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Profitability of different instruments in international climate policies

Abstract:
This article discusses how different climate policy instruments such as CO_2 taxes and renewable energy subsidies affect the profitability of fossil fuel production, given that a fixed global climate target shall be achieved in the long term. Within an intertemporal framework, the model analyses show that CO_2 taxes reduce the short-term profitability to a greater extent than technology subsidies, since the competition from CO_2-free energy sources does not become particularly noticeable until decades later. Due to e.g. discounting of future revenues, most fossil fuel producers therefore prefer subsidies to their competitors above CO_2 taxes. However, this conclusion does not apply to all producers. Oil producers outside OPEC lose the most on the subsidising of CO_2-free energy, while CO_2 taxes only slightly reduce their profits. This is connected to OPEC's role in the oil market, as the cartel chooses to reduce its extraction significantly in the tax scenario. The results seem to be consistent with observed behaviour of important players in the climate negotiations.

Keywords: Climate policy, Energy markets, Technological change

JEL classification: Q32, Q42, O30, Q25

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1. Introduction

Combustion of fossil fuels is the main driver of the climate change problem. Although there are already strong indications of human-induced climate change, significant effects may not be noticed for several years. Since it is accumulated emissions over several decades or centuries that affect the climate, it is a poor strategy to postpone policy measures until climatic changes become too problematic – initiatives must be implemented well in advance.

In the long term, it is clear that the world needs clean and affordable energy technologies in order to achieve major CO_2 emission reductions without excessive costs (and loud objections from the public), cf. e.g. IPCC (2000). Such technologies do not just appear, and a key part of the international climate policy should therefore be to encourage the introduction of new technologies. This opens up for two alternative sorts of climate policy strategies, both at the domestic level and globally.

One strategy is to introduce measures aimed directly at the emission sources, either by introducing CO_2 taxes or by establishing a quota market.[1] Internationally, this is now being realised via the Kyoto protocol and its flexible mechanisms, and at the national level via CO_2 taxes and/or quota markets. When the cost of using fossil fuels increases, it will become more profitable to invest in alternative energy sources.

The second strategy is to stimulate clean energy sources or technologies directly via support for research and development (R&D) and use of such technologies. These support initiatives can be justified, from a theoretical point of view, as a supplement to taxes when there are market imperfections (Johansen, 1965). For example, this may apply if parts of the reward of R&D efforts or learning effects fall to companies other than those that actually do the research or test new technologies. Such support initiatives have been used in a number of countries for many years. At an international level, there are no coordinated instruments aimed at clean energy technologies, other than in the EU where a common green certificate market may be introduced (see e.g. Morthorst, 2003). However, several researchers (e.g., Barrett, 2003) have suggested that future climate agreements must to a greater extent accept the importance of technology, for example by creating an international technology fund which favours CO_2-free energy producers (an overview of various suggestions for climate agreements is presented in Aldy *et al*., 2003).

[1] Other instruments, which are not covered in this article, are direct regulations and voluntary agreements.

The main focus in this article is to study how the two different types of instruments affect the short and long term profitability of fossil fuel producers, given that a fixed global climate target shall be achieved in the long term. This was partly examined in Kverndokk *et al.* (2000), but has otherwise not been studied in the literature (as far as we know). Furthermore, it would be interesting to examine if the results can contribute to explain the behaviour of major fossil fuel producers, either directly or through their domestic governments, in the international climate negotiations. For instance, the OPEC nations and major coal producers have been among the most opposed to the Kyoto protocol, whereas international oil companies have been more divided. Russia, which has mixed interests with respect to the protocol being a large supplier of oil, gas and potentially emission quotas (cf. Holtsmark, 2003), delayed the ratification resolution as long as possible until they ratified the protocol in late 2004.

Although both types of instruments probably reduce the profitability of producing fossil fuels, there are several reasons why the effect may differ, pulling in different directions. We briefly highlight some of these. The first reason is that the instruments as such work differently for oil, gas and coal. For example, a CO_2 tax will entail a greater charge per energy unit for coal because the CO_2 emissions from coal combustion are greater than for oil and gas. Correspondingly, the tax on gas will be the lowest. On the other hand, increased support for cleaner energy sources will not take into account that coal is the most pollutive.

Second, the current end-user prices of fossil fuels are quite different, and this affects both the impact of a CO_2 tax and to what extent new energy sources are competitive. For example, the end-user price of oil is high in many countries, implying that a CO_2 tax will be of less consequence compared to increased competition from new energy sources.

Third, the market conditions for oil, gas and coal are vastly different. For example, new energy sources may primarily become competitive in the power market (cf. IEA, 2003), in which coal and gas are most commonly used today. OPEC's role in the oil market is also important, as the cartel may react differently to the policy instruments than competitive producers do.

Finally, the time aspect is very dissimilar for the two policies. A CO_2 tax will affect the market immediately. However, economic analyses tend to recommend that a CO_2 tax should start low and increase over time in order to have a cost-effective reduction of accumulated CO_2 emissions (see for example Goulder and Mathai, 2000, and Rosendahl, 2004). Support for clean energy sources will have little direct effect initially because there exists no technology today that can compete on a large scale with fossil fuels. Major competition from new energy sources will most likely not take place for a few decades. However, both support of new technologies and a rising CO_2 tax may indirectly affect the profitability for oil and gas producers today, because more producers will accelerate their production when they see that the future profitability will be reduced (see for example Berg *et al.*, 2002).

With respect to modelling climate policies and technological change, there are (at least) two opposite model approaches. In the traditional approach, as Wigley *et al.* (1996), the new technologies will be discovered and developed exogenously over time, thus making abatement cheaper in the future. However, in the more recent approach, cf. e.g. Grübler and Messner (1998), Goulder and Mathai (2000), Rosendahl (2004) and Kverndokk *et al.* (2004), the technological change is not autonomous, but is induced by for instance learning by doing (LBD) (Arrow, 1962). Abatement today leads to experience in using the new technologies and a reduction in future costs. The effects of climate policy measures may differ between these two model approaches.

This article uses two different models, each representing one approach, to illustrate how the profitability of fossil fuels is affected by different instruments. Both CO_2 taxes and technology subsidies are analysed within both models (a combination of these instruments is also discussed in Section 2). The first model takes into account learning by doing for new energy technologies , but does not distinguish between different fossil fuels. The second model describes the markets for all three fossil fuels, but ignores that the technological progress for CO_2-free energy may be affected by experience or other market mechanisms. We therefore believe that these two models can complement each other and give a new insight into the aforementioned problem. The advantage of using two different models rather than one is of course that the results are less dependent on the modelling assumptions. Table 1 shows similarities and dissimilarities between the two models.

Table 1: Overview of central features of the two models

	Learning model (Section 2)	Petro model (Section 3)
Energy goods modelled	Electricity	Oil, Gas, Coal, Carbon-free energy source
Number of demand groups	1	4
Number of technologies	2	1 for each energy product
Market structure	Perfect competition	Oil: OPEC market power Other: Perfect competition
Dynamic behaviour	Forward looking producers and consumers	Forward looking producers Static consumers
Technological development	Endogenous (learning effects) for alternative technology	Exogenous
Restrictions on phasing in/out	Yes	No
Non-renewable resource	No	Oil and gas

2. An equilibrium model with learning effects

In order to see how different policy instruments affect fossil fuel producers, we will first study a model of endogenous technological change for renewable energy sources. This technological change is specified as learning by doing (LBD). Although LBD has been included in several recent models (cf. the references above and a survey in Jaffe *et al.*, 2002), the focus has not been on profitability of energy producers (as far as we know). More details of the present model are presented in Appendix A and in Kverndokk *et al*. (2004), and we will only discuss the main features here, cf. Table 1.

The model simulates both the dynamic optimisation problem of a social planner, and the intertemporal profit maximisation of power producers. The planner in the model is a representative consumer who maximises the total discounted utility over the next 130 years (what happens after this date has no bearing on the results), where the utility is a function of electricity consumption and consumption of other goods. We use a very simple representation of the macro economy, and the time preference is calibrated so that we get a long-term equilibrium where both the electricity consumption and other consumption increase by 2% per annum. The model is therefore a partial equilibrium model that focuses on the electricity market.[2]

[2] The results from the model can also be interpreted as corresponding effects in the transport market and other markets where fossil fuels are used.

