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Abstract:
The aim of this paper is to examine the impacts of a global carbon tax on fossil fuel markets. In particular, the effect on the Norwegian, as well as the global, petroleum wealth is studied. Most empirical models of fossil fuel markets either use an exogenous price path, or model the supply side as being independent of future expectations. Hence, they are not able to test how the exhaustibility feature of fossil fuels affects the sharing of the tax burden between producers and consumers. We study a simple, dynamic model of a competitive fossil fuel market, and we first derive some general theoretical results regarding how a carbon tax may affect the producer and consumer prices. Then, simulations of the global oil market indicate that a fixed carbon tax of e.g. $10/barrel of oil may reduce the petroleum wealth of the average oil producer by 33-42%. The Norwegian petroleum wealth may decrease more than this, by 47-68%. The latter reduction may correspond to a yearly income loss of about 3% of Norwegian GDP. However, the figures should only be considered as very rough estimates, because of the simplistic nature of the model.

Keywords: Carbon Taxes, Exhaustible Resources, Petroleum Wealth

JEL classification: H23, Q30, Q40

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1. Introduction

A global carbon tax may have considerable impact on the petroleum wealth of fossil fuel producers. However, it is not clear to what extent such a tax eventually will decrease the producer prices, rather than increase the consumer prices. Thus, an interesting question is: How will the tax burden be shared between producers and consumers? This question is of course of major importance for countries with relatively large petroleum reserves, like for instance the OPEC-countries as well as Norway. In this study we are addressing this question, trying to reveal how different carbon taxes may change the petroleum wealth, both for the average producer and for Norway in particular.

Even if a global climate treaty at present seems a bit distant, several OECD-countries are or have been discussing a carbon tax to restrict their emissions of CO_2.[1] Hence, there is a fair possibility that such a tax will be imposed in at least the main countries of the OECD-area, which stands for almost 60 percent of the worlds oil consumption. The size of this tax is difficult to foresee, and in addition, the tax may not be constant over time. However, some concrete proposals of a carbon tax have been put forward in e.g. the EU and the US, and several research projects have come up with appropriate suggestions (see e.g. Manne and Richels (1991) and Oliveira Martins *et al.* (1992)).

Taxation of exhaustible resources, like fossil fuels, has been examined theoretically in e.g. Burness (1976) and Dasgupta and Heal (1979), who considered the traditional Hotelling model, and Heaps (1985) and Lasserre (1991), who also examined more extended models. In general they found that some tax systems, like a constant sales tax, may decrease the extraction rate, while other systems, like franchise taxes, may increase the rate. With a constant sales tax, or unit tax, Dasgupta and Heal (1979) found that the tax is shared between producers and consumers during an initial interval. Furthermore, a constant profit tax, or eventually a constant ad valorem tax when extraction costs are zero, has no effect on the depletion path, and the tax is born solely by the producers. Sinclair (1992) hence argued that the optimal ad valorem carbon tax rate should be falling over time in order to reduce the depletion rate. However, Sinclair's argument has been criticised in Ulph *et al.* (1991), who found that the issue of an optimal carbon tax is much more complex.

When a specific unit tax is introduced into a static market model, the supply curve shifts upward by the amount of the tax, and the new market equilibrium is established so that both consumers and producers bear some of the tax burden. The share is determined by the demand and supply elasticities. In a dynamic model of exhaustible resources, the supply curve is changing over time as the shadow price of the resource changes. When a unit tax is introduced into such a model, the shadow prices at different points of time generally change too, and so the supply curve shifts in a less foreseeable way. Hence, the impact on the consumer and producer prices are no longer entirely dependent on the curvature of the immediate supply and demand curves.

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[1] Norway is in fact one of the countries that already have introduced a carbon tax.

Nevertheless, according to Ingham *et al.* (1993), empirical models in this area often ignore the dynamic aspects associated with the imposition of a carbon tax. Furthermore, in dynamic models the oil price is usually set exogenously. Hence, it is not possible to determine within the model how a tax will be shared between producers and consumers. For instance, of the six global energy models compared in Dean and Hoeller (1992), only in the GREEN model (Oliveira Martins *et al.* 1992) the oil price is endogenised. However, the supply side in GREEN is modelled as being independent of future expectations. Hence, the present extraction is not changed by anticipations of e.g. future carbon taxes. This means that the supply function is not fully intertemporal, and the above-mentioned theoretical results cannot be tested within the GREEN model. The same applies for the global energy market model developed by ECON (1990), which also treats the oil price endogenously, but doesn't model future expectations within the supply function.

Several studies have tried to examine economic costs to Norway of introducing a carbon tax, either on a national level (e.g. Glomsrød *et al.* (1992) and Johnsen *et al.* (1994)) or through an international agreement (Moum 1992). Moum, which is the most comprehensive of these studies, found that the impact through reduced petroleum income is clearly dominating the effects on total disposable income. However, the study treats the oil price path before and after tax exogenously, and hence the dominating effect hinges crucially on exogenous assumptions. In the governmental long-term programme (Ministry of Finance 1992-93) the impact of a specific international carbon tax on the petroleum wealth is calculated. Here, too, the effect on the oil price path is assumed exogenously.

The aim of this paper is to try to bridge some of the gap between the theoretical results referred above, and the empirical models like GREEN. We examine a simple, dynamic Hotelling-type model of a fossil fuel market. Empirical findings have not supported the simple Hotelling rule. However, Farzin (1992) has shown that introducing a more comprehensive cost function into such a model is in general sufficient to embrace the empirical findings. In section 2 we derive some general theoretical results on how a constant carbon tax affects the consumer and producer prices. Further, we are particularly interested in the effects on the oil market, and in section 3 we try to find some numerical results about the impact of different carbon taxes on the petroleum wealth of Norway and other oil producers. The supply side in the model is fully intertemporal, incorporating the exhaustibility feature, and hence the effect of a carbon tax is determined in a dynamic way. However, since the model incorporates several simplifications, the numerical results are only valid as rough estimates and as a starting point for further research.

2. A carbon tax and the fossil fuel market

This section describes how we model the fossil fuel market, and derives some theoretical results regarding how a carbon tax influences the resource rent. We use a quite simple Hotelling-type model, with constant unit costs and without market imperfections like the existence of OPEC in the oil market, and the lack of global markets for gas and coal. Moreover, the fact that all fossil fuel markets may be affected by a carbon tax, leading to unclear substitution effects between fossil fuels, is ignored in the model. In our simulations we will mainly be focusing on the oil market, and the discussion of the relevance of the model is delayed to the end of section 3.

We are modelling a global, competitive fossil fuel market. A constant unit cost c of extraction, a constant unit carbon tax v and a fixed, limited amount A of the fossil fuel resource are assumed.[2] Let x_t denote extraction or consumption of the fossil fuel at time t, and let u(x) be the social utility function by consuming x. Finally, let r denote the discount rate. The competitive equilibrium path can then be derived by solving the following optimisation problem:

$$(1) \qquad Max\int_0^\infty e^{-rt}(u(x_t) - cx_t - vx_t)dt \qquad s.t. \int_0^\infty x_t dt \leq A;\ x_t \geq 0$$

The optimal path is realised by letting the consumer price p_t equal marginal utility, i.e. $p_t=u'(x_t)$. The utility function u(x) is assumed to be increasing in x, $u'(x)>0$, and we assume the marginal utility to decline with x, $u''(x)<0$. We further require $u'(0)>(c+v)$, to ensure positive production, and $u'(\infty)=0$. Finally, we assume that $u'(0)<\infty$, and leave the opposite case to the notes. Further below we will introduce a specific utility function.

The resource rent π_t is defined as the difference between the consumer price and the sum of unit cost and unit tax. Moreover, with the producer price q_t we mean the price producers receive net of tax. Thus, the two prices can be expressed in the following way, noting that the carbon tax separates them:

$$(2) \qquad p_t = u'(x_t) = c + v + \pi_t$$

$$(3) \qquad q_t = p_t - v = c + \pi_t$$

We are interested in how the solution path can be characterised, and how an increase in the carbon tax will affect this path. Hotellings rule is obtained from the optimisation problem, i.e. the resource rent π_t is growing exponentially with rate r until the resource is depleted:

$$(4) \qquad \pi_t = \pi_0 e^{rt} \qquad (for\ x_t>0)$$

We observe that the resource rent path is completely determined once we know the resource rent at one specific point of time (as well as the discount rate).

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[2] Different cost levels among producers will be introduced below, as this is of major importance when comparing the average and the Norwegian resource rents.

