g' that separate the area for $K_x < 0$ and $K_x > 0$. These combinations are given by the line ℓ in Figure 1: When $K_x = 0$ each value of $a \in (0, 1)$ will give some positive value of g', with a particular value of a giving the highest possible value of g'consistent with $K_x = 0$. Since K_x is increasing in g', it follows that $K_x < 0$ in region A in Figure 1, while $K_x > 0$ in region B.

Consider next K_I. This function is declining in a. Moreover, for any value of g' there exists a value of a giving $K_I = 0$. It is straightforward to see that this value is

$$\hat{a}(g') = \frac{f''F'' - \beta F''g'}{f''F'' + (-f'' - \beta F'')g'}$$

which approaches a^* as $g' \to \infty$. Since K_I is declining in a, it follows that $K_I > 0$ for combinations of g' and a satisfying $a < \hat{a}(g')$, illustrated as region B in Figure 1. Similarly, $K_I < 0$ for combinations of g' and a satisfying $a > \hat{a}(g')$, illustrated as region C in Figure 1. The borderline between these two regions in denoted m in Figure 1.

In Figure 1, the curves ℓ and m don't intersect for any positive value of g'. The reason for this is that $K_x > 0$ to the right of the curve m, or, alternatively stated, $K_I \leq 0$ implies $K_x > 0$: if $K_I = (1-a)f''F'' + [af'' - (1-a)\beta F'']\, g' \leq 0$, it follows that $-a(1-a)f''F'' - a^2 f''g' + a(1-a)\beta F''g' \geq 0$. But K_x is larger than the l.h.s. of the last inequality, implying that $K_x > 0$.

This concludes the proof of Proposition 1.

Proof of Proposition 4

The term L_x is declining in a. Moreover, for any value of g' there exists a value of a giving $L_x = 0$. It is straightforward to see that this value is

$$\tilde{\alpha}(g') = \frac{-\beta F''g'}{f''F'' + (-f'' - \beta F'')g'}$$

which is increasing in g' and approaches a^* as $g' \to \infty$. Since L_x is declining in a, it follows that $L_x < 0$ for combinations of g' and a satisfying $a > \tilde{\alpha}(g')$, illustrated as region D in Figure 2. Similarly, $L_x > 0$ for combinations of g' and a satisfying $a < \tilde{\alpha}(g')$, illustrated as region E in Figure 2. The borderline between these two regions in denoted n in Figure 2.

This concludes the proof of Proposition 4.

Proof of Proposition 5

The term L_x is positive in region E. The term $[(\gamma-1)g' - \gamma F'')]\,L_x$ will therefore dominate the term $(1-a)F''L_I$ in (27) if γ is sufficiently large. Hence, the whole expression in (27) will be positive in this case.

For the limiting case of $\gamma = 0$ it follows from (25), (26) and (27) that

$$\left(\frac{dD(\gamma x + X)}{ds}\right)_{\gamma=0} = \frac{D'f''F''}{HJ}\,[F'' - g'] < 0$$

By continuity, $\frac{dD}{ds} < 0$ also for small but positive values of γ.

This concludes the proof of Proposition 5.

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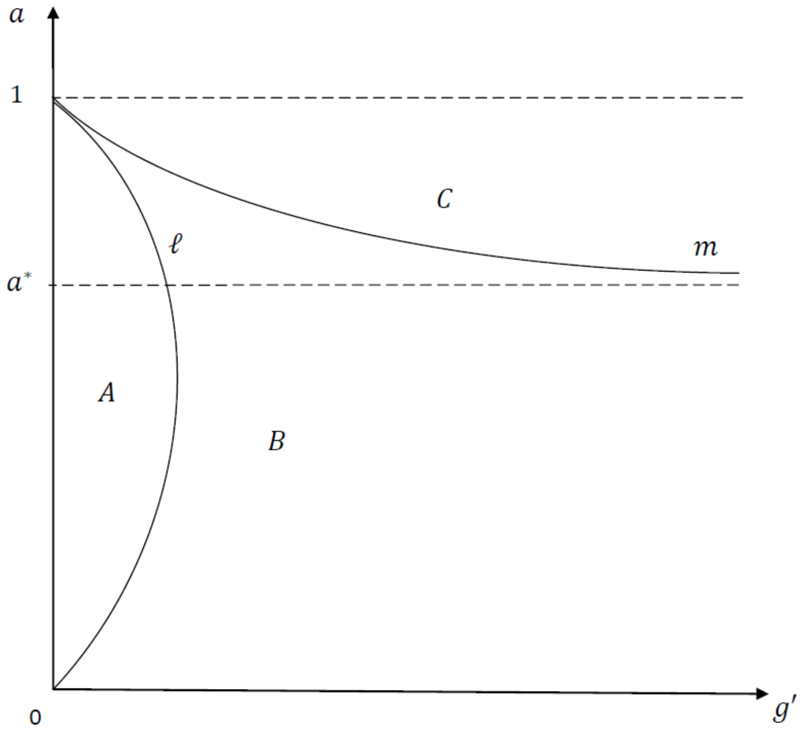

Figure 1

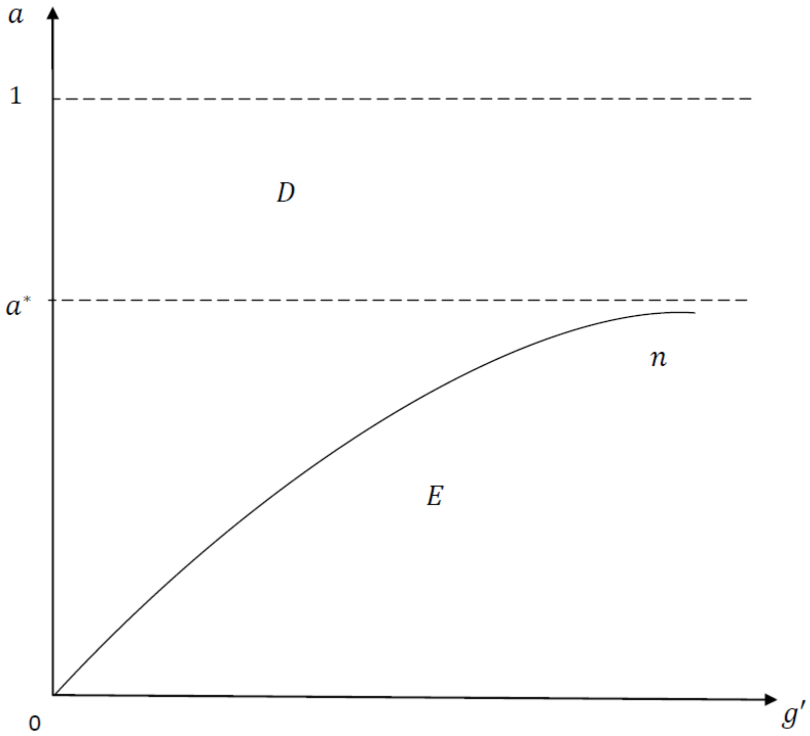

Figure 2

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