Carbon Taxation if Liquefied Coal will (not) Substitute Oil

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Abstract

All current and conceivable near-term climate protection measures only cover a limited fraction of global emissions. In this case, emission reductions in one place are subject to leakage, that is, the complex economic interlinkages between specific emission-generating activities and CO_2 emissions throughout the world imply that parts of local or regional emission reductions are offset in other regions and time periods. The leakage depends on the type of resources involved and the characteristics of the markets in which they are traded. This paper investigates how the leakage rate varies accross different fossil fuels and derives the corresponding, regionally optimal tax structure. A numerical dynamic model accounting for fuel exhaustibility shows that the time dimension is crucial and that the relevant medium-term leakage may be much larger than rates typically suggested in literature. Sensible leakage rates depend on the discount rate for future emissions and on uncertain future technological and political developments. The traditional leakage literature does often not explicitly consider these factors, even though in their absence long-run leakage would typically approach 100 %. Leakage is directly linked to the optimal regional emission tax. Simulations of present-discounted long-term effects indicate that in a business-as-usual scenario the optimal unilateral OECD climate tax rate on CO_2 emissions from oil may be only half of the tax rate on emissions from coal. This is reverted if the CO_2 intensive coal-to-liquids conversion processes become an important additional source of liquid fuels in the future. In this case, negative leakage occurs and the optimal current climate tax on oil emissions may be up to two times the genuine regional willingness to pay for global emission reductions, even if the substitution of crude oil by synthetic liquids starts only in the future.

JEL-Codes: Q54, Q41, H23, H21.

Keywords: Unilateral climate policy, fuel specific carbon tax, fossil fuel depletion, carbon leakage over time, coal liquefaction, OECD.

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1 Introduction and Short Literature Overview

A climate policy aimed at an economically efficient reduction of carbon dioxide (CO_2) emissions may take the form of a CO_2 tax or a cap-and-trade system. The level of the tax, or correspondingly, the tightness of the allowances in the cap-and-trade system, expresses a willingness to pay (WTP) for climate protection, that is, for global greenhouse gas emission reductions. In a first-best world, where an optimal tax scheme can be imposed, all global emissions would be subject to an identical per-unit emission tax. Alternatively, in a second-best case, where a climate policy is implemented only in parts of the world (we refer to this as the policy region), a uniform tax level on emissions may still be optimal in the absence of relevant links between emissions in the policy region and those in the rest of the world. In this case, regional emission reduction would translate one-for-one to reductions in global emissions, for which agents are willing to pay. However, both the first- and this second-best scenario are unlikely to correspond to the reality of current or near-future climate policies. First, all climate protection measures implemented thus far cover only a fraction of global emissions, and there is no global agreement in sight for the remainder of the decade. Second, major sources of fossil energy and anthropogenic CO_2, notably oil, natural gas and to some extent coal, are traded on global markets rather than only on regional markets (as are other goods whose production depends on the fuels). This implies that consumption reductions in one region will directly impact the resource availability and consumption in other regions, that is, the independence of emissions across regions is violated for the most important sources of anthropogenic CO_2 emissions. The global character of the fuel supply is a primary reason why a regional emission change does not generally imply a global emission change of the same magnitude. This is the well-known issue of carbon leakage (e.g., Felder and Rutherford, 1993, and Burniaux and Oliveira-Martins, 2012).

An efficient market measure motivated by climate protection implies uniform marginal emission costs for (indirect) *global* rather than regional emissions. As a regional policy can, however, only sanction regional emissions, an efficient second-best[1] policy must weight these regional emissions by the degree of influence they have on global emissions. The various primary fuels used in today's economy have strongly varying supply characteristics. For example, brown coal is often only consumed regionally[2]; coal reserves are often considered as practically unlimited[3]; oil and gas are globally traded and exploitable in limited amounts at increasing costs; and locally or regionally consumed wood is, in

[1]The policy is considered second-best because it is regional instead of global.

[2]See, e.g., IEA (2011), Part IV: The various Tables '3. Coal and peat production by type' and '8. Coal trade by type of coal' for the various surveyed regions.

[3]See, e.g., van der Ploeg and Withagen (2011, 2012) and Burniaux and Oliveira-Martins (2012). The strong characteristic difference between oil and coal supply is also pointed out in Burniaux et al. (1992) and Golombek et al. (1995).

some circumstances, renewable. Thus, a *regional* change in the consumption of one of the different fuels implies a *specific* variation in the *global* consumption of that fuel as well as other fuels. The optimal regional CO_2 price contains a proportionality factor that reflects the extent to which regional emission changes translate into global emission changes, and this price is, therefore, likely to vary substantially across fuels. This implies that it is inappropriate for a regional market-oriented policy to weight (and thus, to price) all domestic emissions uniformly. This paper addresses the fuel dependency of optimal regional emission weighting.

Neglecting *fuel*-dependent prices, the traditional carbon leakage literature has largely restricted attention to economic sector-specific leakage and terms-of-trade factors that imply *sector*-specific carbon pricing and, eventually, sector-wide policy exemptions. Hoel (1996) provided an extensive analysis of sector-specific differentiation of a unilateral CO_2 tax considering a single aggregated fuel. More recently, Böhringer et al. (2010) introduced a specific technique to distinguish between the efficiency-related leakage motive and the terms-of-trade reason for sector-differentiation of a unilateral tax. In contrast to their analytical model, their numerical analysis of US and EU policies distinguishes between a number of different fuels. However, the considered tax was still wholly sector-specific, and fuel-specific taxes were not considered in their paper. Similarly, Kirchgässner et al. (1998) examines the importance of sectoral exemptions on the economic and environmental impacts of a unilateral climate tax. Kirchgässner (2001) discusses the reasons why the optimal climate taxes may be sector-specific if, according to political economics or ordinary people's preferences, the objective is to limit tax revenue rather than simply the excess burden. Finally, Burniaux and Oliveira-Martins (2012) extensively examine the differences between oil and coal in terms of supply elasticities and global market integration. While they identify the impact of these market characteristics on the leakage rate of unilateral climate policy, their focus remains on a uniform carbon price, optimized not with respect to the carbon leakage but simply for respecting a specific *regional* emission threshold.

While Golombek et al. (1995) have addressed the issue of the optimal regional fuel-specific tax structure, the present analysis extends their study in two important ways. First, their focus remained on a static model, notably assuming an isoelastic, static supply of fossil fuels. This is in contrast to one of the most distinguishable features of the supply of non-renewable resources; that is, the fuels are exhaustible, with extraction costs that are, in the medium-term, increasing in the amounts previously extracted. Here, the exhaustibility of the fuels is explicitly considered, within the framework of a numerical dynamic model of the fuel markets where suppliers strategically allocate the extraction of their fuels over time, maximizing their present discounted net revenues subject to the (increasing) extraction costs. As will be explained, this is crucial, as the concept of a static leakage rate is inherently incompatible with exhaustible emission sources. Second, their static framework did not allow them to consider future developments in the fuel market. In reality, the supply of solid, liquid and gaseous fossil fuels may dramatically change from the currently observed pattern once the relative availability of specific fuels significantly changes due to advanced degrees of exhaustion. As an example, fuel transformation processes, such as coal-to-liquids (liquefaction), may become widespread if the extraction cost of oil increases further and coal remains abundant. Using a general equilibrium model with a detailed representation of the supply of petroleum, and other energy products in general, and a bottom-up implementation of coal-to-liquids processes, Chen et al. (2011) estimate that liquefaction could account for one-third of the global liquid fuel supply in 2050. Allowing for such a fuel transformation process when the fuel prices render it economical, the model developed here is used to investigate the potential implications of these processes for the optimal unilateral climate tax structure.

In addition to these central differences to the study of Golombek et al. (1995), the present analysis focuses on the economic concept of a general WTP for climate protection rather than on a fixed (global) emission reduction, as assumed in the numerical application in Golombek et al. (1995). The present study does, however, follow Golombek et al. (1995) by focusing on the market for fuels. This seems a suitable approach, as, for example, McKibbin and Wilcoxen (2008) and Böhringer et al. (2010) have shown that the trade of non-energy goods is of minor importance for both leakage and terms-of-trade effects – these effects are dominated by the international trade in fuels.[4] Similarly, Oliveira-Martins (1995) and Burniaux and Oliveira-Martins (2012) find that the leakage effects are primarily determined by the fossil fuel market, while trade characteristics of consumer goods are less important.

The optimal regional, fuel-specific carbon taxes determine the time-path of the consumption of the various fossil fuels and the optimal time-path of the consumption of the fuels is the central issue in van der Ploeg and Withagen (2011). Regarding the optimal carbon tax pattern, their analysis, on the one hand, is limited to a focus on *global* policies, and on the other hand they disregard the issue of the imperfect substitutability of the fuels as inputs to specific end-uses. In reality, society does not simply have a demand for a specific amount of 'energy', but it has a demand for different forms of energy carriers that are to be used simultaneously. While, for example, liquid oil could be a valid substitute for many applications that currently feed on solid fuels, the inverse is not true with current technologies. In other words, the substitution would need specific fuel preparation, such as coal liquefaction or the switch from combustion engine-based mobility to vehicles powered by coal-derived grid electricity, with potentially large efficiency losses and overhead costs. This has important repercussions on the second-best time-paths of fuel consump-

[4] The simulation results of Fischer and Fox (2011) suggest the same conclusion.

tion achieved with the second-best policy instrument of unilateral, fuel-specific carbon taxes, as we will demonstrate herein. In this sense, certain portions of the present paper can be considered as a synthesis of the static analysis about fuel-specific unilateral carbon pricing by Golombek et al. (1995) and an analysis of van der Ploeg and Withagen's (2011) study on global policies and the optimal time-path given exhaustibility but without the issue of fuel-specific final energy demand.

The (substantial) uncertainty about the long-term climate damage induced by carbon emissions is here not directly considered. Golosov et al. (2011) develop an integrated dynamic stochastic general-equilibrium model to analyze optimal oil and coal taxes taking into account uncertainty about climate costs that is resolved only in the future. Their analysis is, however, also limited to an optimal global climate policy and thus not concerned with leakage effects. Similarly to van der Ploeg and Withagen (2011), they assume oil and coal to be perfect substitutes, a view which is rejected here. Interestingly, Golosov et al. (2011, p. 28) indicate the possibility of the use of liquefied coal in combustion engines as a reason for their assumption of the perfect substitutability between the fuels. In our view however, while liquefaction is allowed for here as well, the fact that this process may become relevant in future exactly shows that oil and coal are only imperfect substitutes: while in some applications the two fuels may be substitutable without large energy losses and overhead costs (consider, e.g., the replacement of coal by oil in stationary power stations), applications where coal can only be used after liquefaction imply substantial overhead costs in terms of capital, labor and energy.[5] Finally, while Golosov et al. allow for emission discounting, they use a fuel reserve model that is more stilized than that used here – they assume a fixed amount of oil available, worth around 30 years of current consumption and extractable without costs, and coal is assumed to be of limitless supply – and their model does not explicitly take into account the possibility of future climate measures.

In today's economic environment, the different uses of the various types of fuel suggest that demand characteristics vary considerably across fuels. For example, cheap coal can be used for electricity production and for some other immobile purposes, while notably in the transport sector with explosion engines and for simple apartment heating systems, consumers rely on liquid (or gaseous) fuels. Clearly, there exists a certain substitutability. As an example, depending on the prices, one can heat an apartment with electricity (from coal) instead of directly burning oil (or gas). That the fuels are non-perfect substitutes seems logical as expressed by the large amounts of coal, oil and gas that are simultaneously consumed since many decades, despite (short- and longer-term) shifts in relative prices over the past. While therewith the demands for the various fuels are complexly intertwined, corresponding cross-price elasticities should generally allow an acceptable

[5] For example, energy losses in coal-to-liquids processes are very large. Overall energy efficiencies of CTL processes are close to 50 % (Bartis et al., 2008).

approximation of the real demand structure. In the long run, however, it is important to consider, other than this substitutability in the final demand, that significantly large price differences may render the transformation of fuels profitable. Due to the large coal resources, this may lead to coal gasification or liquefaction (i.e., coal to oil transformation) in the future and, eventually, gas to liquid processes.

The literature provides a considerable number of estimates of leakage rates for regional greenhouse gas emission reductions. The suggested rates cover the full range of imaginable values. As an example, Böhringer et al. (2010) find leakage rates of 35–40 % for unilateral action for the EU, and 15–20 % for the US. While a number of studies regarding the effects of the Kyoto agreement find leakage rates of approximately 20 %, several other studies suggest values of approximately 5 % (see Burniaux and Oliveira-Martins, 2012, for a short overview). Still others argue that leakage may exceed 100 %. For example, Babiker (2005) finds leakage rates of up to 130 % when taking into account industry dislocation and economies of scale. Finally, Di Maria and van der Werf (2008) model how directed technical change in the climate policy region provides efficiency enhancements that may reduce emissions in the non-policy region even if the latter is not concerned about the climate.

Independent of the large differences between these values, a policy maker interested in the medium- or longer-run effects of unilateral action has a particular problem with the proposed leakage rates from most of these studies. They neglect the time dimension or treat it only inadequately, and therewith typically do not properly examine the underlying economic reasons why the leakage rates may be modest in reality. Instead, their models find limited leakage rates for mostly technical reasons. To see this, note that the models do typically neither apply any discount rate for future emissions, nor assume any specific future technological or political climate relevant changes to drastically limit the scope for future emissions. If no technical or global political breakthrough in terms of climate protection is foreseeable, any unilateral carbon tax may, however, only postpone the time until which, for example, virtually all oil physically available and reasonably extractable is consumed. In this case, domestic oil consumption reductions from a unilateral climate policy are, in the medium-term, almost entirely compensated by emission increases throughout the rest of the world (ROW). Even if parts of these ROW emission increases occur somewhat later than the domestic emissions would have in the absence of any regulation (it is not *a priori* clear whether the time shift is large or small), the overall expected leakage is, in the absence of the discounting of future emissions, approximately 100 %. Therefore, modest emission leakage rates seem logical only under the assumption of future changes in the fuel market framework or if future emissions are discounted. Yet, the reasons for which most studies have come up with limited carbon leakage rates are of a different nature. For example, Böhringer et al. (2010), Oliveira-Martins (2012), Perroni and Rutherford (1993) and Babiker (2005) use static models. In such static models, the limited leakage rates typically stem from an *ad hoc* concept of a static fuel supply function. Therewith they do not capture that fuel consumption savings in one period may be consumed in later periods when otherwise the fuel reserves would already have been depleted, i.e. the fuel simply lasts longer but will ultimately still be consumed. This applies even to the study of Di Maria and van der Werf (2008) who assume endogenous directed technological change but disregard the fuel-market channel of leakage and the fossil fuels depletion.

Another large fraction of the leakage literature uses dynamic models but exhibits some shortcomings in the treatment of the time dimension. For example, the dynamic models in Bollen et al. (1999), Burniaux (2001), McKibbin et al. (1999), McKibbin and Wilcoxen (2008) and OECD (2009) seem not to feature endogenously depleting fossil fuel reserves, but instead make specific assumptions on the exogenously given resource availability in the different time-periods. Therewith their models do still not fully capture that lower fuel consumption in early periods may simply imply that the saved resources may be consumed later on. The reason for their modest leakage rates may thus also primarily be found in the negligence of the dynamic, endogenous depletion of the resources. That the (fuel) dynamics receives insufficient attention in a large fraction of the leakage studies is not only astonishing because of its obvious importance due to the long term character of climate change and the inherent exhaustibility of the fossil fuels, but also because with Felder and Rutherford (1993) and Manne and Richels (1991), early authors had already used dynamic models with at least partially endogenous fuel depletion mechanisms. Note that, however, the approach in Felder and Rutherford (1993) and Manne and Richels (1991) was rather a hybrid solution between an exogenous and an endogenous fuel depletion path, e.g. with constant ratio depletion elements, not allowing forward looking resource owners to choose a fully flexible fuel extraction path. Other examples of leakage studies that feature endogenously depleting fuels are Manne and Richels (2000) using the MERGE model, and Babiker and Jacoby (1999) using the EPPA model. Similarly to Felder and Rutherford (1993) and Manne and Richels (1991), they use simulation periods that end in 2050 or in 2100 and do neither discount emissions, nor assume that up to this point in time a definite technological or political solution to the carbon emission problem would be found.[6] Thus, it seems that even in these studies the modest leakage rates may be rather technical results. These may be reversed if the model horizons would be longer, allowing a major fraction of the domestically saved emissions to occur in the remainder of the world.[7] Thus, it appears that the most important reasons for which leakage may over

[6] Manne and Richels (2000) explain that any judgement on a Kyoto policy crucially depends on what happens in the decades after the initial committment period centered around 2010, and study scenarios until 2050. They do not model what happens beyond that period. As the dynamic model in section 5 shows, an important fraction of leakage from current policies may occur in the decades after 2050.

[7] Some studies assumed coal to be of infinitely elastic supply without depletion, and allowed for re-

the long run be substantially below 100 per cent, are typically not explicitly addressed in literature. The proposed leakage rates are thus, *per se*, only of limited value for forward-looking, concerned societies resp. their policy makers. This seems especially clear as the primary reason for concern about climate change is that caused *future* global warming is anticipated today – if one exhibited too strong a time-discount rate with respect to future temperature changes, one would hardly be concerned about the climate problem at all. It seems obvious, then, that current policy evaluations must take into consideration the effect that the current policies will have on emissions also in the decades, and perhaps centuries, to come. In the present study, the time dimension, especially in terms of discounting for future emissions and the possibility of future market framework changes, is explicitly taken into account, in a model that in addition features fully endogenously depleting fossil fuel reserves.

After a discussion of the aim of unilateral climate action in in the following section, section 3 introduces the general equilibrium translation factor (GTF), which expresses how regional emission reductions due to specific unilateral action translate into global emission changes – the basis for the calculation of the optimal structure of the regional tax.

Section 4 briefly discusses the nature and energy economics of liquefaction processes in which coal may be transformed into synthetic liquids that provide a direct substitute for oil. In the numerical part of section 5, insight regarding the importance of the discussed effects for the optimal carbon tax pattern is provided, derived from a dynamic numerical model of the oil and coal market, with parameters roughly fitted to real-world characteristics. The model assumes a carbon tax in the OECD and no significant climate protection measures in the rest of the world. In the base specification, the limited substitutabilty of the fuels and the steeply increasing extraction costs for oil imply large overall oil-leakage rates (leakage over space and time) of approximately 50 % and, thus, preferable regional taxes on oil that may be as low as half the OECD's WTP for global emission reductions. At the same time, the significant abundance of coal implies an almost one-for-one reduction of global emissions with respect to regional coal emission reductions and, thus, an optimal climate tax on coal consumption that closely corresponds to the WTP for global emission reductions.

This pattern is reversed in the case where a synthetic liquid fuel from coal liquefaction, twice as carbon-intensive as genuine oil, replaces crude oil in the near-term future. In this case, each barrel of regionally saved crude oil implies that almost an entire barrel less of synthetic fuel needs to be produced worldwide, leading to an optimal carbon price on domestic oil consumption that is close to twice the domestic WTP for global emission

placement of liquid fuels by coal. In the absence of time-discounting of emissions – as well as of specific alternative technologies to replace the fossil fuels –, this approximation is valid only for the medium-term future, as in the long run even coal reserves deplete.

reductions, even during the periods prior to the introduction of the coal liquefaction process. This means that in a scenario with future liquefaction, current unilateral oil savings rates may be subject to a large negative overall leakage rate of close to -100 %; that is, the worldwide emission savings may be even larger than the domestic savings. Interestingly, Felder and Rutherford (1993) have also suggested negative leakage rates from a regional (not fuel-specific) climate tax during the years when liquefaction starts to play a role in the rest of the world. Besides the abovementioned issues with the somewhat *ad hoc* representation of the fuel-extractions in their model, they have restricted their attention to instantaneous leakage rates for each period rather than considering the effect of *current* taxes on *future* emissions.

An extensive sensitivity analysis, allowing for a number of alternative scenarios and parameter specifications, indicates that the findings are largely robust to a large number of deviations from the main assumptions in the model. The finding that reductions in current oil consumption may be especially important if a reduced availability of oil implies an earlier switch to synthetic carbon intense fuels is consistent with Burniaux et al. (1992) who explained the importance of reducing fossil fuel subsidies to prevent the early production of polluting synthetic fuels.

Section 6 provides a discussion of the results, and section 7 concludes. The issue of non-CO_2 greenhouse gas emissions is consciously neglected throughout the discussion, and the identified need to differentiate CO_2 prices across fuels is independent of such additional greenhouse gases. Additionally, reasons beyond direct climate protection, such as distributional concerns and other issues related to governmental revenue requirements, which have been suggested as eventual reasons to impose fuel-specific taxes[8], are not considered in this study.

