Dynamic Carbon Leakage and Taxation with Depletion and Discounting

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Abstract

This treats various aspects of unilateral carbon taxation in presence of exhaustible fuels. A method to disentangle terms-of-trade and pollution components of the committed optimal unilateral tax on exhaustible fossil fuels is provided. The method is used to replicate the optimal dynamic green tax path in a numerical model. We discuss definitions of leakage rates and their relation to optimal taxation and welfare. It becomes apparant that leakage effects are crucially related to intrinsically dynamic aspects such as the time discount rate and future technological and political developments. In a calibrated, dynamic fuel market model with empirical fuel extraction cost curves we study leakage and optimal unilateral tax paths for the OECD. They vary strongly with model assumptions. The strong curvature of marginal oil extraction costs from empirical estimations, and coal liquefaction providing a dirty backstop specifically for oil, as well as a clean backstop for fossil fuels tend to have strong effects on the evolution of leakage rates. Leakage effects can be very large, even if future emissions are discounted. The rates differ strongly across fuels and optimal unilateral oil and coal taxes can have opposite signs; not much is left of the idea that carbon taxes should be uniform. Notably, liquefaction can lead to negative leakage rates from oil emission reductions and consequently optimal oil emission taxes above the WTP for global emission reductions. In presence of an endogenous clean backstop, in contrast, oil savings tend to prolongate the fossil fuel era and increase global fossil fuel emissions. This can imply leakage rates above unity and negative optimal unilateral oil emission taxes, whilst for coal, limited leakage warrants positive taxes. Green Paradox effects tend to lead to increased present value emissions for anticipated taxes. That the welfare relevant leakage rate even for current taxes varies so strongly with discounting and longer term developments causts doubt on the bulk of the existing leakage literature which limits the attention to the next few decades and hardly aggregates effects of a current tax in terms of net present value.

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1 Overview

> "The static-equilibrium type of economic theory which is now so well developed is plainly inadequate for an industry in which the indefinite maintenance of a steady rate of production is a physical impossibility, and which is therefore bound to decline.",
> Hotelling, 1931.

What Hotelling wrote in 1931 with notably oil and coal in mind, 80 years later appears to still not have received due attention in the bulk of the literature that works to answer a question where the dynamics of the resource supply and of technological, and even political changes seem to be of overwhelming importance. This question is the following: how severely is a unilateral effort to contain climate change by reducing regional greenhouse gas (mostly carbon dioxide) emissions undermined by offsetting foreign emission reactions; that is, by the so called carbon leakage? A large fraction of the literature studying carbon leakage uses static models, or dynamic models with static fuel supply, and finds moderate to low leakage rates. This study presents theoretical and numerical results on carbon leakage from a fully dynamic perspective. Fuel exhaustibility implies that medium and long-run leakage can be much higher than previous studies suggested. The main reason for this is that fuels not consumed (imported) by a home region during a specific time-window may be sold by the fuel owners to other regions not only during that specific time-window, but they may instead also be sold at any point earlier or later as long as some demand exists for that fuel in the remainder of the world. In fact, the basic reason why competitively supplied fuels that can be extracted for costs of up to the current market price are not offered today is that the suppliers expect to sell them in future periods with even higher profits. With other words, if a policy is to prevent extraction of some fuels forever, it must necessarily reduce the net demand price for the fuels everywhere and always to a level below the fuels' extraction costs. If this was not the case, a fuel supplier would increase his profit by extracting at one of the periods with a demand price that exceeds the extraction costs. However, if the policy is regionally limited, it can not directly reduce that demand price in the remainder of the world except by increasing the foreign consumption rate. This means that domestic fuel consumption reductions are at least partially offset by foreign consumption increases, induced by a depression of the global fuel price. Assuming, as an approximation expressing the low costs with which fossil fuels are shipped over long distances, a completely globalized fossil fuel market, leakage could even fully offset domestic fuel consumption reductions in the long-run: if a fuel is spared from domestic consumption only due to a specific regional policy, no necessary reason why fuel consumption in the remainder of the world would stop before all of that fuel is extracted exists. In a simple world, a domestic fuel consumption reduction tends thus to mainly prolongate the fossil fuel consumption horizon instead of reducing the total amount consumed. Whether all initially spared fuel is consumed later on depends on whether technical or political developments will in future allow to replace the fossil energy also in the remainder of the world. Moreover, to which degree the leakage is considered a problem even if parts of the emission reduction offsetting occurs many decades later, depends on the time-discounting of emissions. Given a fixed amount of reserves of exhaustible fuels, a welfare assessment of the leakage problem is intrinsically related to the fuel depletion in the medium and long term future, to future developments in the fuel market framework, as well as to emission discounting. These aspects have received scant attention in the existing leakage literature. This chapter presents a step towards filling this gap, using analytical and numerical models to investigate how leakage can sensibly be represented and estimated in a fully dynamic setting.