Together, equations (2), (3) and (4) show that both prices are rising over time. Then, from (2) we see that x_t is falling over time, and since we have assumed that $u'(0)<\infty$, we find that x_t reaches zero at a finite point of time, T. Furthermore, at time T equations (2) and (4) become:

$$u'(0) = c + v + \pi_0 e^{rT} \tag{5}$$

From the condition $p_t=u'(x_t)$ we see that x_t is implicitly a function of the consumer price p_t. Let F() denote the inverse function of $u'(x_t)$, i.e. $F(p_t)=[u']^{-1}(p_t)$. Then we obtain:

$$x_t = F(c + v + \pi_0 e^{rt}) \tag{6}$$

Noting that the whole resource will be extracted (since $u'(0)>c+v$), the constraint in the optimisation problem can be changed to an equality, with ∞ replaced by T. Then, replacing (6) into this constraint, and using (5), the solution can now be completely characterised in the following way, uniquely determining the two unknown variables π_0 and T:[3]

$$\int_0^T F(c + v + \pi_0 e^{rt})dt = A \tag{7a}$$

$$T = \frac{1}{r}\ln\frac{(u'(0) - c - v)}{\pi_0} \tag{7b}$$

The value of the resource wealth (at time t=0) is defined as the discounted value of the resource rent times the extraction at each point of time:

$$\Pi = \int_0^T e^{-rt}\pi_t x_t dt = \int_0^T \pi_0 x_t dt = \pi_0 A \tag{8}$$

We find the well-known Hotelling result that the resource wealth is simply equal to the resource rent at time t=0 times the amount of the resource.

In this study, it is of interest to examine the resource wealth of a small producer, like Norway, facing a unit cost that exceeds the average unit cost of all producers. In our model (as is shown by equation 9 below) it would be optimal for a marginal producer to delay all extraction to the last

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[3] If $u'(0)=\infty$, equation (7b) states that $T=\infty$. Hence, $x_t>0$ for all t. Replacing $T=\infty$ in (7a) leaves us eventually with one equation and one unknown variable, π_0.

period if its unit cost is higher than the average. However, in reality there may be several reasons to choose another production profile. Thus, consider a producer N facing a unit cost $c^N > c$, with a given path of extraction x_t^N, which amounts to its total reserves A^N. Then the resource wealth of this producer is given by the following formula, where the parenthesis $(\pi_t - (c^N - c))$ is equal to the resource rent of producer N at each point of time:

$$\Pi^N = \int_0^T e^{-rt}(\pi_t - (c^N - c))x_t^N dt = \pi_0 A^N - (c^N - c)\int_0^T e^{-rt} x_t^N dt \tag{9}$$

What happens when the tax is increased marginally, i.e. dv>0? The following results, which are also illustrated in figure 1, are shown in the appendix: When the unit tax is increased, the initial resource rent decreases, but not as much as the tax increases, i.e. $0<|d\pi_0|<dv$. This implies that initially the tax burden is shared between the consumers and the producers. The producer price falls because the resource rent decreases (see 3), while the consumer price must rise initially since the tax increase is larger than the initial decrease in the resource rent (see 2 for t=0). As explained in the introduction, this is in accordance with Dasgupta and Heal (1979), and it also corresponds to the result of a static model. However, a higher consumer price implies that the initial extraction

Figure 1 a: Price path before and after tax increase

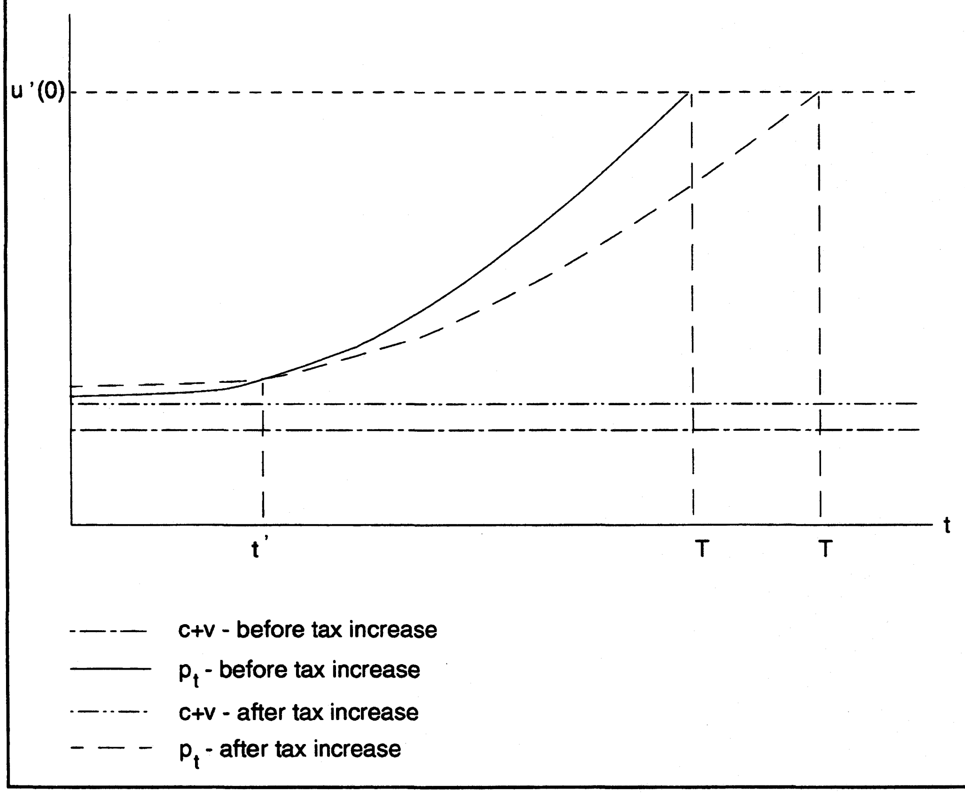
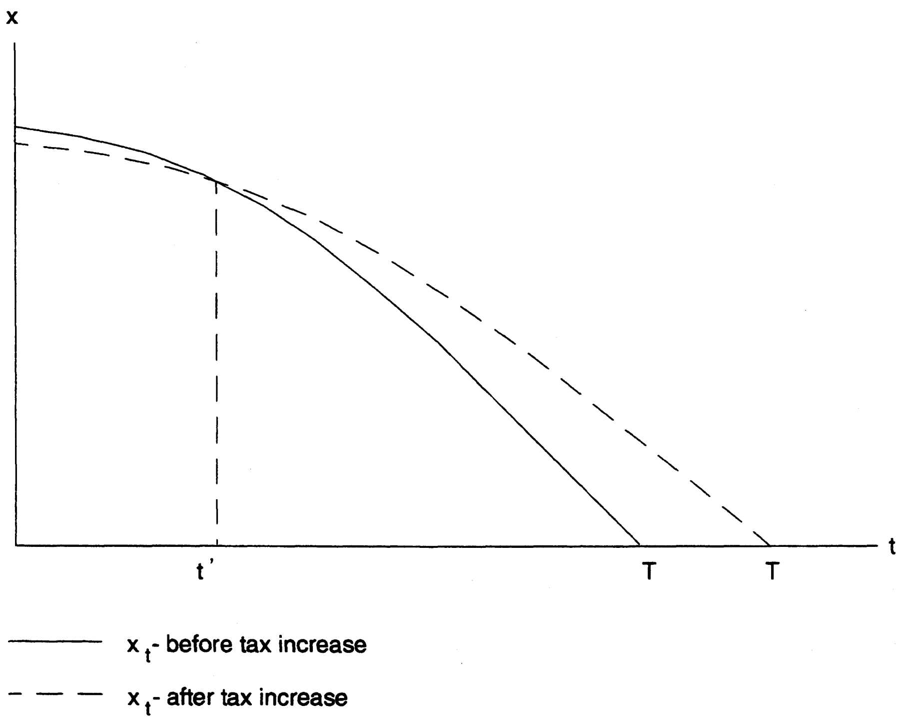


Figure 1 b: Extraction path before and after tax increase



must decline. After some time, then, in order to extract the whole resource, the consumer price must decrease in comparison with the original price path. This means that after a specific time t', extraction is higher and consumer price is lower than on the initial path, and thus the tax burden is more than completely born by the producers in the last extraction time period.[4] Hence, in the end the outcome of this dynamic model becomes completely different from the outcome of a static model.

Finally, from (8) we also establish that the resource wealth is definitely reduced. Actually, the percentage reduction in the resource wealth is equal to the percentage reduction in the initial resource rent π_0. Since we have assumed that the high-cost producer N may choose a sub-optimal production profile, a reasonable assumption is to treat it as exogenous and thus unchanged by a tax increase. Then the percentage reduction in the resource wealth may be derived from (9):

$$\frac{d\Pi^N}{\Pi^N} = \frac{d\pi_0}{\pi_0 - (c^N - c)\frac{1}{A^N}\int_0^T e^{-rt} x_t^N \, dt} \tag{10}$$

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[4] In the appendix it is shown that $t' = (\ln|dv/d\pi_0|)/r < T$.

This expression shows that we have to know the whole extraction path to study the impact on the resource wealth of producer N.

In order to examine price changes more closely, we will consider a specific utility function. In particular we are interested in how different values of the parameters have significance for the change in the resource rent π_0, or how the tax burden is shared between consumers and producers.