2 Efficient Climate Tax

A tax motivated by climate protection is efficient only if it charges every action at a fixed rate per unit of induced global greenhouse gas emission equivalents. Depending on discount factors and the evolution of climate damages related to marginal emissions, the corresponding tax rate may vary over time. Ignoring other emissions and the time-dimension, in a static model concerning only CO_2 emissions, the efficiency criterion implies a constant Pigou tax on global CO_2 emissions. Even if the politically agreed-upon WTP for emissions abatement is lower than the estimated global benefits, basic economic principles explain that a tax may optimally be uniform over all global CO_2 emissions. Generally, a uniform tax of a level equal to the WTP for marginal emission reductions induces all

[8] See, e.g., Poterba (1991), pp. 21–23, where these issues are mentioned.

actors to implement every possible abatement measure that achieves CO_2 savings at a per-unit cost lower than the tax level. Measures with higher per-unit abatement costs will not be undertaken. Thus, the resulting amount of emission reductions could not be achieved in any other way with lower total costs; the abatement achieved with such a tax is efficient. This reason supports the widespread belief that, from an economic point of view, CO_2 taxes ought to be the same for emissions independent from the exact process through which they were created.

For our discussion, it may often be preferable to refer to emission generating processes rather than emissions, even though when global emissions are considered this is only a matter of definition: we may tax processes that create emissions or the therewith generated emissions.

Considering emission generating processes, the efficiency requirement for an emission-pricing scheme suggests that every process should be charged uniformly at the rate of the politically agreed upon WTP per unit of global emissions it induces. This idea is emphasized in Proposition 1.

Proposition 1 *An efficient CO_2 tax can be implemented by charging every emission-generating process at a fixed amount τ per unit of global CO_2 emissions it induces, where τ is the marginal willingness to pay for emission reductions.*

While Proposition 1 addresses emission taxation, it can directly be applied to cap-and-trade mechanisms as well. If functioning well, such mechanisms largely correspond to CO_2 taxes with the level of the equivalent tax being the equilibrium certificate-price in the cap-and-trade system. In the following, we discuss the implication of Proposition 1 on optimal regional climate policy.

3 Regional Policy and General Equilibrium Translation Factor GTF

Currently, and probably for the near future, climate policies are not only less stringent than what economic analysis of presumed climate damage projections suggests, but encompass also a limited fraction of the world respectively of its CO_2 emissions. Thus, emission taxes may not tax all global emissions but only those originating from within the region of the climate coalition subject to the particular climate policy. Because the economies of the climate coalition and of the rest of the world are strongly interlinked, emission processes in one region are likely to be relevant to emission processes in the other. As an example, if fossil fuels consumption – the source of 75 % of anthropogenic

CO_2 emissions – is increased in one region, this drives up worldwide fuel prices and likely lowers consumption in the other region. Any regional process with globally traded net inputs or outputs is likely to substantially influence emissions in the other region. Due to these linkages, a process that creates a specific amount of emissions in one region is likely to imply a substantially different overall change in global emissions. Let the ratio between the induced global emissions and the direct regional emissions of a process be called its General Equilibrium Translation Factor, GTF:

$$\mathrm{GTF} \equiv \frac{e_g}{e_l}, \tag{1}$$

where e_l indicates the locally generated emissions of the process and e_g the implied global emission changes. For the combustion of fossil fuels, the GTF is likely to be substantially lower than 1 but larger than 0 due to the mentioned mechanism relating to the worldwide equilibrium price for globally traded fuels.

As stated in Proposition 1, efficient taxation of different processes requires charging them at a fixed amount per unit of global emissions they induce. This relationship holds independently of whether the policy in question is regional or global. If regional emissions are taxed, the optimal tax on emissions is thus proportional to the GTF, as is emphasized in Proposition 2.

Proposition 2 *The optimal regional tax τ on emissions originating from a specific process equals the willingness to pay for the reduction of global emissions, τ_0, augmented by the GTF,*

$$\tau = \tau_0 \cdot GTF,$$

with GTF defined according to Eq. 1.

As the GTF can depend on various (inter-regionally traded) inputs and outputs of the emission-creating process, it is likely to substantially differ for emissions with different origins. This implies that a uniform tax across emissions from different processes, such as combustions of different types of fossil fuels, is inefficient. Instead, for example, the optimal taxes on emissions created by the combustion of globally traded oil should differ from those created by more regionally consumed low-yield coal.[9] See e.g. Burniaux and Oliveira-Martins (2012) for an extensive discussion on the differences in the market characteristics between oil and coal and how they impact the leakage effects.

[9] The World Coal Institute (2005) explains that only about 18 % of globally produced coal is internationally traded; the remainder is consumed domestically by its respective producers. According to their information, high transportation costs, which can amount to 70 % of consumer prices, imply that there effectively exist two regional markets, the Atlantic and the Pacific markets. As an example, only high-value coking coal is freighted globally from Australia, while less valuable coals are traded more regionally.

While Proposition 2 focuses on a climate tax, it also extends to cap-and-trade mechanisms. For such a mechanism to potentially be efficient, the various emissions must be weighted proportionally to the GTF, i.e., an emitter must hold an amount of emission allowances proportional to the local emissions created, augmented by the GTFs of the corresponding processes.

The GTF is relevant for the leakage discussion to which production sector-specific emission prices resp. abatement targets or even policy exemptions are linked. A key point in this analysis is that the GTF implies not only that sector-specific emission prices may have to be considered but also that the carbon price should be specifically differentiated between the various fuels from which the emissions are generated. This point has largely been neglected not only in practical policy implementations and related discussions but also in the theoretical literature on climate policy. Appendix A proposes a stylized partial equilibrium framework in which the GTF can be derived from basic market characteristics.

In the modern globalized economy, regional consumption of virtually any intermediate or final good, even those that do not directly relate to large amounts of CO_2 emissions, may have some impact on CO_2 emissions globally. In this sense, an optimal regional climate tax may not only tax processes that generate emissions in the climate coalition region but also impose positive or negative taxes on other processes.[10] For the remainder of the analysis, this possibility is neglected, as several studies have found that the most significant current impact of specific regional climate policy choices on emissions in the remainder of the world occurs through general equilibrium channel directly related to fossil fuel market equilibria rather than through non-energy goods (Böhringer et al., 2010; Oliveira-Martins, 1995; Burniaux and Oliveira-Martins, 2012). We thus focus entirely on fuel-specific GTF, i.e., on fuel-specific CO_2 prices.

Appendix A calculates the GTF and the corresponding optimal regional fuel tax in a stylized linear static model and Appendix B provides equivalent calculations in a general equilibrium framework.

[10] As a hypothetical stylized example, consider a good x which not only can be directly consumed without creating emissions but also figures as an essential input for some sorts of energy-related processes y in which large amounts of emissions are generated. Under some circumstances, the climate coalition may, in theory, impose a negative tax on the consumption of x as part of its climate protection policy, which one might like to refer to as an 'indirect global CO_2 tax'. Any additional amount of x consumed in the climate coalition region, which, due to other emission taxes on process y in that region may correspond to increased direct consumption of x rather than increased use of process y in that region, may reduce the supply of x in the remainder of the world and therefore contribute to curbing global emissions by reducing the use of the y-process in the remainder of the world.

4 Liquefaction

Liquefaction of soild fossil fuels (coal) has the potential to strongly change the future availability of liquid fuels. Because the future availability of fossil fuels determines leakage effects induced even by current taxes, liquefaction can therefore have a first-order impact on the optimal structure of current emission taxes. This section discusses this fuel transformation process which will be considered also in the numerical model in the next section.

Several processes exist through which coal can be transformed into synthetic liquid fuel, which can be conditioned for replacing oil and its derivatives in all major applications. South Africa produces 30 % of the liquid fuel that it consumes through such coal liquefaction processes (Sasol Synfuels International, 2005). While this currently makes South Africa the largest coal liquefactor, China has plans for a number of very large coal liquefaction plants, and proposals for plants exist in other countries as well.

Large amounts of coal can, in many places, be extracted cheaply for centuries. The International Energy Agency (IEA) suggests there are approximately 1000 billion tons (Gt hereafter) of proven recoverable reserves and approximatively 14 times that amount in additional estimated resources (IEA, 2011). Meanwhile, the era of cheap crude oil may end soon, given the current trend in annual consumption and the limited reserves. In their World Energy Outlook, the IEA (2010) estimates 1350 billion barrels (Gbbl hereafter) of proven conventional reserves and only 1250 Gbbl of estimated additional recoverable resources (of which 900 Gbbl are yet to be found). Accounting for current worldwide consumption rates[11], this implies reserve-to-production ratios of 46 years for oil and 210 years for coal. With respect to estimated recoverable resources, the ratios become 81 years for oil and 3060 years for coal.[12] Coal-to-liquids processes may become the predominant, or at least a very significant, source for liquid fuels relatively soon in the current century.

As the total economic and environmental costs of the production of synthetic oil remain a matter of dispute, it is unclear whether the fuel market will experience a massive deployment of coal-to-liquids production or, specifically, at what time that transition will occur. What is certain is that an important fraction of the liquefaction costs consist of the price for the approximately 1 ton of coal that is needed per 2 barrel (bbl) of produced synthetic oil (DOE/NETL, 2006 and Bartis et al., 2008).[13]

[11] 31 Gbbl of oil in 2009 and 4.7 Gt of coal in 2008, according to IEA (2010).

[12] Some 2000–3000 Gbbl of unconventional liquid fuels, exploitable only with considerably larger costs and assessed with larger uncertainty, could add another 80 years worth of current oil consumption according to the IEA (2005, 2008, 2010).

[13] In reality, the conversion factor depends on the type of coal used. While a rule-of-thumb estimate for the coal-to-liquids yield from bituminous coal is 2 (barrels of oil per ton of coal), it is slighly lower for subbituminous coal, about 1.8 (Bartis et al., 2008).

The main issue with the liquefaction processes may be their high emission intensity. DOE/NETL (2009) and EPA (2007) estimate that the 'mine-to-wheel' emissions from the resulting synthetic fuel may be more than twice as large as that of standard oil: half a ton of coal contains roughly 1 ton of CO_2, while a bbl of regular oil contains approximately 0.43 tons of CO_2.[14] Unless stringent global climate coalitions form in the near future, this high emission intensity may not prevent many places in the world from using liquefaction processes to produce oil that they can consume or sell at a high price on the future fuel markets.

The prospect of future massive deployment of liquefaction processes has important implications for optimal unilateral climate policy already today. While current oil may contain a specific amount of direct (i.e., in the final consumption) – or, not too much higher, well-to-wheel – emissions, the relevant factor for the optimal regional climate tax on oil emissions depends on the longer-run effect that the current oil consumption has on the global emission path. Liquefaction represents, in a certain sense, an upper bound on the price for which oil may, in the future, be sold on the market. Any oil that is more expensive to extract than the production of synthetic oil may not be exploited. Therewith, the total amount of extracted crude oil becomes, in the medium-run, relatively inelastic with respect to the demand for liquid fuels. In this case, any additional barrel of oil consumed today may imply almost an entire additional barrel of coal liquefaction taking place in the medium-term future. With a limited discounting of climate damages that occur during the time when liquefaction begins to replace a major part of the liquid fuels consumed, this implies that the optimal regional climate tax on oil may be much higher than our genuine WTP for climate protection. This issue is not trivial to deal with in a sensible analytical model that allows for profit-maximizing oil and coal owners. Therefore, it is examined with a numerical model in the next section.

Coal liquefaction may not be the only relevant fuel-transformation process. Depending on the relative availabilities and demands for coal, oil and gas, coal-to-gas and gas-to-liquids processes may, in reality, find rapid expansion at some future time as well.

5 Numerical Analysis in a Dynamic Framework

The models in Appendices A and B assume a static fuel supply. This is a limited view notably because fossil fuels are of finite supply, and extraction costs are expected to increase in the coming decades primarily for oil and gas. This increase is also expected in the longer run for coal because, although very large amounts exist, parts may be exploitable for considerably higher costs than today's coal. Accounting for the exhaustibility of the

[14] Values suggested by Hoel (2010).

fuels in an analytical model is complicated if the profit maximization of the fuel owners, as well as the fuel demand structure with non-zero (cross-)price elasticities, is taken into account. Moreover, in a variant of the model we also account for the possibility of synthetic oil to (partly) substitute crude oil as soon as the relative prices of the fuels allow liquefaction to be economic. To investigate the possible magnitudes of the optimal fuel-specific regional taxes (and, correspondingly, the fuel-specific leakage rates), a numerical model is developed in this section.

5.1 The Model

The model contains two fuel consuming regions, the OECD and the rest of the world (ROW or non-OECD), indexed by $r = \{o, n\}$. The OECD is assumed to impose a carbon tax, while the remainder of the world abstains from comparable climate protection measures. The two fuels considered are oil and coal, indexed by $i = \{1, 2\}$. Because gas has many features similar to oil, e.g. in terms of the exhaustibility and complementarity to coal, one may interpret 'oil' as representative of the ensemble of oil and gas, an approach suggested by van der Ploeg and Withagen (2011). The fuels are traded internationally at prices $p = [p_1, p_2]$.

Regional fuel consumption is denoted by $x_r = [x_{r,1}, x_{r,2}]$. Following Golombek et al. (1995), instantaneous regional welfare W_r is defined with three linearly separable terms: (i) utility from regional fossil fuel consumption $u_r(x_r)$, (ii) the total regional costs for the fuel provision $c_r(x_r)$ and (iii) the regionally perceived environmental costs $D_r(E)$, where E denotes the global carbon emissions[15]:

$$W_r = u_r(x_r) - c_r(x_r) - D_r(E) \,. \tag{2}$$

Each of the variables in Eq. 2 exists at each point in time $t \in [0..T]$, and the total regional welfare is defined as the present discounted integral of all instantaneous welfare values:

$$\mathbb{W} = \int_t W_{r,t}^{\delta \cdot t} \mathrm{d}t,$$

where $\delta < 1$ is the welfare time discount factor. Denoting ρ_{cons} as the discount rate, we can express the discount factor as $\delta = 1 - \rho_{\text{cons}}$.

Assuming the representative consumer in region r maximizes his welfare when he has to pay for his fuel consumption but neglects his emission externality, we find the first-order

[15] See Golombek et al. (1995) for the derivation of this structure from a regional economic setting where fossil fuels are used also as an intermediate input for final goods production.

conditions (FOCs)

$$\frac{\partial u_r(x_r)}{\partial x_{r,i}} \stackrel{!}{=} p_i \underset{i}{\forall},$$

if the emissions are not taxed, and

$$\frac{\partial u_r(x_r)}{\partial x_{r,i}} \stackrel{!}{=} p_i + \tau_i \varepsilon_i \underset{i}{\forall},$$

if emissions are taxed in region r, where τ_i is the tax rate on emissions from domestic consumption of fuel i and ε_i is the emission intensity of fuel i.

Suppliers are assumed to sell their fuels on the international market under perfect competition. The exhaustibility of the fuels is modeled with an extraction cost curve that indicates the marginal cost of extraction after a specific cumulative amount of the fuel has been extracted. This depletion concept is the logical consequence of the Herfindahl rule (Herfindahl, 1967), which states that (given positive real-interest rates) profit-maximizing resource owners extract the fuels ordered in a sequence according to extraction costs: the resources with the lowest extraction costs are extracted first, and the ones with the highest extraction costs are extracted last.[16] Given this standard rule, and assuming the resource owners discount their net revenues with the revenue discount rate $\rho_{\text{res}} > 0$, a current-value Hamiltonian for the profit maximization problem for the owners of one specific fuel reads as follows:

$$\begin{aligned} \mathcal{H} &= r_t \cdot (p_t(r_t) - e(A_t)) - \lambda_t r_t \\ \text{s.t.} \quad & \dot{A}_t = r_t \text{ and } A_0 = 0, \text{ i.e. } A_t = \int_{s=0}^{t} r_s \mathrm{d}s, \end{aligned} \tag{3}$$

where r_t is the amount of the fuel extracted at time t, A_t is the cumulative amount of the fuel extracted from the initial period up to time t, normalized to 0 for $t = 0$, $e(A)$ is the marginal extraction cost after the extraction of the A units of fuel that could be extracted at the lowest costs, and $p_t(r)$ is the inverse demand for the considered fuel at time t: the price p_t results on the international fuel market if r units of the fuel are supplied (with non-zero cross-price elasticities of fuel demand, p_t may depend also on the amount of the other fuel supplied at time t).

The Hamiltonian in Eq. 3 yields the follwing two FOCs:

$$\begin{aligned} \frac{\partial \mathcal{H}}{\partial r_t} = 0: &\quad p_t(r_t) \stackrel{!}{=} e(A_t) + \lambda_t \\ \dot{\lambda}_t = \rho_{\text{res}} \lambda_t + \frac{\partial \mathcal{H}}{\partial A_t}: &\quad \dot{\lambda}_t \stackrel{!}{=} \lambda_t \rho_{\text{res}} - \dot{e}_t, \end{aligned} \tag{4}$$

[16] While in a simple theoretical framework this rule should hold not only in a monopolistic but also in a competitive framework, e.g. Beermann et al. (2011) give reasons why this rule is often only an approximation to reality.

where we define $e_t \equiv e(A_t)$,[17] and λ_t is, at time t, the shadow value for a marginal unit of resource stock after the cumulative extraction of A_t previous units. As the first FOC (Eq. 4) shows, the resource shadow value is the difference between the price that the resources achieve on the market and the extraction costs, that is, the per-unit resource rent received by the resource-owner for sales at time t.

5.2 Numerical Illustration

Following Golombek et al. (1995) we assume quadratic fuel-consumption-derived utilities u_r. These are calibrated using the current regional consumption of oil and coal at current prices in the OECD and the non-OECD region (see Appendix D) and the desired direct- and cross-price elasticities of the demand. Again closely following Golombek et al. (1995), the direct price demand elasticities are set to -0.9 for both fuels in both regions, and the cross-price elasticities are 0.2, on average, in the standard scenario.[18]

The curve of the extraction cost for oil as a function of cumulative extractions is a third-order polynomial fitted to the oil cost curve estimated by the IEA (2005). The third-order polynomial form allows a good fit to the IEA-curve. As detailed estimates for the costs of exploiting substantial parts of the tremendous amount of existing coal resources are unavailable, a modest exponential increase of coal provision costs is assumed, accounting for the estimated amount of existing coal resources. The parameter cd is the amount of coal extractions after which the coal extraction costs are assumed to double.

The OECD is assumed to present-discount its future instantaneous utilities at a pure-time preference rate of $\rho_{\text{cons}} = 5\,‰$,[19] that is, $\delta = 99.5\,\%$, and the less patient resource owners are assumed to have a discount rate of $\rho_{\text{res}} = 3\,\%$. The emission intensity is $0.43\,\text{tCO}_2/\text{bbl}$ for genuine oil and $2\,\text{tCO}_2$ per ton for coal.

Liquefaction is assumed to require 1 ton of coal per 2 barrels of oil produced (DOE/NETL, 2006). In addition to the input costs for this coal, the process is assumed to be subject to a constant additional fixed cost for each barrel of synthetic fuel produced, c_l, which takes

[17] Note that as $r_t = \frac{\partial A_t}{\partial t}$, we have $\dot{e}_t \equiv \frac{\partial e(A_t)}{\partial t} = \frac{\partial A_t}{\partial t}\frac{\partial e(A_t)}{\partial A_t} = r_t \frac{\partial e(A_t)}{\partial A_t}$.

[18] Golombek et al. (1995) used -0.9 for the direct price elasticity for the fuel consumptions in the OECD and -0.75 for the ROW, and they also used lower cross-price elasticities, with an average of 0.1. Here, the (in absolute terms) larger demand elasticity in the Non-OECD region represents the interpretation that as economies of the developing countries progress over time, their fuel demand structure may approach that of the developed countries. The larger cross-price elasticities represent the interpretation that in the longer-run, substantial relative price shifts of the fuels may lead to non-negligible fuel substitution. The cross price elasticities for oil to coal are 0.05 in both regions and the coal to oil elasticities that then follow are 0.46 and 0.21 for the OECD and the ROW.

[19] In their very influential works, Nordhaus (2008) suggests a discount factor for the emisisons of $1.5\,\%$ and Stern (2007) suggests $1\,‰$. The present choice is a compromise between these values. Any extended discussion of the reasons for higher and lower values for the controversial and important discount factor is beyond the aim of the present study whose purpose is explorative rather than to provide precise quantitative results.

on a value of 15 \$/bbl (of produced synthetic oil-substitute) in the standard scenarios. In the simulations that allow for liquefaction, the overall costs of the process represent an upper bound for the oil sales price such that any demand that cannot be met by the standard oil supply for that price will be provided as synthetic fuel from coal-liquefaction.

To cover the period for which the considered processes imply an interesting dynamics, the simulation period stretches over 200 years. Until then, the major fraction of oil that is extractable for reasonable costs is consumed (unless coal liquefaction is cheap enough to replace genuine oil early). In addition, due to the exponential discounting, what happens after the 200 years has only a limited weight in the present-discounted sum of all future utilities.[20]

5.3 Results

Model Dynamics without Tax. Fig. 1 presents the model dynamics in a business-as-usual scenario, that is, without any climate tax and when liquefaction does not become an option in the future. As a standard, the coal extraction costs are assumed to increase slowly, with a doubling of the costs only after the extraction of a large fraction of the estimated coal resources, $cd{=}10\,000$ Gt. This may, on first sight, seem optimistic in terms of the resource availability, but given that the large reserves of coal are only slowly depleted in any case, it does not seem unrealistic that technological progress may almost compensate for the more complicated access to the reserves.[21] Fig. 2 shows the results of the same simulation with the coal extraction costs doubling much more rapidly, after every extracted 1000 Gt, which mainly changes the price increase of the coal but has only a limited effect on the fuel consumption paths, somewhat reducing coal consumption in the later periods.

