Carbon taxes and the green paradox

January 11, 2011

Abstract

A sufficiently high carbon tax will for sure reduce near-term carbon emissions compared with the case of no tax. For lower tax rates that increase faster than some threshold that is at least as high as the rate of interest, near-term emissions may be higher compared with the case of no carbon tax. Even so, such a carbon tax path may reduce total costs related to climate change, since the tax may reduce total carbon extraction. A government cannot commit to a specific carbon tax rate in the distant future. For reasonable assumptions about expectation formation, a higher present carbon tax will reduce near-term carbon emissions. However, if the near-term tax rate for some reason is set below its optimal level, increased concern for the climate may change taxes in a manner that increases near-term emissions.

Keywords: green paradox, carbon tax, climate change, exhaustible resources

JEL classification: Q31, Q38, Q41, Q48, Q54, Q58

1 Introduction

During the last couple of years, there has been a considerable literature discussing the so-called "green paradox". 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 that fossil fuels are nonrenewable scarce 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." 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), carbon emissions increase.[1]

A rapidly increasing carbon tax is not the only possible cause of a green paradox. A declining price of a substitute, either because of increasing subsidies or technological improvement, can give the same effect: see e.g. Strand (2007), Gerlagh (2010) and der Ploeg and Withagen (2010). In a setting of heterogeneous countries and rising fuel prices, Hoel (2008) showed that carbon emissions may increase also as a consequence of an immediate and once and for all downward shift in the cost of producing a substitute.

As mentioned above, Sinclair (1992) pointed out that the time profile of the carbon tax was important for the development of emissions. A thorough analysis of the effects of taxation on resource extraction was given by Long and Sinn (1985), but without explicitly discussing climate effects. The optimal design of the carbon tax path in the presence of carbon resource scarcity has since been analyzed by among others Ulph and Ulph (1994), Withagen (1994), Hoel and Kverndokk (1996), Tahvonen (1997), Chakravorty et al. (2006). One of the insights from the literature is that the principles for setting an optimal carbon tax (or price of carbon quotas) are the same as when the limited availability of carbon resources is ignored: At any time, the optimal price of carbon emissions should be equal to the present value of

[1] Throuout this paper, CCS is ignored. 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).

all future climate costs caused by present emissions. A second insight from the literature is that when actual policies deviate from what is optimal, one might get different results than one would find if carbon resource scarcity were ignored.

The present paper focuses on the effects of carbon taxes that are not necessarily designed optimally. I show that the current level as well as the future time profile of the carbon tax rate influence near-term emissions, and perhaps also total cumulative emissions. While the current tax rate is set by the regulator, the regulator typically cannot commit to the future tax development. Expectations about future tax rates will therefore typically affect near-term emissions.

As mentioned above, Sinn used the term "green paradox" to describe a situation where policies intending to mitigate climate change actually increase near-term emissions. Gerlagh uses the term "weak green paradox" for such a phenomenon, and uses the term "strong green paradox" to describe a situation where policies intending to mitigate climate change increase total climate costs. This distinction is important, since total climate costs depend not only on near-term emissions, but also on all future emissions. One can therefore imagine policies that increase near-term emissions, but that nevertheless reduce future emissions so much that total climate costs decline. This issue will be discussed in more detail in sections 5 and 6. In these sections it is assumed that total climate costs are higher the higher are total emissions, and that for a given amount of total emissions climate costs are higher the earlier these emissions occur.

The introduction of a sufficiently high carbon tax will make carbon emissions decline, no matter what the extraction cost function is and no matter what future carbon taxes are expected to be. This holds under the mild assumption that resource owners will never sell their resource at a price lower than their extraction costs. If the government introduces a carbon tax that at the initial date is higher than the original resource rent (i.e. the resource rent prior to the introduction of the tax), the consumer price must increase in order for resource owners to cover their extraction costs. Hence, the demand for the resource, and therefore also carbon emissions, must decline.

This is discussed in more detail and numerically illustrated in section 2. The possibility of a green paradox is thus not an argument against using a carbon tax as the main climate policy instrument. If anything, the possibility of a (weak) green paradox suggests that the level of the carbon tax should be set relatively high immediately, and not currently low and gradually increasing.

The effects of carbon taxes that may be lower than the initial resource rent are analyzed in more detail in the rest of the paper. Section 3 considers the textbook case in which the total amount of available carbon resources are physically given, and unit extraction costs are constant. Without any carbon tax, all of these resources will be extracted, and there will be a positive resource rent. For a sufficiently high and increasing carbon tax the resource rent will be driven down to zero, and the consumer price will at any point of time be equal to the unit extraction cost plus the carbon tax rate. Since this tax rate is increasing over time, the consumer price is rising over time, and extraction is thus declining. The sum of extraction over the infinite future must be below the physical resource limit for this to be an equilibrium. This condition will only hold if the level of the carbon tax is sufficiently high. For lower tax rates, the resource rent will be positive also in the presence of the carbon tax. In this case all of the resource will eventually be extracted, no matter what the time profile of the tax rate is. However, the time profile of the carbon extraction will depend on the time path of the carbon tax. If the present value of the tax rate is rising over time, resource owners will want to extract the resource more rapidly in order to reduce the present value of total taxes. Compared to the case without a carbon tax, near-term emissions therefore increase. Moreover, this effect is stronger the higher is the *level* of the carbon tax. Near-term emissions will therefore be *higher* the higher is the *level* of the carbon tax if the tax rate is rising sufficiently fast. In this case we thus get a weak green paradox, and also a strong green paradox if early emissions are considered worse for the climate than later emissions (since total emissions in this case are equal to the physically given resource constraint).

The analysis in section 3 is based on the unrealistic assumption that the available carbon resources are homogeneous and have the same extraction costs. This assumption is relaxed in section 4, where it is assumed that the unit cost of extraction is increasing in accumulated extraction. In this case an absolute upper limit on the available resource may be irrelevant from an economic point of view, as resource owners only will extract resources that give them a price higher than the unit extraction costs. When total extraction is determined endogenously in this manner, the level of the carbon tax will affect total extraction. For instance, with a carbon tax that is constant over time, total extraction, and thus total emissions, will be lower the higher is this tax rate. However, near-term emissions may increase in response to a carbon tax also in the case of endogenously determined total extraction, if the tax rate increases rapidly enough. For this to occur, the tax rate must increase at a rate above some threshold that is higher than the rate of interest. For such a time profile of the carbon tax we may thus get weak green paradox. In spite of this, climate costs may decline, since introducing a carbon tax will reduce total emissions.