There are two electricity technologies, both with constant returns to scale: **FOSSIL** is a fossil technology that generates CO_2 emissions. The technology is "mature", which means that there are no learning effects from production. The other technology, **SOLAR**, is a renewable energy technology. No emissions are linked to the use of this technology and there are also learning effects here, which cause the cost per unit to decrease as production increases. The unit costs are initially two times higher than the cost of FOSSIL but can fall via LBD to a minimum that is below the FOSSIL unit cost (25% lower in the base case). The learning effects can be either internal to the firm, or external (spillover effects). The electricity demand is at all times equal to the supply of electricity from the two technologies. There are restrictions on how quickly a technology can grow and how quickly it can contract (measured in relative terms). The first restriction reflects that it takes time to expand production capacity and penetrate the market even if production costs are low. The second restriction reflects that existing capacity will not be abruptly dismantled even though total unit costs get higher than for competing technologies. Therefore, these restrictions may result in a transitional period where both of the technologies are used, despite being perfect substitutes with different unit costs.

As long as there are no climate restrictions (*the reference scenario*) it will not be profitable for SOLAR to enter the market, even if the learning effects are internalised. The costs are too high, although they would fall after learning (this could be different if we had assumed a more optimistic learning potential). The discounting implies that the future gains upon learning are not high enough. In this case, all electricity production will therefore take place by means of the fossil alternative. As we disregard resource scarcity in this model, and also assume that there is perfect competition in the energy market, the discounted profit of the fuel producers (the resource wealth) will also be zero (note that these assumptions are altered in the other model in Section 3).

With climate restrictions, the alternative energy source may eventually be profitable. In order to illustrate this we have included a fairly strict restriction on accumulated CO_2 emissions over the next 130 years; a reduction of more than 70% in relation to the reference scenario. This gives a ceiling on the accumulated emissions that can be fulfilled in different ways. We first investigate the *optimal policy*, i.e., a combination of CO_2 taxes and SOLAR subsidies that maximises total discounted utility given the climate restriction.[3] Note that subsidies are only needed if (some of) the learning effects are external to the firm (see below).

[3] We assume that tax income is redistributed in a lump sum way, and that subsidy outlays are coming from a lump sum confiscation of revenue (i.e., we don't consider marginal cost of fund different from unity).

As discussed in the introduction, a standard result in a model with an aggregate emission target is that the optimal tax increases over time with the interest rate (cf. Goulder and Mathai, 2000); it is of no consequence when a unit of CO_2 is emitted, and the present value of the tax (the shadow price of CO_2) is therefore constant. The CO_2 tax thus starts low in our model, cf. Figure 1, but will gradually reach a level where it is profitable for SOLAR to enter the market.

Production of SOLAR generates learning. If it is assumed that this learning is internalised, no government intervention is required in order to achieve optimal production. However, if learning is a public good, the learning in a company will be freely available for everyone, and the company's gain will be approximately equal to zero. In this case, a production subsidy that is equal to the value of experience would be optimal (cf. Kverndokk *et al.*, 2004). Our simulations show that this subsidy should be highest when a technology is introduced, falling gradually as the learning potential is exhausted, cf. Figure 2.

Figure 1: CO_2 tax in different scenarios. Per cent of energy price (before tax)

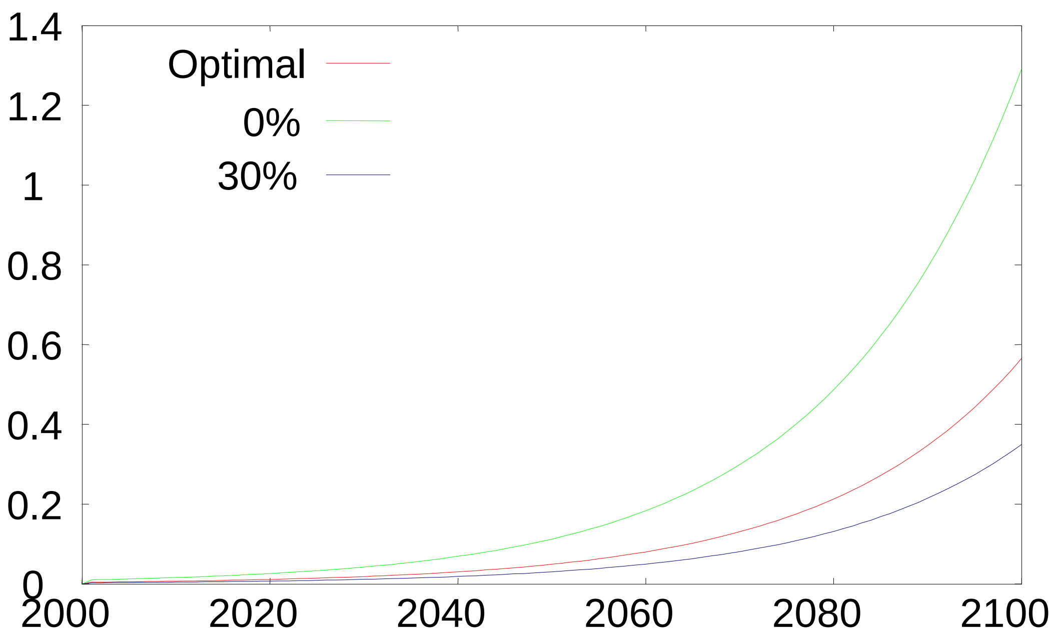
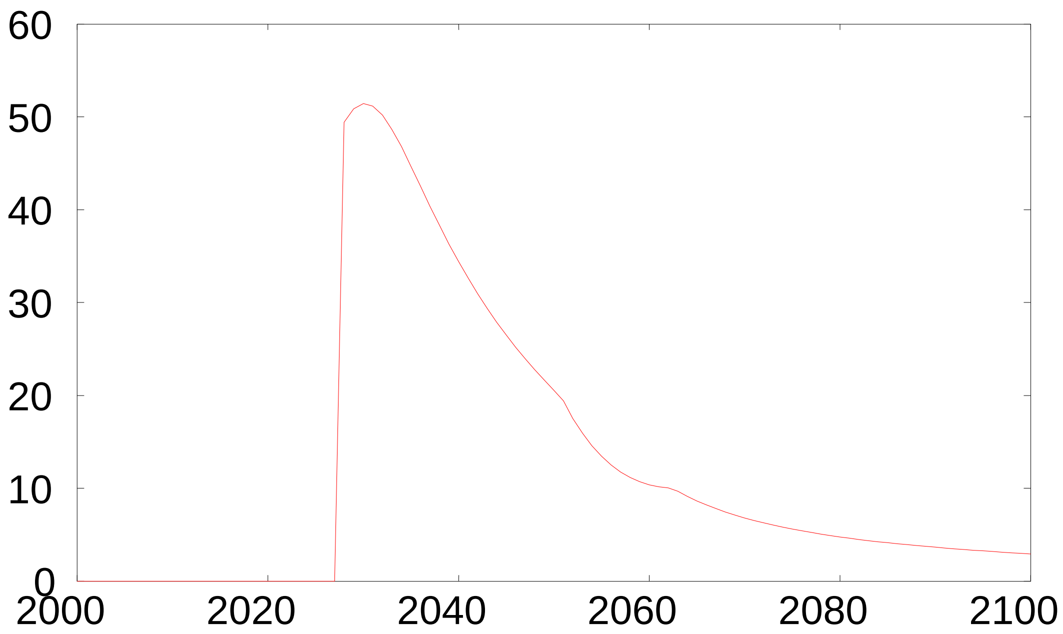


Figure 2: Optimal subsidy on SOLAR. Per cent of energy price



Using an *optimal policy*, SOLAR will be introduced from around 2030 and will gradually take over almost the entire market due to lower costs in the long run, see Figure 3. Whilst we had constant energy prices in the reference scenario, the climate restriction will result in major energy price increases between 2050 and 2060, due to the transition from FOSSIL to SOLAR, see Figure 4. From Figure 3 we see that total energy production falls in this period, as a consequence of the restriction on how quickly FOSSIL production can be reduced. This restriction implies that fossil fuel producers wish to reduce the production early so that the deficit is not too great during the subsequent dismantling period. As an illustration, we can consider producers who refrain from investing in new capacity with a long lifetime, as it is expected that another competitive technology will penetrate the market in a few years. At the same time, SOLAR producers are not able to accelerate its growth in capacity due to the expansion restriction. This could result in less electricity in the market during a transitional period.