2.1 A specific utility function

The following specification of the utility function satisfies the assumptions previously stated. It is an exponential function, where $u'(0)=\beta<\infty$:

(11)
$$u(x) = 1 - e^{-\beta x}$$
$$u'(x) = \beta e^{-\beta x}$$

In order to satisfy earlier assumptions, we require that $(c+v)<\beta$. The intertemporal elasticity of substitution at time t,[5] denoted σ_t, can be shown to be:

(12)
$$\sigma_t = \frac{1}{\beta x_t}$$

Thus, since x_t is decreasing over time, the elasticity will not be constant along the extraction path, but will be strictly increasing, and approach infinity as the resource is extracted.

The unique solution of the optimisation problem, given by relations (7a) and (7b), can now be characterised in the following way:[6]

(13a)
$$\int_0^T \frac{1}{\beta} \ln\left(\frac{\beta}{c + v + \pi_0 e^{rt}}\right) dt = A$$

(13b)
$$T = \frac{1}{r} \ln\left(\frac{\beta - c - v}{\pi_0}\right)$$

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[5] Which in this model is equivalent to the absolute value of the price elasticity.

[6] The chosen utility function requires a certain unit of measurement of x. When we later want to choose a specific unit of measurement, e.g. barrel of oil, and study different values of the parameters, we are only able to interpret empirical values of the price variables (c, v, π_0 and β) or the volume variables (x and A) into the model.

In the general case we found that an increased tax is initially shared by producers and consumers, but we could not tell who has to bear the largest part. Now we want to search for more specific results using the utility function above. By differentiating (13a) with respect to v, we obtain the following expression (see the appendix), stating how the tax increase is born by the producers:

$$\textbf{(14)} \qquad \frac{d\pi_0}{dv} = -\frac{\pi_0(rT-D)}{(c+v)D}$$

Here $D=\ln\beta-\ln(c+v+\pi_0)=\beta x_0>0$. From the derivations in the general case, we know that the value of $d\pi_0/dv$ is negative, but larger than -1, i.e. a tax increase implies initially that the price received by the producers decreases, but not as much as the tax increases. Thus we know a priori that the parenthesis in the numerator must be positive.

As mentioned before, we are interested in how different parameters influence the size of $d\pi_0/dv$.[7] For instance, we want to examine the impact of different sizes of the resource wealth A or, equivalently, how the tax burden changes according to when the tax is enforced along the extraction path. We are also concerned with the impact of different values of the parameter β, which for specific values of consumption level x is determining the intertemporal elasticity of substitution. Finally, changes in the unit cost, the initial tax and the discount rate will also be examined.

Consider the path along which a resource amount A is depleted according to the solution of the optimisation problem (see 13). Then, at each point of time t^*, we can ignore the past, specify $t^*=0$, and regard the rest of the path as a complete solution of a 'new' optimisation problem, with new solution values π_0^* and T^*.[8] Time consistency secures that the new solution path will be identical to the remaining part of the original path. As time goes by, T^* will by definition decline, and we have also found that π_0^* will strictly increase. We now want to study how a tax increase at time t^* is born by the producers at different points of time, i.e. we are interested in how $d\pi_0^*/dv$ develops over time. In figure 2 a tax increase is imposed at two different points of time t^*. One way of studying this is to consider $d\pi_0^*/dv$ as a function of π_0^*, i.e. $d\pi_0^*/dv=g(\pi_0^*)$, and differentiate g() with respect to π_0^*, considering T^* as a function of π_0^* as in (13b).[9] Then we obtain (the expression is derived in the appendix):

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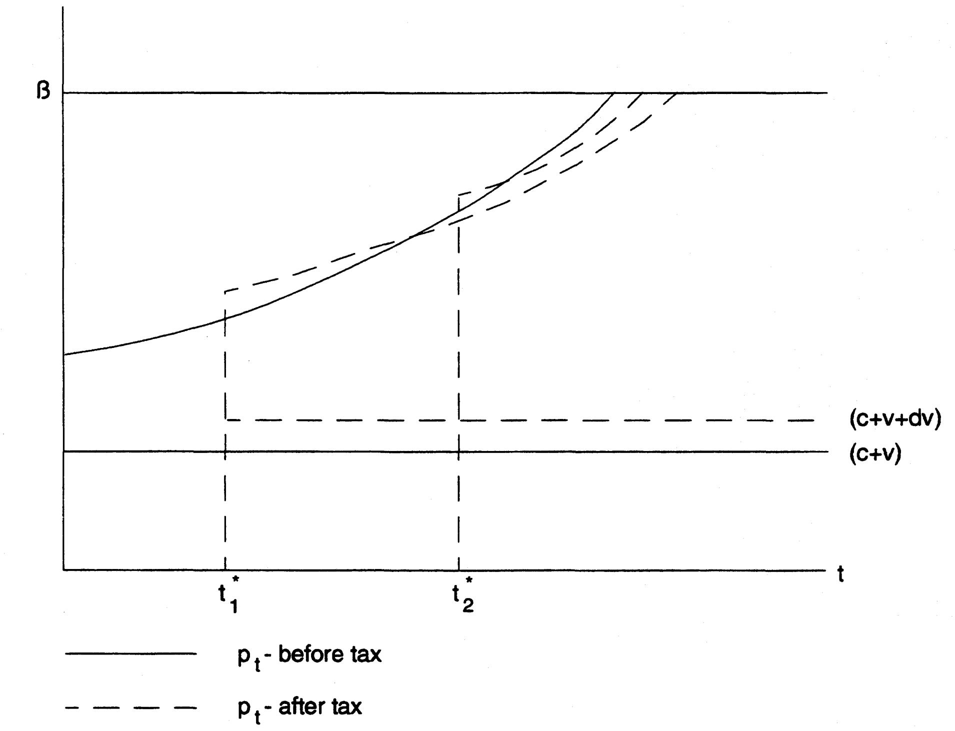
[7] It is important to have in mind that both π_0 and T are functions of all the parameters. Thus, it is not straightforward to draw conclusions.

[8] Variables that are marked with an asterisk, e.g. π_0^* and T^*, are here meant to describe variables that are calculated at time t^*.

[9] Since π_0^* is strictly increasing over time, this is equivalent to differentiating g() with respect to t^*, which is what we are interested in.

Figure 2. Imposition of a carbon tax at different points of time



$$(15) \qquad g'(\pi_0^*) = \frac{d\left(\dfrac{d\pi_0^*}{dv}\right)}{d\pi_0^*} = -\frac{(rT^* - D - 1)D + \dfrac{\pi_0^*}{c + v + \pi_0^*}rT^*}{(c + v)D^2}$$

where $D = \ln\beta - \ln(c+v+\pi_0^*)$ as before. The sign of this expression is the opposite of the sign of the numerator. It can be shown that the numerator is decreasing in π_0^*, and further that the numerator approaches zero as π_0^* approaches its upper limit β-c-v. Thus, the numerator must be positive, which means that the sign of the expression in (15) must be negative. Hence, this finding states that as time goes by, and the resource is depleted, the producers' share of a tax increase becomes larger. We can also observe that when π_0^* is very small, which is true when A is very large, it is not possible for the producers to bear any of the tax burden, and so $g(\pi_0^*) = d\pi_0^*/dv$ is approximately zero. On the other hand, as π_0^* approaches its upper limit β-c-v, i.e. when A is very small, an increase in the consumer price is infeasible, because the consumers already pay the maximum of their willingness to pay. Thus, the producers must decrease their price with the same amount as the tax increases, i.e. $g(\pi_0^*) = d\pi_0^*/dv$ approaches minus one. To sum up, we may conclude that as A increases from zero to infinity, $d\pi_0/dv$ increases monotonously from minus one to zero.

In the general case we found that $(\ln|dv/d\pi_0|)/r<T$ (see note 4). Using (13b), this is equivalent to:

(16)
$$g(\pi_0^*) = \frac{d\pi_0^*}{dv} < -\frac{\pi_0^*}{\Delta} \; ; \qquad \Delta = \beta - c - v$$

Thus, as π_0^* goes from its lower to its upper limit, i.e. from 0 to Δ=(β-c-v), and $g(\pi_0^*)=d\pi_0^*/dv$ goes from 0 to -1, (16) states that $g(\pi_0^*)$ lies strictly below the straight line between its two end points. Δ denotes the difference between the maximum and the minimum feasible consumption price, and we can regard Δ as a sort of surplus which is shared between producers and consumers, with the producers' share equal to π_0^*/Δ. Then, (16) states that the producers' share of the tax burden will always be larger than their initial share of the surplus Δ.