Policy makers can in reality not commit to tax rates in the distant future. In the absence of commitment, resource owners must base extraction decisions on their expectations about future tax rates, which may in turn depend on the current carbon tax rate. This is discussed in more detail in sections 5 and 6, using a two-period model. Particular focus is given to the case in which the future tax rate is assumed to be equal to the Pigovian level, no matter what the current carbon tax rate is.

In section 5 the carbon tax in period 1 is assumed to be exogenous. If resource owners expect the tax in period 2 to be equal to the Pigovian level, extraction is lower in period 1 the higher is the tax in period 2. There is thus no weak green paradox in this case. Since marginal environmental costs in period 2 are assumed to be lower the lower are emissions in period 1, a higher carbon tax in period 1 implies a lower carbon tax in period 2, thus increasing emissions in period 2. However, total emissions are lower the higher is the tax in period 1. Total climate costs are therfore lower the higher is the carbon tax in period 1; hence there is no strong green paradox.

Section 6 finally considers the case in which carbon taxes are set endogenously in both periods, depending on the preferences related to climate change. I show that increased concern for the climate issue might increase near-term emissions, and perhaps also total climate costs. A weak and a strong green paradox is in other words possible in this case. However, this can only occur if there is some obstacle that prevents the near-term tax rates being as high as their optimal levels.

Section 7 gives a brief discussion and summary of the main results.

2 No green paradox with a high carbon tax

As explained in the Introduction, introducing a carbon tax that is higher than the original resource rent (i.e. the resource rent prior to the introduction of the tax) will make carbon emissions decline, no matter what the cost function is and no matter what future carbon taxes are. How high must a carbon tax be for carbon emissions to decline? The answer to this will differ between coal and oil, which are the two most important sources of carbon from fossil fuels.

Current coal prices are about 97 dollars per tonne[2], corresponding to about 50 dollars per tonne of CO_2.[3] This coal price is split between extraction costs and resource rent. The resource rent is probably much lower than 50 dollars per tonne. In any case, a carbon tax above 50 dollars per tonne of CO_2 will for sure increase the consumer price of coal, and therefore also reduce CO_2 emissions from the use of coal.

Turning next to oil, current oil prices are about 78 dollars per barrel, corresponding to about 180 dollars per tonne of CO_2.[4] This oil price is split between extraction costs and resource rent. The resource rent is probably

[2] Coal and oil prices are averages for 2010, obtained from http://www.worldbank.org/prospects/pinksheets, "commodity price data".

[3] The exact amount of CO_2 per tonne of coal depends on the type of coal. Dividing total world CO_2 emissions from coal consumption by total world coal consumption gives a factor of approximately 2 (numbers from http://www.eia.doe.gov/emeu/iea/coal.html for 2006). 97 dollars per tonne of coal threfore corresponds to about $97/2 \approx 50$ dollars per tonne of CO_2.

[4] CO_2 emissions per barrel of oil are approximately 0.43 tonnes (http://www.epa.gov/greenpower/pubs/calcmeth.htm), so that 78 dollars per barrel of oil corresponds to about $78/0.43 \approx 180$ dollars per tonne of CO_2.

much lower than 180 dollars per tonne. In any case, a carbon tax above 180 dollars per tonne of CO_2 will for sure increase the consumer price of oil, and therefore also reduce CO_2 emissions from the use of oil.

A carbon tax above about 180 dollars per tonne of CO_2 will for sure reduce carbon emissions. Since extraction costs for oil are not zero, the threshold is in reality lower. With an extraction cost of oil of e.g. 30 dollars per barrel, this threshold is reduced from 180 to 112 dollars per tonne of CO_2. Even this value is much higher than carbon tax rates or emission quota prices in most countries. For instance, the quota price in EU is only about 19 dollars per tonne of CO_2. However, there are also cases of explicit or implicit carbon taxes above 112 dollars per tonne of CO_2 in some countries (e.g. Sweden), at least for some sectors of the economy. Most integrated assessment models suggest an optimal current price of emissions clearly below 100 dollars per tonne of CO_2 (see e.g. Hoel et al., 2009, for an overview).

For carbon taxes below about 100 dollars per tonne of CO_2 we cannot rule out the possibility of emissions from the use of oil increasing (compared to emissions without any tax). However, emissions from the use of coal will for sure go down provided the carbon tax is above about 50 dollars per tonne of CO_2. Since extraction costs for coal are not zero, the threshold is in reality lower. With an extraction cost of coal of e.g. 50 dollars per tonne, this threshold is reduced from 50 to 24 dollars per tonne of CO_2. Optimal near-term carbon prices derived from integrated assessment models are in many cases above 24 dollars per tonne of CO_2, at least for the more ambitious climate goals. Introducing a world wide carbon tax at a level above 24 dollars per tonne of CO_2 is therefore likely to reduce emissions from the use of coal. However, since we cannot rule out the possibility of oil extraction increasing as a response to a global carbon tax in the range of about 20-100 dollars, we cannot rule out the possibility of near-term emissions increasing as a consequence of introducing a carbon tax in this range.

3 The green paradox when total carbon extraction is given

Consider the simplest possible model of resource extraction: The available amount of the carbon resource is given by $\bar{A}$, and unit extraction costs are constant equal to c. The consumer price of the resource is $q(t)$, and in the absence of taxes this is also the producer price. Producers are price takers and have an exogenous interest rate r. Producers choose the extraction path $x(t)$ to maximize

$$\Pi = \int_0^\infty e^{-rt} \left[q(t) - c \right] x(t) dt \tag{1}$$

s.t.

$$\begin{aligned} \dot{A}(t) &= x(t) \\ A(0) &= 0 \\ x(t) &\geq 0 \quad \text{for all } t \\ A(t) &\leq \bar{A} \quad \text{for all } t \end{aligned}$$

In an equilibrium the chosen extraction path must at all dates satisfy $x(t) = D(q(t))$, where D is the demand function, assumed stationary for simplicity. Moreover, provided $D(c) > 0$, total extraction must be equal to the available amount of the resource:

$$\int_0^\infty x(t) dt = \bar{A} \tag{2}$$

It is well known that the equilibrium of this simple Hotelling model is characterized by

$$\dot{q}(t) = r(q(t) - c) \tag{3}$$

with $q(0)$ determined so the resource constraint (2) is satisfied.

