

Hoel, Michael

Working Paper

Climate change and carbon tax expectations

CESifo Working Paper, No. 2966

Provided in Cooperation with:

Ifo Institute – Leibniz Institute for Economic Research at the University of
Munich

Suggested Citation: Hoel, Michael (2010) : Climate change and carbon tax expectations, CESifo Working Paper, No. 2966

This Version is available at:

<http://hdl.handle.net/10419/30723>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.

Climate Change and Carbon Tax Expectations

Michael Hoel

CESIFO WORKING PAPER NO. 2966
CATEGORY 10: ENERGY AND CLIMATE ECONOMICS
FEBRUARY 2010

PRESENTED AT CESIFO AREA CONFERENCE ON ENERGY & CLIMATE ECONOMICS, OCTOBER 2009

An electronic version of the paper may be downloaded

- *from the SSRN website:* www.SSRN.com
- *from the RePEc website:* www.RePEc.org
- *from the CESifo website:* www.CESifo-group.org/wp

Climate Change and Carbon Tax Expectations

Abstract

If investors fear that future carbon taxes will be lower than currently announced by policy makers, long-run investments in greenhouse gas mitigation may be smaller than desirable. On the other hand, owners of a non-renewable carbon resource that underestimate future carbon taxes will postpone extraction compared with what they would have chosen had the policymakers been able to commit to the optimal tax path. If extraction costs rise rapidly as accumulated extraction rises, near-term emissions increase as a consequence of a downward bias in the expected future carbon taxes. Whether investments in greenhouse gas mitigation go up or down due to the expectation error depends on the time profile of the returns to the investment.

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

Keywords: climate change, exhaustible resources, carbon tax.

Michael Hoel
Department of Economics
University of Oslo
P.O. Box 1095, Blindern
0317 Oslo
Norway
m.o.hoel@econ.uio.no

February 15, 2010

The paper was started during a visit to FEEM in the fall of 2008, and I am grateful for the support of FEEM. I also thank Rolf Golombek, Svern Jensen, Sjak Smulders, and several participants at seminars at FEEM and CESifo for useful comments. The support of the Research Council of Norway, under the PETROSAM programme, is also gratefully acknowledged.

1 Introduction

The most important contribution to the climate problem is CO₂ from the combustion of fossil fuels. The climate problem is thus to a large extent caused by extracting carbon resources and transferring them to the atmosphere. Logically, any discussion of the climate problem therefore ought to be intimately linked to a discussion of the extraction of carbon resources. In spite of this obvious fact, surprisingly little of the literature makes this link. However, there are important exceptions, such as the early contributions by Sinclair (1992), Ulph and Ulph (1994) and Withagen (1994), and more recent contributions, such as Hoel and Kverndokk (1996), Tahvonen (1997), Chakravorty et al. (2006), Strand (2007), Sinn (2008) and Gerlagh (2010).

One of the insights from this literature is that the principles for setting an optimal carbon tax (or price of carbon quotas) are the same as those one finds when ignoring the resource aspect of the problem. In particular, the optimal carbon tax should at any time be equal to the discounted value of all future marginal climate costs caused by the present emission. At an early stage, when the optimal path of carbon in the atmosphere is rising, increasing marginal climate costs will imply a rise over time in the optimal carbon tax (see e.g. Hoel and Kverndokk, 1996, for details).

An obvious problem with implementing an optimal policy is that policy makers cannot commit to a rising 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, see e.g. Laffont and Tirole (1996), Montgomery (2005) and Ulph and Ulph (2009). If this is the case, greenhouse gas emissions may be higher than the optimal outcome, which would be achieved if one could commit to the optimal carbon tax path.

In a recent article, Sinn (2008) has implicitly argued that the opposite may be true: If owners of the non-renewable carbon resources believe the

carbon tax path will grow at a lower rate than what is optimal, they will postpone extraction compared with the extraction path they would have chosen had the policymakers been able to commit to the optimal price path. This argument suggests that although lack of commitment obviously reduces welfare compared with the case of commitment, it is not obvious whether near term emissions will increase or decline as a consequence of lack of commitment.

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. 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, 10-15 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 2-4 describe the market equilibrium for exogenous carbon taxes in the two periods. Section 5 describes the first-best social optimum, and shows what the carbon taxes must be for the market equilibrium to coincide with the social optimum.

Section 6 derives the consequences of the expected future carbon tax deviating from the optimal tax. The results depend on how sensitive extraction costs are to total carbon extraction. If costs rise rapidly with total extraction, near-term emissions are higher the higher is the expected future carbon tax.

However, if extraction costs only rise slowly as total extraction increases, we may get the opposite result. The effect of the expected future carbon tax on investments in a non-carbon substitute 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 increasing 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.