It may seem natural to assume that the consumer's intertemporal elasticity of substitution is decisive for how a tax increase is shared between producers and consumers. In our case, the elasticity is given in equation (12), depending on the parameter β. We therefore want to examine how the ratio $d\pi_0/dv$ changes when β increases. The prior belief could naturally be that an increase in β, which for given x decreases the elasticity, makes the producers better off, i.e. lowering their tax burden. However, as will be shown below, the impact is in general ambiguous. The following three expressions are derived in the appendix:

(17)
$$\frac{d\pi_0}{d\beta} = \frac{r\pi_0}{D}\left(\frac{T}{\beta} - A\right)$$

(18)
$$\frac{dT}{d\beta} = \frac{1}{r}\left(\frac{1}{\beta - c - v} - \frac{1}{\pi_0}\frac{d\pi_0}{d\beta}\right) = \frac{1}{r}\left(\frac{1}{\beta - c - v} - \frac{r}{D}\left(\frac{T}{\beta} - A\right)\right)$$

(19)
$$\frac{d\left(\dfrac{d\pi_0}{dv}\right)}{d\beta} = -K\left(r\left(\frac{T}{\beta} - A\right)\left[rT\left(1 + \frac{1}{D}\frac{\pi_0}{c + v + \pi_0}\right) - D - 1\right] - \frac{rT}{\beta} + \frac{D}{\beta - c - v} \right)$$

where K>0. Even though an increase in β may be thought to make the producers better off, i.e. increasing their rents, the sign of equation (17) is ambiguous. Moreover, simulations affirm that for large values of β and A, the expression is in fact negative. The sign of equation (18) seems to be ambiguous, too, even though one intuitively would think that an increase in β, or a decrease in the elasticity, would imply a longer extraction time. Again, simulations show that for low values of β, the opposite is true. Finally, the sign of expression (19) seems not at all clear, and from the simulations we obtain that both signs are feasible. However, the absolute value is relatively small in most cases, and so the tax burden is not very affected by moderate changes in the parameter β. We will return to the simulation results in the next section.

Since our findings show that the parameter β neither has clear nor considerable impact on the tax burden, we will briefly try to explain the somewhat counterintuitive results for some parameter values. First, note from the marginal utility function that an increase in β inevitably leads to lower demand at low prices, when x is big, and higher demand at high prices, when x is small. In our exhaustible resource case, since x_t is decreasing over time, this implies lower demand in the first period and higher demand in the last period.[10] Thus, the effect on overall demand of an increase in β depends crucially on the initial resource amount A and the ratio between β and (c+v). For instance, if there are ample resources and β is large compared to (c+v), a higher β means lower demand in a major starting period. This helps to explain why the simulations show that for sufficiently high values of A and β, the resource rent may <u>fall</u> if β is increased.

On the other hand, if β is close to (c+v), a higher β means higher demand at each point of time. Then the resource rent presumably increases quite strongly, and we see from (13b) that if the increase in π_0 is so large that the ratio between π_0 and (β-c-v) becomes higher, the upward shift in β leads to a shorter extraction time T. Thus, in this case there will be <u>less</u> uniform consumption than before, even though the consumers' intertemporal elasticity is lower. Moreover, when the resource rent increases that much, it seems natural that the producers must bear a larger share of a tax increase than before, so that the sign of (19) may be negative. This means that the producers' ability to throw the tax burden on the consumers decline, even if the consumers' demand becomes less elastic. As mentioned above, the simulations confirm these hypotheses, indicating that if β is sufficiently low, an increase in β may in fact decrease the extraction time and increase the producers' tax burden.

From (13) we see that we can choose e.g. c or v as numeraire, and obtain the same solution by simultaneously multiplying c, v, π_0 and β and dividing A with the same factor k. The expression in (14) is independent of the scale. Hence, the impact on $d\pi_0/dv$ of an increase in c or v may be found by simultaneously dividing β and multiplying A with the factor k>1. We have found above that increasing A implies that the tax burden on the producers decreases, whereas decreasing β has somewhat ambiguous impacts. However, in most interesting cases we found that a lower β implies an upward, though small, change in the producers' tax burden. Thus, the total effect seems unsettled. Nevertheless, the simulations indicate quite clearly that the first effect is dominating, meaning that the higher the cost and the initial tax is, the less of a tax increase will be born by the

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[10] By differentiating u'(x) with respect to β, and equalising to zero, we find that the first period lasts as long as $x>1/\beta$ and hence $p<\beta/e$. For some parameter values $x<1/\beta$ initially, and hence there is no first period. That is, a larger β means larger demand at each point of time.

producers. If so, we may conclude that the resource rent π_0 is a declining and convex function of the cost and tax, (c+v). This should seem intuitive.

The final parameter in the optimisation problem is the discount rate r. In this Hotelling-style model, a higher discount rate clearly leads to a lower resource rent π_0 and shorter extraction time T. Moreover, as is shown in the appendix, differentiating (14) with respect to r gives the following expression:

$$(20) \qquad \frac{d\left(\frac{d\pi_0}{dv}\right)}{dr} = - \frac{(rT - D - 1)D + \frac{\pi_0}{c + v + \pi_0} rT}{(c + v)D^2} \cdot \frac{d\pi_0}{dr}$$

Except for the last factor, which is negative, this expression is identical with the one in (15). Thus, we may conclude that the sign of (20) must be positive. This means that an increase in the discount rate implies that a tax increase will be born more by the consumers and less by the producers than before. However, remember that a higher discount rate at first lowers the initial resource rent and consumer price.

In this section we have found some theoretical results regarding the way a tax increase is shared between producers and consumers in an ideal fossil fuel market. As mentioned in the beginning of this section, our main focus will be on the oil market, and this is where we now turn our attention. By running simulations on our model, where we try to calibrate it to the oil market, we obtain numerical estimates of the impact of possible carbon taxes on the resource wealth of different oil producers. We will also shortly discuss possible effects on the Norwegian natural gas rents. Our aim is to learn something about the size of the effects, not the precise numbers.

3. Wealth reductions in the oil market

Before we go on to the simulations, we have to shortly discuss the current supply and demand conditions in the oil market. We are looking for parameters that yield results *reasonably* consistent with the oil market situation today.

3.1 Features of the current oil market

According to PIW (1994), the average cost of finding and developing oil has been halved since the early 1980s to around \$5 per barrel. With current oil prices around \$15 per barrel, the resource rent π_0 for new fields should accordingly be twice the unit cost c. However, the extraction costs differ enormously. On the one hand, according to a Norwegian parliament report (Ministry of Industry and Energy 1993-94), average unit costs for Norwegian oil fields seem to be in the range 80-90 1994-Nkr, or around \$12 per barrel. On the other hand, extraction costs in Saudi-Arabia and other areas of the Middle East are extremely low. According to Fesharaki (1994), OPEC can increase their supply by 6-7 million barrels per day (25% of today's supply) at the cost range $2-3 per barrel. Hence, while the North Sea producers obtain quite small resource rents at current prices, low-cost producers receive rents more than fourth-fold their costs.

Turning to demand, we are concerned with the price elasticity of oil, which in our model is equivalent to the negative of the intertemporal elasticity of substitution. Pindyck (1979) has made a comprehensive study of long-run elasticities of energy demand in OECD-countries, and he found total own-price elasticities of oil averaging -1.16 in the residential sector, and -0.77 in the industrial sector (the latter ranging from -0.06 to -1.17). Dahl and Erdogan (1994) present an updated survey of studies of energy elasticities, concluding that different studies obtain quite different results. They state that recent studies tend to obtain lower elasticities than earlier ones. Moreover, the elasticities seem to be larger for secondary (and delivered) energy like oil products than for primary energy like crude oil. For oil demand long-run price elasticities seem to roughly be in the range between -0.5 and -1.

If a climate agreement imposing a global carbon tax is agreed upon, it is difficult to know how large such a tax eventually will be, and how it will evolve over time.[11] However, both the US Administration and the EU have made proposals of specific carbon/energy taxes, although for the time being they have not been imposed. For our purpose, they give a rough estimate of possible sizes of a global tax. The US proposal, which was opposed by the Congress, suggested a tax of about $3.2 per barrel of oil.[12] The EU proposal suggested originally that a combined carbon/energy tax should increase from $3 per barrel of oil in 1993 to $10 in the year 2000. The proposal remains to be imposed. From another point of view, a comparison of several global carbon/energy models is referred in Dean and Hoeller (1992). Focusing on the average of the four dynamic, long-term models that are studied, achieving the medium reduction scenario require carbon taxes in the OECD area rising from about $15 per barrel of oil in the year 2000 to about $25 in 2010.[13] Thus, when studying potential effects on the oil market, we may consider a large range of tax rates.

When implementing these figures into our model, one has to be aware of that some oil *products* are taxed quite considerably in most countries. For instance, motor gasoline taxes cover around one third of the final price in the US, and around two third in Europe (see IEA 1994). Other products are less taxed or not taxed at all. Furthermore, refining crude oil to oil products is not costless, and unit refinery costs seem to be in the range $1-3 per barrel (see Saint-Antonin *et al.* 1994). Thus, it may be relevant to ask whether the crude or the oil product market is the most appropriate to

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[11] The assumption of a constant carbon tax over time is surely a simplification, as mentioned in the introduction.

[12] The tax was actually intended to be based on the BTU content of various energy sources, and was thus an energy tax rather than a carbon tax.