Figs. 1 and 2 confirm the expectations that oil is depleted relatively quickly over time, and its price on the market rises rapidly, such that parts of the oil are replaced by coal in the longer run. This then leads to an increase in coal consumption over time during the initial periods before the increasing coal extraction costs eventually lead to the decline of the coal consumption rate as well (as observed after some 140 years in Fig. 2).

Fig. 3 shows the dynamics for a baseline scenario in which liquefaction is possible with an overhead cost of $c_l = 15$ \$/bbl.

The dynamics in Fig. 3 is more complex than in the two previous figures. After approximately 80 years, liquefaction becomes economical and takes off. The price curves explain

[20] For the resource owners, with a discount rate of 3 % p.a., it is virtually negligible, with a weight of 0.2 % for revenues accruing in 200 years, and for the consumers, with a discount factor of 5 ‰ p.a., a weight of around 35 % for the utility after 200 years, and around 20 % after 300 years obtains.

[21] The model does not explicitly account for technological progress.

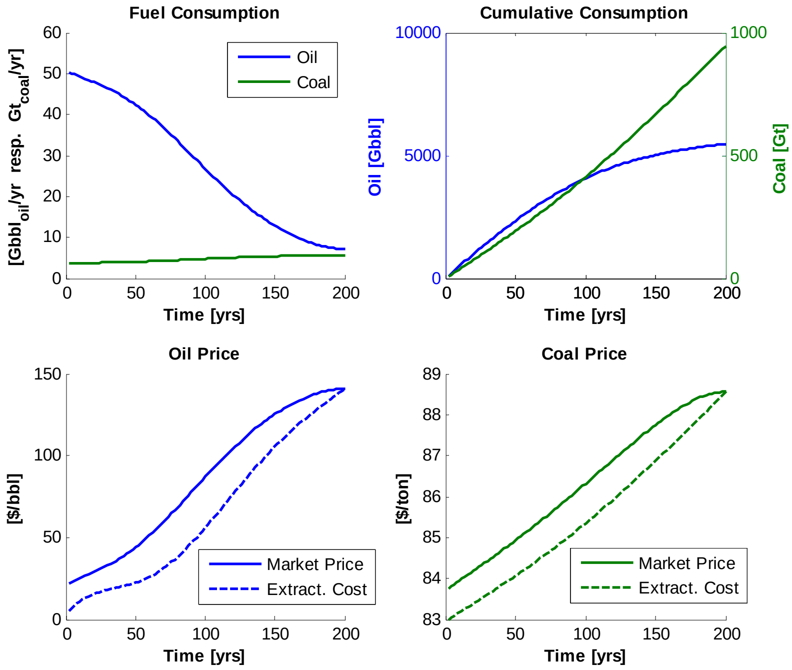


Figure 1: Dynamics without liquefaction, cd=10 000 Gt

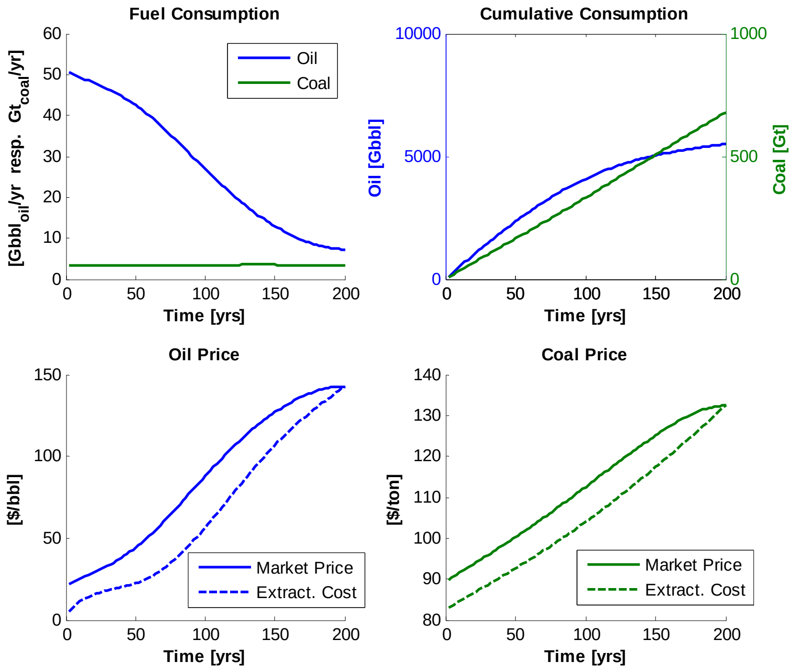


Figure 2: Dynamics without liquefaction, cd=1000 Gt

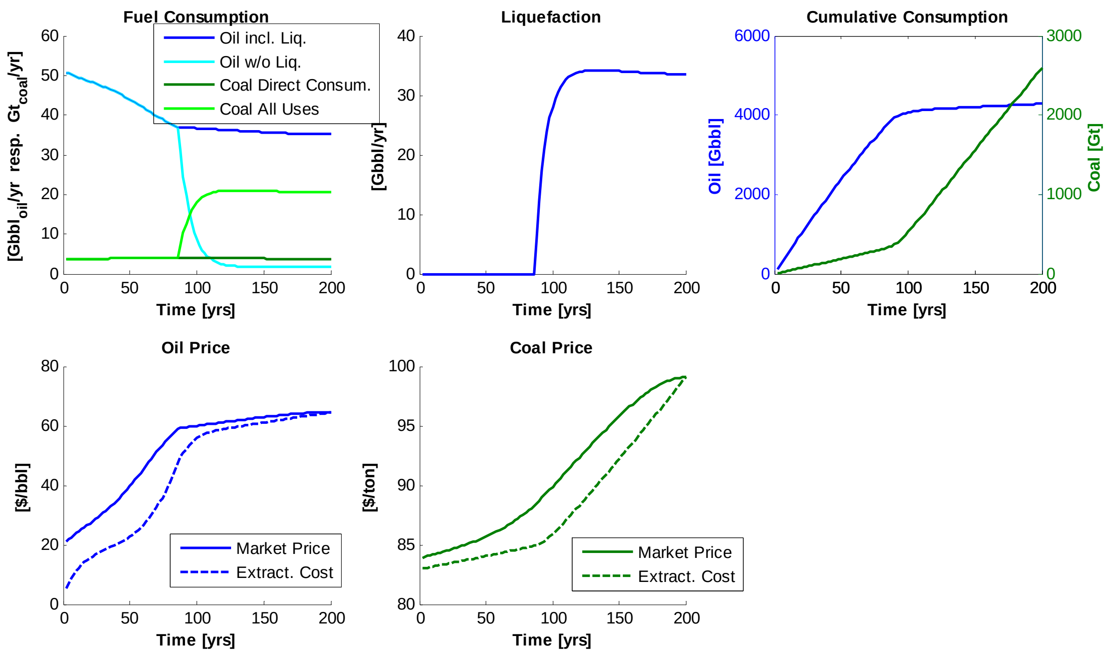


Figure 3: Dynamics with liquefaction, c_l ***= 15 $/bbl***

this point in time: with coal being sold at approximately 90 $/t and the overhead cost of 15 $/bbl,[22] the production costs for synthetic fuel are approximately 60 $/bbl. This corresponds to the oil market price indicated at the time when liquefaction begins. From that point forward, the extraction rate of genuine oil drops rapidly to a low level, while the overall extraction rate of coal increases rapidly to a level much higher than during the first 80 years: considerable amounts of coal are used for the production of synthetic liquid fuel to replace most of the genuine oil. Accordingly, oil extraction costs and prices increase slowly after the first 80 years, while coal costs and coal market prices start to increase more rapidly after 80 years than initially. Synthetic fuel never replaces genuine oil completely because the (still slowly) increasing coal extraction costs (resp. sales price on the market) imply that in each period a specific (small) additional amount of genuine oil reserves become cost competitive against synthetic liquid fuel.

While Figs. 1 and 3 show the dynamics for the standard model setting with constant fuel demand, Figs. 4 and 5 depict the fuel consumption dynamics for a path of increasing fuel demand calibrated approximately according to IEA projections, and for a lower discount rate of resource owners, $\rho_{\text{res}} = 5\,‰$ instead of the standard $\rho_{\text{res}} = 3\,\%$. In these figures, the fuel consumption paths are consistent with current observations: the current oil consumption is very close to the real consumption of 31 Gbbl/yr for oil and 5 Gt/yr for coal (IEA, 2010), especially in the case without liquefaction. While it may not seem intuitive that the typical fossil fuel owners are very patient and discount their future net revenues only

[22] Recall that a ton of coal yields 2 barrels of synthetic oil.

at a rate of 0.5 % p.a., one reason why the model yields realistic current fuel consumption results when assuming such a low profit discount rate could be the fact that in reality, notably for oil extraction the marginal extraction costs are typically increasing not only in the cumulative extractions but also in the rate of extraction, as more capital is needed and physical constraints increase the energy needed to extract the fuel at a higher rate, and geological factors often imply risks of a perturbation of the fuel reservoir if the oil is pumped too rapidly. Extraction costs that increase in the rate of extraction can have a similar effect of postponing parts of the fuel extractions as lower discount rates have. In the case of the assumed path of growing fuel demand, liquefaction starts in approximately 50 years. Interestingly, this compares well to the starting time for liquefaction suggested by the model results in Felder and Rutherford (1993), where liquefaction started mainly around 2050. Similarly, the dynamic general equilibrium model developed by Chen et al. (2011) suggests that around this time liquefaction replaces more and more crude oil.

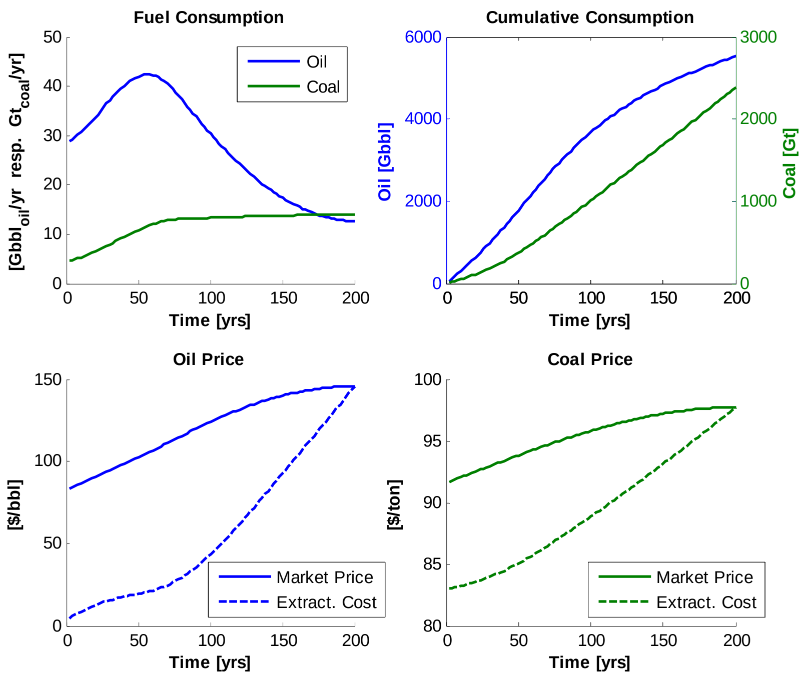


Figure 4: Dynamics without liquefaction, **growing demand and** $\rho_{\text{res}} = 5\,‰$

For brevity, we do here not provide the regional split of the fuel consumptions. Corresponding plots are found in the next subsection, for the tax effects. Notably in the scenario with growing demand, the initial fuel consumption in both parts of the world corresponds to actual values (well within the 10 %-range) and the regional fuel consumption growth rates in the two regions correspond closely to those from the IEA projections (see the growing demand part of the sensitivity analysis for a description of the IEA growth path).

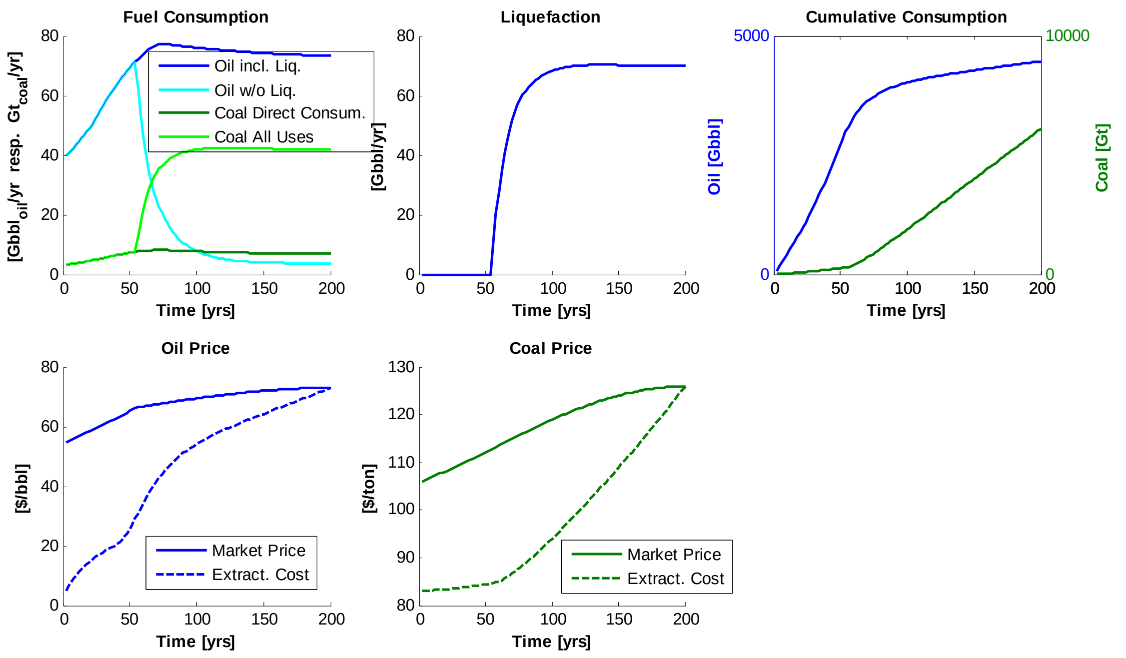


Figure 5: Dynamics with liquefaction, $c_l = 10\,\$/bbl$***, growing demand and*** $\rho_{\text{res}} = 5\,‰$

Finally, Fig. 6 presents the situation when oil is supplied monopolistically instead of competitively. Because the monopolistic supplier takes into account the effect of additional sales on the price he achieves for each of the sold units, he leaves some units of the oil in the ground even if they could be extracted for costs below the oil sales price – because their price-depressing effect would make the sales of all other units sold during the same period less profitable, the monopolist leaves these additional reserves in the ground. This explains why the extraction costs and the market price of oil do not fully converge anymore in Fig. 6. Else the graph is qualitatively similar to the grpahs from the standard scenario without liquefaction, besides that the oil consumption is now smaller initially but decreases more slowly over time. This is also due to the larger resource rent of the monopolist: in the early phases where the monopolist sells relatively large amounts of oil, he sells less than competitive suppliers would overall, because further sales of him in the initial periods would decrease the price of the many other units of oil he simulataneously sells. With other words, the monopolis tends to smoothen the resource sales over time. Interestingly, Fig. 6 shows that in the monopolistic case the calculated initial oil consumption, 24.4 Gbbl/yr, is just below the actual worldwide oil consumption of 30.7 Gbbl/yr (IEA, 2010, Table 3.1), while under perfect competition the calculated initial consumption was, with 50.4 Gbbl/yr (Fig. 1), too large. This is comforting, as for the most realistic case, an oligopolistic fuel supply, the predicted sales would be expected to lie between the values for monopolistic and competitive supply, that is, if modeled they could correspond to the real consumption data. The monopolist's case is further discussed in the sensitivity analysis on monopolistic oil supply.

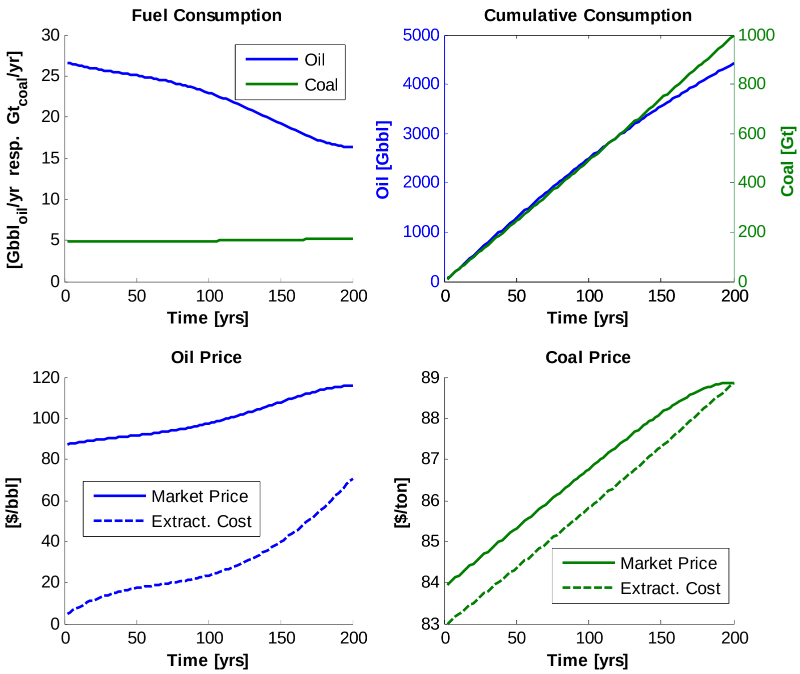


Figure 6: Dynamics without liquefaction, monopolistic oil supply

Tax Effects. Figs. 7 and 8 show the effect of a 40 $/t$CO_2$ tax imposed solely on emissions from oil (Fig. 7), resp. solely on the emissions from coal (Fig. 8), for a scenario without liquefaction. For the oil tax, a major fraction of the oil saved domestically in the OECD region leaks to the ROW, where it is consumed notably in future periods. This is different in the case of the tax on coal emissions. Fig. 8 shows that almost the full amount of emissions regionally saved translates into global emission savings, as leakage is negligible in this case. The observation of the shift of current oil consumption to the future in the case of the oil tax may be interesting when we think about potential empirical estimates of near-term leakage and static leakage rates. Such estimates may caputre only the part of the induced emission increase in the ROW that occur in the first few years, which constitutes a minor fraction of the overall leakage of the unilateral oil tax. This underlines the skepticism about estimates of leakage rates in static models.

Figs. 9 and 10 depict the same situations as Figs. 7 and 8, but with liquefaction becoming an economical alternative as soon as the price differential between oil and coal extractions is large enough. In this case liquefaction also prevents leakage of the oil-only emissions tax (Fig. 9), with respect to the absolute volume of liquid fuel consumption: consuming less oil regionally primarily implies that liquefaction starts somewhat later, but it does not have a strong influence on the global energy prices, as the scarcity value of the oil is limited to values that are below the point at which coal liquefaction becomes interesting.

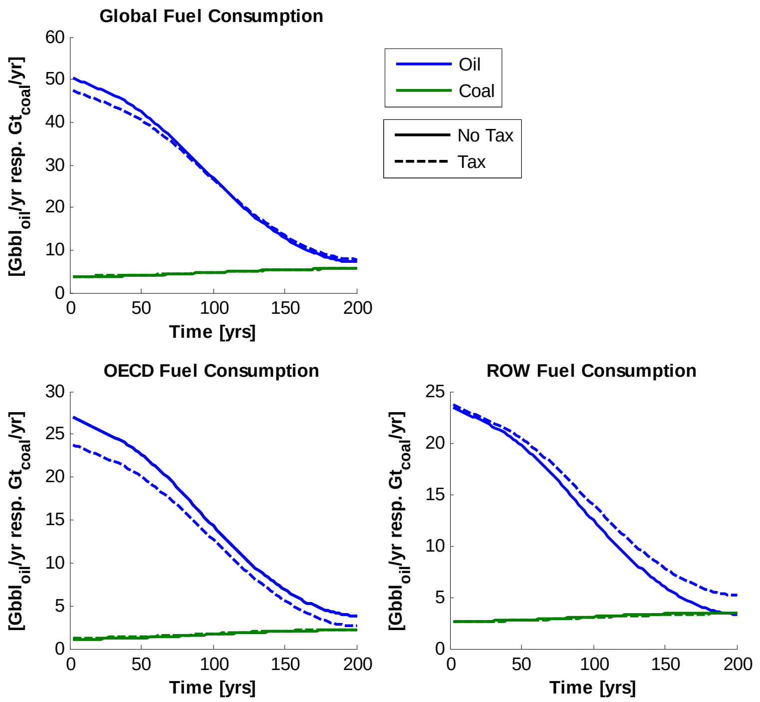


Figure 7: Dynamic impact of oil-only OECD emission tax, scenario without liquefaction
Oil tax rate 40 \$/tCO_2.