In section 7 it is assumed that climate costs are higher the higher are total emissions, and also higher the higher are near-term emissions for a given value of total emissions. With these assumptions it is shown that if extraction costs rise rapidly with total extraction, climate costs are *higher* the higher is the expected future carbon tax. However, if extraction costs only rise slowly as total extraction increases, we may get the opposite result.

In several countries, 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. An obvious question is whether a subsidy to the carbon substitute brings us closer to the first-best optimum. This is analyzed in Section 8. A small subsidy to non-carbon energy will move near-term emissions and investments in non-carbon energy towards their socially optimal values if a sufficiently large part of the returns to the investments come in the distant future. However, if a sufficiently large part of the the returns to the investments come in the near future, either near-term emissions or investments will be moved in the same direction by a subsidy as by a low expected future carbon tax.

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 $\tilde{F}(A - x, I)$, where x is carbon extracted and used in period 1 and $A - x$ 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 (although the special cases in which either \tilde{f}_I or \tilde{F}_I is zero also will be considered). 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 $\tilde{F}_{(A-x)I}$ are negative, so that the marginal productivity of using the carbon resource is lower the higher is the capital good I . While this general specification is used in the derivation of the market equilibrium, the formal analysis is restricted to the case in which the carbon resource and the substitute are perfect substitutes in the study of the consequences of errors in carbon tax expectations. For this part of the analysis we thus have functions of the type $f(x + \alpha I)$ and $F(A - x + (1 - \alpha)I)$ instead of the more general functions $\tilde{f}(x, I)$ and $\tilde{F}(A - x, I)$. The parameter α tells us what share of the total returns to investment are obtained already during period 1.

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 .¹ Finally, the exogenous discount factor is β (equal to $(1+r)^{-1}$, where r is the exogenous discount rate²).

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

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

The maximization gives

$$\tilde{f}_x(x, I) - (p+q) = 0 \tag{1}$$

$$\tilde{F}_{A-x}(A-x, I) - (P+Q) = 0 \tag{2}$$

$$\tilde{f}_I(x, I) + \beta \tilde{F}_I(A-x, I) - c = 0 \tag{3}$$

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. 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 continuous variable z , and let $g(z)$ be the cost of extracting unit z , with $g' \geq 0$. In the two-period model x is extraction in period 1, and $A-x$ is extraction in

¹With the interpretation of I as investment in the capacity to produce a substitute, c includes the present value of the operating costs of the substitute at full capacity.

²Notice that r is the consumption discount rate; introducing a utility function and making r endogenous according to the Ramsey rule would add notation but otherwise leave the analysis unchanged.

period 2. The cost of extracting x is thus given by $G(x) = \int_0^x g(z)dz$, and the cost of extracting $A-x$ is $\int_x^A g(z)dz = \int_0^A g(z)dz - \int_0^x g(z)dz = G(A) - G(x)$. Notice that these relationships imply that $G'(x) = g(x)$ and $G'(A) = g(A)$. 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 $G(A) - G(x) = g \cdot (A - x)$ (up to \bar{A}). 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 $x < \tilde{z} < A$ for all relevant values of x and A .³ This implies that $g'(x) = 0$, while $G'(A) = g(A) > g(x)$ and $G''(A) = g'(A) > 0$; $g'(A)$ is henceforth denoted g' .

Producers of the carbon resource maximize

$$px - G(x) + \beta [P \cdot (A - x) - (G(A) - G(x))]$$

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

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

and

$$P = g(A) \tag{5}$$

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.

³This 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, A, I as functions of the exogenous tax rates q and Q . The 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 A 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 A will be different from what agents planned.

Eliminating p and P , the market equilibrium (1)-(5) may be rewritten as

$$\tilde{f}_x - \beta \tilde{F}_{A-x} - (1 - \beta)g(x) - (q - \beta Q) = 0 \quad (6)$$

$$\tilde{F}_{A-x} - g(A) - Q = 0 \quad (7)$$

$$\tilde{f}_I + \beta \tilde{F}_I - c = 0 \quad (8)$$

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

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

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

5 The social optimum

Due to the time lag of the climate system, the effect of emissions in period 1 on the climate in period 1 are assumed to be negligible; this is certainly true

if the length of period 1 is no longer than about 10-20 years. Climate costs are therefore assumed to depend on the temperature increase T in period 2 (from some base level). Let the climate costs be given by a damage function $\tilde{D}(T)$, which is assumed to be increasing and strictly convex. The climate depends on emissions in both periods:

$$T = \tilde{T}(x, A - x) = T(x, A) \quad (10)$$

The function \tilde{T} is assumed to be increasing in both its arguments. The variable x in \tilde{T} is due partly to the lagged response of temperature to the stock of carbon in the atmosphere, and partly due to the fact that emissions in period 1 affect the stock of carbon in the atmosphere both in period 1 and 2. It is not obvious that the net affect x on T for a given A is positive, although this seems reasonable if one cares about how rapidly the climate changes.⁴ Although T_x has an ambiguous sign, T_A is positive since \tilde{T} is increasing in both arguments.