[13] The referred scenario consists of a reduction (from the BaU path) in the rate of growth of carbon emissions by 2 percentage points per annum in each region, and would require absolute cuts in emissions in the OECD and the former Soviet Union, while allowing some continued, albeit very low growth elsewhere (Dean and Hoeller 1992).

implement in our model. In the latter case it is reasonable to consider the unit tax v to be larger than zero initially, although it may be a pure financial tax and may differ very much between products and countries. Moreover, as mentioned above, the size of the elasticity may also depend on which market we simulate. Instead of ruling out one of the markets, we choose to simulate both, and then compare the results.

According to BP (1994), world reserves of oil resources exploitable with today's technology and prices were 137 billion toe at the entrance of 1994. This amounts to 43 times the total extraction in 1993. OPEC countries cover 77% of these reserves, while Norwegian reserves cover around 1% and amount to only 11 times her production in 1993. Following note 6, we are only able to interpret either price variables or volume variables. The first ones seem most appropriate, and so the reserve-over-production ratio is more relevant for the simulations than the number of barrels left in the ground.

The Norwegian petroleum wealth consists of both oil and gas reserves, and according to Ministry of Industry and Energy (1993-94), its total value is estimated to 600 bill. 1994-Nkr. It is not clear how this number is split between the two types of petroleum wealth. Hence, to obtain a rough estimate of the monetary loss of a given oil price reduction, we will make the simple assumption that the resource rent of Norwegian natural gas is equal to the Norwegian oil rent, both before and after a carbon tax is imposed. Since Norwegian oil and gas are often developed from the same fields, production costs are often equalised between the two fuels. Moreover, natural gas prices are often set equal to the prices of competing fuels, which in Western Europe are mostly oil products (Vrieling *et al.* 1989). However, since natural gas contains less carbon per energy unit than oil, one may presume that the producer prices of natural gas would not fall as much as the producer prices of oil. Still, ECON (1990) finds in their model that a carbon tax may reduce natural gas demand even more than oil demand, and Moum (1992) follows up by arguing for its assumption of equal producer prices of oil and natural gas in its carbon tax scenario.

3.2 Simulation results

The equation system (13) derived in the last section has been simulated for different values of the parameters. We normalise the sum of unit cost and unit tax to $(c+v)=5$.[14] Moreover, our main choice for the discount rate r is 0.07, as this is the normal rate of return used in e.g. Norwegian government projects. However, we also make use of a lower discount rate for sensitivity analyses.

Two exogenous variables then remain to be specified. That is the amount of the reserves, A, of which size cannot be interpreted in a meaningful way, and the utility parameter β, which also indicates the maximum price. Here we have tried different values of A and β, searching for results of the endogenous variables that are reasonably consistent with the description of the oil market

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[14] This should make the transformation from the crude market easy.

given above.[15] These variables are the resource rent π_0, the extraction time T, and the elasticity at time zero, σ.[16] Then the producers' share of a tax increase may be calculated using (14).

Table 1 ; Simulated values of endogenous variables; c+v=5 ; r=0.07

β	Reserves, A	0.2	0.4	0.8	2
15	π_0	4.40	3.03	1.75	0.45
	T	12	17	25	44
	σ	2.14	1.60	1.25	0.99
	$d\pi_0/dv$	-0.67	-0.55	-0.41	-0.19
25	π_0	7.68	5.03	2.68	0.60
	T	14	20	29	50
	σ	1.47	1.09	0.85	0.67
	$d\pi_0/dv$	-0.63	-0.51	-0.38	-0.16
50	π_0	12.88	7.33	3.15	0.45
	T	18	26	38	66
	σ	0.97	0.71	0.55	0.45
	$d\pi_0/dv$	-0.56	-0.43	-0.29	-0.10
100	π_0	16.88	7.93	2.48	..
	T	25	36	52	
	σ	0.66	0.49	0.39	
	$d\pi_0/dv$	-0.46	-0.34	-0.20	

Table 1 displays a selection of the results for different parameter choices. First, it is useful to compare these figures with the findings from the last section. One of the main theoretical results obtained was that the absolute value of $d\pi_0/dv$ increases when the resource amount A decreases (equation 15). This is confirmed by the simulations, and table 1 also shows that the increase is quite considerable. Hence, the tax share between producers and consumers depends indeed on how much resources are left. The inequality (16) stated that the producers' share of the tax burden would always be larger than their share π_0 of the surplus Δ, defined as (β-c-v). This is also confirmed in

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[15] Alternatively, we could have specified β as the expected price of a carbon-free backstop technology. This is done in e.g. Manne and Richels (1991), where the price amounts to about $110 per barrel of oil (1988-$), which in fact is close to one of our alternatives, see note 17.

[16] We have chosen to calculate and apply the elasticity at time zero, which in this model will be the smallest along the solution path. The reason is obviously that present studies, which we have referred to, estimate parameter values of today, and not of the future.

table 1, and we observe that the inequality is fulfilled by a wide margin. Moreover, the effect of a change in β was found to be generally ambiguous. In table 1, however, which covers the most relevant results in our case, an increase in β implies a decrease in the absolute value of $d\pi_0/dv$, as expected originally: Decreasing the elasticity decreases the tax burden on the producers. However, as mentioned in the last section, the change is relatively modest. Finally, in the second column from the right we note the somewhat surprising result that decreasing the elasticity through an increase in β from 50 to 100 <u>reduces</u> the resource rent π_0 (see the previous section for an explanation).

What the most reasonable figures for our purpose are (with price variables measured in \$/barrel of oil), depends on whether the crude oil market or the oil product market is the most topical. First, considering the crude market, it is reasonable to let v=0. Moreover, we found that the average resource rent π_0 is around 10. Assuming the initial elasticity to lie between 0.5 and 1, the bottom left corner of table 1 seems the most appropriate. Searching for combinations of β and A that satisfy $\pi_0=10$ and $\sigma \in (0.5,1)$, we obtain that $|d\pi_0/dv|$, i.e. the first order decrease in the resource rent following a unit tax increase, lies somewhere between 0.36 ($\sigma=0.5$) and 0.56 ($\sigma=1$).[17] Initially, both the consumers and the producers seem to bear a considerable share of the tax burden, with perhaps the consumers suffering most. Note that when the elasticity is relatively low, the impact on the producers is less than otherwise, as expected. By running new simulations with different sizes of the unit tax, keeping the other parameters constant, we obtain new values of the resource rent π_0. Then we may calculate the impact on the global (average) resource wealth of carbon taxes discussed above (see equation 8). Assuming the cost estimate for Norway referred earlier, i.e. $c^N=12$ and hence $\pi^N_0=3$, and using an updated version of the Norwegian petroleum production profile used in Aslaksen *et al.* (1990),[18] we may also calculate the impact of these carbon taxes on the Norwegian resource wealth (see equation 10). Table 2a shows the results for the interval of $d\pi_0/dv$ discussed above. Given the percentage reduction of the Norwegian resource wealth, and the estimated value of the Norwegian petroleum wealth referred above, we are able to indicate the size of the corresponding yearly income loss, too.[19] Assuming 7% rate of return per year, table 2a shows the yearly loss in permanent income in bill. Nkr and as a percentage of GDP in 1993.[20]

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[17] The values of β that yield the resulting figures, are $\beta=111$ for $\sigma=0.5$ and $\beta=41$ for $\sigma=1$.

[18] This profile covers both oil and gas production. If we are only interested in the impact on the Norwegian <u>oil</u> wealth, we should be aware that the production profile of oil is nearer in time than that of gas. Hence, equation (10) shows that the wealth reductions will be somewhat understated.

[19] The referred value of the petroleum wealth is estimated based on other assumptions than those in this study. Hence, the calculations of the yearly income loss must only be taken as rough indications.

[20] In 1993 the Norwegian GDP was 734 billion 1993-Nkr (Statistics Norway 1994).