Consider a carbon tax $w(t)$, i.e., a tax equal to $w(t)$ per unit of x. It is useful first to consider a "large" carbon tax, defined as a time path $w(t)$ that satisfies

$$\int_0^\infty D(c + w(t))dt \leq \bar{A} \tag{4}$$

For a carbon tax satisfying (4), the resource constraint is not a binding constraint; the competitive supply of the carbon resource is like the supply of any non-resource good, and the resource rent is therefore zero. For this case there is clearly no green paradox, as the resource extraction at any time is simply equal to demand $D(c + w(t))$, and thus independent of the future carbon tax rate.

It might seem unrealistic to even consider a carbon tax path that is so high that it drives all carbon resource rents to zero. However, in a richer model with heterogeneous resources differing in extraction costs, a carbon tax of the magnitude needed to reach moderately ambitious climate goals may very well drive the resource rent to zero for the resources with the highest costs. This issue is treated in the next section.

Consider next a carbon tax path that does not satisfy (4). Let Ω denote the present value of total carbon taxes:

$$\Omega = \int_0^\infty e^{-rt} w(t)x(t)dt \tag{5}$$

The price to the producer is now $p(t) = q(t) - w(t)$, and instead of maximizing Π producers now maximize $\Pi - \Omega$. Assume that the carbon tax rises at a constant rate g. From (5) it follows that

$$\Pi - \Omega = \Pi - w(0)\bar{A} - w(0) \int_0^\infty \left[e^{(g-r)t} - 1\right] x(t)dt \tag{6}$$

Consider first the case of $g = r$, i.e., the present value of the carbon tax rate is constant. In this case the last of the three terms in (6) is zero. The second term is just like a lump-sum tax (since $\bar{A}$ is given), so that the extraction profile that maximizes Π also maximizes $\Pi - \Omega$. This result generalizes to all cost functions, as long as the total amount extracted is unaffected by the carbon tax.

Consider next the case of $g > r$, implying that the term in square brackets is increasing over time. To maximize $\Pi - \Omega$, resource owners will therefore extract more earlier and less later compared to the case of no taxation. This is the (weak) green paradox: We get more extraction and hence also more emissions in the present and the near future than without a carbon tax. Moreover, this effect is stronger the higher is $w(0)$, so that for a given value of $g(> r)$, present and near-term emissions increase as the current carbon tax increases.

Finally, consider the case of $g < r$. Theoretical and numerical models that derive optimal climate policy typically find that it is optimal for the carbon tax to rise at a rate lower than the rate of interest, provided high carbon concentrations in the atmosphere are considered bad also when the carbon concentration is below some exogenously given upper limit.[5] For this case the result is exactly the opposite of the case $g > r$; extraction and hence also emissions are lower in the present and the near future than without a carbon tax. Moreover, this effect is stronger the higher is $w(0)$, so that for a given value of $g(< r)$, present and near-term emissions decline as the current carbon tax increases.

4 Total carbon extraction is endogenous

The model used in section 3 had the unrealistic feature that the available carbon resources are homogeneous and have the same extraction costs. A more interesting case is when the unit cost of extraction is increasing in accumulated extraction, denoted $c(A)$ where A as before is accumulated extraction. This is a specification frequently used in the resource literature, see e.g. Heal (1976) and Hanson (1980). If there is an absolute limit on total carbon extraction also in this case (*i.e.* $A(t) \leq \bar{A}$ for all t), and this limit is binding both with and without the carbon tax, there will be no significant changes compared with the case of constant extraction costs. A more interesting case

[5]This result may be found in several contributions to the literature, as examples see Hoel et al. (2009) or Hoel and Kverndokk (1996).

is when the total amount extracted is determined endogenously. This is the case analyzed below.

To simplify the discussion, it is assumed that demand is zero if the price is sufficiently high. Formally, it is assumed that there is a choke price $\bar{q}$ such that $D(q) = 0$ for $q \geq \bar{q}$, and $D(q) > 0$ and $D'(q) < 0$ for $q < \bar{q}$. This is a purely technical assumption. If it instead had been assumed that $D(q) > 0$ for all q but approached zero as $q \to \infty$, it would nevertheless be true that for some high price $\bar{q}$ (e.g. a million dollars per barrel of oil) demand would be so small that it would be of no practical interest (e.g. 1 barrel of oil per year).

The profit of the resource owners is as before given by (1), except that c must now be replaced by $c(A)$. The first three of the four constraints given earlier remain valid, but there is no longer a binding constraint of the type $A(t) \leq \bar{A}$ where $\bar{A}$ is exogenous.[6]

The analysis of the present case is given in the Appendix. Without any carbon tax, the equilibrium is as before characterized by $x(t) = D(q(t))$ and by equations (2) and (3), except that c in (3) is replaced by $c(A)$. Furthermore, total extraction $\bar{A}$ is in the present case not exogenous, but determined by

$$c(\bar{A}) = \bar{q} \tag{7}$$

All resources that have an extraction cost below the choke price $\bar{q}$ are thus extracted, and with a positive resource rent.[7]

Introducing a carbon tax $w(t)$, the producer price is changed to $p(t) = q(t) - w(t)$. Equation (3) remains valid, but with q replaced by p, giving

$$\dot{q}(t) = r\left(q(t) - c(A(t)\right) + \left[\dot{w}(t) - rw(t)\right] \tag{8}$$

As before, all resources that have an extraction cost below the price buyers are willing to pay to the resource owners, which is $\bar{q} - w(t^*)$, will be extracted.