Inserting (10) into $\tilde{D}(T)$ gives us

$$D(x, A) \equiv \tilde{D}(T(x, A))$$

which is increasing in A , while the sign of D_x will be the same as the sign of T_x . To make the derivations slightly simpler without changing anything of substance, it is assumed that the function $D(x, A)$ takes the simple form

$$D(x, A) \equiv C(A + \gamma x) \quad (11)$$

where γ is a parameter that may be positive ($D_x > 0$) or negative ($D_x < 0$). One interpretation of the case of $\gamma < 0$ is that we only care about the carbon in the atmosphere in period 2, and that a fraction δ of the carbon emitted

⁴Such a consideration cannot be captured in a 2 period model, but see the discussion in Hoel (2008) in a continuous time model.

in period 1 is transferred to the ocean and other carbon sinks at the end of period 1, so that only $(1 - \delta)x$ of the emissions in period 1 remain in the atmosphere in period 2. Emissions in period 2 are $A - x$, so climate costs are in this case $C((1 - \delta)x + (A - x)) = C(A - \delta x)$, implying $\gamma = -\delta$ in our notation. In most of the subsequent analysis, it is assumed that $\gamma > 0$, i.e., "a postponement of emissions is good for the environment". The case of $\gamma < 0$ is left to the reader.

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

$$\tilde{f}(x, I) - G(x) - I + \beta \left[\tilde{F}(A - x, I) - (G(A) - G(x)) \right] - \beta C(A - \gamma x)$$

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

$$\tilde{f}_x - \beta \tilde{F}_{A-x} - (1 - \beta)g(x) - \beta \gamma C'(A + \gamma x) = 0 \quad (12)$$

$$\tilde{F}_{A-x} - g(A) - C'(A + \gamma x) = 0 \quad (13)$$

$$\tilde{f}_I + \beta \tilde{F}_I - c = 0 \quad (14)$$

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

$$q = \beta(1 + \gamma)C'(A + \gamma x)$$

$$Q = C'(A + \gamma x)$$

Notice that this implies that

$$\frac{Q}{q} = \frac{1}{\beta(1 + \gamma)}$$

If $\gamma = 0$ the carbon tax thus rises at a rate equal to the rate of interest ($= 1 + r = \beta^{-1}$), while it rises at a lower rate if $\gamma > 0$.⁵

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

While q is known when decisions are made for the first period, Q has the status of an expected price. To make this clear we use Q^e to denote the expected future carbon tax. Similarly, the variables x and I are decided upon in the first period, while A has the status of a planned variable for the resource owners, and an expected variable for the other agents. We therefore use A^e to denote this variable.

With this modified notation the three equations (6)-(8) define x , I and A^e as functions of q and Q^e . This section describes how changes in Q^e affect x and I . The next section shows how the actual second period value of A is affected by Q^e , via the effect of Q^e on x and I .

As mentioned in the Introduction, the formal analysis is on the case in which the capital good that affects the demand for the resource is a perfect substitute for the resource. However, it is useful first to consider the opposite limiting case, where the cross derivatives between the capital good and the resource are zero, i.e. $\tilde{f}_{Ix} = \tilde{F}_{I(A-x)} = 0$. For this case it follows from (8) that I is independent of Q^e . Moreover, by using (1) and (2), it follows that x is decreasing in Q^e . In this case near-term emissions are higher the higher is the expected future carbon tax. In other words, a bias downward in the expected future carbon tax implies a reduction in near-term emissions. It can also be shown that this effect (i.e., the size of the derivative $\frac{\partial x}{\partial Q^e}$) is smaller the smaller is the derivative $g'(A)$.

⁵If $\gamma < 0$, the carbon tax rises at a rate higher than the rate of interest. This corresponds to what one finds in continuous time models when there is a constraint on the content of carbon in the atmosphere but no climate cost function.

We now turn to the more interesting case in which the cross derivatives \tilde{f}_{Ix} and $\tilde{F}_{I(A-x)}$ are negative. The analysis is restricted to the case where I is a perfect substitute for the resource, i.e.