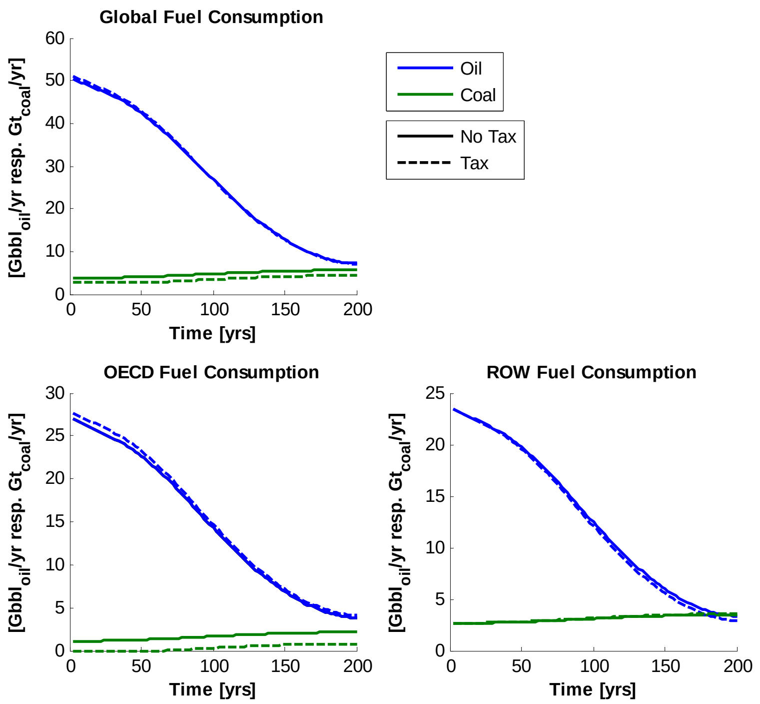


Figure 8: Dynamic impact of coal-only OECD emission tax, scenario without liquefaction
Coal tax rate 40 \$/tCO_2.

Therefore, leakage in terms of end-consumption volumes is in this case limited also for a tax on oil emissions.

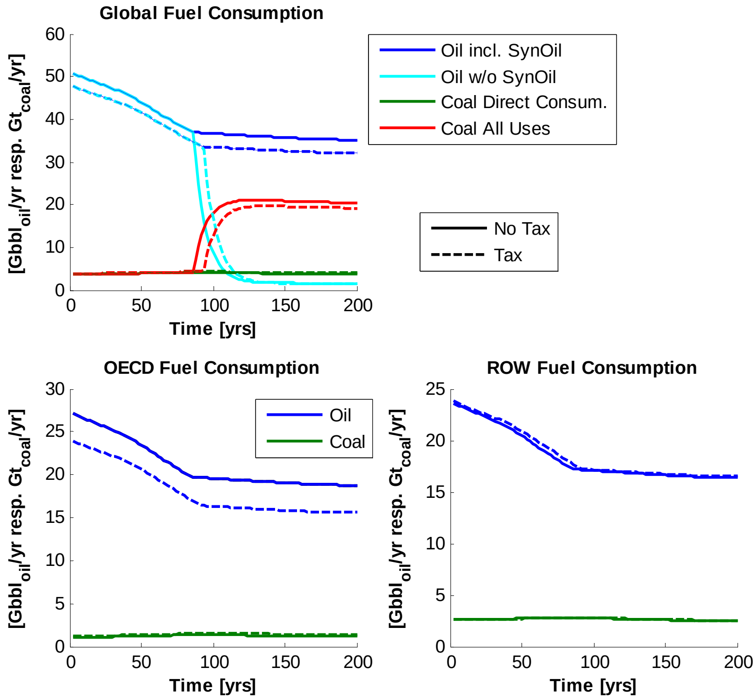


Figure 9: Dynamic impact of oil-only OECD emission tax, scenario with liquefaction
Oil tax rate $40\,\$/\mathrm{tCO_2}$, $c_l = 15\,\$/\mathrm{bbl}$.

Figs. 7 through 10 confirm that leakage from an oil tax appears to be much more important than leakage from a coal tax. Thus, it is interesting to examine the effects of an oil tax more closely. Fig. 11 respectively shows the dynamic impact of a temporary (plots *a* and *c*) and a permanent (plots *b* and *d*) OECD oil-emission tax ($40\,\$/\mathrm{tCO_2}$) on the oil-consumption emissions occurring in the OECD and in the ROW and on the emissions from synthetic oil provisions in the scenarios with liquefaction. For the sake of brevity, the effect of the oil tax on coal end-consumption is not considered at this point because, due to the large abundance of coal, the coal market channel has here a comparatively smaller impact on leakage.

Plots *a* and *b* in Fig. 11 show how, in the longer term, domestic oil savings from a temporary or a permanent, unilateral oil-emissions tax is compensated by consumption increases in the ROW, resp. in later periods, in a business-as-usual scenario without liquefaction. For this 200-year simulation, the oil-to-oil leakage rate is 91 % for the temporary tax (where even increased domestic consumption in later years contributes to the compensation of initial savings) and 68 % for the permanent tax. Even if future emissions are present-discounted at an annual rate of 5 ‰, these values remain above 50 %. In a scenario with liquefaction (plots c and d in Fig. 11), the temporary or permanent tax-induced

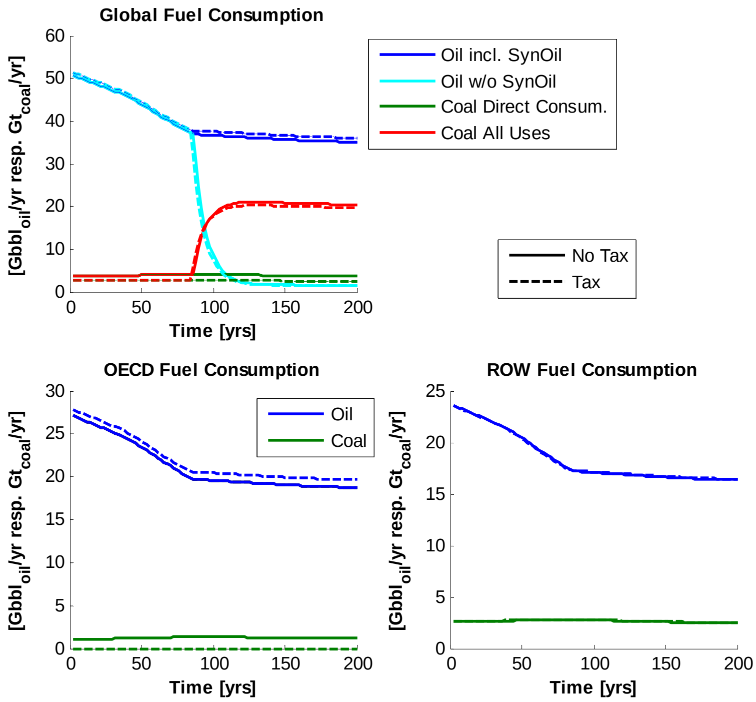
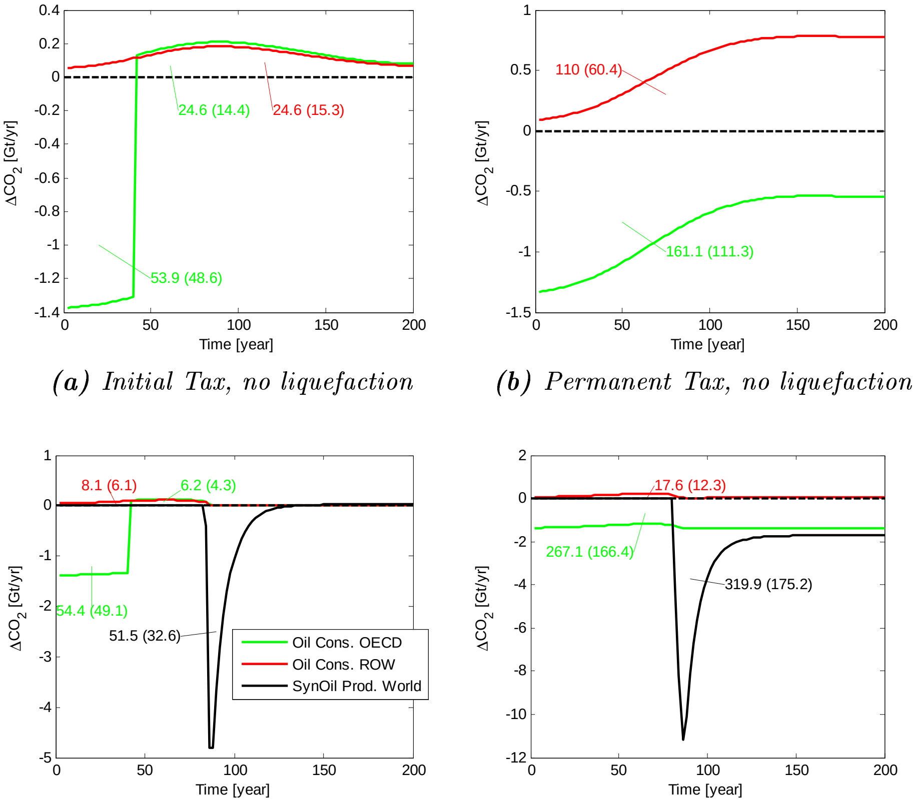


Figure 10: Dynamic impact of coal-only OECD emission tax, scenario with liquefaction
Coal tax rate 40 \$/tCO_2, $c_l = 15$ \$/bbl.

domestic oil consumption reductions only minimally affect the longer-run price of oil, due to the abundance of the synthetic substitute. Thus, there exists only a small effect on foreign or future overall liquid fuel consumption.[23] The domestic oil consumption reduction primarily changes the amount of synthetic fuel that must be produced worldwide, and because of the missing end-consumption leakage, this change occurs almost on a one-per-one ratio. Because synthetic oil is, overall, approximately twice as emission-intensive as oil when considering end-consumption emissions, the oil-to-oil leakage rates are, in this situation, negative with values of up to almost -100 %: each unit of oil-emissions domestically spared reduces worldwide medium-term, oil-associated[24] emissions by approximately two units. In this scenario with future liqufaction, undiscounted (discounted) oil-to-oil leakage rates are, thus, for the temporary resp. the permanent tax, -68 % (-45 %) and -113 % (-98 %).

To simplify the discussion, the previous paragraph and Fig. 11 focused only on oil-to-oil leakage, that is, we considered the oil tax and only its effects on oil-related emissions. Due to the substitute character of the fuels, a tax on one fuel also has a direct influence on the consumption of the other fuel. In the following, we focus on the general leakage

[23] The limited effect that exists is mainly concentrated in the pre-liquefaction periods, where the depletion of oil has a non-negligible effect on the oil price.
[24] Meant is genuine plus synthetic oil.



(a) Initial Tax, no liquefaction *(b) Permanent Tax, no liquefaction*

(c) Initial Tax, with liquefaction *(d) Permanent Tax, with liquefaction*

Figure 11: Dynamics of oil-emission leakage from OECD oil-emission tax
Tax of 40 \$/tCO_2 on oil consumption emissions in OECD, during the first 40 years ('initial tax') resp. for 200 years ('permanent tax'). *Green* indicates OECD oil-consumption emission changes, *red* ROW oil-consumption emission changes, *black* changes in emissions from external SynOil production (liquefaction). Values in brackets are present discounted sums ($\rho = 5$ ‰). Resulting undiscounted (discounted) oil-only leakage rates are *(a)* 0.91 (0.61), *(b)* 0.68 (0.54), *(c)* -0.68 (-0.45), *(d)* -1.13 (-0.98). These rates ignore the effecte on coal end-consumption, which are smaller (see Table 1 for overall leakage rates).

effect of permanent taxes.

We write $\Delta Emiss_r$ and $\Delta OilEmiss_r$ for the integral (over the entire simulation period) of the oil tax induced change in emissions – the total, resp. those from oil end-consumption – in region r. The leakage rate of the reduced emissions from the tax on oil, while ignoring the discounting of the emissions, can be calculated as

$$-\frac{\Delta Emiss_{\text{ROW}}}{\Delta OilEmiss_{\text{OECD}}}. \tag{5}$$

This expression does not consider the effect of the domestic oil tax on the domestic coal consumption. This choice expresses the thought that the domestic coal emissions can be subject to a domestic tax as well, making those emissions of secondary importance from a domestic welfare perspective.

Alternatively, if the emissions are discounted with the annual discount factor $\delta_e < 1$, denoting $\Delta Emiss_{r,t}$, resp. $\Delta OilEmiss_{r,t}$ the total resp. the oil-only emissions change in region r at time t, induced by the considered oil tax, the leakage rate for that tax becomes

$$-\frac{\int_{\underline{t}}^{\bar{t}} \delta_e^t \Delta Emiss_{\text{ROW},t} \mathrm{d}t}{\int_{\underline{t}}^{\bar{t}} \delta_e^t \Delta OilEmiss_{\text{OECD},t} \mathrm{d}t}, \tag{6}$$

where $\underline{t}$ and $\bar{t}$ are the beginning and the end of the considered period.

Numerical values for Eqs. 5 and 6 (and their counterparts for the tax on coal), considering the next 200 years, are given in Table 1.

Table 1: Leakage Rates from unilateral OECD taxes

Present Discounting	Leakage Rate of Unilateral Tax of 40 $/tCO$_2$ on OECD emissions from combustion of a specific fuel			
	No Liquefaction		Liquefaction	
	Oil Tax	Coal Tax	Oil Tax	Coal Tax
No Discounting	0.50	0.01	-1.09	0.22
Discounting $\rho_{\text{cons}} = 5\,‰$	0.40	0.01	-0.93	0.19

Recalling the concept of the GTF and the optimal regional tax, related to the leakage of domestic emission savings activities, the rates indicated in Table 1 may already raise some expectations about the pattern of the optimal regional tax rates in the modeled two-region situation with oil and coal: leakage rates of approximately 50 % in the case of the oil-tax in a scenario without liquefaction (column 2 in Table 1) suggest that the optimal oil tax may be on the order of 50 % of the region's WTP for global emission reductions. In the absence of relevant leakage from the coal tax in the same case where liquefaction is ruled out (column 3 in Table 1), the optimal tax on coal is, in this case, close to the WTP. For the case where liquefied coal provides an emission-intensive substitute for standard oil in the future, the leakage rates of approximately -1 (column 4 in Table 1) imply that the optimal tax on oil be on the order of two times the genuine WTP. Finally, the coal tax is subject to a slightly larger interregional leakage effect in the case *with*, compared to the case *without*, liquefaction (column 5 vs. column 4 in Table 1), suggesting a somewhat lower optimal regional coal tax if liquefaction becomes an option in the future. The following subsection examines the optimal regional tax rates. These rates do, qualitatively and quantitatively, correspond to the leakage pattern found here. The values do not, however, precisely correspond to what one would estimate based on the observed leakage rates and the GTF concept. This may be explained by two facts. First, in the non-linear simulation model, the leakage rates depend on the level of the tax rates in general, so at any potentially optimal tax rate, the leakage rates do not need to mach those indicated in Table 1 for the taxes of 40 $/tCO_2$. Second, the effects of the taxes on the two fuels interact with each other in a non-linear way as well, thus potentially influencing leakage rates when both taxes are applied simultaneously, as is done in the following subsections. First, however, let us examine with the numerical model, the case for our claim that there is close to 100 % leakage in the long-run in the absence of discounting and of major future climate relevant developments.

Full Leakage without Discounting and Future Developments. The simulations above generally exhibited limited leakage rates. Reasons that limited them were the present discounting of future emissions, the limited time-horizon (of secondary importance for the scenarios with discounting of emissions but relevant for the case of undiscounted emissions), and the presence of technological changes, that is, coal liquefaction which provided a dirty substitute for oil in the future, leading even to negative leakage rates for the oil tax. But these are not the primary reasons why most leakage studies find limited leakage rates: they typically do not discount future emissions, and most do not explicitly assume that future political or technological developments would, e.g., prevent emissions from occuring after a specific time period. Instead, even those studies which employ dynamic models with endogenous fuel depletion seem to restrict their attention typically to the next few decades and it must be assumed that the leakage estimates would increase if calculated in their way – i.e. without discounting and political or technological developments – but with longer simulation horizons. To underline this point, in this subsection we consider the case of various emission discount rates, notably that of zero discounting, and look at the resulting (very) long-run leakage rates. The hypothesis is that in the case without discounting, the overall leakage rate converges towards 100 %, or

–in the case where fuel demand exhibits a somewhat lower choke price[25] in the ROW than in the OECD prior to the tax – to a somewhat lower but in any case very large leakage rate.

We use a slightly adapted version of the model. To reduce the time horizon that must be considered, we introduce a (clean and perfect) backstop that is available as a substitute for coal at the price of 180 $/t. The primary effect of this is to reduce both regions' maximal WTP for coal from a value that otherwise is beyond 200 $/t. Besides the desired effect of limiting the time horizon which has to be considered, this has also the effect of neutralizing the difference between the two regions' choke prices for coal.[26]

The time horizon during which the leakage rates grow before eventually reaching their final values depends strongly on the amount of coal overall extractable, that is, the speed with which the coal extractions costs increase as reserves deplete, and on whether the current fuel demand remains constant or whether it continues to grow also in the future. In order to account for both possibilities, of slow and of rapid fuel exhaustion, we first look at the situation how it could be if the coal extraction costs rise rapidly and the fuel demand continues to grow over time (case 1), and as a second step examine how the situation could look like if most of the existing coal resources are extractable for rather modest costs (the standard coal extraction cost scenario) and fuel demand is constant over time (case 2). In the two scenarios, the time it takes for the leakage rates (of undiscounted or discounted emissions) to converge to their final values differs strongly, with around 150 years in case 1, compared to several thousand years for case 2 (see Figs. 12 and 13).

Fig. 12 shows, for the case 1-parameterization, that is, with a demand growing at an annual rate of 2 % and the coal extraction costs doubling after each 1000 Gt, the leakage rate of a uniform unilateral OECD climate tax of 40 $/t$CO_2$ as as a function of the model time-horizon of up to 250 years. While if only the first few years are considered, the overall leakage rate is with less than 10 % low independent of the discount rate, the leakage rate grows steadily with the widening of the model horizon to take on values of around 20 % if the coming 50 years are considered and around 40 % for 100 years considered, with the interest rate playing a relevant role only if more than 50 years are considered. Interestingly, the found leakage rates during these 50 to 100 years compare

[25]The price for which the fuel demand just becomes zero, corresponding thus in a sense to the WTP for the 'last drop of oil' (or coal).

[26]In the original model, the two calibrated demand systems exhibit somewhat different coal choke prices. More than reflecting a real difference in the two regions' economies, this difference is to be considered as an artefact of a calibration of the demand system to current fuel prices and consumption levels and chosen (cross-)price elasticities. Notably if the ROW countinues to catch up with the developed cuntries, there exists in reality no obvious reason why there should exist a major difference in the long-run choke price for a fuel between the two regions. As one would expect given that in the original model the choke price in the OECD is somewhat larger than in the ROW, a long-horizon model run without the clean coal-backstop resulted in a long-run leakage rate of somewhat less than 1, 70 %, much larger than the bulk of the estimates in the leakage literature.

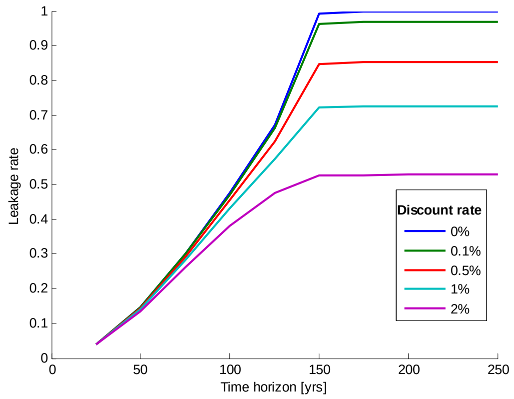


Figure 12: Undiscounted and discounted leakages for case 1
Uniform OECD CO_2 tax of 40 \$/t, for growing demand (growth rate 2 %) and low coal availability ($cd = 1000$ Gt).

fairly well to values from traditional leakage studies. As the figure shows, however, the leakage rates grow considerably larger if a longer future is considered, converging – in already around 150 years – to 100 % for the undiscounted emissions and slightly more than 50 % even for emissions discounted at 2 % p.a.

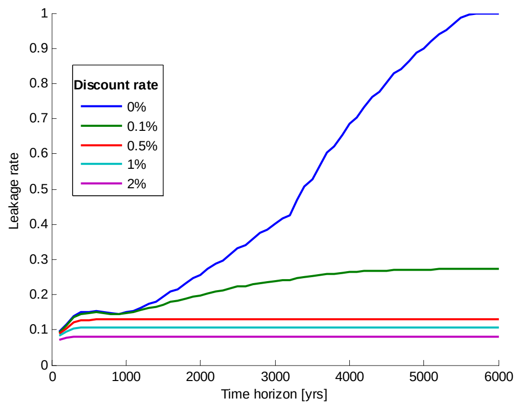


Figure 13: Undiscounted and discounted leakages for case 2
Uniform OECD CO_2 tax of 40 \$/t, for static demand and abundant coal ($cd = 10\,000$ Gt).

Fig. 13 indicates the leakage pattern for the second case where coal availability corresponds to the standard case considered in the model. Simulations were run for 6000 years and the curves show how the leakage rates depend on the number of years (the 'time horizon') whose emissions are taken into account. That is, considering, for example, the emissions projected to occur in the next 3000 years, the leakage rate for undiscounted emissions (blue curve) would be around 40 %.[27]

[27] Here simulations were run for 6000 years and the leakage rates calculated using the emissions that occur from today up to a certain number of years in the future. While this may provide a more realistic picture of the timing of expected tax-induced changes of future emissions in the future, a second possibility would be to look at the predicted overall leakage rates estimated with model runs simulating only a limited

The long time it takes for the leakage rates to converge in case 2 are in stark contrast to the relatively rapid convergence in case 1. This emphasizes on one hand the importance of projections of economic (or at least fuel-demand) growth rates and on the other hand shows the important role of an accurate representation of the supply of the (endogenously) depleting fossil fuels. As a second difference to Fig. 12, Fig. 13 shows that here even very low discount rates suffice to reduce overall long-run leakage rates to very modest values, of less than 30 % even for a discount rate as low as 1 ‰. This is no surprise, given the very long time it takes for most leakage to occur in case 2.