[6] The case of such a binding constraint can, however, be approximated by assuming that $c(A) \to \infty$ as $A \to \bar{A}$.

[7] For q to reach $\bar{q}$ we must have $\dot{q} > 0$ for $A < \bar{A}$, i.e. $q > c(A)$ from (3).

Instead of (7) and (2) we therefore have

$$c(A^*) = \bar{q} - w(t^*) \tag{9}$$

$$\int_0^\infty x(t)dt = A^* \tag{10}$$

where $w(t^*)$ will depend on the time t^* at which $A(t)$ reaches A^*.

From these equations it is clear that unless $c'(A^*) = \infty$, the introduction of a carbon tax will reduce total extraction. Some resources that would have been extracted if there were no carbon tax will thus be left unextracted with a positive carbon tax. Total emissions therefore decline as a response to a carbon tax, no matter what time profile the carbon tax has.

What about present and near-term extraction and emissions? Consider first the case in which the carbon tax rises at the rate r. From the previous section we know that the whole extraction profile was unaffected by the carbon tax when total resource extraction was exogenous (provided the carbon tax was not so high that (4) held). When total resource extraction goes down as a response to the carbon tax, emissions must obviously go down in some time periods. Does it go down in the present and near term? In other words, does the initial consumer price $q(0)$ go up as a response to the carbon tax? The answer is yes, and follows from (8) and (9): If $q(0)$ had not increased as a response to the carbon tax, it would not increase at later dates either as long as $\dot{w}(t) - rw(t) \leq 0$. But if this were the case, the consumer price would not reach the choke level $\bar{q}$ when resource extraction stops (remember that $A^* < \bar{A}$). This would violate the equilibrium conditions.

The argument above applies also to the case in which the carbon tax rises at a rate below r. For $\dot{w}(t) \leq rw(t)$, the introduction of a carbon tax will therefore reduce present and near-term emissions as well as total emissions.

If $\dot{w}(t) - rw(t)$ is positive and sufficiently large, it follows from (8) that q may reach $\bar{q}$ as A reaches A^* even if $q(0)$ is lower with a carbon tax than without. For a sufficiently rapidly rising carbon tax we may thus have a green paradox in terms of present and near-term emissions. However, even in this case the carbon tax may be desirable, since it reduces total emissions.

5 Governments cannot commit to future carbon tax rates

So far, the analysis has been based on an implicit assumption that market participants have full knowledge about the future carbon tax. However, in reality policy makers cannot commit to tax rates in the distant future. It might be possible to make a political commitment for the development of the carbon tax rate for a period of up to 10-15 years, but resource owners would like to know the carbon tax for a longer period in order to make optimal decisions regarding their resource extraction. In the absence of commitment, resource owners must base their decisions on their expectations about future tax rates, which may in turn depend on the current carbon tax rate.

To illustrate the above issues, this section considers a two-period model of resource extraction. Period 1 should be interpreted as the near future, for which resource owners have reasonable confidence about the size of the carbon tax. Period 2 is the remaining future. As argued above, 10-15 years might be a crude estimate of the length of period 1.

The assumptions about the extraction cost are the same as in section 3. Formally, let each unit of the resource be indexed by a continuous variable z, and let $c(z)$ be the cost of extracting unit z, with $c' \geq 0$. In the two-period model x is extraction in period 1 and $A-x$ is extraction in period 2. The cost of extracting x is thus given by $G(x) = \int_0^x c(z)dz$, and the cost of extracting $A - x$ is $\int_x^A c(z)dz = \int_0^A c(z)dz - \int_0^x c(z)dz = G(A) - G(x)$. Notice that these relationships imply that $G'(x) = c(x)$ and $G'(A) = c(A)$. To simplify the expressions in the subsequent analysis, I assume that extraction costs are zero for z up to the value of x in all relevant equilibria so that $G(x) = 0$[8]. I also assume that $G'(A) = c(A) > 0$ and $G''(A) = c'(A) > 0$.

Producers of the carbon resource maximize

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

where p and P are the producer prices in period 1 and 2, respectively. This

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

gives the standard Hotelling equation

$$p = \beta P$$

and the equation determining total resource extraction (using $G'(A) = c(A)$)

$$c(A) = P$$

The relationship between prices and extraction rates is given by the following equations, where w is the carbon tax in period 1 and W is the expected carbon tax in period 2:

$$\begin{aligned} q &\equiv p + w \\ Q &\equiv P + W \\ x &= d(q) \qquad (11) \\ A - x &= D(Q) \qquad (12) \end{aligned}$$

where $d(q)$ and $D(Q)$ are demand functions for the two periods. The six equations above give the following two equations in the two endogenous variables q and Q:

$$q - \beta Q = w - \beta W \tag{13}$$

$$Q - c\left(D(Q) + d(q)\right) = W \tag{14}$$

It is straightforward to verify that these equations imply that an increase in W (holding w constant) will give a reduction in q, i.e., an increase in x. A more policy relevant question is how a change in w will affect q (and hence x) when the expectation about W might depend on w. Let this expectation be given by some function $W = h(w)$. Inserting this into (13) and (14) and differentiating with respect to w gives

$$\frac{\partial q}{\partial w} = \frac{1}{M}\left[1 + (1 - \beta h')(-D')c'\right]$$

where $M = 1 + (-D')c' + \beta(-d')c' > 0$.

What are the conditions for a weak green paradox, i.e. that an increase in the period 1 carbon tax gives an increase in period 1 emissions? This will occur if and only if the derivative above is negative, i.e. if and only if

$$\beta h' > 1 + \frac{1}{-D'c'}$$

Consider first the case of $c' = "\infty"$, i.e., total resource extraction A is exogenous. In this case a green paradox occurs if and only if $\beta h' > 1$. If this inequality holds, an increased tax in period 1 will give an expectation of an increased tax in period 2 that in present value is at least as large as the tax increase in period 1. This corresponds to the finding in section 3 that an increase in the current carbon tax will increase current extraction and emissions if the tax rate is assumed to grow at a rate larger than the interest rate.