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

With this specification the market equilibrium (1)-(5) can be rewritten as

$$f'(x + \alpha I) - \beta F'(A^e - x + (1 - \alpha)I) - (1 - \beta)g(x) - (q - \beta Q^e) = \mathbf{(15)}$$

$$F'(A^e - x + (1 - \alpha)I) - g(A^e) - Q^e = \mathbf{(16)}$$

$$af'(x + \alpha I) + \beta(1 - \alpha)F'(A^e - x + (1 - \alpha)I) - c = \mathbf{(17)}$$

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

$$\begin{aligned}\Pi(x, A^e, I, q, Q^e) &= [f(x + \alpha I) - G(x) - I - qx] \\ &\quad + \beta [F(A^e - x + (1 - \alpha)I) - (G(A^e) - G(x)) - Q^e(A^e - x)]\end{aligned}\tag{18}$$

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

Differentiating the three equations (15), (16) and (17) with respect to Q^e gives the following three linear equations (using $g'(x) = 0$ and $g'(A^e) = g'$):

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

where

$$\mathbf{M} = \begin{pmatrix} f'' + \beta F'' & -\beta F'' & \alpha f'' - \beta(1 - \alpha)F'' \\ -F'' & F'' - g' & (1 - \alpha)F'' \\ \alpha f'' - \beta(1 - \alpha)F'' & \beta(1 - \alpha)F'' & \alpha^2 f'' + \beta(1 - \alpha)^2 F'' \end{pmatrix} \quad (19)$$

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

$$\frac{\partial x}{\partial Q^e} = \frac{\beta}{H} \{-\alpha(1 - \alpha)f''F'' - [\alpha^2 f'' + \beta(1 - \alpha)^2 F''] g'\} \quad (20)$$

$$\frac{\partial I}{\partial Q^e} = \frac{\beta}{H} \{(1 - \alpha)f''F'' + [\alpha f'' - (1 - \alpha)\beta F''] g'\} \quad (21)$$

where $H = -|\mathbf{M}| > 0$ due to the concavity of the function Π defined by (18).

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

Proposition 1: There exists a threshold value $\hat{\alpha}(g') = \frac{f''F'' - \beta F''g'}{f''F'' + (-f'' - \beta F'')g'}$, and for g' sufficiently low also two threshold values $\alpha^(g')$ and $\alpha^{**}(g')$ where $\alpha^*(g') < \alpha^{**}(g') < \hat{\alpha}(g')$ and where $\alpha^*(g')$ is increasing in g' and $\alpha^{**}(g')$ is decreasing in g' , such that*

$$\begin{aligned}
\text{Case I} & : \alpha < \alpha^*(g') : \frac{\partial x}{\partial Q^e} > 0 \text{ and } \frac{\partial I}{\partial Q^e} > 0 \\
\text{Case II} & : \alpha^*(g') < \alpha < \alpha^{**}(g') : \frac{\partial x}{\partial Q^e} < 0 \text{ and } \frac{\partial I}{\partial Q^e} > 0 \\
\text{Case III} & : \alpha^{**}(g') < \alpha < \hat{\alpha}(g') : \frac{\partial x}{\partial Q^e} > 0 \text{ and } \frac{\partial I}{\partial Q^e} > 0 \\
\text{Case IV} & : \alpha > \hat{\alpha}(g') : \frac{\partial x}{\partial Q^e} > 0 \text{ and } \frac{\partial I}{\partial Q^e} < 0
\end{aligned}$$

For g' sufficiently low, case II does not exist, giving case I/III for $\alpha < \hat{\alpha}(g')$.

To interpret this result, we start with cases I/III and IV (which will be the only possible cases if g' is sufficiently large). As Q^e increases, extraction in period 2 becomes less profitable, so $A - x$ goes down and x goes up. The increase in x reduces the period 1 payoff to the investment, while the reduction in $A - x$ increases the period 2 payoff. The former effect will dominate if α is large (case IV), while the latter effect will dominate if α is small (cases I and III).

If g' is sufficiently small, the direct effect of Q^e on x (i.e. holding I constant) is small, cf. the discussion in the beginning of this section. This implies that it is the change in payoff in period 2 that is important for how I is affected by the change in Q^e . If $(1 - \alpha)$ is sufficiently large, I therefore increases with Q^e , since a higher Q^e gives a lower $A - x$. If α is sufficiently large, the increase in αI , which tends to reduce x , will outweigh the direct affect of Q^e on x . In this case x will therefore decline as a response to increased Q^e .

7 Climate costs and carbon tax expectations

Assume that the carbon tax is set optimally in period 2, i.e. so that equation (13) is satisfied, no matter how x and I are determined in period 1. This implies that the actual value of A is determined by

$$F'(A - x(Q^e) + (1 - \alpha)I(Q^e)) = g(A) + C'(A + \gamma x(Q^e))$$

implying that

$$\frac{\partial A}{\partial Q^e} = J^{-1} \left\{ -(F'' + \gamma C'') \frac{dx}{dQ^e} + (1 - \alpha)F'' \frac{dI}{dQ^e} \right\} \quad (22)$$

where $J = C'' + g' - F'' > 0$. Total climate costs depends on $A + \gamma x$, and it follows from (20), (21) and (22) that

$$\frac{\partial(A + \gamma x)}{\partial Q^e} = \frac{\beta}{HJ} \{ [\gamma g' - (1 + \gamma)F''] B_x + (1 - \alpha)F'' B_I \} \quad (23)$$

where B_x and B_I are the terms in curly brackets in (20) and (21), respectively, i.e.