Figure 3: Supply of FOSSIL and SOLAR in the optimal policy scenario. Per cent of FOSSIL supply in reference scenario

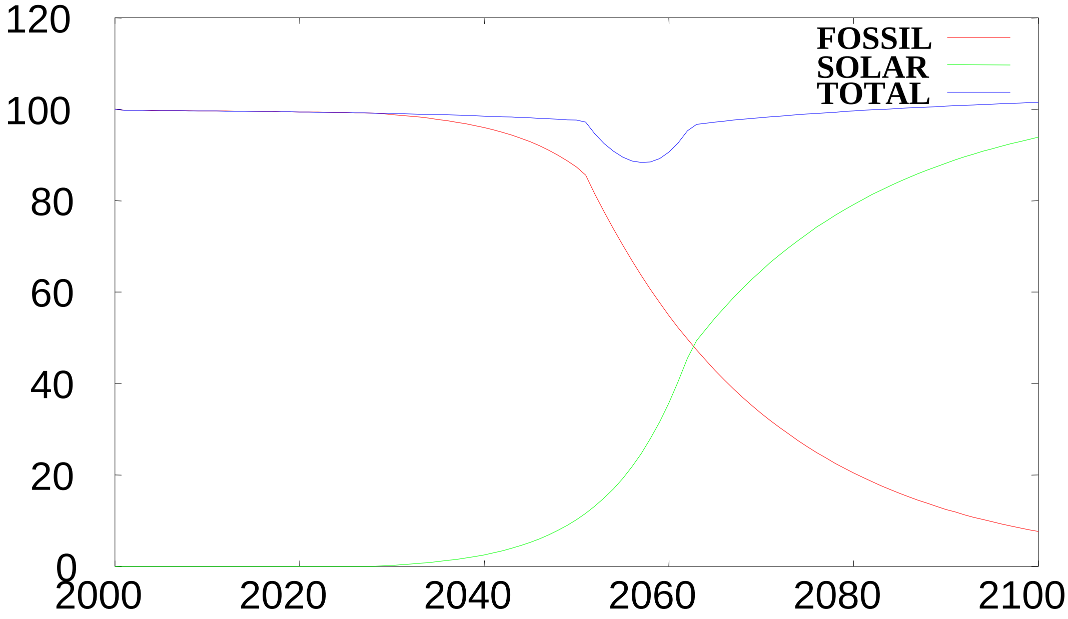
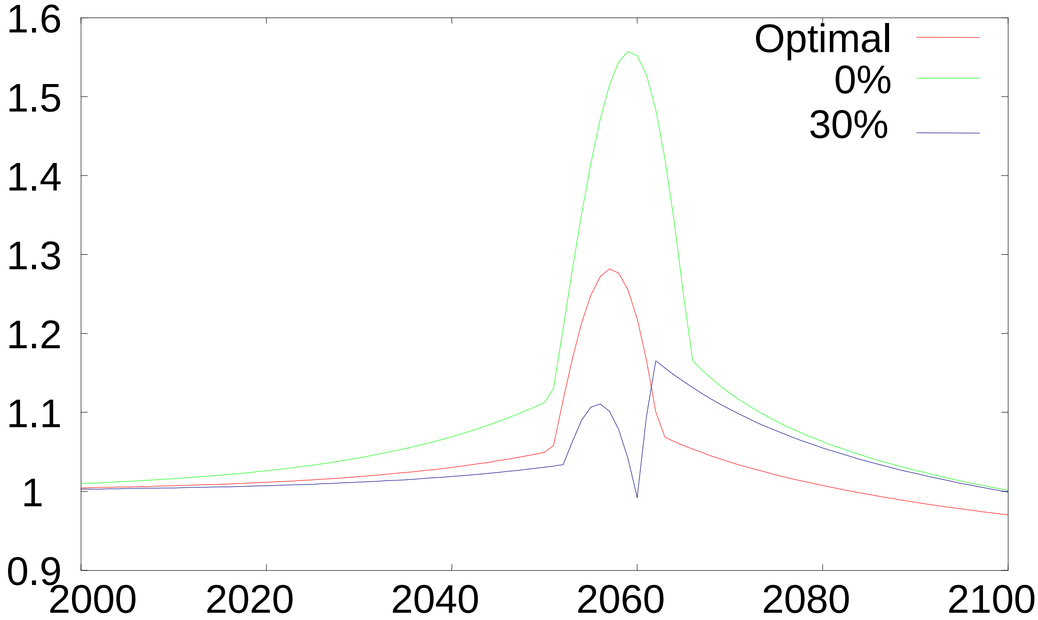


Figure 4: Energy price in different scenarios, relative to the price in reference scenario



Thus, as we will see below, the climate policy may well lead to *higher* producer prices for fossil fuels in a transition period when a new clean energy technology is expected to lower the price of electricity. New fossil capacity will not be built, benefiting existing fossil fuel plants (at least temporarily).

In order to study the effect of different instruments, we have also looked at *sub-optimal policies*, i.e., other combinations of taxes and subsidies than the optimal one: we have simulated fixed subsidy rates for SOLAR of 0 and 30% of the electricity prices, whilst the CO_2 tax is always set to achieve the emission target at lowest cost given the subsidy rate. The subsidies are constant for a limited period, up to 2060. By comparison, the optimal subsidy starts at around 50% of the electricity price around 2030, but falls quickly, and is less than 10% in 2060, see Figure 2.[4] The optimal CO_2 tax will be higher the lower the subsidies are, see Figure 1.

Figure 5: The producer price of FOSSIL in the different scenarios, as a share of the costs per unit

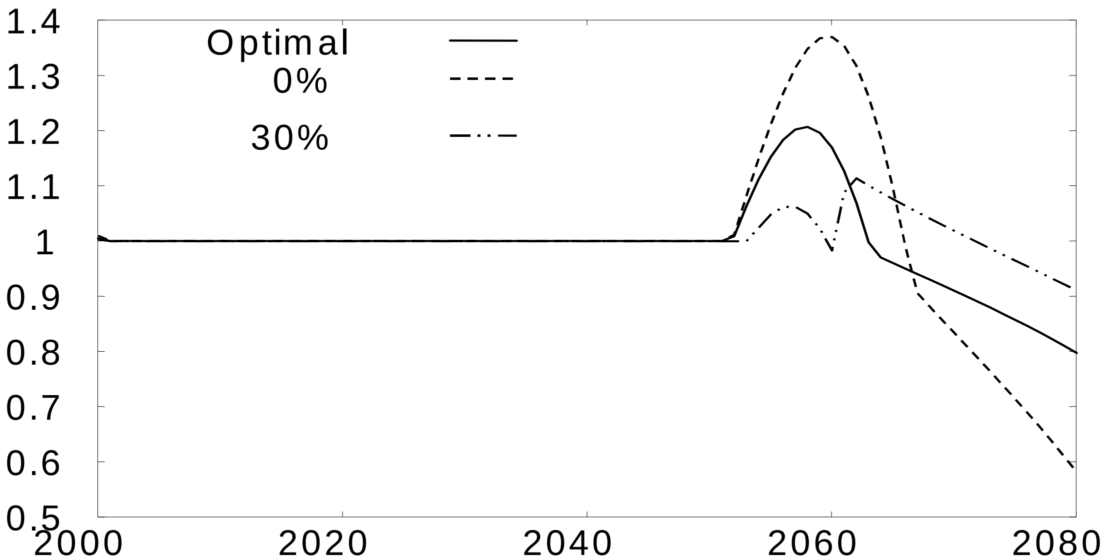


Figure 5 shows how the producer price of FOSSIL will develop in the different scenarios. The producer price is equal to the electricity price minus the carbon tax. As discussed above, the climate policy will result in a major price increase in the middle of the century as a result of restrictions on how fast FOSSIL can be reduced. Wee see that the price increase will be lower with a higher subsidy

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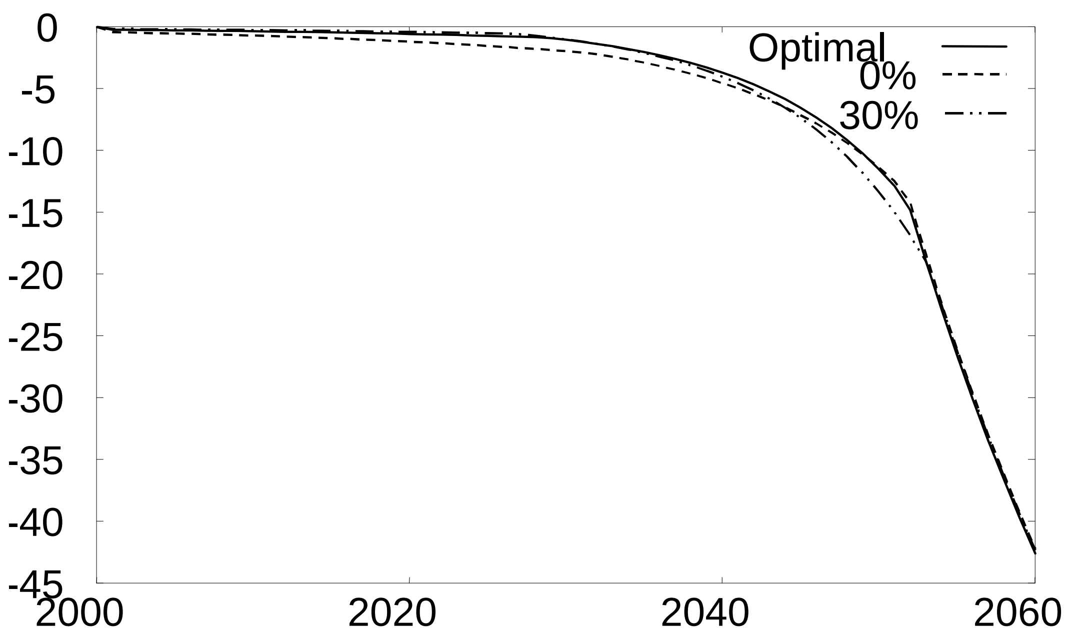
[4] In our model, where there are restrictions on phasing in a new technology, the magnitude of the subsidy in the beginning (up to around 2050) will not be so significant for the SOLAR production. This is also the reason that we do not get major fluctuations in Figure 5.