Table 2a ; Possible impacts on the resource wealth at different tax rates;
The crude market.*

		low tax (dv=3)[1]	medium tax (dv=10)[2]	high tax (dv=20)[3]
Global resource wealth	percentage reduction	11-16%	33-50%	58-85%
Norwegian resource wealth	percentage reduction	15-28%	47-87%	83-149%
	yearly loss ; bill. Nkr (% of GDP 1993)	6-12 (0.9-1.6%)	20-36 (2.7-5.0%)	35-62 (4.7-6.5%)

Table 2b ; Possible impacts on the resource wealth at different tax rates;
The oil products market.**

		low tax (dv=3)[1]	medium tax (dv=10)[2]	high tax (dv=20)[3]
Global resource wealth	percentage reduction	9-13%	27-42%	48-74%
Norwegian resource wealth	percentage reduction	12-22%	37-68%	67-121%
	yearly loss ; bill. Nkr (% of GDP 1993)	5-9 (0.7-1.2%)	16-28 (2.1-3.9%)	28-51 (3.8-6.9%)

* Assumtions: $\pi_0=10$, $\pi_0^N=3$, $c=5$, $c^N=12$, $v=0$, $r=0.07$

** Assumtions: $\pi_0=10$, $\pi_0^N=3$, $c=7.5$, $c^N=14.5$, $v=5$, $r=0.07$ (to compare with table 1, divide by 2.5)

[1] Corresponds to the US and the initial EU proposal

[2] Corresponds to the EU proposal for the year 2000

[3] Corresponds to the average tax between the year 2000 and 2010 in Dean and Hoeller (1992); 2 percent scenario

Before discussing the results for the crude oil market, let us consider the case of the oil product market. As mentioned earlier, the end-user markets may be equally appropriate for our purpose as the crude market, especially because most taxes are imposed in this market at present. In this case we have to take the already existing taxes into consideration. Since these taxes vary to a large degree for different products and countries, we concentrate on a chosen average value. Observing that the taxes range from zero to two-third of the end-user prices (IEA 1994), we choose a tax level of \$5 per barrel of crude. Furthermore, a refinery cost of \$2.5 per barrel is also assumed. The other parameters are as before. Transforming table 1 to these figures, we find the most reasonable values of π_0, T and σ in the middle of the table. Going through the same procedure as above for a global resource rent of \$10 per barrel and $\sigma \in (0.5,1)$, we obtain that $|d\pi_0/dv|$ should lie between 0.29 and

0.47, with the lowest impact still corresponding to the lowest elasticity, σ=0.5.[21] Thus, initially the consumers seem to bear a somewhat larger share of the tax burden than the producers, particularly if their elasticity is relatively small. The impacts on the resource wealth, as well as the yearly Norwegian income loss, are once again found for the new interval of $|d\pi_0/dv|$. The results are displayed in table 2b.

Comparing this table with table 2a, we find that the reductions in the resource wealth are about 20% lower in this case than in the crude market case. This applies to all entries in the two tables. The reason for this conclusion is formally difficult to explain, since the parameter choices are quite different in the two cases. Intuitively, however, the reason is that in the product case the initial cost plus tax is larger than in the crude case, while the resource rent is the same. Then for a given elasticity, there are more room available for consumer price increases in the former case than in the latter. Hence, the resource rent may be less reduced. Equal wealth reductions in the two cases are only attained when the elasticity is lower in the crude than in the product market case.

As mentioned earlier, Dahl and Erdogan (1994) state that elasticities tend to increase when moving from primary to secondary to delivered energy. Thus, it is reasonable to assume that the actual elasticity in the crude market case should be lower than in the product market case. This is consistent with the different results obtained for equal elasticities in the two cases, as commented on above. Therefore, we choose to rely on the results from <u>both</u> cases, assuming they are consistent. Furthermore, we assume the elasticity in the crude market to be larger than 0.5, but less than the elasticity in the product market, which in turn is assumed to be less than 1. Thus, we now construct a new interval for each entry of table 2a (or b), so that the new interval is covered by both corresponding intervals in table 2a and 2b. This means that the derived value of $|d\pi_0/dv|$ is between 0.36 and 0.47.[22] The results are shown in table 3.

We are now in place to discuss the results. The first column tells us that even a relatively small carbon tax of about \$3 per barrel of oil, as proposed by the US Administration and the EU, could imply a 11-13% reduction of the global resource wealth. In this case, the model predicts that the consumer price initially increases by \$1.7-1.9 per barrel of oil. Imposing globally the proposed EU tax for the year 2000, i.e. \$10 per barrel, could reduce the resource wealth of the average oil producer by between 33 and 42 percent. This means that the end-user price initially may rise by \$5.8-6.7 per barrel of oil. This case is shown in figure 3a. Somewhere in the next century it is in no way unlikely that an even higher carbon tax, e.g. like the one in the last column, could be imposed. Then table 3 indicates that in the present market situation the tax could lead to a loss of 58-74% of the global resource wealth. The consumer price could then increase by \$12.6-14.2 per barrel of oil in the first period.

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[21] The values of β that yield the resulting figures, are β=166 for σ=0.5 and β=61 for σ=1.

[22] Following note 4, we then find that 10-15 years after a marginal tax increase the consumer price is unchanged compared to the reference path, and the whole tax increase is born by the producers.

Table 3 ; Possible impacts on the resource wealth at different tax rates; Combinating the crude and the oil products market.*

		low tax (dv=3)[1]	medium tax (dv=10)[2]	high tax (dv=20)[3]
Global resource wealth	percentage reduction	11-13%	33-42%	58-74%
Norwegian resource wealth	percentage reduction	15-22%	47-68%	83-121%
	yearly loss ; bill. Nkr (% of GDP 1993)	6-9 (0.9-1.2%)	20-28 (2.7-3.9%)	35-51 (4.7-6.9%)

* Assumption: r=0.07

[1] Corresponds to the US and the initial EU proposal

[2] Corresponds to the EU proposal for the year 2000

[3] Corresponds to the average tax between the year 2000 and 2010 in Dean and Hoeller (1992); 2 percent scenario

For the Norwegian resource wealth, the impacts are even larger. The low tax scenario could reduce the wealth by 15-22%, with the initial resource rent being reduced by 37-43%. This indicates a permanent income loss of 6-9 billion Nkr per year (about \$1 billion), or about 1% of the current GDP. Moreover, a \$10 per barrel tax could remove between 47 and 68 percent of the wealth (see figure 3b). Actually, in the initial periods, the Norwegian resource rent may in this case become negative. However, as time goes by, the price will increase sufficiently so as to ensure a still positive, though considerably reduced, resource wealth. In this scenario, the yearly income loss could be around 3% of GDP. Finally, if a relatively high carbon tax is imposed, e.g. \$20 per barrel of oil, the resource wealth could more or less vanish. In the worst case, the simulations indicate that the Norwegian resource wealth could actually become negative. This may happen if the outcome is not anticipated, because investment expenditures are usually sunk costs, and will not be covered if production is halted because of an unexpected carbon tax imposition. Moreover, oil project investments are generally both huge and have very long time horizons, and so large amounts of invested capital may become more or less of no value if an extreme event should happen. The estimated value of the petroleum wealth referred earlier, corresponds to a yearly permanent income of about 6% of the current GDP, and hence this tax scenario may lead to a yearly income loss in this order of magnitude.

So far, we may conclude that if these simulations and parameter choices are relevant for the current oil market, the impacts on the oil producers of a global climate agreement implementing a global carbon tax, might be quite dramatic, particularly for high-cost producers such as Norway. As a comparison, Moum (1992) found that an international carbon tax increasing from about \$10 per barrel of oil in the year 2000 to about \$20 in 2025, would decrease the Norwegian disposable