$$\begin{aligned} B_x &= -\alpha(1 - \alpha)f''F'' - [\alpha^2 f'' + \beta(1 - \alpha)^2 F''] g' \\ B_I &= (1 - \alpha)f''F'' + [\alpha f'' - (1 - \alpha)\beta F''] g' \end{aligned}$$

The term in front of B_x is positive (since $\gamma > 0$), while the sign in front of B_I is negative. If B_x and B_I have opposite signs, $\frac{\partial(A + \gamma x)}{\partial Q^e}$ is therefore unambiguously signed. From Proposition 1 the following therefore follows:

Proposition 2: The sign of $\frac{\partial(A + \gamma x)}{\partial Q^e}$ depends on the size of α in the following manner:

$$\begin{aligned}
\text{Case I} & : \alpha < \alpha^*(g') : \frac{\partial(A + \gamma x)}{\partial Q^e} \text{ has an ambiguous sign} \\
\text{Case II} & : \alpha^*(g') < \alpha < \alpha^{**}(g') : \frac{\partial(A + \gamma x)}{\partial Q^e} < 0 \\
\text{Case III} & : \alpha^{**}(g') < \alpha < \hat{\alpha}(g') : \frac{\partial(A + \gamma x)}{\partial Q^e} \text{ has an ambiguous sign} \\
\text{Case IV} & : \alpha > \hat{\alpha}(g') : \frac{\partial(A + \gamma x)}{\partial Q^e} > 0
\end{aligned}$$

Going back to equation (23), 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 $-\gamma[\alpha^2 f'' + \beta(1 - \alpha)^2 F''] (g')^2$. The term in square brackets is negative no matter what value α has, implying that the whole expression is positive for $\gamma > 0$. We therefore have the following proposition:

Proposition 3: No matter what value α has, climate costs are increasing in the expected carbon tax, i.e. $\frac{\partial(A + \gamma x)}{\partial Q^e} > 0$, for g' sufficiently large.

Notice that this result follows immediately for the limiting case of A being exogenous, since $\frac{\partial x}{\partial Q^e} > 0$ in this case.

Intuitively, one might think that expectations about a low future carbon tax are bad for the climate. This may be true, and Proposition 2 shows that it is certainly true if $\alpha^*(g') < \alpha < \alpha^{**}(g')$, which may occur if g' is not too high. However, if g' is sufficiently high we get the opposite result: Expectations about a low future carbon tax are *good* 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 brings us closer to the first-best optimum, in the sense that it moves x and I in the opposite direction of what the error in the carbon tax expectation moves these variables.

Differentiating the three equations (15), (16) and (17) with respect to investment costs c gives

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

where M as before is given by (19). Solving these equations we find that $\frac{\partial I}{\partial c} < 0$, while

$$\frac{\partial x}{\partial c} = \frac{1}{H} \{ \alpha f'' F'' - [\alpha f'' - \beta(1 - \alpha) F''] g' \} \quad (24)$$

From (24) it immediately follows that $\frac{\partial x}{\partial c}$ has the same sign as $\alpha - \tilde{\alpha}(g')$, where

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

From the expression for $\hat{\alpha}(g')$ in Proposition 2 it follows that $\tilde{\alpha}(g') < \hat{\alpha}(g')$.

The results above combined with Proposition 2 give us the following proposition:

Proposition 4: No matter what values g' and α have, $\frac{\partial I}{\partial c} < 0$. Moreover, for g' so large that case II in Proposition 2 does not exist, $\frac{\partial x}{\partial Q^e}$ is positive, while the signs of $\frac{\partial I}{\partial Q^e}$ and $\frac{\partial x}{\partial c}$ depend on the size of α in the following manner:

$$\begin{aligned}
 \text{Case } i & : \alpha < \tilde{\alpha}(g') : \frac{\partial I}{\partial Q^e} > 0 \text{ and } \frac{\partial x}{\partial c} < 0 \\
 \text{Case } ii & : \tilde{\alpha}(g') < \alpha < \hat{\alpha}(g') : \frac{\partial I}{\partial Q^e} > 0 \text{ and } \frac{\partial x}{\partial c} > 0 \\
 \text{Case } iii & : \alpha > \hat{\alpha}(g') : \frac{\partial I}{\partial Q^e} > 0 \text{ and } \frac{\partial x}{\partial c} > 0
 \end{aligned}$$

For a subsidy (which reduces c) to partly offset the effects on x and I of Q^e being too low, we must have $\frac{\partial x}{\partial Q^e} \frac{\partial x}{\partial c} < 0$ and $\frac{\partial I}{\partial Q^e} \frac{\partial I}{\partial c} < 0$. From Proposition 4 we see that this is the case only for $\alpha < \tilde{\alpha}(g')$. For higher values of α either first period emissions or investments will be moved in the same direction by a subsidy as by a low expected future carbon tax. Small values of α corresponds to investments where most of the benefits occur in the distant future. Proposition 4 thus gives an argument for subsidizing such investments, provided one believes that market participants typically underestimate the size of future carbon taxes.