rate. This is primarily due to a higher production of SOLAR, but also because the FOSSIL producers expect a more smooth reduction in their producer price, cf. the figure. Additionally, the CO_2 tax will be lower. Towards the end of the century the fall in the producer price is stronger, the lower the subsidy rate is. This results from the combination of exponential growth in the CO_2 tax, and this tax starting at a higher level the lower the subsidy rate is (in order to reach the same target), cf. Figure 1. As a result of these factors, a low subsidy rate will pull in the direction of a high producer price in the middle of the century, but a lower producer price towards the end of the century.

With a restriction on accumulated emissions, which is proportional to the production of FOSSIL, the accumulated production of FOSSIL over the time horizon will naturally be the same in the different scenarios. SOLAR will emerge stronger from the middle of the century with a high subsidy rate, squeezing FOSSIL production harder than with a low subsidy rate. This means that the production of FOSSIL will have to be higher in the first part of the century and lower in the second, the higher the subsidy rate is, see Figure 6.

Figure 6: Production of FOSSIL in the different scenarios. Percentage change in relation to the reference path



Although the price effect in the transition period is more advantageous for fossil producers in the case with *low* subsidy rates, it turns out that the discounted value of the fossil production increases the *higher* the subsidy rate is.

To summarise the results from this model, fossil fuel producers will lose more from a climate policy based on taxation compared to a policy based on subsidies for renewable energy sources. We will now investigate how a different type of energy market model affects the profitability of different types of instruments.

3. An equilibrium model for oil, gas and coal

Petro is a model that describes the international markets for fossil fuels, i.e., oil, gas and coal, cf. Table 1 (a formal description is given in Appendix B). It is assumed that the producers have perfect foresight, and consequently they do not only take into account existing prices and market conditions, but also the future development of these variables. The producers seek to extract their resources at such a rate that their discounted resource wealth is maximised. In contrast to the previous model, no restrictions have been included on how quickly the production can be changed. The consumer demand in a period is assumed to solely depend on income and prices in that period. The model takes into account the market power of the oil market (in contrast to the previous model), whereby OPEC acts as a joint player. Other oil producers are regarded as price-takers (the oil market is modelled as a Nash-Cournot game). The gas market is split into three regions, which are modelled as competitive markets; OECD-Europe (including Russian export to this market), Rest-OECD and Non-OECD, whilst the coal market is a global competitive market. The extraction costs for oil and gas rise as a result of increased extraction, and falls in technological progress. Due to large coal reserves in the world, future extraction costs for coal are assumed to be unaffected by the production level (similar to the fossil fuel in the previous model), while the technological progress leads to somewhat lower costs over time. A renewable, carbon-free energy source is believed to exist, being a perfect substitute for each individual fossil fuel. The cost of this energy source is high, but it is reduced over time as a result of technological progress. With regard to demand, the model has 4 regions: OECD-Europe, Rest-OECD, a region consisting of Central and Eastern Europe, Russia and the Ukraine, and a region consisting of the rest of the world. Consumers regard fossil fuels as imperfect substitutes, i.e., the demand for a fossil fuel diminishes with the price of this fuel and increases with the price of the other two fuels. For a further description of the model and data basis, see Berg *et al*. (1997).

The two alternative climate policy instruments, technology subsidies and CO_2 taxes, are introduced as follows: The CO_2 tax is constant in all periods, and for oil this corresponds to \$10 per barrel or around \$90 per ton of carbon. Due to the different carbon content, the tax on gas and coal will be \$7.1 and \$12.4 per barrel of oil equivalent respectively. The other alternative is a subsidy on the costs of the carbon-free energy source that is just large enough to give the same reduction in accumulated CO_2 emissions over the time period, which extends to 2130.

We shall first look at the reference paths for the production of fossil fuels and the alternative energy source, cf. Figures 7-10. With respect to gas production, we will use OECD-Europe as an example, but we will comment on the two other regions as well. The analysis has been carried out on the assumption that the costs of the renewable energy source exogenously fall by 1.5% per annum, compared to 0.5-1% for fossil fuels. We have also looked at how changes in this rate affect the results, and this is reported at the end of this section.

In the reference scenario oil and gas extraction comes to an end in the second half of this century as the extraction costs of remaining resources get too high, cf. Figure 7 and 8.[5] OPEC's market power and large reserves imply that Non-OPEC terminates its production a couple of decades before the cartel. The price of oil (and gas) increases until it meets an upper bound determined by e.g. the price of the alternative energy source (see Figure 11), a pattern that is consistent with dynamic theories of non-renewable resources (cf. e.g. Dasgupta and Heal, 1979). The production of coal increases immensely throughout the entire period (cf. Figure 9), and will not be replaced by the alternative energy source due to low prices and low existing taxes on coal. Figure 10 shows that the alternative energy source is gradually introduced from 2060 when the production costs have fallen sufficiently to be competitive with oil and gas. Thus we have production of both fossil fuels and alternative energy in a transitional phase.

Table 2 shows the reduction in the petroleum wealth and discounted value of coal production in the two policy alternatives respectively. We see that all the fossil fuel producers lose less when the climate target is achieved by means of subsidies to their competitors rather than taxes, apart from the oil producers outside OPEC, who lose the least of their oil wealth in the tax scenario. The coal producers lose relatively most of all the producers when CO_2 taxes are introduced, whilst they almost do not suffer any losses when the alternative energy source is subsidised. Note that the coal producers are

[5] The sudden drop in production at the end of the production profiles reflects that the Petro model does not include restrictions on how quickly a technology can be downsized (in contrast to the model in section 2).

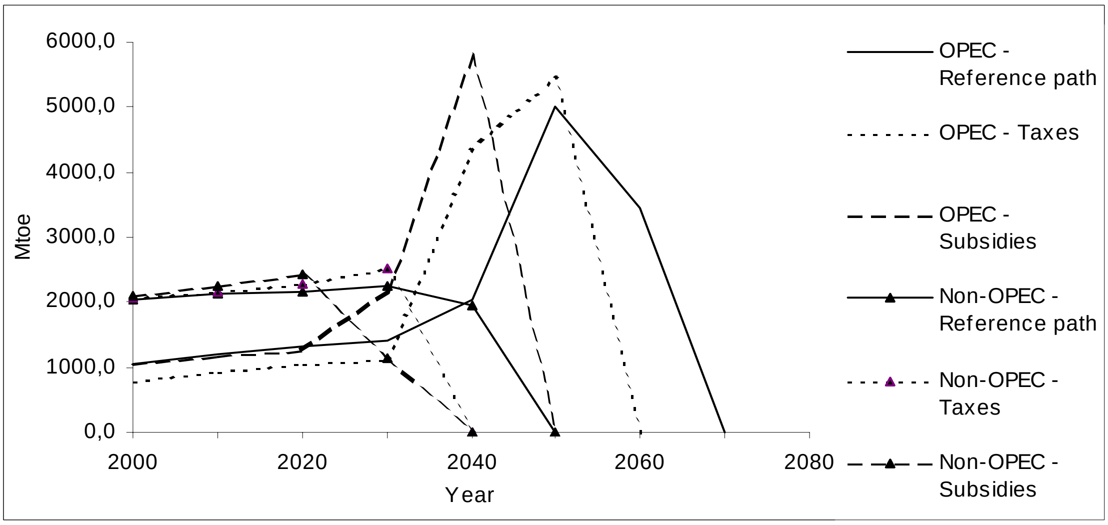
most comparable to the FOSSIL producer in the previous model, as the marginal costs are unaffected by extraction and the market is competitive.