Interestingly, the model results in Fig. 13 indicate a non-monotonicity of the leakage rates as a function of the number of years for which the (undiscounted or weakly discounted) emissions are considered: the undiscounted overall leakage rate rises to 15 % for the first 600 years' emissions, to decrease by about one percent if instead the first 900 years are considered, before steadily rising towards the final leakage rate of 100 % if emissions during several millennia are taken into account. The simple reason for this non-monotonicity is that an important fraction of oil, which is available primarily during the first few centuries, leakes relatively rapidly, but the very abundant coal is subject to low leakage rates during the first centuries. The large leakage rate of oil in the first few centuries drives up the overall leakage rate during these years, but with the extension of the considered time-horizon coal starts do dominate the overall tax-induced emission changes, leading accordingly to a lower overall leakage rate that only for even longer time-horizons rises again and ultimately converges to the larger values in the course of several millennia. Fig. 20 in Appendix E, which shows the time path of OECD and ROW emission changes separately from oil and from coal consumption changes induced by the OECD tax, confirms this interpretation.

For a tax that is, instead of permanent, only applied during the first 50 years, the emission convergence is somewhat faster[28] but the overall leakage pattern resembles to that found with the permanent taxes (Fig. 21 in Appendix E).

Optimal Climate Taxes. The numeric models were used to determine the optimal OECD climate taxes for the standard situations with and without liquefaction. In addition to the climate tax, the optimal regional tax theoretically contains an import tariff not directly related to climate change: even in the absence of any pollution externality, a relevant fossil fuel importing country has an incentive to tax these fuels to extract parts of the fossil fuel scarcity rent. These optimal import tariffs can be substantial. This is notably the case if a region imports all the fuels it consumes, as is assumed in the

number of future years, which would correspond more closely to typical studies in the literature. Fig. 22 in the Appendix E shows that the differences between the results from the two methods are very small.

[28]Naturally, the total amount of economically extractable fuels is used up earlier if the tax reduces consumption in one region only during a short instead of permanently.

standard scenarios in this study (see the sensitivity analysis in the next subsection for a relaxation of this assumption). Following, for example, Golombek et al. (1995), we use the concept of the optimal (pure) climate tax defined as the optimal regional tax on the fuels given a specific WTP for global emission reductions, minus the optimal regional tax on the fuels if there is no externality (i.e., with the WTP for climate protection as zero).[29] The subtracted import tariff components are not assumed to be imposed, notably as they could enter into conflict with WTO rules.[30] Appendix F shows the levels of the optimal import tariffs for the standard model parameterizations.

Table 2 presents the optimal climate taxes for a WTP of the OECD for global emission reductions of 40 \$/tCO_2. Considering the insights from the previous paragraph, it is no

Table 2: Optimal OECD climate taxes for standard cases

	No Liquefaction	Liquefaction
Oil	20.4	70.7
Coal	38.7	36.6

All values in \$/tCO_2, for a WTP of 40 \$/tCO_2 for global emission reductions.

surprise that, in the case without future liquefaction, the optimal carbon price on emissions from oil is much lower than the genuine WTP for global emission reductions: 20.4 \$/tCO_2 on oil emissions versus a WTP of 40 \$/tCO_2 for global emission reductions. In the absence of future liquefaction, a large fraction of domestic oil-consumption savings falls victim to the fuel leakage mechanism; a large fraction of the domestic oil savings is compensated by an increased non-OECD oil consumption primarily in the future (Fig. 14). Accordingly, the optimal regional carbon tax on oil emissions amounts only to approximately half of the WTP for emission reductions. For coal, which is only minimally affected by leakage (due to its abundance, which prevents large price changes from OECD consumption reductions), the optimal climate tax on emissions has a level of 38.7 \$/tCO_2. In other words, it almost equates to the assumed WTP for global emission reductions of 40 \$/tCO_2.

The most interesting case is the case where liquefaction allows for the transformation of the abundant coal into a synthetic liquid fuel, thereby substituting oil in the end-consumption.

[29] Böhringer et al. (2010) introduce a technique that considers the compensation of the no-policy region by the taxing region, in order to estimate the pure climate tax component.

[30] The incentive for individual OECD countries to impose such import tariffs on the fuels may in any case be very small: the optimal import tariffs are large for the whole OECD acting as one country, because a reduction in their fuel demand will have a significant impact on the worldwide fuel market, reducing the sales price of the fuel owners. Any individual OECD member-country does, however, hardly have any substantial incentive to impose any fuel taxes in addition to the agreed-upon climate taxes: an individual country's demand has only a limited impact on global fuel prices. Thus, the country itself would primarily distort prices for its own economy - the main beneficiaries being the remaining oil-consuming countries which can buy at least slightly cheaper fuels on the worldwide markets.

In this case, the optimal regional tax on oil is, at 70.7 $\$/tCO_2$, nearly twice as great as the genuine regional WTP for global emission reductions (40 $\$/tCO_2$). This stems from the fact that synthetic oil from liquefaction is, overall, twice as emission-intensive as standard oil. Furthermore, because of the 'backstop' represented by coal liquefaction, the long-run oil price varies less with regional oil consumption, implying that only a limited interregional leakage of end-consumption of liquids takes place. Turning to the coal tax, due to the assumed large coal reserves, although an important amount of it is used in the future for the liquefaction process, coal remains abundant enough for the leakage rate from domestic coal savings to remain low. This ultimately implies that the optimal regional tax on coal, 36.6 $\$/tCO_2$, still closely corresponds to the region's WTP for global emission reductions. Figs. 14 and 15 show the dynamics for the cases without and with liquefaction.

We primarily focus on regionally optimal *constant* tax rates. It is important to understand that the optimal flexible paths of taxes over time seem not to deviate strongly from a constant tax. Especially, there is no reason for a notable difference of the optimal tax on oil immediately prior to and after the onset of liquefaction. Even before liquefaction has started, if OECD consumes one unit less of standard oil, the overall 'marginal' unit of oil that is prevented from being burned is primarily a unit of liquefied oil as the initially saved unit of standard oil primarily implies that standard oil lasts slightly longer before coal liquefaction begins to replace genuine oil. In other words, the major fraction of the unit of crude oil spared initially will later be consumed anyway, and the marginal unit of oil spared worldwide in the medium run is a unit of synthetic oil from liquefaction with the high emission intensity that goes along with it. Therewith, the optimal tax on oil is initially already large, similarly to the later periods after liquefaction has commenced. The sensitivity analysis in Appendix G confirms the stability of the optimal tax level over time.

The exact optimal regional taxes on the fuel emissions depend on the assumptions in the model. To understand how the results change under different assumptions, Appendix G examines twelve specific types of extensions and alternative parameterizations. It shows that the key findings outlined above are rather robust with respect to the key model assumptions.

6 Discussion

Partial and general equilibrium analyses analytically demonstrate the need for fuel- dependent emission pricing, and the results of a numerical model suggest that the fuel-differentiation of the optimal carbon price on emissions is substantial for the case of an OECD-wide climate tax scheme. Some additional words regarding the intuition behind

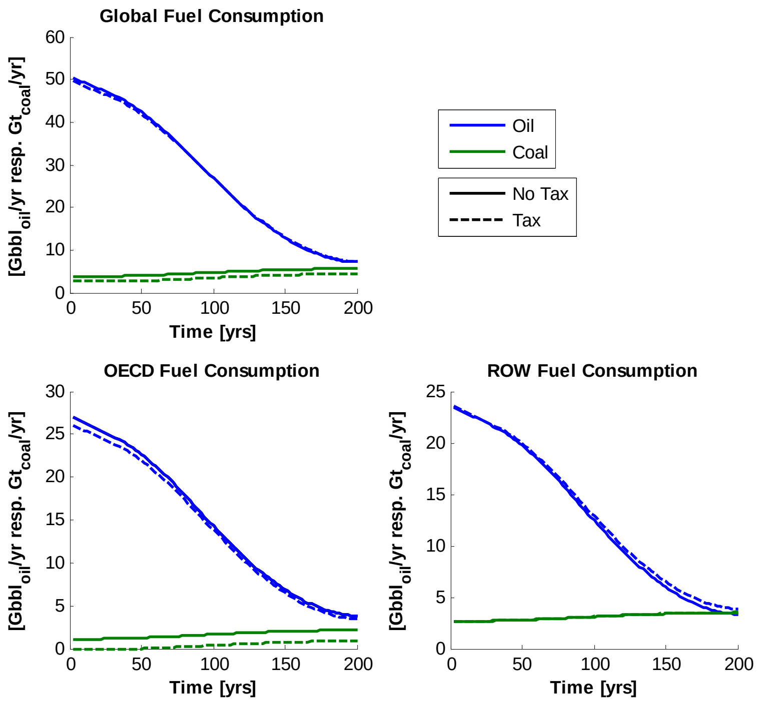


Figure 14: Dynamic impact of an optimal OECD fuel-emission tax, scenario without liquefaction

Tax of 20.4 \$/tCO_2 on oil and 38.7 \$/tCO_2 on coal.

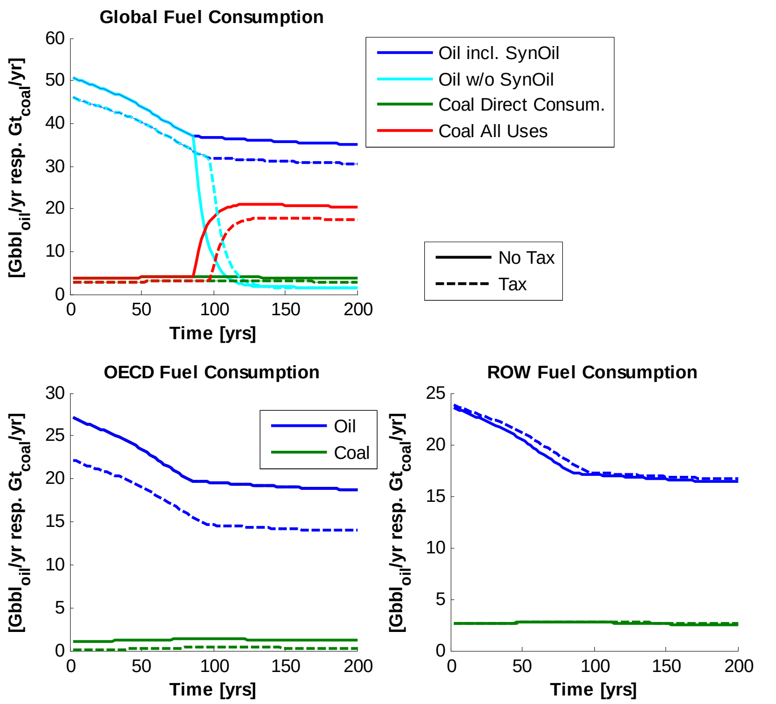


Figure 15: Dynamic impact of an optimal fuel-emission tax, scenario with liquefaction

Tax of 70.7 \$/tCO_2 on oil and 36.6 \$/tCO_2 on coal.

the claim that optimal regional carbon accounting is fuel-dependent may be in order. Thus, consider the examples from the partial-equilibrium analysis in Appendix A. If a fuel is globally supplied in a fixed, price-independent amount and if demands for different fuels are independent, the optimal regional climate tax on that fuel may be zero, as regional consumption reductions are fully compensated by fuel consumption increases in the remainder of the world. This seems intuitive: there is no reason to specifically care about the emissions from a specific consumption if in the world, an exact, exogenous fixed amount of that specific consumption takes place anyway, that is, if your own action does not have any effect on the relevant amount of global emissions. In reality, no fuel supply is completely inelastic in the medium-term, but we stress that the optimal regional tax gradually changes with supply elasticity. Additionally, the fact that real consumptions of different fuels are not fully independent does not alter the findings qualitatively. As long as the fuels are not perfect substitutes for all uses, some requirement to differentiate among fuels for the efficient CO_2 tax remains. To see this, one may consider the example of a wizard who transforms an irrelevant piece of land into a deposit of a specific type of fuel with the amount being defined as the equivalent of a certain amount of CO_2. This transformation will have repercussions on global fuel use and emissions. The associated increase in global emissions may strongly depend notably upon the type and quality of fuel in the additional deposit. For example, peat, coal, oil or wood may be 'extractable' at highly specific per-unit costs. Additionally, the fuels are of specific scarcities as specific regional and global extraction possibilities and demands exist for each of them. Thus, most would probably agree that the implications that the additional reserve from the wizard's transformation will have on short-, medium-, and long-term emissions depend on the type of fuel the wizard created.[31] Finally, reducing domestic emissions by taxing domestic fuel consumption has, in a first approximation, the same effect as (i) an equivalent reduction in regional emissions plus (ii) an increase of available fuels (corresponding to the domestic savings) in the remainder of the world. Thus, the wizard's example does, to a certain extend, correspond to the domestic fuel-saving policy. In reality, the additional fuels are not created by a wizard but by the domestic fuel savings, yet they cause a similar additional fuel 'deposit' to be available in the remainder of the world, with the effects on the current and later (leakage) emissions depending on the type of fuel.

The dynamic analysis in section 5 has several important implications. It explains why, notably for oil, the relevant leakage rates may be much larger than most previous studies

[31] As a further aspect supporting this point of view, one may also note the importance the various types of available fossil fuels have on the discussions on climate change and mitigation strategies. If scholars, policy makers or society in general would really consider the *types* of the fuels stored underground of secondary importance (which, in general, can be considered a necessary condition for the question, which fuels we save through a unilateral climate policy, to be irrelevant), they should collapse the discussions about how much of which fuel is available into a single amount of overall carbon contained in all the fuels together. The fact that they do not do so in general is an indirect support for the non-negligible difference it makes for the climate, which carbon source a region prevents from being domestically consumed.

suggested, but, depending on the future developments, that leakage may also be very strongly negative instead of positive (i.e., emissions in the remainder of the world may be reduced, adding to the domestic reduction). It also has the uncomfortable implication that any attempt for a sensible assessment of the leakage effects will not only require considerable information about the current fuel market conditions but also significant information about the prospects for technical developments (e.g., the development of fuel transformation processes, alternative energy sources, technologies that may change our lifestyle and, therfore, the fuel demand pattern) or political developments (e.g., global climate treaties) concerning greenhouse gas emissions. Equally problematic is that any sensible leakage index will strongly depend on the controversial time-discounting of future greenhouse gas emissions. Yet, explicitly making and stating such assumptions along with any proposed leakage rate seems to be the only viable option. Nothing is gained from neglecting uncertainties and by implicitly assuming these away, e.g., by relying on a dubious concept of a static fuel supply or considering only contemporaneous leakage during the next few years despite the long-term character of the climate problem. If, with an important but controversial probability, massive liquefaction will occur in the future and if, in this case, domestic oil savings would – as the present analysis suggests – be subject to a negative leakage rate of approximately -75 %, and if, without that liquefaction, domestic oil savings would be subject to a large positive leakage rate of approximatively 50 % – as also suggested in our model – then economic models should take both possibilities into account, despite the uncertainties attached, rather than solely focusing on a business-as-usual baseline and implicitly attributing a 100 % probability to its materialization. Finally, the scepticism expressed in this article against the traditional leakage literature may be rephrased as follows: many will agree that one can not be sure whether a major fraction of the realistically exploitably fossil fuels will in the long run be left underground or whether practically all of these fuels will be consumed by future generations. In the latter case, it seems clear that regional emission savings during the next few decades are ultimately subject to a leakage of close to 100 % in terms of undiscounted emissions. The surveyed studies hardly provide any substantive economic reasons why this scenario should be impossible. Yet, they suggest deterministic, modest leakage rates. As far as sensible economic depletion models for the fossil fuels are used, those rates will, notably, depend on the time-horizon of the model simulations. It may in some cases indeed make some sense to assume limited rather than quasi-infinite horizons, as one may attach a value even to know that emissions be at least delayed for a couple of decades, a preference that may also be funded in the belief that technological or political progress hopefully prevents the emissions from a certain point in time on anyway. The judgement on the value of such a delay strongly depends on personal perceptions and beliefs about the future. A corresponding leakage rate should therefore be proposed together with explicit statements about the assumptions under which it is obtained. If this was broadly acknowledged, gradual discounting of emissions rather than a simple and somewhat arbitrary cutoff of the simulation time-horizon would surely be preferred.

The numerical analysis in the present study is based on a relatively simple fuel demand – or fuel utility – system with parameter values calibrated to fit current fuel consumption and prices, and some (cross-)price elasticity values inspired by the literature. Although the sensitivity analysis has shown the key findings to be robust to changes in a variety of parameters and assumptions, it would be interesting to further examine the core issues of this paper – the time dimension of carbon leakage from a market-based regional climate policy and the fuel-dependent structure of the optimal regional policy – in an analysis within a multisectoral framework. An adequate representation of the fuel substitutabilities (in specific applications) and fuel transformation processes, such as coal-to-liquids, would be crucial for accurate modeling (see, e.g., Lanz and Rausch, 2011, who show that the inclusion of bottom-up elements is necessary for a general equilibrium model to accurately represent the electricity sector and its emissions). Thus, complementing a multisectoral top-down model with bottom-up elements concerning the substitutability of fossil fuels in the major fuel-consumption domains could be an interesting point for future research on the topic addressed here (see, e.g., Chen et al., 2011, for a dynamic model in which a top-down approach is coupled with a bottom-up representation of coal liquefaction processes).

Some words on the practical implementability of a fuel-dependent carbon pricing scheme may be in order. Contrary to how it may initially appear, an adaptation of the regional carbon tax scheme in the proposed direction would not make the final implementation of a climate policy more complicated. Even today, carbon emissions are not measured directly 'at the stacks'. Instead, the systems track the amounts of different fuels used and multiply these values by some fuel-specific emission factors, according to the carbon content of the fuels. Once agreed on estimates of applicable GTF factors, the hitherto used emission factors would simply have to be multiplied by the GTF factors and then used as new accountable emission factors, while the remainder of the accounting system could be left wholly unchanged. Thus, the fuel-specificity of a climate policy would barely complicate the system, and a policy refinement, as proposed herein, may be sensible even in times when the simplicity of a climate agreement is crucial for its implementability and even when carefully designed income tax systems are challenged by more simple flat tax alternatives.

Finally, that leakage effects would imply that fuels not consumed in climate-protecting regions would be consumed elsewhere in the world is one of the strongest political arguments against a stringent unilateral climate policy. Thus, properly accounting for such leakage effects in the dimension of *fuel*-specific carbon accounting may not only imply an efficiency gain but also increase the political acceptance of unilateral action.

7 Conclusion

Optimally, regional climate protection schemes would weight emissions according to the fuel type from which they are generated. Using uniform CO_2 pricing or allowing only production-sector differentiation, rather than fuel-specific pricing, implies economic excess costs, which may be substantial.

Due to interregional leakage, the optimal tax on a specific fuel is generally positively related to the price elasticity of the global supply of that fuel. This conclusion also holds for fuel-specific emission accounting in cap-and-trade systems where the rules for optimal prices in a tax scheme can be adopted to weight emissions for the quantity-based policies.

Because fuel supply and demand are complexly intertwined with other activities in all major economic sectors, the estimation of optimal fuel-specific weights on emissions for a regionally defined policy is complicated and may best be addressed by numerical dynamic general equilibrium models featuring a detailed description of regional supplies of the major currently consumed fuels. The present analysis, based on a dynamic model considering the exhaustibility of oil and coal and calibrated fuel demand systems for OECD and for the rest of the world, suggests that in a business-as-usual scenario without liquefaction, oil savings in the OECD are subject to a leakage rate of 50 %. Thus the optimal tax should equate to half of the domestic WTP for global emission reductions, while coal emission savings do barely leak and coal emissions should, therefore, be taxed at a value close to the WTP for global emission reductions. In the case where liquefaction will, in the future, substitute the depleted crude oil, this pattern is reversed: oil consumption reductions imply that, sooner or later, a lower amount of emission-intensive synthetic oil must be produced, implying a negative leakage rate of up to 75 %, that is, an optimal regional tax on oil emissions close to twice the domestic WTP for global emission reductions. While an extensive sensitivity analysis showed these findings to be relatively robust to a number of key assumptions in the applied model, an increase of the worldwide fuel demand over time could increase the leakage and lead to even lower optimal regional taxes relative to the WTP for emission reductions. The possibility of future technological developments, such as alternative technologies (clean backstops) and potentially future stringent global political agreements, could lower the leakage rates. The fact that the leakage rates depend so strongly on future developments casts doubt on the numerous semi-empirical estimates provided in the literature without any explicitly stated assumptions about future technical or political developments on the fossil fuel markets; the concept of static leakage rates, and of undiscounted leakage throughout a specific and limited time-period, must be reconsidered.