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 these variables depend to a large extent on the properties of the extraction costs of carbon resources. In much of the economics literature on climate policy the resource aspect of carbon is ignored, so that the production of oil, gas and coal is treated in the same manner as the production of other goods. In most of the papers that explicitly treat the resource aspect, it is assumed that there is a strict physical limit of the available resource, and that all of the resources up to this limit sooner or later will be extracted. However, a much more realistic description of the real world is that no such absolute physical limit exists, but that extraction costs are increasing in total extraction. This is the assumption used in the present paper, as well as by Hoel and Kverndokk (1996) and Gerlagh (2010).

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.

Appendix

The signs of the derivatives (20) and (21) are equal to the signs of the respective curly brackets, i.e., on

$$B_x(\alpha) = -\alpha(1 - \alpha)f''F'' - [\alpha^2f'' + \beta(1 - \alpha)^2F'']g'$$

and

$$B_I(\alpha) = (1 - \alpha)f''F'' + [\alpha f'' - (1 - \alpha)(\beta + (1 - \beta)h)F'']g'$$

respectively.

Consider first $B_x(\alpha)$. This function is quadratic in α , and is positive for $\alpha = 0$ and for $\alpha = 1$. The first term in this expression is negative (for $0 < \alpha < 1$), 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 (α^*, α^{**}) of α -values giving $B_x(\alpha) < 0$. It is straightforward to see that α^* is increasing in g' and that α^{**} is declining in g' .

Consider next $B_I(\alpha)$. This function is declining in α . Moreover, $B_I(0) > 0$ and $B_I(1) < 0$, implying that there exists a value $\hat{\alpha}$ such that $B_I(\hat{\alpha}) = 0$. It is straightforward to see that this value is

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

Consider a value of α giving $B_x(\alpha) < 0$ (when such a value exists). It follows from the definition of $B_x(a)$ that if $B_x(\alpha) < 0$ then

$$(1 - \alpha)f''F'' + \left[\alpha f'' + \beta \frac{(1 - \alpha)^2}{\alpha} F'' \right] g' > 0$$

implying that

$$(1 - \alpha)f''F'' + \alpha f''g' > 0$$

From the definition of $B_I(a)$ we immediately see that this last inequality implies that $B_I(a) > 0$. It follows that $\hat{\alpha} > \alpha^{**}$, which concludes our proof of Proposition 1.

References

- Gerlagh, R. (2010), Too much oil. Unpublished, Tilburg University.
- Hanson, D. A. (1980), Increasing extraction costs and resource prices: some further results. *Bell Journal of Economics* 11 (Spring), 335–342.
- Heal, G. M. (1976), The relationship between price and extraction cost for a resource with a backstop technology. *Bell Journal of Economics* 7 (Autumn), 371-378.
- Hoel, M. (2008), Bush meets Hotelling: Effects of improved renewable energy technology on greenhouse gas emissions. Memorandum 30/2008, Department of Economics, University of Oslo.
- Hoel, M. and S. Kverndokk (1996), Depletion of fossil fuels and the impacts of global warming. *Resource and Energy Economics* 18, 115-136.
- Laffont, J.-J. and J. Tirole (1996), Pollution permits and environmental innovation. *Journal of Public Economics* 62, 127-140.
- Montgomery, W. D. and A. E. Smith (2005), Price, quantity, and technology strategies for climate change policy", in M. Schlesinger, H. Kheshgi, J. Smith, F. de la Chesnaye, J. M. Reilly, T. Wilson and C. Kolstad (eds.), *Human-Induced Climate Change: An Interdisciplinary Assessment*. Cambridge, UK: Cambridge University Press, pp. 328–342.
- Sinclair, P. (1992), High does nothing and rising are worse: Carbon taxes should be kept declining to cut harmful emissions. *Manchester School*, 60: 41-52.
- Sinn, H. W. (2008), Public policies against global warming: A supply side approach." *International Tax and Public Finance* 15(4), 360-94.

- Strand, J. (2007), Technology treaties and fossil fuels extraction. *The Energy Journal*, 28(4), 129-142.
- Tahvonen, O. (1995), Dynamics of pollution control when damage is sensitive to the rate of pollution accumulation. *Environmental and Resource Economics* 5, 9-27.
- Tahvonen, O. (1997), Fossil fuels, stock externalities, and backstop technology. *Canadian Journal of Economics* 30, 855-874.
- Ulph, A. and D. Ulph (1994), The optimal time path of a carbon tax, *Oxford Economic Papers* 46, 857-868.
- Ulph, A. and D. Ulph (2009), Optimal climate change policies when governments cannot commit. Discussion paper 0909, University of St. Andrews, School of Economics and Finance.
- Withagen, C. (1994), Pollution and exhaustibility of fossil fuels. *Resource and Energy Economics* 16, 235 - 242.