Table 2: Percentage reduction in petroleum wealth and discounted value of coal production

	Taxes	Subsidies
OPEC's oil wealth	22.2	16.0
Non-OPEC's oil wealth	7.7	20.1
OECD-Europe's gas wealth	26.1	14.8
Rest-OECD's gas wealth	23.0	14.2
Non-OECD's gas wealth	30.9	17.7
Value of coal production[1]	39.2	1.7

[1] Due to large coal reserves and the assumption of perfect competition and linear costs in this market, the discounted coal wealth will be equal to zero. We therefore look at the production value instead, since reduced production hits employment in the coal industry (cf. the modelling of FOSSIL in section 2).

Figure 7: Oil production in and outside OPEC

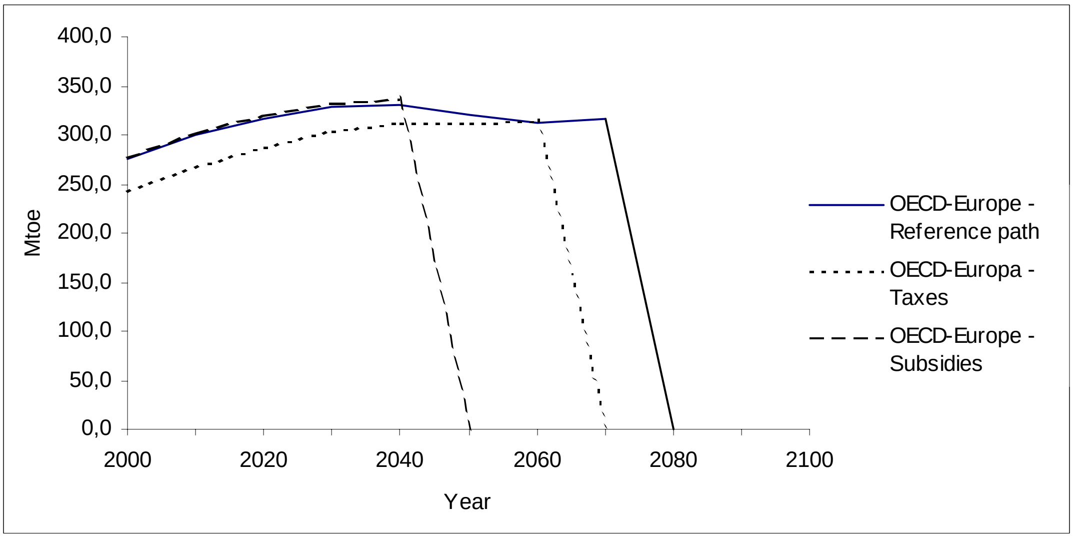


In order to explain these results, we need to take a closer look at how the introduction of taxes[6] and subsidies affects the production (and consumption) of energy. We start with *CO_2 taxes*, and will consider the gas and coal markets first. The tax leads to a decline in the producer price of gas and reduced gas production in all regions (cf. Figure 8 for OECD-Europe). Actually, despite gas being a cleaner fuel than oil, the (producer) price reduction for gas is relatively higher than for oil, and

[6] A more detailed description of how the taxes work in the model can be found in Berg et al. (1997, 2002).

consumption of gas drops more than oil consumption (at least initially). The reason for this is partly that the consumer price of gas (and coal) is lower than for oil, and the relative price increase of a CO_2 tax is therefore stronger. Thus, gas demand reacts more heavily to the consumer price increase than oil demand, which is quite insensitive. Another reason is the market structure of the oil market (see below). From Table 2 we see that gas producers lose around a quarter of their petroleum wealth in this tax scenario.

Figure 8: Gas production in OECD-Europe



However, it is primarily coal consumption and production that is reduced when taxes are introduced, cf. Figure 9. The main reason is that a CO_2 tax, measured by energy content, is higher for coal than for oil and gas. Additionally, as with gas, the consumer price of coal is lower than for oil, which results in a large relative price fall compared with the other fuels. This is showing up as a large reduction in the discounted value of coal production, cf. Table 2.

Introduction of the CO_2 tax only brings about a slight increase in the future production of the alternative energy source, cf. Figure 10. Note that in the Petro model the cost of this technology is exogenous, and therefore not affected by learning effects as in the previous model in Section 2. Remember that in the model analyses in the previous section alternative energy (SOLAR) was only produced in the various climate scenarios, and not in the reference scenario.

When the same CO_2 target is reached by *subsidising* the alternative energy source instead of introducing CO_2 taxes, the alternative energy production becomes competitive earlier, and the impact on production is much higher than in the tax scenario. The main reason is that taxes and subsidies have opposite impacts on total energy demand. The tax scenario *decreases* overall energy use (end-user prices rise), whereas the subsidy scenario *increases* energy use (end-user prices fall). Thus, in order to reach the same target for CO_2, which is almost equivalent to having the same accumulated use of fossil fuels, it is necessary to have a much higher share of alternative energy production in the subsidy scenario than in the tax scenario. This is induced by introducing a very high subsidy rate (more than double the CO_2 tax rate measured in oil equivalent terms).

Since alternative energy does not come into production before after several decades, there are only marginal effects on initial production of gas and coal, see Figure 8 and 9. Actually, there is a marginal *increase* in gas production in all regions. The reason is that the price increases less than in the reference path, and it will therefore be profitable to move some of the production to earlier periods. As the subsidy makes alternative energy production competitive before, production of gas is terminated several decades earlier than in the reference and tax scenarios. The same applies in the coal market. Note that the overall restriction mentioned above on accumulated CO_2 emission and thus fossil fuel use implies that production must terminate earlier in the subsidy scenario than in the tax scenario, as initial production is less reduced. From Table 2 we see that gas producers in all three regions now lose less of their gas wealth, whereas the value of coal production is only marginally reduced. The main reason is that the impacts of subsidies are mostly seen in the second half of the century, and the discounting makes these impacts less significant.

Figure 9: Global coal production

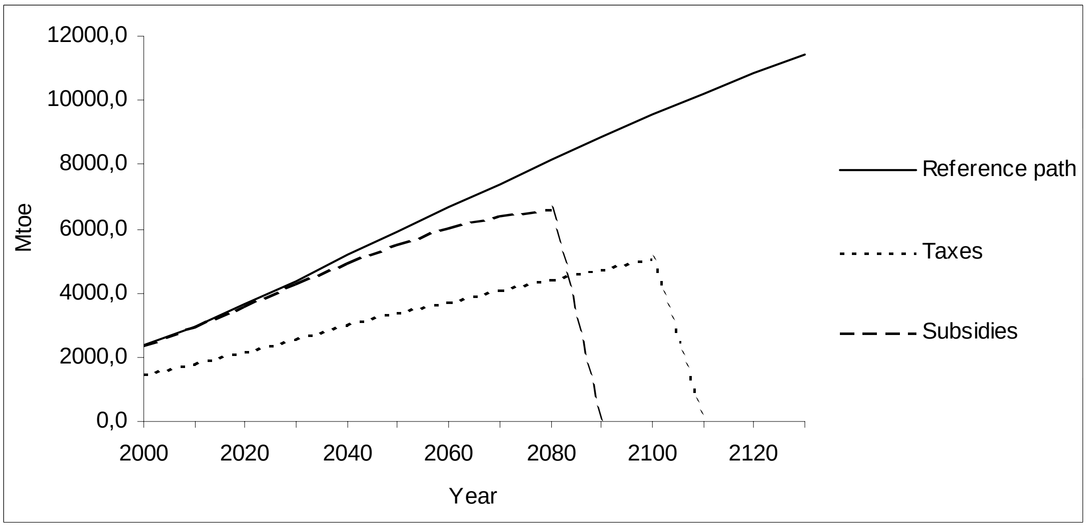
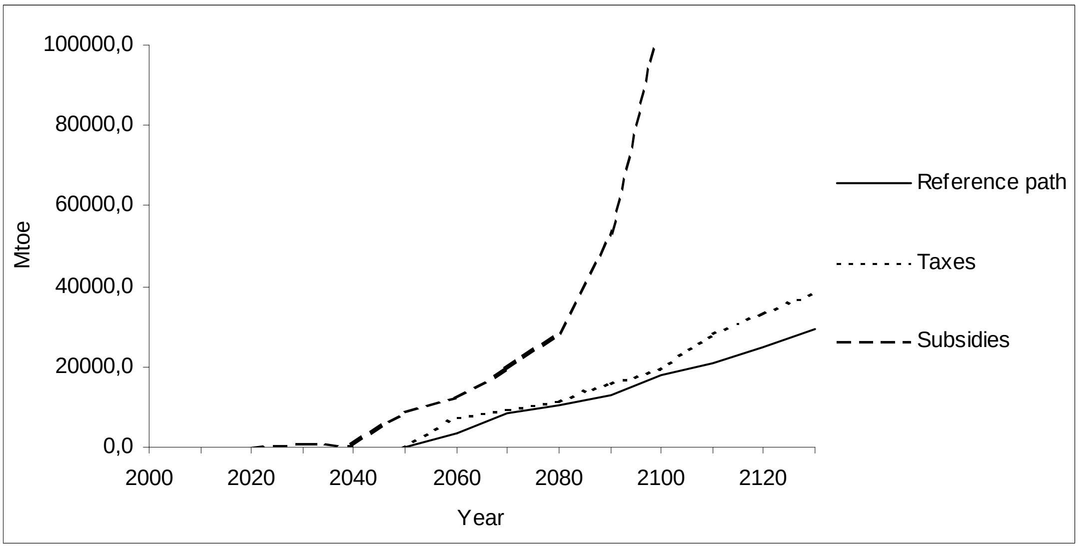