For finite values of c', $\beta h'$ must be higher than some threshold that is larger than 1 in order to get a green paradox. This confirms the analysis of section 4, where it was shown that an increase in the current carbon tax would reduce current emissions even if if the tax rate was assumed to grow at a rate slightly larger than the interest rate.

Can we say anything about the expectation function $h(w)$? One possibility would be that expectations are rational in the sense that market participants believe that the government in period 2 will set the carbon tax optimally based on the government's preferences. 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 A. 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 A. A simple way of capturing this it to assume that climate costs are given by a function $E(A + \gamma x)$, where $E' > 0$ and $\gamma > 0$.[9] I also assume that $\gamma < 1$, i.e. that one additional ton of total carbon emissions is worse for the climate than one ton of carbon emissions moved from the future to the present.

The optimal carbon tax in period 2 is the Pigou tax

$$W = E'(A + \gamma x)$$

Inserting from the demand functions (11) and (12) gives

$$W = E'(A - x + (1 + \gamma)x) = E'(D(Q) + (1 + \gamma)d(q)) \tag{15}$$

Together with (13) and (14) we thus have three equations determining q, Q and W as a function of the period 1 tax w. In particular, the expected future carbon tax rate W depends on the current carbon tax rate w.

Notice that the expectation formation described above ignores all types of uncertainties. Even if one believes that the future tax rate will be equal to the Pigovian rate, this rate will depend on factors that are uncertain as seen from the present. Sources of uncertainty that immediately come to mind in the context of the climate issue are uncertainties related to how the climate will be affected by emissions and how climate change will affect the economy. These factors will make the function $E(A + \gamma x)$ uncertain. In addition, there will be uncertainties related to technological development, making the demand function $D(Q)$ uncertain. These important issues are discussed more extensively by e.g. Ulph and Ulph (2009) and Hoel (2010), but are beyond the scope of the present analysis.

To see how consumer prices in both periods are affected by a change in the

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

carbon tax in period 1, the equilibrium conditions (13)-(15) are differentiated with respect to w. From the Appendix it follows that

$$\frac{\partial q}{\partial w} = \frac{1}{H}(1 - c'D' - E''D') \tag{16}$$

$$\frac{\partial Q}{\partial w} = \frac{1}{H}(c'd' + (1+\gamma)E''d') \tag{17}$$

where H under reasonable conditions is positive.[10] Assuming $H > 0$ it follows from (16) and (17) that an increase in the carbon tax in period 1 increases the consumer price in this period. Use and extraction of the carbon resource therefore decline in period 1, implying that there is no weak green paradox with this assumption about how expectations of future taxes are created.

Inserting (16) and (17) into (15) give

$$\frac{\partial W}{\partial w} = \frac{E''}{H}\left[(1+\gamma)d' - \gamma f'D'c'\right] < 0$$

In other words, as the present carbon tax increases, the expected future carbon tax declines. Obviously, with such expectations a weak green paradox cannot occur.

An increased carbon tax in period 1 reduces the consumer price in period 2 (see (17)), and thus increases emissions in period 2. The effect on total emission follows from (16) and (17) using $A = d(q) + D(Q)$:

$$\frac{\partial A}{\partial w} = \frac{d'}{H}\left[1 + \gamma D'E''\right]$$

If all that matters for the climate is total emissions ($\gamma = 0$), total emissions go down as a response to a higher carbon tax in period 1 $\left(\frac{d'}{H} < 0\right)$. This remains true if one also is concerned about *when* emissions occur ($\gamma > 0$), provided $-\gamma D'E'' < 1$, which holds if the condition of footnote 10 holds. Since both early emissions and total emissions decline as w is increased, neither a weak nor a strong green paradox can occur when expectations are formed in the

[10] In the Appendix I show that asufficient condition for $H > 0$ is that the social cost of carbon increases by less than one dollar per unit of carbon if consumer prices of carbon are permanently reduced by one dollar.

manner described above.[11]

6 A green paradox with endogenous carbon taxes

So far the carbon tax rate, at least in period 1, has been considered exogenous. In reality, tax rates will be determined endogenously, with the government's preferences being an important factor. What are the effects in this case of an increased concern for the climate? I analyze this below, and show that a green paradox may occur if the tax in the first period is lower than its ideal level.

Like in the previous section, the government's preferences are given by the function $E(A+\gamma x)+s$, where s is a shift parameter. The social optimum is achieved if the carbon taxes in each period are equal to the Pigovian levels, i.e. if (see Appendix for details)

$$w = \beta\,(1+\gamma)\,(E'+s) \tag{18}$$

$$W = E'+s \tag{19}$$

These two equations show how the optimal carbon taxes in the two periods depend on the preferences of the government, represented by the function $E(A+\gamma x)+s$. A slightly generalized version of the period 1 tax is

$$w = \mu\beta\,(1+\gamma)\,(E'+s) \tag{20}$$

where the positive parameter $\mu \leq 0$ represents the possibility that the tax rate in period 1 is set at a level below its optimal level. There could be several reasons why $\mu < 1$. One possibility could be implemetation lags. After a shift in prefereces that increases the Pigovian tax rate in both periods, there may be many political, legislative, and regulatory hurdles to be passed before

[11] It is straightforward to derive $\frac{\partial(A+\gamma x)}{\partial w} = \frac{d'}{H}\left[1+\gamma-\gamma c' D'\right] < 0$, implying that climate costs decline with increased w even if $-\gamma D' E'' > 1$.

the tax change can be fully implemented.[12] In the present two period model it seems natural to model such implementation lags as the tax change being fully implementet in period 2, but only partially implemented in period 1.

A second reason for $\mu < 1$ could be that the present model represents the global economy, and that E' thus represents global marginal climate costs. If these costs are not fully internalized in period 1 due to the lack of an international climate agreement, taxes throughout the world would typically be set below their optimal values. In spite of the current lack of an international climate agreement, one might expect that such an ageement will come into effect within a couple of decades, implying that the carbon tax in the future will be equal to the Pigovian level.