CESifo Working Paper Series

for full list see www.cesifo-group.org/wp

(address: Poschingerstr. 5, 81679 Munich, Germany, office@cesifo.de)

- 2901 Donatella Gatti, Christophe Rault and Anne-Gaël Vaubourg, Unemployment and Finance: How do Financial and Labour Market Factors Interact?, December 2009
- 2902 Arno Riedl, Behavioral and Experimental Economics Can Inform Public Policy: Some Thoughts, December 2009
- 2903 Wilhelm K. Kohler and Marcel Smolka, Global Sourcing Decisions and Firm Productivity: Evidence from Spain, December 2009
- 2904 Marcel Gérard and Fernando M. M. Ruiz, Corporate Taxation and the Impact of Governance, Political and Economic Factors, December 2009
- 2905 Mikael Priks, The Effect of Surveillance Cameras on Crime: Evidence from the Stockholm Subway, December 2009
- 2906 Xavier Vives, Asset Auctions, Information, and Liquidity, January 2010
- 2907 Edwin van der Werf, Unilateral Climate Policy, Asymmetric Backstop Adoption, and Carbon Leakage in a Two-Region Hotelling Model, January 2010
- 2908 Margarita Katsimi and Vassilis Sarantides, Do Elections Affect the Composition of Fiscal Policy?, January 2010
- 2909 Rolf Golombek, Mads Greker and Michael Hoel, Climate Policy without Commitment, January 2010
- 2910 Sascha O. Becker and Ludger Woessmann, The Effect of Protestantism on Education before the Industrialization: Evidence from 1816 Prussia, January 2010
- 2911 Michael Berlemann, Marco Oestmann and Marcel Thum, Demographic Change and Bank Profitability. Empirical Evidence from German Savings Banks, January 2010
- 2912 Øystein Foros, Hans Jarle Kind and Greg Shaffer, Mergers and Partial Ownership, January 2010
- 2913 Sean Holly, M. Hashem Pesaran and Takashi Yamagata, Spatial and Temporal Diffusion of House Prices in the UK, January 2010
- 2914 Christian Keuschnigg and Evelyn Ribi, Profit Taxation and Finance Constraints, January 2010
- 2915 Hendrik Vrijburg and Ruud A. de Mooij, Enhanced Cooperation in an Asymmetric Model of Tax Competition, January 2010

- 2916 Volker Meier and Martin Werding, Ageing and the Welfare State: Securing Sustainability, January 2010
- 2917 Thushyanthan Baskaran and Zohal Hessami, Globalization, Redistribution, and the Composition of Public Education Expenditures, January 2010
- 2918 Angel de la Fuente, Testing, not Modelling, the Impact of Cohesion Support: A Theoretical Framework and some Preliminary Results for the Spanish Regions, January 2010
- 2919 Bruno S. Frey and Paolo Pamini, World Heritage: Where Are We? An Empirical Analysis, January 2010
- 2920 Susanne Ek and Bertil Holmlund, Family Job Search, Wage Bargaining, and Optimal Unemployment Insurance, January 2010
- 2921 Mariagiovanna Baccara, Allan Collard-Wexler, Leonardo Felli and Leeat Yariv, Gender and Racial Biases: Evidence from Child Adoption, January 2010
- 2922 Kurt R. Brekke, Roberto Cellini, Luigi Siciliani and Odd Rune Straume, Competition and Quality in Regulated Markets with Sluggish Demand, January 2010
- 2923 Stefan Bauernschuster, Oliver Falck and Niels Große, Can Competition Spoil Reciprocity? – A Laboratory Experiment, January 2010
- 2924 Jerome L. Stein, A Critique of the Literature on the US Financial Debt Crisis, January 2010
- 2925 Erkki Koskela and Jan König, Profit Sharing, Wage Formation and Flexible Outsourcing under Labor Market Imperfection, January 2010
- 2926 Gabriella Legrenzi and Costas Milas, Spend-and-Tax Adjustments and the Sustainability of the Government's Intertemporal Budget Constraint, January 2010
- 2927 Piero Gottardi, Jean Marc Tallon and Paolo Ghirardato, Flexible Contracts, January 2010
- 2928 Gebhard Kirchgässner and Jürgen Wolters, The Role of Monetary Aggregates in the Policy Analysis of the Swiss National Bank, January 2010
- 2929 J. Trent Alexander, Michael Davern and Betsey Stevenson, Inaccurate Age and Sex Data in the Census PUMS Files: Evidence and Implications, January 2010
- 2930 Stefan Krasa and Mattias K. Polborn, Competition between Specialized Candidates, January 2010
- 2931 Yin-Wong Cheung and Xingwang Qian, Capital Flight: China's Experience, January 2010