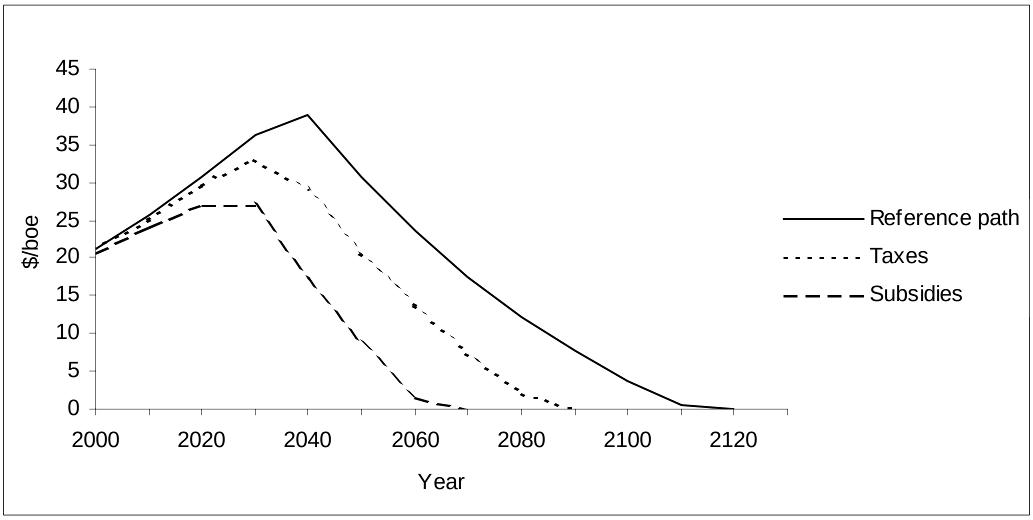
Figure 10: Global production of alternative energy



To sum up the effects on the gas and coal markets, the result from the previous model is upheld; introducing subsidies leads to a smaller reduction in fossil fuel consumption than taxes in the first periods, but to a greater reduction in the consumption in later periods. The discounting of future impacts is the main explanation of the finding that fossil fuel producers seem to lose less of their wealth or production value when the climate target is achieved by subsidising carbon-free energy. However, Table 2 shows that this result does not necessarily apply in the oil market. Whilst subsidies are preferred for OPEC, taxes will be most favourable for producers outside OPEC. In order to explain this result, we need to take a closer look at the oil market.

OPEC's market power means that the cartel considers the oil price as a decreasing function of its own production, taking production from other producers for granted (Nash-Cournot game). This implies that the fringe producers outside OPEC produce about twice as much as the cartel in the first periods in the reference scenario, despite OPEC's costs being much lower (cf. Figure 7). Since increased production today increases the future costs, both OPEC and Non-OPEC producers have incentives to limit their production. Initially this scarcity effect is most important for Non-OPEC as OPEC's costs are fairly constant in the first periods. Non-OPEC stops producing when extraction is no longer profitable, and OPEC then takes over the entire market. OPEC stops producing when the price of the alternative energy source is lower than the cartel's unit costs.

Figure 11: The producer price of oil



When a CO_2 *tax* is introduced, OPEC finds it profitable to reduce production in the first 30 years in order to keep the oil price at roughly the same level as it was in the reference scenario, cf. Figure 7 and 11. This is good news for Non-OPEC producers, taking the oil price for granted. Their production increases slightly compared to the reference scenario up to 2030. The reason is that a slower rise in the oil price path gives them incentives to accelerate their extraction. On the other hand, this also implies that Non-OPEC's production ends sooner than in the reference scenario. Yet, from Table 2 we see that their petroleum wealth is only moderately reduced by this tax scenario.

Why does OPEC choose this response to the CO_2 tax? From models of Nash-Cournot games we know that a tax reduces the aggressiveness of the Cournot players, as it curbs demand (see, e.g., Tirole, 1988, ch. 8). On the other hand, as we commented on above, the dynamic behaviour implies that Non-OPEC producers become *more* aggressive initially, whereas the dynamic aspect has less influence on OPEC's behaviour in the first decades. When the oil price approaches its peak level, the cartel notes that it will have complete market dominance in a couple of decades also in this scenario, which also reduces the need to accelerate extraction. Although OPEC's strategy is most beneficial for other oil producers, the cartel does not lose more than other fossil fuel producers, cf. Table 2.

When a *subsidy* is introduced for the carbon-free energy source, oil demand is practically not affected before the carbon-free energy becomes competitive. Thus, it is no longer decisive for OPEC to reduce initial production, as in the tax scenario. However, since the required subsidy rate is much stronger than the CO_2 tax (cf. our arguments above), the upper bound for the oil price is much lower in the subsidy scenario, cf. Figure 11. This implies that overall oil production terminates earlier than in the tax scenario, and that the oil price rises less steeply. For Non-OPEC producers this means that it is even more profitable than in the tax scenario to accelerate extraction, cf. Figure 7. However, the expansion is short-lived, and producers outside OPEC end up losing considerably more than in the tax scenario (see Table 2).

For OPEC a reduction in production cannot be caught up with later in the same way as in the tax scenario, due to the low price of the alternative energy source from around 2040. Thus, the cartel is more willing to accept a lower price also before the upper bound becomes binding, leaving room for more production. Altogether, OPEC loses less when subsidies are applied – despite losing more because of lower oil prices, they produce considerably more than in the tax scenario in the first 40 years. Consequently, the results for OPEC are at least qualitatively similar to the results for gas and coal producers, as well as the FOSSIL producers in Section 2. For the fringe producers, however, the results are quite the opposite.[7] Thus, market structure seems to have a stronger influence on the conclusions than the characteristics of technological change in carbon-free energy production (cf. the modelling in Section 2).

The qualitative results hold when we do similar analyses in scenarios with higher or lower technological progress for the renewable energy source. This means that taxes, to a greater extent than subsidies, reduce the petroleum wealth for OPEC and for gas producers, and in particular reduce the value of coal production. On the other hand, oil producers outside OPEC ought to prefer taxes as a climate initiative.

The aforementioned main conclusion is also unchanged when less ambitious climate targets are used. However, if we halve the discount rate from 7% to 3.5%, the conclusions differ somewhat. In this case, all oil and gas producers will prefer CO_2 taxes to subsidies, with coal producers still preferring subsidies. This supports the explanation of the results above as well as in Section 2, namely that the discounting of future revenues is a determining factor for which instrument is preferred. In the case of a small discount rate, it counts more that CO_2 taxes give a much greater percentage increase in the coal price compared with the oil and gas price. A rate of 3.5% is, however, extremely low for fossil fuel producers, despite many of these being controlled by the public authorities.

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[7] We believe that the oil market is best described whereby OPEC uses its market power (cf. Berg et al, 2002). In the event of perfect competition in the oil market, both the producers in and outside OPEC would lose relatively more of their wealth when taxes are applied. The fringe producers lose more than in the case where OPEC acts as a collective player, primarily because no one slows production down in order to keep the oil price high after the taxes have been introduced.

4. Conclusion

This article discusses how different types of international climate policies, which give the same long-term climate target, affect the profitability of fossil fuel producers. We have seen that CO_2 taxes, even if they are low initially, reduce the profitability in the short term to a greater extent than technology subsidies because the competition from CO_2-free energy sources is not particularly noticeable until after several decades. It is interesting to note that this conclusion was found both in a model with induced technological change (through LBD), and a model with only autonomous technological progress. Because of the discounting of future revenues, the subsidising of competitors seems more preferable for the fossil producers as opposed to taxes on own production. When lower discount rates are applied, we have seen that this can change.

The main conclusion, however, does not apply to all producers. From analyses in the Petro model, we found that oil producers outside OPEC lose most on the subsidising of CO_2-free energy, whilst CO_2 taxes only reduce their wealth to a small degree (many of those producers are also producing gas, however). This is related to OPEC's role in the oil market – the cartel reacts quite differently in the two scenarios and ends up preferring subsidies compared to taxes in our analysis.