The rate of change in the tax rate follows directly from (19) and (20):

$$\frac{W}{w} = \frac{1}{\mu\beta\left(1+\gamma\right)}$$

Hence, the growth rate of the tax is lower than the interest rate $\left(\beta^{-1}\right)$ if and only if $\mu\left(1+\gamma\right) > 1$. If this inequality holds, it follows from the previous analysis that there will be no weak green paradox: Carbon emissions in period 1 are lower when taxes are given by (20) and (**??**) than they would have been if there were no taxes. If on the other hand $\mu\left(1+\gamma\right) < 1$, which will occur if μ is sufficiently small, the carbon tax will rise at a rate that is higher than the interest rate. From the prievious analysis we know that if this is the case near-term emissions *may* be higher with carbon taxes than without.

Inserting the tax equations (19) and (20) into the demand functions (11) and (12) gives two equations determining the consumer prices q and Q as functions of the shift parameter s. In the Appendix it is shown that a shift in the governmnet's prefereces affect consumer prices as follows:

$$\frac{\partial q}{\partial s} = \frac{\beta}{J}\left[\mu\left(1+\gamma\right) + \left(1-\mu\left(1+\gamma\right)\right)c'D'\right] \tag{21}$$

and

[12] See Di Maria et al. (2010) for a further discussion and analysis of such implementation lags.

$$\frac{\partial Q}{\partial s} = \frac{1}{J}\left[1 - \beta\left(1 - \mu\left(1 + \gamma\right)\right)c'd'\right] \tag{22}$$

where J is positive under reasonable conditions[13]. Moreover, since total emissions $A = d(q) + D(Q)$ it follows from these two eqations that

$$\frac{\partial A}{\partial s} = \frac{1}{J}\left[\beta\mu\left(1 + \gamma\right)d' + D'\right] < 0 \tag{23}$$

Increased concern for the climate, represented by a positive shift in the function E', thus for sure makes total emissions decline. However, it is not obvious that emissions decline in both periods. To study this it is useful to distinguish between the two cases $\mu = 1$ and $\mu < 1$

If $\mu = 1$ we have

$$\frac{\partial q}{\partial s} = \frac{\beta}{J}\left[\left(1 + \gamma\right) - \gamma c'D'\right]$$

A positive shift in the function E' thus for sure makes q larger and therefore near-term emissions decline. Since both near-term emissions and total emissions decline with an increase in s, climate costs will for sure be smaller the larger is the concern for the environment.[14]There can therefore be no green paradox in this case.

Although total emissions decline with increasing climate concern even if $\mu < 1$, it is not obvious that near-term emissions decline. The term in square brackets in (21) is positive for $\mu = 1$, but is declining in μ and becomes negative for sufficiently low positive values of μ . Formally,

$$\frac{\partial q}{\partial s} < 0 \text{ for } \mu < \frac{c'D'}{\left(1 + \gamma\right)\left(1 + c'D'\right)} \tag{24}$$

Notice that the threshold value of μ for the weak green paradox case of $\frac{\partial q}{\partial s} < 0$ to occur is higher the larger is c', with the threshold being $(1 + \gamma)^{-1}$ for the

[13]The condition in footnote 10 is sufficient for $J > 0$.

[14]When $\mu = 1$ we have $\frac{\partial Q}{\partial s} = \frac{1}{J}\left[1 + \beta\gamma c'd'\right]$. It follows from this expression that it is not obvious that future emissions decline with increased s: If c' is sufficiently large, Q will decline and future carbon emissions will increase.

limiting case of $c' \to \infty$.

If x increases in response to an increase in s, we cannot rule out the possibility of $A + \gamma x$ increasing, even if A declines (an example of this is given below). It is thus possible to have a strong green paradox if μ is sufficiently low.

Finally, consider the two limiting case of $c' = 0$ and $c' =$ "∞". The case of $c' = 0$ means that there is no scarcity of the resource, neither of a physical or economic type. If $c' = 0$ it follows from (21) and (22) that

$$\begin{aligned} \frac{\partial q}{\partial s} &= \frac{\beta}{J} \left[\mu \left(1 + \gamma \right) \right] > 0 \\ \frac{\partial Q}{\partial s} &= \frac{1}{J} > 0 \end{aligned}$$

Hence, in this case emissions unambiguously decline in both periods as a response to increased concern for climate change, so there cannot be any green paradox in this case.

For the case of $c' =$ "∞" it follows from (21) and (22) that

$$\frac{\partial q}{\partial s} = \frac{\beta D'}{\tilde{J}} \left(1 - \mu \left(1 + \gamma \right) \right)$$

and

$$\frac{\partial Q}{\partial s} = \frac{-\beta d'}{\tilde{J}} \left(1 - \mu \left(1 + \gamma \right) \right)$$

where $\tilde{J} = -D' - \beta d' - \beta \gamma d' D' E'' \left(1 - \mu \left(1 + \gamma \right) \right) > 0$ for the same reason as J was assumed positive.

By assumption, total emissions are not affected by preferences in this case.[15] Moreover, from the equations above we see that $\frac{\partial q}{\partial s}$ and $\frac{\partial Q}{\partial s}$ have opposite signs. If $\mu > (1 + \gamma)^{-1}$, $\frac{\partial q}{\partial s} < 0$ and $\frac{\partial Q}{\partial s} > 0$, while the opposite is true if $\mu < (1 + \gamma)^{-1}$. If there are no obstacles preventing the near-term tax rate being equal to its optimal value ($\mu = 1$), increased concern for the environment thus gives a postponement of extraction and emissions in this

[15] Formally, this follows from (23) and the fact that $J \to \infty$ as $c' \to \infty$.

case, and total climate costs therefore decline (since $\gamma > 0$). However, if $\mu < (1+\gamma)^{-1}$, increased concern for the environment speeds up extraction and emissions, and since total emissions are given, climate costs increase. In this case we therefore get both a weak and strong green paradox.

7 Concluding remarks

There are six important lessons from this paper:

1. Analyses of climate policy without taking into consideration the fact that fossil fuels are scarce non-renewable resources can give misleading conclusions. Although the principles for the design of an optimal carbon tax are not affected, the consequences of deviating from the optimum may be different than one might believe if the scarcity of carbon resources is ignored.