Figure 3a. Possible impacts on global resource rents of a $10/barrel carbon tax

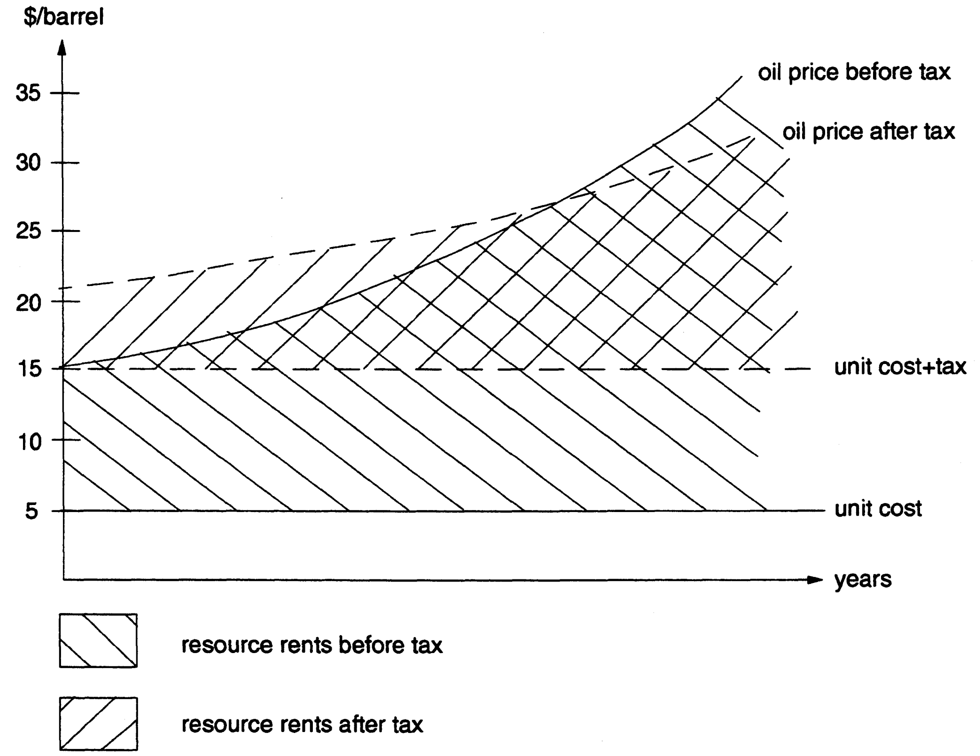
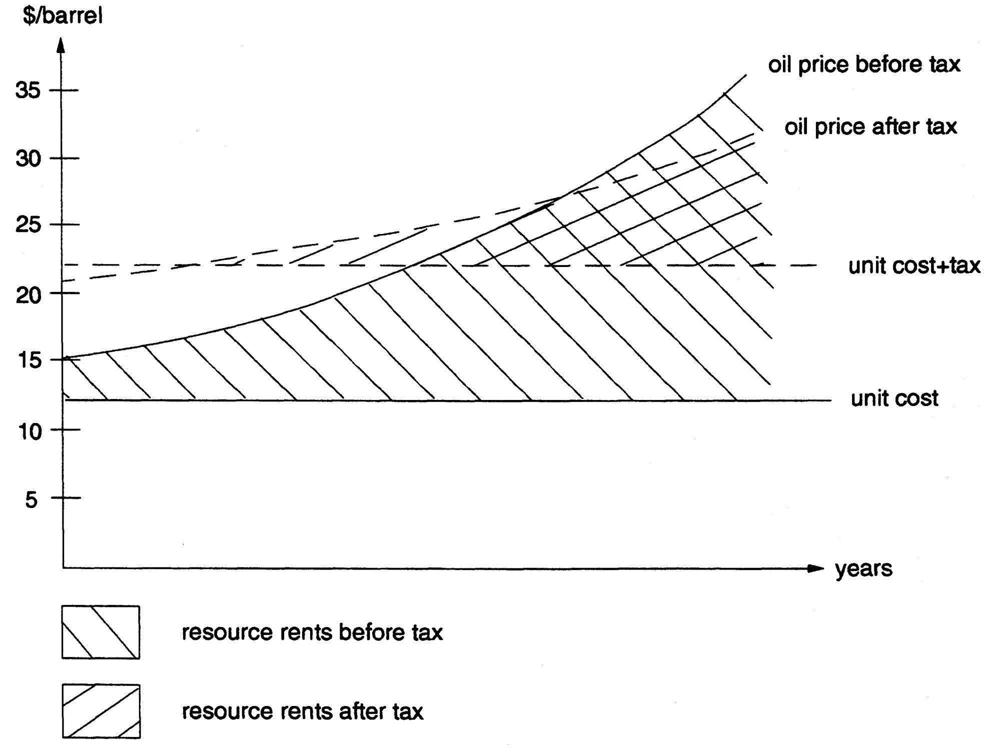


Figure 3b. Possible impacts on Norwegian resource rents of a $10/barrel carbon tax



income in 2025 by 6.3% compared to the reference scenario. (The study is only concerned with yearly variables, and not with stock variables like the petroleum wealth.) As the GDP would only be reduced by 3.2%, the largest impact would come through the terms of trade change. However, as mentioned in the introduction, the price changes in the petroleum markets are set exogenously. The carbon tax is assumed to reduce the producer prices by 20% in the year 2000 and by 12% in the year 2025. In our medium tax scenario the producer prices fall by 22-28% in the first year, and by 30-39% in the 25th year. However, since the price rises more steeply in our model, the impact on the resource rents may not be very different from that in Moum.

Finally, to study the impact of different discount rates, we have examined the case of $r=0.05$.[23] The last section showed that compared to a discount rate of $r=0.07$, this lower rate would make the tax burden on the producers larger. Table 4 shows the values of $d\pi_0/dv$ for these two discount rates at different parameter values. Decreasing the rate from $r=0.07$ to $r=0.05$ seems to imply that the producers will have to pay another 5-7% of a tax increase. However, the table also states that at the same time the resource rent is increased by a large number. If on the other hand a discount rate of e.g. $r=0.10$ is applied,[24] the consumers will have to bear a larger part, i.e. another 6-8%, of a tax increase compared to $r=0.07$. Hence, the discount rate applied in the oil market is important for the outcome of a carbon tax.

Table 4 ; Simulated values of $d\pi_0/dv$ (and π_0) for different discount rates

β	Reserves, A	0.2	0.4	0.8
15	$r=0.05$	-0.71 (5.03)	-0.61 (3.70)	-0.49 (2.36)
	$r=0.07$	-0.67 (4.40)	-0.55 (3.03)	-0.41 (1.75)
25	$r=0.05$	-0.68 (8.96)	-0.57 (6.31)	-0.45 (3.80)
	$r=0.07$	-0.63 (7.68)	-0.51 (5.03)	-0.38 (2.68)
50	$r=0.05$	-0.61 (15.71)	-0.50 (9.84)	-0.36 (4.98)
	$r=0.07$	-0.56 (12.88)	-0.43 (7.33)	-0.29 (3.15)
100	$r=0.05$	-0.52 (22.23)	-0.40 (11.88)	-0.27 (4.65)
	$r=0.07$	-0.46 (16.88)	-0.34 (7.93)	-0.20 (2.48)

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[23] A low discount rate may be defended by the concern for future generations. For a discussion of what is the correct discount rate, see Lind (1982).

[24] If the oil producers are uncertain about the future demand, e.g. because of development of cheaper substitutes, they may choose a higher discount rate than otherwise.

As commented on in the beginning of section 2, the model we have used is relatively simple. Thus, before hastening to our conclusions, we have to ask whether the results are reliable. First, there are several objections against the competitive behaviour described in (1). Uncertainty about the future market conditions seems to be an important decision factor for most oil producers. There may be developed a cheap, renewable substitute before the oil reserves are extracted, and hence the producers may want to accelerate their own extraction in stead of waiting for large, but risky, resource rents in the future (see also note 24).

Further, the oil market consists of some large producers, and especially OPEC has power enough to affect the oil market considerably. There is widespread belief that OPEC will not stay passive if a carbon tax is imposed in e.g. the OECD-area. If they choose to restrict their supply so as to avoid price reductions, the impact on other producers will improve considerably. However, the OPEC-countries have also shown desire to retain their market shares, and hence a major supply reduction may not be feasible, although OPEC's market share is expected to grow the next decades. A theoretical study of the effect of taxing nonrenewable resources in the case of monopoly power, is given by Tahvonen (1994).

A carbon tax will affect both the total demand of fossil fuels, as well as the division between the different fuels. Thus, a more detailed model would have to take into account the substitutability between oil and gas etc. In this study we have applied own-price elasticities for oil, which means that price increases in the other fossil fuel markets have been disregarded. This have probably overstated somewhat the demand reductions, and hence the wealth reductions. Moreover, in the Norwegian case, we assumed that the impact on the natural gas prices would be similar to that on the oil prices, even though gas is the cleanest of the fossil fuels and accordingly will get a lower tax per energy content. Hence, this assumption may be too pessimistic, although it is based on an earlier study (ECON 1990). A survey of empirical models given in Ingham *et al.* (1993) suggests that inter-fuel substitution between fossil fuels may cause the producer price of natural gas to rise if a carbon tax is introduced. Even the producer price of oil may not decline in some cases. As the proposals from the EU and the US indicate, however, an energy tax may be equally realistic as a carbon tax.

Finally, the model assumes fixed costs, taxes and reserves, and a constant demand over time. These are obvious simplifications. Farzin (1992) has shown that introducing cost functions that depend on extraction rate, cumulative extraction and technological change, into an Hotelling-type model may lead to more empirically sound resource rent paths. The question here is how much our model choice affects the results. It is difficult to say in which direction this leads us, and so we leave the question open.

To sum up, several objections could be raised against our model specifications. Nevertheless, the aim of this study is to arrive at some rough results about the impact of a carbon tax on the petroleum wealth, and our belief is that as a first guess the results have their value. However, the objections seem to suggest that the wealth reductions may be less severe than our results have indicated.

4. Conclusions

The study presented in this paper indicates that a global carbon tax of some size will severely reduce the Norwegian petroleum wealth, and to a lesser extent the petroleum wealth of the average oil producer. With possible taxes ranging from $3 to $20 per barrel of crude oil, the Norwegian petroleum wealth could be reduced by about 20% at the low tax and about 100% at the high tax. In the latter case, the wealth could in fact become negative. These reductions may amount to a yearly loss in permanent income of between 1 and 7 percent of the current Norwegian GDP. The average oil producer could lose about 12% of its petroleum wealth at the low tax and around two-third of the wealth at the high tax. These figures are rough estimates, and as mentioned at the end of the previous section, critical objections indicate that the reductions may be somewhat overstated, particularly in the Norwegian case.

These results were obtained after the simulations indicated that a marginal carbon tax increase would reduce the producer price, or the resource rent, by between one-third and one-half of the tax increase, whereas the consumer price would take the rest. Hence, even if the supply is assumed to be totally inelastic in the long run, it seems that initially the consumers must take the largest share of the tax burden. In the final periods, however, the producers' share becomes larger than one.