Those who appear to lose the most from an international climate policy with the emphasis on CO_2 taxes or quotas, i.e. as in the Kyoto protocol, are thus coal producers, gas producers and OPEC. As discussed in the introduction, both major OPEC countries, basing their national income on oil exports, and major coal companies have been vociferous opponents of the protocol. The US position might be partly explained by the dominance of the coal industry within this country. Russia, being the world's largest gas exporter and also a large oil exporter, has been sitting on the fence longer than any other countries. The conditions in the Kyoto protocol are very favourable for Russia, but according to our results the revenues from gas export may be hurt. International oil companies have become quite divided in their position towards the protocol, with European companies being less negative than their American counterparts. According to our results, oil producers outside OPEC should have little to fear from a Kyoto-like agreement, although most international oil companies also are engaged in gas extraction.

The strongest advocates of the Kyoto protocol have been the Western European countries, which are mainly fossil fuel importing countries. Although their consumers may experience higher end-user prices, the countries will improve their terms-of-trade through lower energy prices on the world markets. Another point that we have not discussed, is who receives the tax income and who pays the subsidies. Whereas most tax income would accrue to the governments of main consuming countries, it is likely that any subsidy payments would have to come from governments of industrialised countries. This should increase the preference for a Kyoto-like protocol in most OECD countries compared to an agreement based on subsidies to carbon-free energy sources.

Although the models we have used do not capture all relevant factors (e.g., the division between power production and other use of fossil fuels), it is interesting to note how the results are consistent with the behaviour of key players in the international climate negotiations. It will also be interesting to follow the negotiations of the next commitment period, and see how the different players react to alternative suggestions of international climate policy.

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Model description of the learning model in Section 2

The model is a simple dynamic partial equilibrium model, which explores the economic cost of carbon abatement in a model with learning by doing (LBD). In this version of the model we consider two existing electric energy technologies.[8] These technologies are:

- FOSSIL; the average type of unit on line in the year 2000; a predominantly fossil mix of technologies, but it also includes hydroelectric and nuclear; it is neither subject to LBD nor resource scarcity within the relevant time horizon;
- SOLAR; the challenger - the average type of carbon-free technology available in 2000; this is high-cost but subject to LBD;

In the model there is a fixed present value of income that can be allocated across time at a fixed interest rate, and used either for non-electric consumption or electricity. Both the social planner as well as electricity producers face an intertemporal optimization problem. The modeling of the non-electric part of the economy is simplified in order to focus on the market for electricity.

A representative agent seeks to maximize discounted utility of electric and non-electric consumption over a 130 year planning horizon, subject to a budget constraint and technological constraints.

Below we show the model equations, starting with a list of symbols. For more information about the model, e.g. parameter choices, we refer to Kverndokk *et al.* (2004).

A1. List of symbols

$u\left(E_t, C_t\right)$	represents a consumption index at period t, or the intra period utility
E_t	represents electric energy demand in period t
C_t	represents non-electric consumption in period t
Δ	is the time preference discount factor, calibrated to be $(1.02)^2/(1.05)$[9]
θ	is the reference value share of electric energy (set equal to 5%)
ρ	is the electric energy substitution parameter (set equal to -1)
ρ_T	is the intertemporal substitution parameter (set equal to -1)

[8] In Kverndokk *et al.* (2004) the model also includes a future, advanced technology.

[9] This is consistent with a baseline growth rate of 2% in the consumption index, an interest rate of 5%, and an intertemporal substitution parameter of -1 (see below).

X_{jt}	is the electricity supply from technology *j* in year *t*
$\overline{X}_j$	is initial production of electricity from technology *j*
$\overline{X}_{j,t}$	are bounds on electricity production for technology *j*
p_t	is the present-value price of period t goods, equal to $(1/1.05)^t$ [10]
EC_t	equals electric energy costs in year *t*
$\overline{M}$	is the (fixed) present value of income which may be used on electricity or other consumption[11]
c_{jt}	is the unit cost of electricity from technology *j* in year *t*
$\bar{c}_j$	is the static (constant) cost coefficient for technology *j*
l_j	is the initial learning cost coefficient
Y_{jt}	is the accumulated experience (measured in aggregated production) for technology *j* in year *t*
$\overline{Y}_j$	is the initial accumulated experience for technology *j*
γ_j	is the learning exponent for technology *j*
δ	is the maximum decline rate per annum which ensures technologies are not replaced too rapidly ($\delta = 0.03$).
ε	is the maximum expansion rate which ensures that new technologies are not introduced too rapidly ($\varepsilon = 0.15$)
β	is the introduction limit which specify how much a new technology can produce the first year of production. The value of β is chosen to ensure that a new technology cannot supply more than 1% of the market during the first decade in which it is introduced.

[10] As mentioned in the former footnote, the interest rate is set to 5% p.a.

[11] M is calibrated so that the value of non-electric and electric consumption is 20 times the value of electricity sales (i.e., electricity represents 5% of GDP).

A2. The formal model

(A1) $$\max_{E_t, C_t} \left(\sum_{t=0}^{130} \Delta^t u(E_t, C_t)^{\rho T} \right)^{\frac{1}{\rho T}}$$

(A2) $$u(E_t, C_t) = \left[\theta \left(\frac{E_t}{\theta} \right)^{\rho} + (1-\theta) \left(\frac{C_t}{1-\theta} \right)^{\rho} \right]^{1/\rho}$$

(A3) $$E_t = \sum_j X_{j,t}$$

(A4) $$\sum_t p_t \left(C_t + EC_t \right) = \overline{M}$$

(A5) $$EC_t = \sum_j c_{j,t} X_{j,t}$$

(A6) $$c_{j,t} = \bar{c}_j + l_j \left(\frac{Y_{j,t}}{\overline{Y}_j} \right)^{\gamma_j}$$

(A7) $$Y_{j,t+1} = Y_{j,t} + X_{j,t}$$

(A8) $$X_{j,t} / (1+\delta) \leq X_{j,t+1} \leq X_{j,t} (1+\varepsilon) + \beta$$

(A9) $$X_{j,0} = \overline{X}_j$$

(A10) $$0 \leq X_{j,t} \leq \overline{X}_{j,t}$$

Appendix B

Model description of the Petro model in Section 3

In the model there are three fossil fuels produced: Oil (O), natural gas (G) and coal (K). We consider the model of the world oil market with OPEC as a cartel (C) and a competitive fringe (F). Consumers are situated in four regions: OECD-Europe (1), Rest-OECD (2), EIT (3) and Non-Annex B (4). There is a natural gas market with perfect competition in each region, that is region $i = 1,2$ and $3+4$ together. The coal market is assumed to be a competitive world market.

Below we show the model equations, starting with a list of symbols. All variables are functions of time. However we will suppress the time notation in the following. The functional forms are constant over time. For more information about the model, e.g. parameter choices, we refer to Berg *et al.* (1997).

B1. List of symbols

P_O	international producer price of oil
P_K	international producer price of coal
P_G^i	producer price of natural gas in region *i*,
Q_j^i	consumer price of fuel *j* in region *i*,
$\overline{P}$	international backstop price
z_j^i	unit costs of transportation, distribution and refining of fuel *j* in region *i*,
v_j^i	existing taxes on fuel *j* in region *i*
Y^i	gross national income in region *i*
x_j^k	production of fuel *j* by producer *k*
X_j^i	consumption of fuel *j* in region *i*
A_j^k	accumulated production of fuel *j* by producer *k*
$\overline{A}_j^k$	accumulated production of fuel *j* by producer k over the entire time horizon
C_j^k	unit cost of production of fuel *j* for producer *k*
λ	the shadow cost associated with cumulative extraction up to the current time
π_j^k	scarcity rent in production of fuel *j* for producer *k*

MR^C	marginal revenue of OPEC
τ^k, γ^i, ψ	rate of technological change in production of oil, gas and coal respectively
μ	rate of technological change in backstop technology
η_j^k	parameter of convexity in the cost function for fuel *j* for producer *k*
$a_j^i, b_j^i, c_j^i, d_j^i$	price and income elasticities in demand function for fuel *j* in region *i*
ω_j^i	constant in demand function for fuel *j* in region *i*
$\alpha, \beta, \sigma^i, \theta$	constants in cost functions
κ	initial backstop price
r	discount rate
t	time
T_j^k	last period of production of fuel *j* for producer *k*

B2. Demand

On the demand side we assume loglinear demand functions in all regions. Demand takes into account the imperfect substitution possibility between the different fossil fuels.