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Appendix

(A) GTF in a Linear Static Two-Region Partial Equilibrium Model

Let us focus on a partial equilibrium process with two regions indexed by $r = \{t, n\}$: region t (the *taxing* region) imposes a tax, and the remainder of the world, region n (the *no-tax* region) does not impose any comparable measure. The considered emissions are created through the combustion of a globally traded fossil fuel, where p is the market price of the fuel, f_r is the consumption in region r, and s is the supply of fuels provided by global producers. The regions have independent linear fuel demands, $f_r(p) = a_r - b_r p$. The supply is given by the simple function $s(p) = s_0 + cp$. The parameters a_r, b_r and c are nonnegative.

Consider first the case where region t does not impose any tax. In equilibrium a price p^* for which supply meets global demand obtains, $f_t(p^*) + f_n(p^*) \stackrel{!}{=} s(p^*)$, implying the price $p^* = \frac{a_t + a_n - s_0}{c + b_t + b_n}$ and global supply $s^* = s_0 + cp^* = s_0 + c\frac{a_t + a_n - s_0}{c + b_t + b_n}$ for the taxless benchmark. Equilibrium consumption in region t is $f_t^* = f_t(p^*) = a_t - \frac{a_t + a_n - s_0}{c + b_t + b_n} b_t$.

If region t imposes a tax of rate τ on its consumption of the fuel, this tax is added on the price of the fuel on the global market, p, so that its demand becomes $f_t(p + \tau) = a_t - (p + \tau)b_t$, and the equilibrium price and supply are

$$p^* = \frac{a_t + a_n - \tau b_t - s_0}{c + b_t + b_n} \quad (7)$$

$$\text{and} \qquad s^* = s_0 + c\frac{a_t + a_n - \tau b_t - s_0}{c + b_t + b_n}.$$

The equilibrium fuel consumption in region t is thus

$$f_t^* = f_t(p^* + \tau) = a_t - \left(\frac{a_t + a_n - \tau b_t - s_0}{c + b_t + b_n} + \tau \right) b_t.$$

The tax reduces *global* equilibrium consumption s^* by $\frac{c\tau b_t}{c + b_t + b_n}$. The consumption reduction in region t is $(\frac{-\tau b_t}{c + b_t + b_n} + \tau)b_t = b_t \tau (\frac{c + b_n}{c + b_t + b_n})$. Thus, the ratio between global reduction and reduction in region t is $\frac{c}{c + b_n}$. This ratio, which indicates by how much global emissions are reduced due to a reduction of regional emissions, corresponds to the GTF as follows:

$$\text{GTF} = \frac{c}{c + b_n} < 1, \quad (8)$$

i.e., the global reduction will in this framework always be lower than the regional reduction. The global reduction will be smaller if the demand elasticity of the other region is large (b_n large) and if the supply decreases slowly when the sales price drops (c is low).

Given the specified supply function in a competitive market, the same market equilibrium is found if instead of imposing a tax, region t reduces its consumption using a different market mechanism such as an internal cap-and-trade scheme: both regions buy the resource at the same pre-tax price, implying that the market clears for the price p^* from Eq. 7 with a τ that corresponds to the level of reduction in region t imposed by the cap-and-trade policy. Thus, the cap-and-trade scheme would be subject to the same GTF.

The implications of Eq. 8 may best be illustrated by means of four extreme cases:

- Let the global supply of the fuel be perfectly inelastic, which holds for $c = 0$, and let the demand in region n be decreasing in the fuel price, which implies $0 < b_n < \infty$. This situation is depicted in Fig. 16.

  In such a market, the tax on the fuel-based emissions in region t should be set to

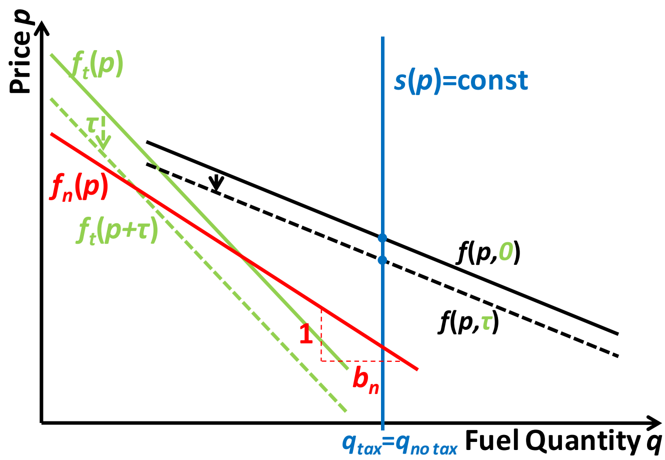


Figure 16: Partial equilibrium: perfectly inelastic global fuel supply
Aggregate fuel consumption is not changed by the tax τ. Demand in the *tax-region*, $f_t(p)$, in the *no-tax region*, $f_n(p)$, and *aggregated worldwide* demand, $f(p, \tau)$, for the fuel are given in *green*, *red*, and *black* respectively. Blue indicates the supply *s(p)* of the fuel. The dotted curves indicate demand if the tax-region imposes the tax τ.

  zero despite the externality; the global emissions are constant independent of the climate coalition's emission reduction effort. Given that region n does not adhere to any climate protection treaty, for efficiency reasons, region t's welfare is maximized if it imposes no tax on its emissions from that fuel, despite its WTP for global emission reductions. This corresponds to the expression of the GTF in Eq. 8 as follows: GTF $= \frac{c}{c+b_n} = \frac{0}{0+b_n} = 0$.

- Let the global supply of the fuel be infinitely elastic, implying $c = \infty$, and the demand in region n be decreasing in the fuel price, i.e., $0 < b_n < \infty$, as depicted in Fig. 17.

  In this situation, the tax on the fuel-based emissions in region t should correspond to the general willingness in the region to pay for global emission abatements, $\tau =$

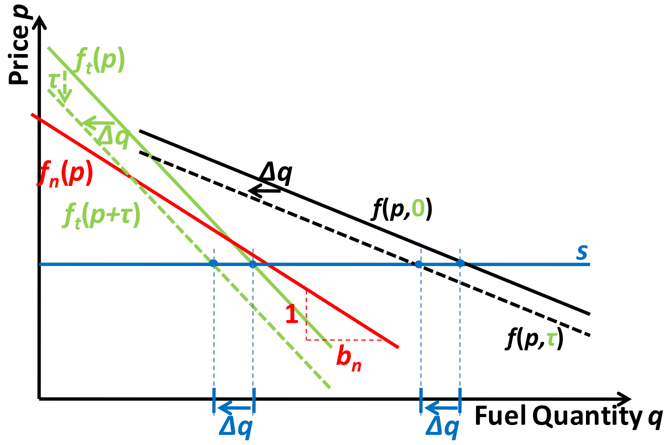


Figure 17: Partial equilibrium: infinitely elastic global fuel supply
Aggregate fuel consumption changes one-per-one with domestic fuel savings. See Fig. 16 for the figure key.

τ_0. Given that the price of the resource is fixed independent of global demand, consumption in region t influences neither the demand for this fuel in region n nor the related emissions in region n. This also matches the GTF according to Eq. 8 as follows: $\text{GTF} = \frac{c}{c+b_n} = \frac{\infty}{\infty+b_n} = 1$.

- Let the global supply of the fuel increase in the price, implying $0 < c < \infty$, and the demand in region n be perfectly inelastic, i.e., $b_n = 0$, as depicted in Fig. 18.

  Here, the tax on the fuel-based emissions in region t should also correspond to

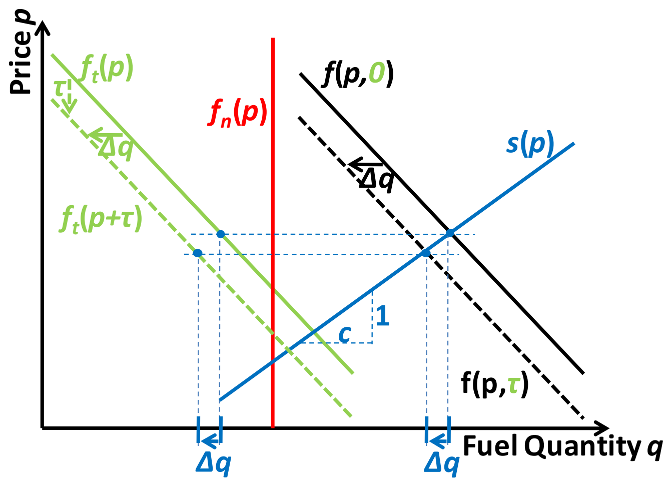


Figure 18: Partial equilibrium: perfectly inelastic demand in the no-policy region
Aggregate fuel consumption changes one-per-one with domestic fuel savings. See Fig. 16 for the figure key.

the general willingness in the region to pay for global emission abatements, $\tau = \tau_0$. Given that the demand for the fuel in region n is fixed independent of its price,

the consumption in region t influences neither the demand for this fuel in region n nor the related emissions in that region. Emission changes in region t translate one-for-one to global emission changes. This corresponds to the expression of the GTF in Eq. 8 as follows: GTF $= \frac{c}{c+b_n} = \frac{c}{c+0} = 1$.
This market setting can be of some practical relevance, notably, if the considered fuel has a low energy density that prevents global trade, such as could be the case for some peat stocks. In this case, the demand for peat from region t in the remainder of the world is likely to be zero due to trade frictions such as transport costs. Replacement of domestic consumption of peat in the climate-protecting region with a climate-neutral fuel (such as sustainably grown local wood could eventually be) would thus be fully translated into global emission reductions, i.e., GTF $= 1$.

- Let the global supply of the fuel be increasing in the price, as is the case for $0 < c < \infty$, and the demand in region n be infinitely elastic, i.e., $b_n = \infty$, as depicted in Fig. 19.

  In this situation, the tax on the fuel-based emissions in region t should be zero

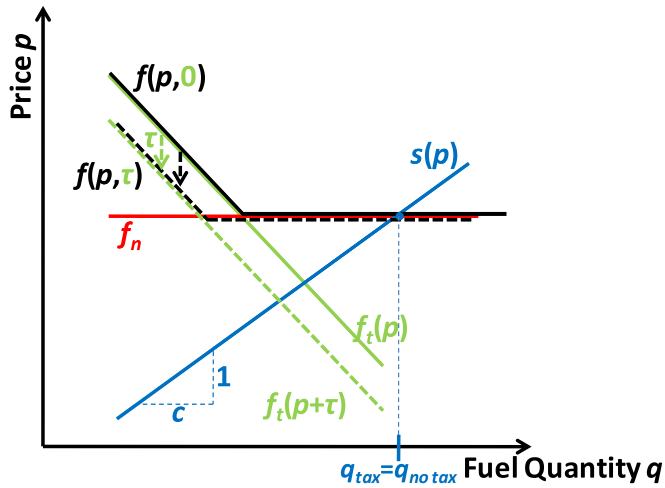


Figure 19: Partial equilibrium: infinitely elastic demand in the no-policy region
Aggregate fuel consumption is not changed by the tax τ. See Fig. 16 for the figure key.

  despite the externality. A tax on region t's emissions will only change the proportion of the global consumption of the fuel between the two regions but leave the total consumption unchanged and, therefore, not influence global emissions. Similar to the case of a constant supply of the fuel, imposing no tax yields the highest welfare level for region t despite its WTP for global emission reductions. As before, this result corresponds with the GTF according to Eq. 8 as follows: GTF $= \frac{c}{c+b_n} = \frac{c}{c+\infty} = 0$.

In reality, characteristics of emission-related markets may more likely correspond to more moderate scenarios than these four extreme cases, and the GTF will accordingly take on a value strictly between 0 and 1. The complexity of economic interregional relations may, however, not allow ruling out *a priori* the possibility of specific more-than-compensating or amplifying feedbacks, i.e., cases where the GTF is below 0 or greater than 1 may, in theory, be possible.

(B) Fuel Dependence in a General Equilibrium Framework

In this section, we examine the optimal regional emission tax in a general equilibrium model.[32] We again assume a world split into two regions r, the taxing region t and the non-tax region n, i.e. we use the same indexation as in the partial equilibrium analysis above, $r = \{t, n\}$, where the taxing region t imposes climate taxes. There are two types of energies e, indexed with $i = \{1, 2\}$. The regions have a level of final good consumption, c_r, and regional energy consumption, e_r^i.

Regional final good production y_r is given by $y_r = f(e_r^1, e_r^2, l_r^y)$, where l_r^y designates the labor dedicated for this production and the two energies are not perfect substitutes. The regional energy production E_r^i is given by $E_r^i = g^i(l_r^i)$, where g^i is an increasing function of the labor l_r^i used for the production of the energy of type i. The regional total labor endowment is normalized to 1 in both regions, $l_r^y + l_r^1 + l_r^2 = 1$. Both the final good and the energies are tradable between the regions; only labor is immobile. The regional consumption of the final good is c_r, and the regional consumption of the energies is e_r^i.

Market clearances require $c_t + c_n = y_t + y_n$ for the final good, and $e_t^i + e_n^i = E_t^i + E_n^i$ for both energies. The energy clearances can also be written as $e^i = E^i$ when defining $e^i \equiv e_t^i + e_n^i$ and $E^i \equiv E_t^i + E_n^i$. In order for the optimal regional tax structure to be analyzed efficiently, we consider a specific global emission constraint that must be respected. We thus consider tax structures, which respect the global emission threshold $\overline{E}$. When the energies are quantified in emission equivalent units, a specific global emission constraint to a level $\overline{E}$ can be written as $e^1 + e^2 \leq \overline{E}$.

The taxing region imposes a tax of rates τ_i on energies. The final good has a price p_y. The energies are traded globally for prices p_{ei}, and the regional prices are p_{ei}^r. In the no-tax region, which abstains from taxation, the two prices are the same, i.e., $p_{ei}^n = p_{ei}$. In the taxing region, the taxes are added to the prices, i.e., $p_{ei}^t = p_{ei} + \tau_i$.

In a decentralized equilibrium with competitive production the following first-order conditions hold:

$$p_y f_{ei}(e_r^1, e_r^2, l_r^y) = p_{ei}^r, \quad p_y f_l(e_r^1, e_r^2, l_r^y) = p_l^r, \quad p_{ei}^r g_l^i(l_r^i) = p_l^r \quad \underset{r\epsilon\{t,n\}, i\epsilon\{1,2\}}{\forall} \tag{9}$$

[32] The analysis in this section is an adaptation of the analysis in Böhringer et al. (2010), where a slightly different model was used to focus on sector-specific taxation but the question of specifically differentiating between fuels instead of or in addition to differentiating between sectors was ignored.

The following Euler equations are obtained:

$$\frac{f_{ei}(e_r^1,e_r^2,l_r^y)}{f_{ej}(e_r^1,e_r^2,l_r^y)} = \frac{p_{ei}^r}{p_{ej}^r}, \quad \frac{f_l(e_r^1,e_r^2,l_r^y)}{f_{ej}(e_r^1,e_r^2,l_r^y)} = \frac{p_l^r}{p_{ej}^r} \underset{r\epsilon\{t,n\},i,j\epsilon\{1,2\}}{\forall}$$

Balanced regional budgets mean

$$p_y c_r = p_y y_r + p_{e1}(E_r^1 - e_r^1) + p_{e2}(E_r^2 - e_r^2) \underset{r\epsilon\{t,n\}}{\forall}. \tag{10}$$

Optimal regional taxes for the taxing region are those that maximize the domestic final consumption c_t with respect to τ_i such that $e^1 + e^2 \leq \overline{E}$. Differentiating with respect to τ_i and introducing the shadow price for (avoided) emissions μ yields the following first-order condition:

$$p_y \frac{\mathrm{d}c_t}{\mathrm{d}\tau_i} - \mu \left(\frac{\mathrm{d}e^1}{\mathrm{d}\tau_i} + \frac{\mathrm{d}e^2}{\mathrm{d}\tau_i} \right) = 0 \underset{i\epsilon\{1,2\}}{\forall} \tag{11}$$

The optimal regional taxes can readily be analyzed using derivations based upon the total differentials of the budget constraint presented in Eq. 10 and the efficiency conditions of the decentralized equilibrium of Eq. 9. Appendix C demonstrates that this yields the following:

$$\begin{aligned} p_y \frac{\mathrm{d}c_t}{\mathrm{d}\tau_i} &= \frac{\mathrm{d}p_y}{\mathrm{d}\tau_i}(y_t - c_t) + \left[\tau_1 \frac{\mathrm{d}e_t^1}{\mathrm{d}\tau_i} + \tau_2 \frac{\mathrm{d}e_t^2}{\mathrm{d}\tau_i} \right] \\ &\quad + \frac{\mathrm{d}p_{e1}}{\mathrm{d}\tau_i}(E_t^1 - e_t^1) + \frac{\mathrm{d}p_{e2}}{\mathrm{d}\tau_i}(E_t^2 - e_t^2) \underset{i\epsilon\{1,2\}}{\forall} \end{aligned} \tag{12}$$

Using Eq. 12 in the first-order condition Eq. 11 and recalling that $e^i \equiv e_t^i + e_n^i$, yields the following:

$$\sum_j \left[(\tau_j - \mu) \frac{\mathrm{d}e_t^j}{\mathrm{d}\tau_i} \right] + \frac{\mathrm{d}p_y}{\mathrm{d}\tau_i}(y_t - c_t) - \mu \left(\frac{\mathrm{d}e_n^1}{\mathrm{d}\tau_i} + \frac{\mathrm{d}e_n^2}{\mathrm{d}\tau_i} \right) + \sum_j \frac{\mathrm{d}p_{ej}}{\mathrm{d}\tau_i}(E_t^j - e_t^j) \overset{!}{=} 0 \underset{i\epsilon\{1,2\}}{\forall}$$

Normalizing the price of the final consumption good, $p_y \equiv 1$ in order to consider real prices, we find the following efficiency conditions:

$$\sum_j \left[(\tau_j - \mu) \frac{\mathrm{d}e_t^j}{\mathrm{d}\tau_i} \right] \underbrace{- \mu \left(\frac{\mathrm{d}e_n^1}{\mathrm{d}\tau_i} + \frac{\mathrm{d}e_n^2}{\mathrm{d}\tau_i} \right)}_{\text{fuel depend. leak.}} + \underbrace{\sum_j \frac{\mathrm{d}p_{ej}}{\mathrm{d}\tau_i}(E_t^j - e_t^j)}_{\text{terms of trade}} \overset{!}{=} 0 \underset{i\epsilon\{1,2\}}{\forall} \tag{13}$$

In the absence of leakage and terms-of-trade effects, Eq. 13 would hold for uniform taxation of emissions across all sources, $\tau_j = \tau \underset{j\epsilon\{1,2\}}{\forall}$. As the leakages, $\frac{\mathrm{d}e_n^j}{\mathrm{d}\tau_i}$, and energy-trade balances are typically non-zero and vary across the types of energy used, Eq. 13 requires heterogeneous emission taxation, i.e., fuel-dependent emission prices. There is no reason why the homogenous taxes $\tau_j = \tau \underset{j\epsilon\{1,2\}}{\forall}$ could satisfy Eq. 13 in general for different fuel resources, for example, which all have specific extraction cost paths and different regional demand curves.

We have shown that for a single production sector, producing a single product, y_t, with two different fuels as inputs, the optimal policy would not charge a unitary tax on the producing entity's emissions but would apply a different tax rate for each fuel the sector consumes.