2. A rapidly rising carbon tax may give a green paradox in the sense that near-term emissions become higher than they would be without any carbon tax. The threshold of how rapidly the tax must increase is higher when the resource is not limited in an absolute physical sense, but more realistically by extraction costs increasing with accumulated extraction.

3. If the resource is not limited in an absolute physical sense, but by extraction costs increasing with accumulated extraction, total climate change costs may go down even if the carbon tax path gives increased near-term emissions.

4. In reality, governments do not set carbon tax paths extending into the distant future. Instead, they set a carbon tax for a relatively short period, and market participants form expectations about the carbon tax in the more distant future. For reasonable modeling of these expectations, a higher current carbon tax will reduce near-term emissions.

5. If a sufficiently high carbon tax is introduced, emissions will for sure decline. The possibility of a green paradox is therefore not an argument against the use of a carbon tax, but rather an argument against setting the carbon tax too low.

6. If the near-term tax rate for some reason is set below its optimal level, increased concern for the climate may change taxes in a manner that increases near-term emissions.

Appendix

Carbon taxes and resource extraction with endogenous total extraction

The simplest way to analyze the market equilibrium in section 4 is to consider this equilibrium as the outcome of maximizing the sum of consumer benefits of using the resources and the costs, including taxes, of extracting the resource. Let $B(x)$ be the consumer benefit, with $q = B'(x)$ and $\bar{q} = B'(0)$. I assume that $c(0)+w(0) < B'(0)$ and $c(A) > B'(0)$ for sufficiently high values of A (where $w(0)$ is the initial carbon tax). Moreover, I restrict the analysis to the case of a non-decreasing carbon tax path $w(t)$, so that extraction will be declining.

The objective function of the private sector is

$$V = \int_0^\infty e^{-rt} \left[B(x(t)) - c(A(t))x(t) - w(t)x(t) \right] dt$$

This objective function is maximized subject to

$$\begin{aligned} \dot{A}(t) &= x(t) \qquad (25) \\ x(t) &\geq 0 \\ A(0) &= 0 \end{aligned}$$

The current value Hamiltonian is (written so the shadow price of A, denoted π, is positive, and ignoring time references where this cannot cause misunderstanding)

$$L = B(x) - c(A)x - wx - \pi x$$

The optimum conditions are

$$B'(x) - c(A) - w - \pi \leq 0 \ \ [= 0 \text{ for } x > 0] \tag{26}$$

$$\dot{\pi} = r\pi - xc'(A) \tag{27}$$

$$Lim_{t \to \infty} \left[e^{-rt}\pi(t) \right] = 0 \tag{28}$$

Using (25) and $q = B'$ it follows from (26) and (27) that the consumer price development is given by

$$\dot{q} = r\,(q - c(A)) + [\dot{w} - rw] \tag{29}$$

which corresponds to equation (8) in the text.

It is useful to distinguish between the case of w constant ($= \bar{w}$) and w increasing. For $w = \bar{w}$ (which may be zero or positive) carbon extraction is positive for all t. To see this assume the opposite, i.e. that $x(t) = 0$ for $t \geq T$. From (27) this implies that $\dot{\pi} = r\pi$ for $t \geq T$. From (28) it follows that $\pi(T) = 0$, so that (26) implies

$$B'(0) - c(A(T)) - \bar{w} \leq 0$$

Going backwards in time from T, we see from the differential equations (25) and (27) that $\pi(t) = 0$ and $B'(0) - c(A(t)) - \bar{w} \leq 0$ will hold also for all $t < T$. But this violates the assumption $c(0) + w(0) < B'(0)$. This completes the proof that $x(t) > 0$ for all t when $w(t) = \bar{w}$.

Although $x(t) > 0$ for all t when $w(t) = \bar{w}$, $x(t)$ will asymptotically approach zero. To see this, assume instead that $x(t) > \delta > 0$ for all t. Then

$A(t)$ become so large that $c(A) > B'(0)$, so that (26) would be violated for any non-negative $w + \pi$.

As $x(t)$ approaches 0 asymptotically, $\pi(t)$ approaches 0, and from (26) it follows that $A(t)$ approaches $\bar{A}$ given by

$$c(\bar{A}) + \bar{w} = B'(0) \tag{30}$$

The case of $w(t)$ increasing over time is not much different from w constant. However, if w is unbounded, extraction cannot be positive extraction for all t, since eventually we would have $B'(0) - c(A) - w(t) < 0$ for any value of A. In the present case there is thus a date t^* at which extraction stops. At this date we have $\pi(t^*) = 0$, as (28) otherwise would be violated. Since $x(t)$ is positive immediately prior to t^*, it therefore follows from (26) that

$$c(A^*) + w(t^*) = B'(0) \tag{31}$$

Since the time path of extraction depends on the carbon tax also prior to t^*, the values $A^*$and $w(t^*)$ are determined endogenously by the condition (31) in combination with the differential equations (25) and (29) as well as $q = B'(x)$.

The relationship between the current carbon tax rate and the expected future tax rate

Inserting (15) into (13) and (14) and differentiating with respect to w gives

$$\begin{pmatrix} 1 + \beta(1+\gamma)E''d' & -\beta + \beta E''D' \\ -c'd' - (1+\gamma)E''d' & 1 - c'D' - E''D' \end{pmatrix} \begin{pmatrix} \frac{\partial q}{\partial w} \\ \frac{\partial Q}{\partial w} \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

Solving gives (16) and (17) where H may be written as

$$H = (1 - \beta d') - D' \left[E'' + c'(1 - \gamma\beta(-d')E'') \right]$$

The term $(1 - \beta d')$ is positive and $-D' > 0$. A sufficient condition for H to be positive is therefore that the term in square brackets is positive, and a sufficient condition for this is that $\gamma\beta\,(-d')\,E'' < 1$. I assume that this holds, since it is implied by

$$\beta E'' \left[(1+\gamma)(-d') + (-D') \right] < 1 \tag{32}$$

The term in square brackets tells us how much $A + \gamma x$ is increased if consumer prices of carbon are reduced permanently by one dollar per unit of carbon, giving increased emissions in both periods. The social cost of carbon emissions in period 1 is $\beta E'(A + \gamma x)$. Hence, the inequality above says that the social cost of carbon increases by less than one dollar if consumer prices of carbon are permanently reduced by one dollar. This seems a reasonable assumption.