First, let $\hat{X}_j^i$ be defined by

(B1) $$\ln \hat{X}_j^i = \ln \omega_j^i + a_j^i \ln Q_O^i + b_j^i \ln Q_K^i + c_j^i \ln Q_G^i + d_j^i \ln Y^i$$

where

(B2) $$\begin{aligned} Q_O^i &= P_O + z_O^i + v_O^i \\ Q_K^i &= P_K + z_K^i + v_K^i \\ Q_G^i &= P_G^i + z_G^i + v_G^i \end{aligned}$$

Then the demand for energy type j in region i is given by

(B3) $$\begin{aligned} X_j^i &= \hat{X}_j^i, Q_j^i < \overline{P} \\ X_j^i &= 0, Q_j^i > \overline{P} \\ X_j^i &\in [0, \hat{X}_j^i], Q_j^i = \overline{P} \end{aligned}$$

The restriction of market clearing in the world oil market can then be written

(B4) $$x_O^C + x_O^F = \sum_{i=1}^{4} X_O^i$$

From (B1)-(B4), we can derive the producer price of oil:

(B5) $$P_O = P_O\left(x_O^C + x_O^F, z_O^1 + v_O^1, z_O^2 + v_O^2, z_O^3 + v_O^3, z_0^4 + v_0^4, Q_K^1, Q_K^2, Q_K^3, Q_K^4, Q_G^1, Q_G^2, Q_G^3, Q_G^4, \overline{P}, Y^1, Y^2, Y^3, Y^4\right)$$

In a similar way, we can derive the producer prices of natural gas and coal.

B3. The optimisation problem for OPEC in the Nash-Cournot model

When the oil market is modelled as a Nash-Cournot model, the cartel (OPEC) is facing a downward sloping demand schedule at each point of time, and takes the extraction path of the fringe as given. OPEC seeks to maximise the present value of the net revenue flow. The control variable in the optimisation problem is the extraction path of the cartel, and the state variable is accumulated production. $\mathrm{P_O}(\cdot\cdot)$ in (B6) is the producer price given in (B5).

(B6) $$\max_{x_O^C} \int_0^\infty \left[P_O(\cdot\cdot) - C_O^C\right] x_O^C \cdot e^{-rt} dt$$

s.t.

(B7) $$\dot{A}_O^C = x_O^C$$

(B8) $$x_O^C \geq 0$$

(B9) $$C_O^C = \alpha e^{\eta_O^C A_O^C - \tau^C t}$$

(B10) $$\overline{P} = \kappa e^{-\mu t}$$

B4. Solving the problem

The current value Hamiltonian in the optimisation problem of OPEC, H^c, is given by

(B11) $$H^c = \left[P_O(\cdot) - C_O^C\left(A_O^C, t\right)\right] x_O^C + \lambda x_O^C$$

where $\lambda_t (< 0)$ is the shadow cost associated with cumulative extraction up to time t. The scarcity rent for the cartel is defined as $\pi_{O\,t}^C = -\lambda_t$.

The necessary conditions for an optimal solution are given by the Pontryagin's maximum principle. From this maximum principle we get the time path of the shadow cost

(B12) $$\dot{\lambda} - r\lambda = -\frac{\partial H^c}{\partial A_O^C} = \frac{\partial C_O^C}{\partial A_O^C} x_O^C$$

(B12) can be rewritten using the definition of the scarcity rent

(B13) $$\dot{\pi}_O^C = r\pi_O^C - \frac{\partial C_O^C}{\partial A_O^C} x_O^C$$

x_O^C maximises the Hamiltonian for all $x_O^C \geq 0$ which for an interior solution requires

(B14) $$\frac{\partial H^c}{\partial x_O^C} = P_O - C_O^C + \frac{\partial P_O}{\partial x_O} x_O^C + \lambda = 0$$

which gives the producer price of oil when OPEC produces

(B15) $$P_O = C_O^C + \pi_O^C - \frac{\partial P_O}{\partial x_O^C} x_O^C$$

where $-\frac{\partial P_O}{\partial x_O^C} x_O^C$ is the cartel rent. The marginal revenue of OPEC is defined as

(B16) $$MR^C = P_O + \frac{\partial P_O}{\partial x_O^C} x_O^C = C_O^C + \pi_O^C$$

Using (B13) and (B16) we find the time path of the marginal revenue

(B17) $$\dot{MR}^C = r\pi_O^C - \tau^C C_O^C$$

The cartel will stop producing at time $T_O^C \in (0, \infty)$ when the unit cost reaches the backstop price minus region specific costs and taxes. Let $\overline{A}_O^C$ be the aggregate production of OPEC over the entire time horizon. The transversality condition is then

(B18) $$\max_i \left(\overline{P}_{T_O^C} - z_O^i - v_O^i \right) = C_O^C \left(\overline{A}_O^C, T_O^C \right)$$

B5. The optimisation problem for the competitive fringe

The optimisation problem of a competitive fringe producer in the oil market is similar to the one of OPEC above, with the exception of the producer price which is regarded exogenously. In a competitive market, the optimisation problem of OPEC producers is again similar to this.

(B19) $$\max_{x_O^F} \int_0^\infty \left[P_O - C_O^F \right] x_O^F \cdot e^{-rt} dt$$

s.t.

(B20) $$\dot{A}_O^F = x_O^F$$

(B21) $$x_O^F \geq 0$$

(B22) $$C_O^F = \beta e^{\eta_O^F A_O^F - \tau^F t}$$

From the first order conditions of this maximisation problem, we get for an interior solution

(B23) $$P_O = C_O^F \left(A_O^F, t \right) + \pi_O^F$$

(B24) $$\dot{P}_O = rP_O - \left(r + \tau^F \right) C_O^F = r\pi_O^F - \tau^F C_O^F$$

where π_O^F is the scarcity rent for the fringe defined as the negative of the shadow cost associated with cumulative extraction.

In a market equilibrium, OPEC's first order and transversality conditions as well as the market condition (B4) and the development in the backstop price (B10) must be satisfied.

The transversality condition of the fringe, where $T_O^F \in (0, \infty)$, is

(B25) $$\max_i \left(\overline{P}_{T_O^F} - z_O^i - v_O^i \right) = C_O^F \left(\overline{A}_O^F, T_O^F \right)$$

B6. The optimisation problems in the natural gas markets

As in the oil market, the gas producers also maximise the present value of the net revenue flow. We consider three separate regional natural gas markets with perfect competition. There are similar restrictions and first order conditions for the optimisation problems for all markets $i = 1, 2$ and $3 + 4$ together. Each producer faces the following optimisation problem:

(B26) $$\max_{x_G^i} \int_0^\infty \left[P_G^i - C_G^i \right] x_G^i \cdot e^{-rt} dt$$

s.t.

(B27) $$\dot{A}_G^i = x_G^i$$

(B28) $x_G^i \geq 0$

(B29) $C_G^i = \sigma^i e^{\eta_G^i A_G^i - \gamma^i t}$

The first order conditions give

(B30) $P_G^i = C_G^i \left(A_G^i, \gamma^i, t \right) + \pi_G^i$

(B31) $\dot{P}_G^i = rP_G^i - \left(r + \gamma^i \right) C_G^i = r\pi_G^i - \gamma^i C_G^i$

In a market equilibrium the development of the backstop price (B10) and the market condition (B32) must hold.

(B32) $P_G^i = P_G^i \left(x_G^i, z_G^i + v_G^i, Q_O^i, Q_K^i, \overline{P}, Y^i \right)$

The transversality conditions in the natural gas markets, where $T_G^i \in \left(0, \infty\right)$, are similarly

(B33) $\overline{P}_{T_G^i} - z_G^i - v_G^i = C_G^i \left(\overline{A}_G^i, T_G^i \right)$

B7. The optimisation problem in the coal market

We assume that there is one global coal market with perfect competition. Since the coal resources in the world are so huge compared to those of oil and gas, we ignore the dynamic aspect of the resource extraction and treat the optimisation problem in the coal market as a static problem, where the coal producers maximise the profit in every period. Each producer faces the following problem:

(B34) $\max_{x_K} \int_0^\infty \left[P_K - C_K \right] x_K \cdot e^{-rt} dt$

s.t.

(B35) $x_K \geq 0$

(B36) $C_K = \theta e^{-\psi t}$

The unit cost in coal production is assumed to be independent of accumulated production. The first order condition is simply,

(B37) $P_K = C_K$

In a market equilibrium, (B10) and the market condition (B38) must hold.

(B38) $P_K = P_K\left(x_K, z_K^1 + v_K^1, z_K^2 + v_K^2, z_K^3 + v_K^3, z_K^4 + v_R^4, Q_O^1, Q_O^2, Q_O^3, Q_0^4, Q_G^1, Q_G^2, Q_G^3, Q_G^4, \overline{P}, Y^1, Y^2, Y^3, Y^4\right)$

The transversality condition, where $T_K \in (0,\infty)$, is

(B39) $\max_i\left(\overline{P}_{T_K} - z_K^i - v_K^i\right) = C_K(T_K)$.

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