Following the earlier discussion, a further step could be to construct a more robust model, e.g. by studying the substitutability between the different fossil fuels. Another interesting project would be to study the impact of a carbon tax on other large oil producers. Finally, instead of carbon taxes, a climate treaty may eventually end up with introducing tradable CO_2 permits. This will probably affect the fossil fuels markets in a different way (see e.g. Berger *et al.* 1992).

Norway appears to be one of the countries most eagerly arguing for global carbon taxes. This may seem a bit strange, looking at the results obtained in this study. However, Norway is well equipped with hydro power, too, which may become more valuable if CO_2 emissions get restricted. Moreover, a more detailed study incorporating the substitutability between fossil fuels may perhaps reveal a more optimistic result for the Norwegian petroleum wealth, since it consists mostly of natural gas. Finally, the environmental concern is relatively deep in Norway, and so far this appears to have got the heaviest weight.

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Appendix

a) We first want to examine what happens when the tax is increased marginally, i.e. dv>0. By differentiating (7a) and (5) (the latter being equivalent to 7b), we obtain:

$$\text{(A1)}\quad \int_0^T F(c+v+\pi_0 e^{rt})(dv+e^{rt}d\pi_0)dt + F(c+v+\pi_0 e^{rT})dT = 0 \Leftrightarrow \int_0^T \frac{1}{u''(x_t)}(dv+e^{rt}d\pi_0)dt = 0$$

$$\text{(A2)}\qquad 0 = dv + e^{rT}d\pi_0 + r\pi_0 e^{rT}dT$$

First, we show that $\underline{d\pi_0 \leq 0}$. Assume the contrary, ie. $d\pi_0 \geq 0$. Then, since u''(x)<0 for all x, the expression in the integral in (A1) is negative for all t, which is impossible. Thus, $d\pi_0<0$, and then (8) shows that $d\Pi<0$. Second, we show that $\underline{|d\pi_0|<dv}$. Again, assume the contrary, ie. $|d\pi_0| \geq dv$. Then the parenthesis in (A1) is negative for all t>0 and zero at t=0. This is not feasible either, and so $|d\pi_0|<dv$. Furthermore, we show that $\underline{dT>0}$. Assume that $dT \leq 0$. Then (A2) states that $(dv+e^{rT}d\pi_0) \geq 0$. This implies that for t<T, we have $(dv+e^{rt}d\pi_0)>0$ (since $d\pi_0<0$). However, this contradicts with (A1), and thus dT>0. Finally, we see that t', i.e. the time when the two consumer price paths cross, is obtained when the parenthesis in (A1) is equal to zero. Hence, $t'=(\ln|dv/d\pi_0|)/r$. Moreover, since dT>0, we see from (A2) that T<t'.

b) Next, we are interested in how π_0 changes when the tax increases, and so we differentiate (13a) with respect to v ($1/\beta$ has been moved to the right hand side):

$$\ln\left(\frac{\beta}{c+v+\pi_0 e^{rT}}\right)\frac{dT}{dv} + \int_0^T \frac{(c+v+\pi_0 e^{rt})}{\beta}\,\frac{-\beta\left(1+e^{rt}\frac{d\pi_0}{dv}\right)}{(c+v+\pi_0 e^{rt})^2}dt = 0$$

The first term is equal to zero ($c+v+\pi_0 e^{rT}=p(T)=\beta$), and then we obtain:

(A3)
$$\frac{d\pi_0}{dv} = - \frac{\displaystyle\int_0^T \frac{1}{c+v+\pi_0 e^{rt}}dt}{\displaystyle\int_0^T \frac{e^{rt}}{c+v+\pi_0 e^{rt}}dt}$$

The integrals in (A3) can be solved to give the following expression for $d\pi_0/dv$:

(A4)
$$\frac{d\pi_0}{dv} = - \frac{\dfrac{1}{r(c+v)}(rT-\ln\beta+\ln(c+v+\pi_0))}{\dfrac{1}{r\pi_0}(\ln\beta-\ln(c+v+\pi_0))} = - \frac{\pi_0(rT-D)}{(c+v)D}$$

where $D=\ln\beta-\ln(c+v+\pi_0)=\beta x_0>0$.

c) Now let $d\pi_0^*/dv=g(\pi_0^*)$ as defined in section 2. Moreover, consider T^* as a function of π_0^*. First, from (13b) and the expression $D=\ln\beta-\ln(c+v+\pi_0^*)$ we find that:

(A5)
$$\frac{dT^*}{d\pi_0^*} = \frac{1}{r}\,\frac{\pi_0^*}{\beta-c-v}\,\frac{-(\beta-c-v)}{(\pi_0^*)^2} = -\frac{1}{r\pi_0^*}$$

(A6)
$$\frac{dD}{d\pi_0^*} = -\frac{1}{c+v+\pi_0^*}$$

Next, differentiating g() with respect to π_0^* using (A4), (A5) and (A6) gives:

$$g'(\pi_0^*) = -\frac{\left[1(rT^* - D) + \pi_0^*\left(-\frac{1}{\pi_0^*} + \frac{1}{c+v+\pi_0^*}\right)\right](c+v)D - \pi_0^*(rT^* - D)(c+v)\,\frac{-1}{c+v+\pi_0^*}}{(c+v)^2D^2}$$

which can be reduced to:

(A7)
$$g'(\pi_0^*) = -\frac{(rT^* - D - 1)D + \frac{\pi_0^*}{c+v+\pi_0^*}rT^*}{(c+v)D^2}$$

d) We now want to examine the effects of a shift in β. First, we study the effect on π_0, and differentiate (13a) with respect to β:

$$\frac{1}{\beta}\ln\frac{\beta}{c+v+\pi_0 e^{rT}}\frac{dT}{d\beta} + \int_0^T\left(-\frac{1}{\beta^2}\ln\frac{\beta}{c+v+\pi_0 e^{rt}} + \frac{1}{\beta}\frac{c+v+\pi_0 e^{rt}}{\beta}\frac{(c+v+\pi_0 e^{rt}) - \beta e^{rt}\frac{d\pi_0}{d\beta}}{(c+v+\pi_0 e^{rt})^2}\right)dt = 0$$

The first term is zero. Further, the first term in the integral can be replaced by using (13a). Then we obtain:

$$-\beta A + \int_0^T 1dt - \int_0^T \frac{\beta e^{rt}}{c+v+\pi_0 e^{rt}}\frac{d\pi_0}{d\beta}dt = 0$$

which gives the following expression, using the derivations in (A4):

$$\text{(A8)} \qquad \frac{d\pi_0}{d\beta} = \frac{r\pi_0}{D}\left(\frac{T}{\beta} - A\right)$$

Now, the effect on T can be found by differentiating (13b) in the following way, using (A5) and (A8):

$$\text{(A9)} \quad \frac{dT}{d\beta} = \frac{\delta T}{\delta\beta} + \frac{\delta T}{\delta\pi_0}\frac{d\pi_0}{d\beta} = \frac{1}{r}\frac{\pi_0}{\beta - c - v}\frac{1}{\pi_0} - \frac{1}{r\pi_0}\frac{r\pi_0}{D}\left(\frac{T}{\beta} - A\right) = \frac{1}{r}\left(\frac{1}{\beta - c - v} - \frac{r}{D}\left(\frac{T}{\beta} - A\right)\right)$$

Finally, the effect on $d\pi_0/dv$ can be found by differentiating (A4) with respect to β, and using the results in (A8) and (A9). The derivation is straightforward, but rather tedious, and so we only show the final expression:

$$\text{(A10)} \qquad \frac{d\left(\frac{d\pi_0}{dv}\right)}{d\beta} = -K\left(r\left(\frac{T}{\beta} - A\right)\left[rT\left(1 + \frac{1}{D}\frac{\pi_0}{c + v + \pi_0}\right) - D - 1\right] - \frac{rT}{\beta} + \frac{D}{\beta - c - v}\right)$$

Here $K = \pi_0/[(c+v)D^2] > 0$.

e) The final effect we want to examine is how $d\pi_0/dv$ changes when r changes. Replacing rT with $(\ln(\beta - c - v) - \ln\pi_0)$ in (A4) (see 7a), we differentiate (A4) with respect to r:

$$\frac{d\left(\frac{d\pi_0}{dv}\right)}{dr} = -\frac{\left[\frac{d\pi_0}{dr}(rT - D) + \pi_0\left(-\frac{1}{\pi_0}\frac{d\pi_0}{dr} + \frac{1}{c + v + \pi_0}\frac{d\pi_0}{dr}\right)\right](c+v)D - \pi_0(rT - D)(c+v)\frac{-1}{c + v + \pi_0}\frac{d\pi}{dr}}{(c+v)^2D^2}$$

This can be simplified to obtain:

(A11)
$$\frac{d\left(\frac{d\pi_0}{dv}\right)}{dr} = -\frac{(rT - D - 1)D + \frac{\pi_0}{c + v + \pi_0}rT}{(c + v)D^2} \cdot \frac{d\pi_0}{dr}$$

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