(C) Calculations for Analytical General Equilibrium Model

Differentiating budget Eq. 10 for the domestic region we have the following:

$$\begin{aligned} p_y\frac{dc_t}{d\tau_i} &= \frac{dp_y}{d\tau_i}(y_t-c_t)+p_y\frac{dy_t}{d\tau_i}+\frac{dp_{e1}}{d\tau_i}(E_t^i-e_t^i) \\ &+p_{e1}(\frac{dE_t^1}{d\tau_i}-\frac{de_t^1}{d\tau_i})+\frac{dp_{e2}}{d\tau_i}(E_t^2-e_t^2)+p_{e2}(\frac{dE_t^2}{d\tau_i}-\frac{de_t^2}{d\tau_i})\underset{i\epsilon\{1,2\}}{\forall}. \end{aligned}$$

We can now differentiate the respective production functions and obtain the following:

$$\begin{aligned} p_y\frac{dc_t}{d\tau_i} &= \frac{dp_y}{d\tau_i}(y_t-c_t)+p_y\left[f_l^t\frac{dl_t^y}{d\tau_i}+f_{e1}^t\frac{de_t^1}{d\tau_i}+f_{e2}^t\frac{de_t^2}{d\tau_i}\right]+\frac{dp_{e1}}{d\tau_i}(E_t^1-e_t^1) \\ &+p_{e1}(g_l^t(l_t^1)\frac{dl_t^1}{d\tau_i}-\frac{de_t^1}{d\tau_i})+\frac{dp_{e2}}{d\tau_i}(E_t^2-e_t^2)+p_{e2}(g_l^t(l_t^2)\frac{dl_t^2}{d\tau_i}-\frac{de_t^2}{d\tau_i})\underset{i\epsilon\{1,2\}}{\forall}. \end{aligned}$$

When recalling $p_yf_{ei}(e_r^1,e_r^2,l_r^y)=p_{ei}^r$, $p_yf_l(e_r^1,e_r^2,l_r^y)=p_l^r$ and $p_{ei}^rg_l^i(l_r^i)=p_l^r$ from Eq. 9, Eq. 11 leads to the following:

$$\begin{aligned} p_y\frac{dc_t}{d\tau_i} &= \frac{dp_y}{d\tau_i}(y_t-c_t)+p_y\left[f_l^t\frac{dl_t^y}{d\tau_i}+f_{e1}^t\frac{de_t^1}{d\tau_i}+f_{e2}^t\frac{de_t^2}{d\tau_i}\right]+\frac{dp_{e1}}{d\tau_i}(E_t^1-e_t^1) \\ &+p_{e1}(g_l^t(l_t^1)\frac{dl_t^1}{d\tau_i}-\frac{de_t^1}{d\tau_i})+\frac{dp_{e2}}{d\tau_i}(E_t^2-e_t^2)+p_{e2}(g_l^t(l_t^2)\frac{dl_t^2}{d\tau_i}-\frac{de_t^2}{d\tau_i}) \\ &= \frac{dp_y}{d\tau_i}(y_t-c_t)+p_l^t\frac{dl_t^y}{d\tau_i}+\left[\underbrace{p_{e1}^t}_{p_{e1}+\tau_1}\frac{de_t^1}{d\tau_i}+\underbrace{p_{e2}^t}_{p_{e2}+\tau_2}\frac{de_t^2}{d\tau_i}\right]+\frac{dp_{e1}}{d\tau_i}(E_t^1-e_t^1) \\ &+p_l^t\frac{dl_t^1}{d\tau_i}-p_{e1}\frac{de_t^1}{d\tau_i}+\frac{dp_{e2}}{d\tau_i}(E_t^2-e_t^2)+p_l^t\frac{dl_t^2}{d\tau_i}-p_{e2}\frac{de_t^2}{d\tau_i} \\ &= \frac{dp_y}{d\tau_i}(y_t-c_t)+p_l^t\frac{dl_t^y}{d\tau_i}+\left[(p_{e1}+\tau_1)\frac{de_t^1}{d\tau_i}-p_{e1}\frac{de_t^1}{d\tau_i}+(p_{e2}+\tau_2)\frac{de_t^2}{d\tau_i}-p_{e2}\frac{de_t^2}{d\tau_i}\right] \\ &+\frac{dp_{e1}}{d\tau_i}(E_t^1-e_t^1)+p_l^t\frac{dl_t^1}{d\tau_i}+\frac{dp_{e2}}{d\tau_i}(E_t^2-e_t^2)+p_l^t\frac{dl_t^2}{d\tau_i} \\ &= \frac{dp_y}{d\tau_i}(y_t-c_t)+p_l^t\frac{dl_t^y}{d\tau_i}+\left[\tau_1\frac{de_t^1}{d\tau_i}+\tau_2\frac{de_t^2}{d\tau_i}\right]+\frac{dp_{e1}}{d\tau_i}(E_t^1-e_t^1) \\ &+p_l^t\frac{dl_t^1}{d\tau_i}+\frac{dp_{e2}}{d\tau_i}(E_t^2-e_t^2)+p_l^t\frac{dl_t^2}{d\tau_i}\underset{i\epsilon\{1,2\}}{\forall} \end{aligned}$$

Noting that total labor supply is fixed, $l_t^y + l_t^1 + l_t^2 = 1$ and thus $\frac{dl_t^y}{d\tau_i} + \frac{dl_t^1}{d\tau_i} + \frac{dl_t^2}{d\tau_i} = 0$, this yields Eq. 12 as follows:

$$\begin{aligned} p_y \frac{dc_t}{d\tau_i} &= \frac{dp_y}{d\tau_i}(y_t - c_t) + \left[\tau_1 \frac{de_t^1}{d\tau_i} + \tau_2 \frac{de_t^2}{d\tau_i}\right] \\ &\quad + \frac{dp_{e1}}{d\tau_i}(E_t^1 - e_t^1) + \frac{dp_{e2}}{d\tau_i}(E_t^2 - e_t^2) \quad \forall_{i \epsilon \{1,2\}} \end{aligned}$$

(D) Details for the Numerical Model

Current Prices and Regional Consumption of Fuels for Calibration.

See Table 3.

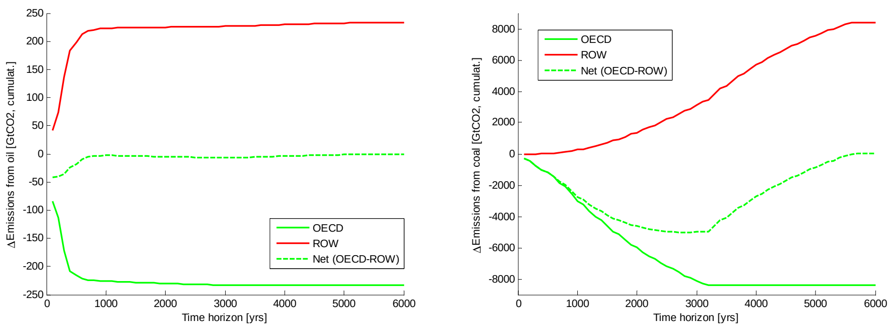
Table 3: Current fuel consumption and prices

Current Consumption		
Using IEA WEO2010 Data	Oil (bio.bbl/yr)	Coal (bio. t/yr)*
OECD	16.4	1.61
Non-OECD	14.3	3.12
World	30.7	4.74
* in Mtce		
Relevant Current Prices (average from 2006-2010, in US 2010 $)		
Using Worldbank Pink Sheet Data (2011)	Price	
Oil ($/bbl)	76	
Coal ($/t)	83	

Sources: IEA (2010) and World Bank (2011)

(E) Details of Emission Leakage from Uniform OECD-tax

See Figs. 20 through 22.



(a) Oil *(b) Coal*

Figure 20: Dynamics of regional oil- and coal-emission changes from OECD tax

Regional emission changes resulting form a permanent uniform CO_2 tax of 40 \$/t in the OECD.

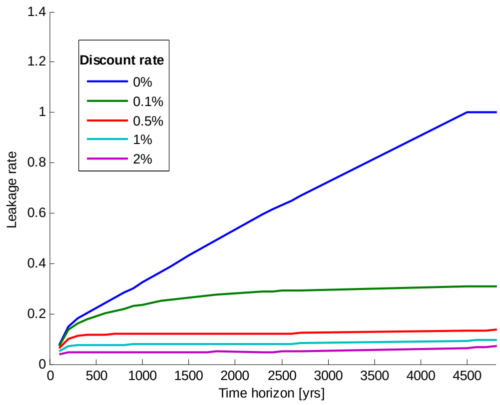


Figure 21: Undiscounted and discounted leakages for initial tax

Uniform OECD CO_2 tax of 40 \$/t during first 50 years, for static demand.

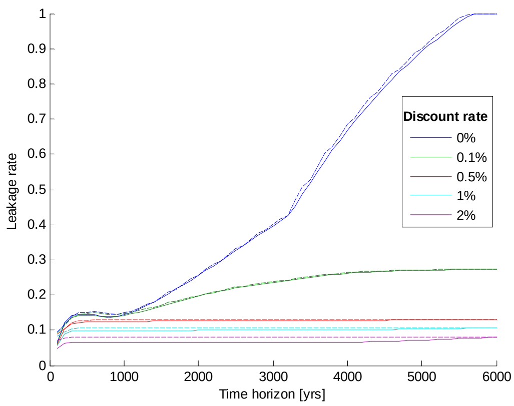


Figure 22: Limited simulation horizons vs. accounting emissions for different time-horizons

Uniform OECD CO_2 tax of 40 \$/t. Overall leakages estimated with limited model simulation horizons (plain curves) and leakages for emissions occuring up to a limited time (from today on) calculated from long model simulations (dashed curves).

(F) Optimal Terms-of-Trade Import Tariffs for Coalition of all OECD-Countries in Standard Model

See Table 4.

Table 4: Optimal OECD trade and climate taxes on the imported fuels

<table>
<tr><th colspan="3" rowspan="2">Optimal OECD Taxes [$/tCO$_2$]</th><th colspan="2">Standard Scenarios</th></tr>
<tr><th>No Lique-faction</th><th>Liquefaction</th></tr>
<tr><td rowspan="4">Optimal Overall Tax</td><td rowspan="2">WTP $= 0\,\$/tCO_2$ (1)</td><td>Oil</td><td>65.7</td><td>25.1</td></tr>
<tr><td>Coal</td><td>0.7</td><td>2.8</td></tr>
<tr><td rowspan="2">WTP $= 40\,\$/tCO_2$ (2)</td><td>Oil</td><td>86.1</td><td>95.8</td></tr>
<tr><td>Coal</td><td>39.4</td><td>39.5</td></tr>
<tr><td colspan="2" rowspan="2">Optimal Climate Tax (= 2 - 1)</td><td>Oil</td><td>20.4</td><td>70.7</td></tr>
<tr><td>Coal</td><td>38.7</td><td>36.6</td></tr>
</table>

(G) Model Extensions and Sensitivity Analysis

The exact optimal regional taxes on the fuel emissions depend on the assumptions in the model. To understand how the results change under different assumptions, twelve specific types of extensions and alternative parameterizations have been examined. As the following results show, the key findings outlined above are found to be rather robust with respect to these model assumptions.

Longer Simulation Horizon. Doubling the length of the simulation horizon to 400 years from the 200 years in the standard scenario, barely changes the qualitative results. The main results, reported in Table 5, show that in the case without liquefaction, the optimal OECD tax on emissions from oil consumption is now below 50 % of the region's WTP for emission reductions, at $18.0\,\$/tCO_2$. This is because, over the longer run, the total amount of oil consumed is limited even more by the physical resource stocks rather than by the amount demanded from it. With respect to coal emissions, the optimal climate tax remains slightly below the WTP, at $38.3\,\$/tCO_2$. For the case where liquefaction will, in the future, allow the production of synthetic liquid fuel from coal, the extension of the simulation period from 200 to 400 years has an even lower impact on the optimal tax rates. For oil emissions, it is now $70.1\,\$/tCO_2$, and for coal emissions, it is $34.7\,\$/tCO_2$. The slight drop in the optimal regional coal tax in both scenarios with the extended simulation horizon, stems from the fact that in the very long run, coal is also a scarce resource, implying that current regional consumption reductions tend to create some leakage to future periods instead of representing true genuine worldwide eternal fuel savings. The effect is, however, still very small due to (i) the abundance of coal even in terms of centuries' consumption, and (ii) the exponential discounting of future emissions, which, over several centuries, becomes relevant despite the limited discount rate of $\rho_{\text{cons}} = 5\,‰$ p.a.

Table 5: Optimal OECD climate taxes for simulation horizon of 400 years

Optimal Climate Tax [$/t$CO_2$]	No Liquefaction	Liquefaction
Oil	18.0	70.1
Coal	38.3	34.7
WTP	40	

Alternative Cross-Price Elasticities. Table 6 shows the results for the case when cross-price elasticities of half, resp. double of the standard cross-price elasticities are assumed. Most optimal tax values are only slightly affected. Some are changed to a relevant extent, but qualitatively the results remain similar and the changes go into the expected direction: given lower cross-price elasticities of the fuel demand, the optimal tax on oil, if there is no liquefaction, becomes 17.5 $/t$CO_2$, i.e., lower than in the standard case and even lower than half of the WTP. This was expected because the lower cross-price elasticity means that regional reductions in oil consumption and the induced reduction of the world market price imply a lower reduction of the coal consumption in the other region, thus overall leading to an even lower global impact (in terms of worldwide carbon emissions) of the regional oil consumption reductions. Analogously, the inverse is observed for the scenario with the larger cross-price elasticities, where the optimal tax on emissions from oil combustion rises to 26.3 $/t$CO_2$.

Table 6: Optimal OECD climate taxes for alternative cross-price elasticity values

Optimal Climate Tax [$/t$CO_2$]	Low Cross-Elast. (average 0.1)		High Cross-Elast. (average 0.4)	
	No Liquefaction	Liquefaction	No Liquefaction	Liquefaction
Oil	17.5	70	26.3	72.5
Coal	38.7	36.5	38.8	37
WTP	40			

Resources Belonging to OECD and ROW rather than to External Entities. In the standard model, fuel owners are external to the two economic regions whose fuel demand is modeled. This may be defensible, for example, for oil, where a large fraction of the reserves are concentrated in a few countries with relatively small populations that are responsible only for a minor fraction of global CO_2 emissions.

The assumption of an import of 100 % of the consumed fuels also drives the substantial optimal trade-taxes found in the simulations (see the detailed results in Appendix F).

However, primarily for coal, important fractions of worldwide reserves are situated within OECD countries. Therefore, the reserve distribution between the two modeled regions is here accounted for. As an approximation based on BGR and IEA data, 13 % of the worldwide oil resources and 43 % of the coal resources are assumed to be situated in the OECD region,[33] implying that these fractions of the resource rents are attributed to the OECD.

Note that liquefaction-emissions are still assumed to occur outside of the OECD region. This is the logical consequence of the absence of stringent border tax adjustments and free trade in fossil fuels, as well as emissions taxes strictly imposed on domestically occurring emissions. Theoretically, even OECD-coal may be exported for the liquefaction processes in regions not taxing the large amount of CO_2 emissions generated during the liquefaction process. However, because close to 60 % of all coal reserves are situated in non-OECD territory, such an export may, even in the longer run, not be necessary as most synthetic fuel would, in any case, be produced in the non-OECD regions and OECD coal-export restrictions or duties would not significantly change the picture of the global emissions.

Table 7 indicates the optimal environmental taxes for this case. Comparing the values with those of the standard case where all resources are assumed to be imported (Table 2), shows that the values remain almost entirely unchanged (all values change by less than 2 %). While representing comforting evidence for the adequacy of the here used concept for the disentangling of trade and climate components of the regionally optimal overall tax, these results are not surprising: the distribution of the freely traded resources has much less to do with the optimal *environmental* tax, than with the optimal trade tax on these fuels. The details on the optimal regional trade tax on the fuels are reported in Appendix H. They show a significant decrease in the import tax on oil and a decrease of the very low import tax on coal. This makes sense because the import tax allows a region that imports a scarce good to extract parts of the good-owner's scarcity rent as it depresses the equilibrium price on the world market. As the share of the good that a country or a region owns increases, that region profits less from market-price-lowering import tariffs because of its already higher own share of the resource rent. See Appendix H for a further discussion of this optimal trade-tax pattern based on results from additional

[33]Sources: BGR (2009), Table A 3-4, and IEA (2011), Table II.4.

simulations.

Table 7: Optimal OECD climate taxes with regionally distributed resource stocks

Optimal Climate Tax [$/$tCO_2$]	No Liquefaction	Liquefaction
Oil	20.4	72.0
Coal	38.8	36.9
WTP	40	

Monopolistic Oil Supply. In the standard scenarios all fuels are assumed to be supplied competitively. If one considers the overall large number of fossil fuel suppliers around the world, and notably the limited means OPEC seems to have to enforce compliance of its member states to respect their respective quotas, this may not be a completely implausible assumption. However, an oligopolistic structure would probably be a more realistic representation of the market than perfect competition. To consider the effect that the market supply structure could have on the optimal regional climate taxes, we here consider the case of a monopolistic supply, which is the opposite extreme of perfect competition and should thus allow to approximate the maximal effect the 'imperfectness' of the fuel supply competition may have on the market outcome, beyond even any oligopoly with a limited number of competitors.

For the case without liquefaction, the model was thus extended to allow for monopolistic oil supply.[34] Table 8 indicates the optimal taxes in the case where oil is supplied monopolistically. The numbers indicate that the optimal taxes are almost the same as in the competitive case: while the coal tax is unaffected, the optimal oil tax is only slightly increased in the monopolistic case, by less than 3 %, from the standard value of 20.4 to 21.1 $/$tCO_2$. Fig. 6 shows the fuel consumption and price dynamics under monopolistic oil supply.

Alternative (Emission) Discount Rates of Consumers. As is intuitive and as Figs. 12 and 13 suggest, the discount rate by which the future emissions are present-discounted

[34] It would be more comlicated to extend the case with liquefaction to monopolistic fuel supply, because, e.g., the oil owner could not easily calculate, for each period, the effect of a variation of its supply on the amount of coal supplied in the current and other periods. While in the case without liquefaction it is, due to the low substitutability between the two fuels, most likely unproblematic that the monopolistic supplier does not take into account his effect on the supply of the other fuel, taking into account the effect of oil supply on the supply of synthetic fuel would be central for the monopolist in the case where liquefaction is allowed.

Table 8: Optimal OECD climate taxes with monopolistic oil supply

Optimal Climate Tax [$/tCO$_2$]	No Liquefaction
Oil	21.1
Coal	38.7
WTP	40

can have a substantial impact on the calculated leakage rate and therefore on the optimal regional fuel-emission taxes. Table 9 indicates the optimal taxes if the consumers (resp. the policy maker) do not apply any discounting at all, resp. if they us a discount rate of 2 %, instead of the 0.5 % in the standard case. While the optimal coal tax is barely influenced by the discount rate, the oil tax changes in the directions that one may have anticipated: in the absence of the discount rate, the optimal OECD oil taxes become more extreme than in the standard case, while with the large discount rate, the oil taxes are closer to the genuine WTP for climate protection, with the oil tax in the case with liquefaction remaining only slightly above the genuine WTP of 40 $/CO$_2$.

Table 9: Optimal OECD climate taxes for alternative (emission) discount rate of consumers

Optimal Climate Tax [$/tCO$_2$]	Discount rate: No Discounting ($\rho_{\text{cons}} = 0$)		Discount rate: High ($\rho_{\text{cons}} = 2\,\%$)	
	No Liquefaction	Liquefaction	No Liquefaction	Liquefaction
Oil	17.0	78.5	21.5	46.3
Coal	38.0	34.7	38.3	36.9
WTP	40			

Faster Coal Depletion. Table 10 provides results for the case where coal reserves deplete more rapidly with declining reserves, assuming $cp = 2000\,\text{GtCO}_2$. In the case without liquefaction, this changes the optimal unilateral climate tax on oil only slightly, to slightly below 20 $/tCO$_2$, but primarily lowers the optimal coal tax, to 33.7 $/tCO$_2$. The lower optimal tax on coal suggests that the increased scarcity of coal implies that even regional coal consumption reductions now have a significant impact on the international coal prices, leading to an increased coal consumption in ROW, that is, to a significant leakage rate. This is further accentuated in the case with liquefaction, which requires a substantial amount of additional coal. In this case, because coal is now subject to a relevant interregional leakage effect, and the future synthetic substitute for oil is also coal-derived, both fuels are now subject to lower optimal unilateral emission taxes than in the case with standard coal depletion. With approximately 50 $/t$CO_2$, the optimal tax on oil remains, however, significantly larger than the region's WTP for global emission reductions, and it remains almost exactly twice as high as the optimal tax on coal at 26.6 $/t$CO_2$.

Table 10: Optimal OECD climate taxes with fast coal depletion (cp = 2000 Gt)

Optimal Climate Tax [$/t$CO_2$]	No Liquefaction	Liquefaction
Oil	19.6	50.1
Coal	33.7	26.6
WTP	40	

Lower Discount Rate of Resource-Owners. Notably Middle Eastern countries have large oil reserves that are exploitable for very low costs. As the oil price plots in Figs. 1 through 3 suggest, if the fuel owners were to act rationally as assumed in the present model and exhibited a discount rate of $\rho_{res} = 3\,\%$, the oil owners would be expected to offer their oil more cheaply under current market conditions than what is actually observed on global oil markets (even though only a few years ago the difference would have been much smaller). To account for this apparent differences, we run the model with a lower discount rate for the fuel owners, of $\rho_{res} = 5\,‰$, corresponding also to the policy maker's discount rate ρ_{cons} in the standard scenario. While besides a low discount rate there exist various other physical and economic factors that potentially explain why the current resource rent for oil producers is so high despite relatively large reserves of cheap resources, a rate of $\rho_{res} = 5\,‰$ results indeed in a modeled resource path with initial consumption rates and prices close to actual observations. Tested for the case without liquefaction, regional consumption values of both fuels are in a 15 %-range around observed regional consumption in 2008/2009 (for more details on a case with a lower discount rate, see Figs. 4 and 5, where also a growing demand was used in accordance with IEA estimates, further improving the match between the model and reality). Table 11 gives the optimal OECD climate taxes found for the case with $\rho_{res} = 5\,‰$. The tax rates differ only slightly from the optimal taxes in the standard case; all key findings are preserved. This is especially encouraging as it seems not trivial to model the behavior of the various actors on the supply side of the fuel market in a very precise way. The fact that a large change in the fuel owners' discount rate seems not to have any major impact on the optimal fuel taxes in the cases examined here, suggest that even if some details of the fuel supply market are not represented in a model, the calculated effect of climate policies may still be closer to reality than one may assume on first sight.