The effects of a change in preferences

Let let $b(x)$ and $B(A - x)$ be the consumer benefit of using the resource in the two periods, with $q = b'$ and $Q = B'$. The fist best optimum is found by maximizing

$$b(x) + \beta \left[B(A-x) - G(A) - E(A + \gamma x) \right]$$

and the first order conditions are (using $q = b'$, $Q = B'$ and $c(A) = G'(A)$)

$$\begin{aligned} q - \beta Q &= \beta \gamma E'(A + \gamma x) \\ Q - c(A) &= E'(A + \gamma x) \end{aligned}$$

Comparing with (13) and (14), it is clear that the first best optimum is achieved if the carbon taxes in the two periods are given by (18) and (19) (with $s = 0$).

To see in more detail what the consequences are of a positive shift in the marginal climate costs function E', I insert (19) (20) back into the equilibrium conditions (13) and (14). Using the demand functions (11) and (12) this gives

$$q - \beta Q = \beta \left[\mu (1+\gamma) - 1 \right] \left[E'(D(Q) + (1+\gamma) d(q)) + s \right] \tag{33}$$

$$Q - c\left(D(Q) + d(q)\right) = E'(D(Q) + (1+\gamma)d(q)) + s \tag{34}$$

Differentiating (33) and (34) with respect to s gives

$$\begin{pmatrix} 1-\beta\left[\mu\left(1+\gamma\right)-1\right](1+\gamma)E''d' & -\beta-\beta\left[\mu\left(1+\gamma\right)-1\right]E''D' \\ -c'd'-(1+\gamma)E''d' & 1-c'D'-E''D' \end{pmatrix}\begin{pmatrix} \frac{\partial q}{\partial s} \\ \frac{\partial Q}{\partial s} \end{pmatrix}$$
$$= \begin{pmatrix} \left[\mu\left(1+\gamma\right)-1\right]\beta \\ 1 \end{pmatrix}$$

Solving gives (21) and (22), where

$$\begin{aligned} J &= 1-c'D'-\beta c'd'-D'E''-\beta\gamma c'd'D'E'' \\ &\quad +\mu\left[\left(1+\gamma\right)\beta\gamma c'd'D'E''-\beta d'E''-\beta\gamma^2 d'E''-2\beta\gamma d'E''\right] \end{aligned}$$

is an increasing function of μ. Even for $\mu = 0$ it is reasonable to assume that $J > 0$. A *sufficient* condition for this is that $-D'c' - \beta c'd' - \beta\gamma c'd'D'E'' > 0$, i.e. that $\gamma E''(-D') < 1 + \frac{D'}{\beta d'}$, which holds when (32) holds, since $\gamma < 1$.

References

Allen, M. R., D. J. Frame, C. Huntingford, C. D. Jones, J. A. Lowe, M. Meinshausen and N. Meinshausen (2009). Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature*, *458*(7242), 1163–1166.

Amigues, J.-P., G. Lafforgue and M. Moreaux (2010). Optimal capture and sequestration from the carbon emission flow and from the atmospheric carbon stock with heterogeneous energy consuming sectors. Paper presented at the SURED conference 2010.

Chakravorty, U., B. Magne and M. Moreaux (2006). A Hotelling model with a ceiling on the stock of pollution. *Journal of Economic Dynamics & Control*, *30*(12), 2875–2904.

der Ploeg, F. V. and C. A. Withagen (2010). Is There Really a Green Paradox? CESifo Working Paper no. 2963.

Di Maria, C., S. Smulders and E. van der Werf (2010). Optimal tax paths with stock pollution and implementation lags. Paper presented at the CESifo ECE conference, October 2010.

Gerlagh, R. (2010). Too Much Oil. *CESifo Economic Studies*, *forthcoming*.

Hanson, D. A. (1980). Increasing Extraction Costs and Resource Prices: Some Further Results. *The Bell Journal of Economics*, *11*(1), 335–342.

Heal, G. (1976). The Relationship between Price and Extraction Cost for a Resource with a Backstop Technology. *The Bell Journal of Economics*, *7*(2), 371–378.

Hoel, M. (2008). Bush Meets Hotelling: Effects of Improved Renewable Energy Technology on Greenhouse Gas Emissions. CESifo Working Paper no. 2492.

Hoel, M. (2010). Climate change and carbon tax expectations. CESifo Working Paper 2966.

Hoel, M., M. Greaker, C. Grorud and I. Rasmussen (2009). Climate policy - costs and design. TemaNord 2009:550, Nordic Council of Ministers.

Hoel, M. and S. Jensen (2010). Cutting Costs of Catching Carbon: Intertemporal effects under different climate policies. Unbuplished work in progress, Department of Economics, University of Oslo and Ragnar Frisch Centre for Economic Research.

Hoel, M. and S. Kverndokk (1996). Depletion of fossil fuels and the impacts of global warming. *Resource and Energy Economics*, *18*(2), 115–136.

Le Kama, A., M. Fodha and G. Lafforgue (2010). Optimal carbon capture and storage policies. Paper presented at the SURED conference 2010.

Long, N. and H.-W. Sinn (1985). Surprise Price Shifts, Tax Changes and the Supply Behavior of Resource Extracting Firms. *Australian Economic Papers*, *24*(45), 278–289.

Sinclair, P. (1992). High does nothing and rising and worse: carbon taxes should be kept declining to cut harmful emissions. *Manchester School of Economic and Social Studies*, *60*, 41–52.

Sinn, H. (2008a). *Das Grüne Paradoxon. Plädoyer für eine Illusionsfreie Klimapolitik*. Econ.

Sinn, H. (2008b). Public Policies against Global Warming: a supply side approach. *International Tax and Public Finance*, *15*, 360–394.

Strand, J. (2007). Technology Treaties and Fossil Fuels Extraction. *The Energy Journal*, *28 (4)*, 129–142.

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, Department of Economics, University of St. Andrews.

Withagen, C. (1994). Pollution and exhaustibility of fossil fuels. *Resource and Energy Economics*, *16*, 235–242.