- 2932 Thomas Hemmelgarn and Gaetan Nicodeme, The 2008 Financial Crisis and Taxation Policy, January 2010
- 2933 Marco Faravelli, Oliver Kirchkamp and Helmut Rainer, Social Welfare versus Inequality Concerns in an Incomplete Contract Experiment, January 2010
- 2934 Mohamed El Hedi Aroui and Christophe Rault, Oil Prices and Stock Markets: What Drives what in the Gulf Corporation Council Countries?, January 2010
- 2935 Wolfgang Lechthaler, Christian Merkl and Dennis J. Snower, Monetary Persistence and the Labor Market: A New Perspective, January 2010
- 2936 Klaus Abberger and Wolfgang Nierhaus, Markov-Switching and the Ifo Business Climate: The Ifo Business Cycle Traffic Lights, January 2010
- 2937 Mark Armstrong and Steffen Huck, Behavioral Economics as Applied to Firms: A Primer, February 2010
- 2938 Guglielmo Maria Caporale and Alessandro Girardi, Price Formation on the EuroMTS Platform, February 2010
- 2939 Hans Gersbach, Democratic Provision of Divisible Public Goods, February 2010
- 2940 Adam Isen and Betsey Stevenson, Women's Education and Family Behavior: Trends in Marriage, Divorce and Fertility, February 2010
- 2941 Peter Debaere, Holger Görg and Horst Raff, Greasing the Wheels of International Commerce: How Services Facilitate Firms' International Sourcing, February 2010
- 2942 Emanuele Forlani, Competition in the Service Sector and the Performances of Manufacturing Firms: Does Liberalization Matter?, February 2010
- 2943 James M. Malcomson, Do Managers with Limited Liability Take More Risky Decisions? An Information Acquisition Model, February 2010
- 2944 Florian Englmaier and Steve Leider, Gift Exchange in the Lab – It is not (only) how much you give ..., February 2010
- 2945 Andrea Bassanini and Giorgio Brunello, Barriers to Entry, Deregulation and Workplace Training: A Theoretical Model with Evidence from Europe, February 2010
- 2946 Jan-Emmanuel De Neve, James H. Fowler and Bruno S. Frey, Genes, Economics, and Happiness, February 2010
- 2947 Camille Cornand and Frank Heinemann, Measuring Agents' Reaction to Private and Public Information in Games with Strategic Complementarities, February 2010
- 2948 Roel Beetsma and Massimo Giuliadori, Discretionary Fiscal Policy: Review and Estimates for the EU, February 2010

- 2949 Agnieszka Markiewicz, Monetary Policy, Model Uncertainty and Exchange Rate Volatility, February 2010
- 2950 Hans Dewachter and Leonardo Iania, An Extended Macro-Finance Model with Financial Factors, February 2010
- 2951 Helmuth Cremer, Philippe De Donder and Pierre Pestieau, Education and Social Mobility, February 2010
- 2952 Zuzana Brixiová and Balázs Égert, Modeling Institutions, Start-Ups and Productivity during Transition, February 2010
- 2953 Roland Strausz, The Political Economy of Regulatory Risk, February 2010
- 2954 Sanjay Jain, Sumon Majumdar and Sharun W. Mukand, Workers without Borders? Culture, Migration and the Political Limits to Globalization, February 2010
- 2955 Andreas Irmen, Steady-State Growth and the Elasticity of Substitution, February 2010
- 2956 Bengt-Arne Wickström, The Optimal Babel – An Economic Framework for the Analysis of Dynamic Language Rights, February 2010
- 2957 Stefan Bauernschuster and Helmut Rainer, From Politics to the Family: How Sex-Role Attitudes Keep on Diverging in Reunified Germany, February 2010
- 2958 Patricia Funk and Christina Gathmann, How do Electoral Systems Affect Fiscal Policy? Evidence from State and Local Governments, 1890 to 2005, February 2010
- 2959 Betsey Stevenson, Beyond the Classroom: Using Title IX to Measure the Return to High School Sports, February 2010
- 2960 R. Quentin Grafton, Tom Kompas and Ngo Van Long, Biofuels Subsidies and the Green Paradox, February 2010
- 2961 Oliver Falck, Stephan Heblich, Alfred Lameli and Jens Suedekum, Dialects, Cultural Identity, and Economic Exchange, February 2010
- 2962 Dimitrios Koumparoulis and Apostolis Philippopoulos, The Current Version of the Bank of Greece Econometric Model, February 2010
- 2963 Frederick van der Ploeg and Cees Withagen, Is There Really a Green Paradox?, February 2010
- 2964 Ingo Vogelsang, Incentive Regulation, Investments and Technological Change, February 2010
- 2965 Jan C. van Ours and Lenny Stoeldraijer, Age, Wage and Productivity, February 2010
- 2966 Michael Hoel, Climate Change and Carbon Tax Expectations, February 2010