Table 11: Optimal OECD climate taxes with low resource-owner discount rate ($\rho_{\text{res}} = 5$ ‰)

Optimal Climate Tax [$/$tCO_2$]	No Liquefaction	Liquefaction
Oil	18.4	69.4
Coal	38.1	35.3
WTP	40	

Growing Demand. The standard model assumes the demand system to be constant over time. In reality, fuel demand is projected to grow over the next few decades notably in the emerging economies of the ROW. To take this into consideration, an extended model version that allows for a time-varying demand system is employed. Based on projections of the IEA World Energy Outlook 2009 for their reference scenario (IEA, 2009), we consider a scenario where fuel demand is constant in the OECD and growing at 2.6 % p.a. in the ROW during the first 25 years. In the long run we assume that, as the ROW economies are maturing, their energy demand *growth rates* slowly decline over time after the first 25 years, by 0.05 % p.a., until the time the economies reach a state where autonomous energy efficiency improvements set off any final demand increases; from then on the energy demand growth rate is 0.[35] This scenario still leads to the same central conclusions of a low tax on oil emissions if there is no liquefaction in the future and a high oil emission

[35] In the World Energy Outlook 2009 reference scenario lasting through 2030, oil consumption is assumed to decline by 0.3 %p.a. between 2008 and 2030 in the OECD, while it increases by 2.3 % p.a. in the ROW (IEA, 2009, p.81, Table 1.3). Correcting these *consumption* changes for the average annual oil consumption changes during the same period in our standard model with *constant demand* (these changes are -0.3 % p.a. in the OECD and -0.2 % p.a. in the ROW) to approximate *demand* changes, we find a constant oil *demand* in the OECD, and an increase in the ROW of 2.5 % p.a.

In the same World Energy Outlook scenario, coal consumption declines by 0.2 % p.a. between 2007 and 2030 in the OECD and increases by 2.8 % p.a. in the ROW (IEA, 2009, p.90, Table 1.5). Correcting these *consumption* changes for the average annual coal consumption changes during the same period in our standard model with *constant demand* (these changes are +0.2 % p.a. in the OECD and -0 % p.a. in the ROW) to approximate *demand* changes, we find coal *demand* in the OECD changing by -0.4 % p.a., and increasing by approximately 2.8 % in the ROW.

Thus, in each region, average demand growth rates are very close to each other accross the fuels during the period from 2007/2008 through 2030 and we approximate them by assuming a constant demand for both fuels in the OECD and an annual growth of 2.6 % for both fuels in the ROW. Note that for the coal demand in the OECD, the difference between our assumption (0 %) and what the World Energy Outlook data implies (0.4 %) is in the medium-run smaller than what the here cited numbers suggest on first sight: OECD consumption is in the World Energy Outlook assumed to slightly decrease only until 2015, from then on the projected consumption change is already approximately zero until 2030.

tax if the future is marked by liquefaction. Quantitatively, the growing demand does have a significant impact on the optimal regional OECD tax rates on emissions from the two fuels (Table 12). All four considered optimal climate tax rates are lower than in the case without demand growth. In the case without liquefaction, the optimal climate tax on oil is decreased to approximately one-third of the WTP for global emission reductions. Similarly, the optimal climate tax on coal decreases almost to 30 $/t$CO_2$ in the case with liquefaction. These observations can be explained by the larger leakage rates. That is, due to the growing demand, oil becomes even more scarce over time, leading to a larger overall oil leakage rate, particularly in the case without liquefaction. Finally, especially if liquefaction is possible, the growing demand causes even coal to become a truly scarce resource, implying that, in this scenario, even a lowering of regional coal consumption has a relevant impact on global coal prices, thus leading through this channel to significant leakage rates.

While Table 12 indicates the optimal regional climate taxes for the above described demand paths and the standard discount rate of fuel owners, in the case of the same increasing demands but a lower resource-owner discount rate of $\rho_{\text{res}} = 5$ ‰ – this is the situation whose dynamics is plotted in Figs. 4 and 5 –, the optimal OECD oil resp. coal climate taxes are (in $/t$CO_2$) 13.1 resp. 35.3 in the case without liquefaction and 62.5 resp. 29.6 with liquefaction. If all demands grow at a rate of 1 % p.a. throughout the entire simulation period, they are, in the same order, 13.5 resp. 36 (without liquefaction) and 63.6 resp. 28.9 (with liquefaction), assuming standard discount rates.

Table 12: Optimal OECD climate taxes with demand growth close to IEA scenario

Optimal Climate Tax [$/t$CO_2$]	No Liquefaction	Liquefaction
Oil	13.9	66.5
Coal	36.7	31.9
WTP	40	

Increased Carbon Intensity of Unconventional Oil. Unconventional fuels are supposed to have 23 % higher well-to-wheel emissions than conventional oil (Brandt, 2011). Here, an extended version of the model assumes that the emission intensity of oil increases linearly in the amount of oil already extracted, such that after the 2500 Gbbl of remaining conventional oil are consumed, the overall emission intensity of oil is 23 % higher than initially.[36]

[36] 2500 Gbbl is the approximate value of remaining conventional oil according to IEA (2010). In line with the general model assumptions in the standard parameterization, the oil is here supposed to be

Table 13 shows the main results for this scenario: as one would expect, the optimal regional tax on the final-combustion-emissions of oil are here somewhat higher than in the standard scenario with the constant emission intensity, primarily in the case where crude oil is not replaced by liquefied coal in the near future.

Table 13: Optimal OECD climate taxes when the oil well-to-wheel emission intensity increases with cumulative extractions

Optimal Climate Tax [$/t$CO_2$]	No Liquefaction	Liquefaction
Oil	26.2	72.4
Coal	38.7	36.8
WTP	40	

Different Overhead Costs of Liquefaction Process. In the standard parameterizations, the overhead cost of the liquefaction process is assumed to be 15 $ per barrel of synthetic oil produced. As shown in Fig. 3, in this case liquefaction starts after almost 100 years. Table 14 reports the optimal regional tax rates for the cases where (i) liquefaction requires no overhead costs, $c_l = 0$, resp. where (ii) liquefaction requires large overhead costs of 70 $/bbl.

Table 14: Optimal OECD climate taxes for alternative liquefaction overhead costs

Optimal Climate Tax [$/t$CO_2$]	$c_l =$ 0 $/bbl	$c_l =$ 70 $/bbl
Oil	75.8	41.2
Coal	36.1	38.0
WTP	40	

The values in Table 14 show how the change in the overhead costs of liquefaction imply a gradual shift of the optimal regional tax rates: for high liquefaction overhead costs, i.e., when liquefaction occurs only late (column 3 in Table 14) the tax rates approach those without any liquefaction. For low overhead costs, i.e., when liquefaction occurs earlier (column 2 in Table 14), the ratio of the optimal OECD tax rates on the two fuels

extracted by some external producers. As the excess-emissions thus occur during the external production process and not primarily during end-use combustion, they are not taxed, but they are taken into account by the OECD as part of the global emissions.

approaches that of the ratio of the emission intensity of oil from liquefied coal and that of standard oil.

Accounting for the Possibility of an Exogenous Clean Backstop. The possibility that technical advancements provide alternative energy sources that may replace the fossil fuels as major primary energy sources cannot be excluded. As Habermacher and Kirchgässner (2011) have shown, this can reverse the effects of climate policy measures that one would find if excluding that possibility. There does not exist, however, any consensus on a specific value for the probability of such a drastic technological development, and the timing when such a development may materialize, or more precisely, the stochastic joint distribution of various potential future developments, is unclear as well. In addition, so called backstop technologies may, in reality, not be perfect.[37] For example, they may be available only in limited quantities (of energy delivered), or their development may occur so gradually that the price path of the conventional energy sources can be crucial for the time and speed of introduction of the backstop technologies. It is beyond the scope of this study to consider these aspects in detail. Instead, the simple concept of a perfect backstop is considered whose introduction is stochastic with an exogenous annual probability of introduction. In this case, it can be intuitively understood, and it has been shown by Dasgupta and Heal (1974), that the behavior of all forward-looking agents, such as the tax-setting institution of the OECD and the suppliers, can be modeled in the same way as in the case without any possible backstop while augmenting their discount rates by the annual probability of the introduction of the backstop. Table 15 provides results for the cases of an annual probability (ap) of the introduction of a backstop of 1 % and 2 %.

Table 15 shows that the possibility of future switches to backstop technologies do not reverse the main findings with respect to the optimal regional emission tax structure The optimal OECD tax on coal emissions remains close to the region's WTP for global emission reductions in all four cases. The optimal tax on emissions from oil remains substantially below the WTP in the case where liquefaction is impossible and substantially above the WTP in the case where liquefaction substitutes crude oil in the medium-term future, even if all four values for the optimal oil-emission tax are now closer to the WTP than in the standard case where a backstop was implicitly ruled out for the next 200 years.

Optimal Early versus Future Tax Levels. In reality, the optimal committed regional fuel emission taxes may describe non-constant time-paths rather than constant values, as assumed in this study. Here, the aim is to verify how close the found optimal-constant

[37] As a perfect backstop we consider an emission-free energy source, abundant enough in terms of amount and cost for it to fully replace its competing fossil fuels from the time on it is introduced.

Table 15: Optimal OECD climate taxes accounting for the possibility of clean backstop technologies

Optimal Climate Tax [$/tCO_2$]	Probability for Alternative Developments (annual probability *ap*)			
	Low ($ap = 1^{*}$)		High ($ap = 2^{**}$)	
	No Liquefaction	Liquefaction	No Liquefaction	Liquefaction
Oil	26.3	55.7	30.6	46.6
Coal	39.1	38.0	39.3	38.7
WTP	40			

$^{*}ap$=1 % implies that the cumulative probability of an alternative development to make fossil fuels redundant is 18 % after 20 years, and 40 % after 50 years.

$^{**}ap$=2 % implies that the cumulative probability of an alternative development to make fossil fuels redundant is 33 % after 20 years, and 64 % after 50 years.

values for constant taxes may be to the truly optimal flexible tax paths. For this purpose, the extent to which a deviation from the optimal constant taxes found above would be optimal during the first 40 years is analyzed. Table 16 shows the main results.

Table 16: Optimal initial deviations from optimal constant OECD tax rates

	All values in $/tCO_2$	No Liquefaction	Liquefaction: Standard (c_l = 15 $/bbl)	Liquefaction: Early (c_l = 0 $/bbl)	Liquefaction: Standard, but low consumer discount rate ($\rho_{\text{cons}} = 2$ ‰ instead of 5 ‰)
Optimal Constant Climate tax	Oil	20.4	70.7	75.8	75.1
	Coal	38.7	36.6	36.1	36.2
Optimal Initial Deviation (first 40 yrs)	Oil	1.7	-15.7	-14.7	-13.8
	Coal	-0.2	0.1	0.1	-0.5
Optimal Initial Tax (first 40 yrs)	Oil	22.0	55.1	61.0	61.4
	Coal	36.8	36.8	36.3	35.7

For the situation without any liquefaction, the optimal initial environmental tax shows only an insignificant deviation from the optimal constant tax rate, suggesting that the optimal tax path may be close to constant over all the periods. This may have been expected, as parts of any unit of fuel spared regionally during any specific period may leak in parts to any other periods, independent of the exact time when the regional fuel saving may have occurred.

The situation for the case with liquefaction differs to a certain extent. The optimal oil emission tax rates in the initial periods are still substantially above the WTP for global emission reductions, but they are lower than for the later periods, resp. lower than the optimal constant tax would be. As an example, the results in column 3 of Table 16 show for the standard scenario with liquefaction (c_l =15 \$/bbl) that while the optimal constant oil-tax rate would be approximately 70 \$/tCO_2, the optimal value during the initial periods is lower, at 55 \$/tCO_2. If liquefaction starts earlier (column 4 in Table 16, c_l =0 \$/bbl) or if the discount rate ρ_{cons} for future emissions is low (column 5, 2 ‰ instead of 5 ‰), the optimal climate tax on oil remains, however, larger also in the initial periods: the optimal initial tax, in these cases, continues to remain at 61 \$/tCO_2.

Fig. 23 shows how the fuel consumption and emission paths respond to a change in the initial oil-tax rate in the standard scenario with liquefaction and explains the optimal initial tax rates. An increase of the OECD tax on oil-emissions during the initial periods (until year 40), leads to a substantial direct reduction of the region's oil consumption during that period in the standard scenario with liquefaction (corresponding to column 3 in Table 16). Thus, 21.5 Gt CO_2 are saved (depression of the green curve on the left-hand side plots in Fig. 23). Because of the (dirty) 'backstop', that is, the liquefaction of abundant coal, the initial reduction of domestic oil consumption has only a minimal impact on the future fuel prices, limiting the leakage in terms of end-consumption of fuels. It has, however, a strong impact on the amount of synthetic oil (SynOil) produced through liquefaction in the future. Notably, due to the low leakage in terms of oil consumption, the initial oil savings imply that oil will last longer and ultimately translate to an almost one-per-one reduction in the amount of oil demand that is to be met through coal liquefaction during the time when SynOil begins to replace crude oil. This leads to 19.2 Gt of CO_2 saved because crude oil lasts longer (the depression of the black curve on the left-hand side plots in Fig. 23). This is the mechanism through which current oil-savings imply, over the coming centuries, even higher than one-per-one emission savings if liquefaction of abundant coal becomes a relevant process for meeting sustained demand for liquid fuels. The optimal unilateral initial tax rate of 55.1 \$/tCO_2 on emissions from oil use in the OECD corresponds primarily to the combined present discounted effect of the noted initial emission savings and those savings during the time when liquefaction begins. The initial tax applies to the 21.5 Gt of CO_2 saved initially, but it also induces an additional reduction of emissions of 19.2 Gt of CO_2, which occurs approximately 110 years later. Given the discount rate of 5 ‰, the latter are discounted by a factor of approximately $0.995^{110} = 0.576$. Taking this discounting into account when reusing the concept of the GTF from Chapter 3, a rough approximation of the optimal initial tax rate is given by

$$\tau_{ini}^* \approx \underbrace{\tau_0}_{\text{WTP}} \cdot \underbrace{\frac{21.5\,\text{Gt} + 0.576 \cdot 19.2\,\text{Gt}}{21.5\,\text{Gt}}}_{\text{GTF}} \approx 60.6\,\$/\text{tCO}_2.$$

Considering the rawness of this approximation, and given that the leakage in the pre-liquefaction periods, which is not entirely negligible (see green and red curves in the left plots in Fig. 23), would lead to some reduction of the optimal initial tax, this value compares reasonably well to the numerically found value of 55.1 $/t$CO_2$ in the simulation.

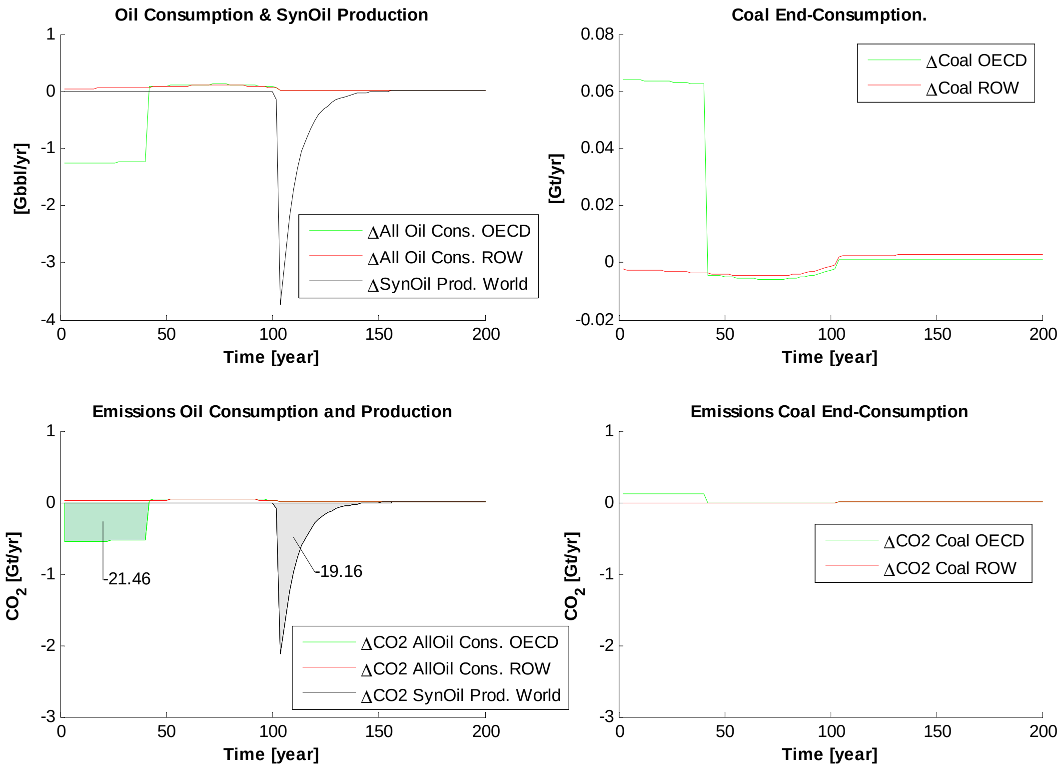


Figure 23: Impact of the change of the oil-tax rate for the initial 40 years from the optimal initial value to the optimal constant-value

In conclusion, the evidence gathered in this section suggests that the optimal tax rates may, in many cases, be fairly constant over time, notably in the case where no backstop (in the form of the liquefaction process) for the scarce crude oil is available in the future. Even if liquefaction dramatically increases the intensity of the liquid fuel production process in the future, this higher future emission intensity is already strongly reflected in the optimal initial unilateral tax rates on oil. Thus, in all considered situations with future liquefaction, the optimal initial tax rate on genuine oil is much larger than the WTP for global emission reductions, which is explained due to the negative leakage of saved oil, this is, because oil saved during the initial periods reduces the production of SynOil in the future. In this scenario where liquefaction plays a role in the future, the (i) lower the production costs of liquefaction and the (ii) lower the discount rate used to present-discount future emissions, the greater are the optimal initial tax rates on oil, as can intuitively be understood.

In the present modeling, we do not assume subgame-perfectness of the OECD tax path choices. Instead, the policy maker in the OECD is supposed to commit for the entire simulation period to the initially set tax plan, which can, however, foresee a different tax during the initial time-period than for the remainder of the simulated time horizon.

(H) Optimal Terms-of-Trade Import Tariffs for Coalition of all OECD-Countries if they own Parts of the Resources

Taking into account that the OECD-coalition owns 13% of worldwide oil reserves, and 43% of the coal reserves, reduces the optimal import taxes significantly, in the case without liquefaction from 65.7 \$/tCO_2 for oil and 0.67 \$/tCO_2 for coal (Table 4) in the case with external fuel owners to 57.6 \$/tCO_2 and 0.33 \$/tCO_2 (Table 18) if the fuel stocks are distributed according to today's situation. This was expected, because if OECD receives a share of the resource rent, it is less important to artificially reduce its fuel demand in order to lower the market price of the globally traded fuels. Interestingly, the relative reduction of the optimal import taxes corresponds quite precisely to the fraction of the fuels situated in the OECD ($65.7 \times (1 - 13\,\%) = 57.1$, i.e. close to 57.6, and $0.67 \times (1 - 43\,\%) = 0.38$, i.e. close to 0.33).

Table 17: Optimal OECD taxes with regionally distributed resource stocks

Optimal OECD Taxes [\$/tCO_2]			Current OECD Fuel-Reserve shares (Oil: 13 %, Coal: 43 %)	
			No Liquefaction	Liquefaction
Optimal Overall Tax	WTP = 0 \$/tCO_2 (1)	Oil	57.6	19.8
		Coal	0.33	1.93
	WTP = 40 \$/tCO_2 (2)	Oil	78.1	91.8
		Coal	39.1	38.3
Optimal Climate Tax (= 2 - 1)		**Oil**	**20.4**	**72.0**
		Coal	**38.8**	**36.9**

Column 2 in Table 18 shows what happens if OECD were a net exporter of the fuels, which could be expected if it owned 60 % of the worldwide fuel stocks. Interestingly, the optimal regional trade tax (the import tariff) is still positive, notably for oil. The remaining columns in the table confirm that this is related to the alleged shortsightedness of the resource owners: as the resource owners discount their future revenues by a rate of 3 % while the consumer's discount rate is 5 ‰, the planner chooses to impose a positive tax on the fuel consumption in order for the fuels not to be thrown on the market too rapidly. For the same fuel shares of 60 %, but with patient resource owners that discount their future real revenues by the same 5 ‰ as the society discounts its future utility flows, the optimal border tax on the fuels becomes indeed a positive export duty (column 3 in Table 18). With this duty the hypothetically fuel exporting OECD could raise the market price for fuels, increasing the scarcity rent from its sales. Finally, the results in column 4 in Table 18 show that the optimal oil trade tariff turns again into an import tax if OECD's share in the fuel stocks were assumed to be 40 %, even if resource owners were still assumed to be as patient as the remainder of the society. Given that the demand from OECD corresponds to almost 50 % of the worldwide demand this is what one would have expected. For coal the optimal tax is still slightly negative, which is sensible as the OECD's share of the worldwide coal consumption is only 34 %, i.e., OECD would still be an exporter of coal, suggesting a positive export duty on that fuel.

Table 18: Optimal OECD climate taxes with hypothetical regional resource stock distributions and hypothetical discounting

	Optimal trade tax [$/tCO_2$], no liquefaction		
	Very high OPEC shares (Oil: 60 %, Coal: 60 %), standard discounting ($\rho_{\text{res}} = 3\,\%$ p.a., $\rho_{\text{cons}} = 5\,‰$ p.a.)	OPEC shares >50 % (Oil: 60 %, Coal: 60 %), patient resource owners ($\rho_{\text{res}} = \rho_{\text{cons}} = 5\,‰$ p.a.)	OPEC shares <50 % (Oil: 40 %, Coal: 40 %), patient resource owners ($\rho_{\text{res}} = \rho_{\text{cons}} = 5\,‰$ p.a.)
Oil	26.7	-10.3	21.5
Coal	0.1	-0.6	-0.1

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