Section 2 provides an extensive motivation for this study and refers to different strands of related literature. Part 1 analyzes optimal unilateral fuel taxes in the presence of global pollution. Among other things, it confirms that a hypothetical compensation method can disentangle terms-of-trade and climate tax components, and it provides expressions for the optimal climate tax and relates them to a welfare relevant damage leakage rate. The different leakage rate notions are also defined. Part 2 uses a calibrated dynamic market model of substitutable and exhaustible fuels, oil and coal. The two fuels are consumed as a constant elasticity of substitution energy aggregate. The energy demand curves are exogenous and modeled as independent functions for the OECD and the rest of the world (ROW), and may grow over time.[1] Fuels are extracted at costs that increase with cumulative extractions, by competitive, forward-looking suppliers which maximize their net present profits. Fuel consumption maps directly to global carbon emissions, and climate damage is assumed a linear or convex function of cumulative emissions. Model extensions allow the transformation of coal to synthetic oil, and a clean backstop. First, the model is used to replicate the findings from Part 1. Then, different leakage rates are analyzed in different scenarios. Key findings include that oil is subject to very large absolute leakage rates in a basic framework. Interestingly, and contrary to what one might think on first sight, this appears to be less due to the limited relative size of the reserves (compared, e.g., to the more abundant coal) but more to the strong curvature in the empirical oil extraction cost curve: it is shown that, for the example of linear extraction costs, a scaling of reserve sizes may not affect leakage rates; intuitively, however, with a strongly, convexly kinked cost curve, a regional fuel consumption reduction can mainly postpone by a few years the time until the cheap 'pre-kink' fuel is used up, rather than to delay fuel use for a long time. This is related to the Green Paradox effect, where under the assumption of a fixed reservoir, supplied at limited costs – as corresponds closely to the case of an 'infinitely strongly kinked' curve where costs rise infinitely rapidly after the

[1] That is, we neglect direct industry dislocation effects of the tax. These would, in the basic model, tend to increase the overall leakage rate.

extraction of a certain threshold amount – it is found that a tax may only affect the timing but not the absolute amount of fuel used (Sinclair, 1992; Sinn, 2008). Due to the foresight of the fuel owners, leakage, as a response to a specific time t's domestic consumption perturbation, tends to occur with a substantial spread across time and is centered around t in basic models: recognizing, e.g., that a future tax reduces the profitability of future sales, they will increase current sales (and potentially those after the period with the tax). With substantial discount rates, this implies that even when leakage offsets the major fraction of the domestic emission reductions in terms of absolute emissions, the relevant leakage rates may be low for today's taxes, but they may easily exceed unity for anticipated future taxes, where parts of the foreign emission offsets occur prior to the domestic reduction and are thus weighted relatively more (strong Green Paradox for future taxes). As therefore a regional oil tax may increase rather than reduce the net present value of global emissions, the optimal regional policy can contain negative taxes. This contrasts to an optimal global policy, where the positive emission damages warrant strictly positive tax rates throughout time. Above-unity leakage rates are, however, significantly less likely for coal, even with substantial discounting. As discussed, this seems to occur not as much because of the pure abundance of coal, but more because of the weaker curvature of the cost curve.

When the substitutability of the fuels is taken into account in a basic setup (no liquefaction and no backstop), the overall leakage rate for domestic oil emission reductions (in the following sections we tend to simplify the terminology, writing *oil leakage*) can become negative as the coal-to-oil substitution effect in the foreign CES demand dominates the direct oil price effect as oil becomes increasingly scarce over time. Introducing endogenous liquefaction in the model can lead to negative oil leakage rates already for today's tax: When liquefaction[2] supplements a synthetic substitute for crude oil in future, saving oil (today or in future) delays the start of the dirty liquefaction process employed abroad and therewith reduces global emissions even beyond the amount saved domestically. The increased demand for the input into liquefaction, i.e. coal, on the other hand, increases the coal leakage rate. A further extension of the model contains an endogenously emerging clean backstop, available at costs that decrease over time and modeled as a perfect substitute for the fossil fuel aggregate. Its effect may surprise. Rather than reducing leakage by limiting the time available for the foreign offsetting of domestic reductions, the backstop implies very high leakage rates above unity – for current and future oil consumption reductions. The latter prolongate the time during which the fossil fuels can compete against the backstop. Given that during the final phase of fossil consumption the energy

[2]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 issues with the somewhat ad hoc representation of the fuel-extractions in their model (cf. below), they have restricted their attention to instantaneous leakage rates for each period rather than considering the (NPV) effect of current taxes on future emissions.

is very coal intensive, a bit more oil increases emissions strongly during that phase.

2 Motivation and Literature

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; in other words 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, a regional emission reduction would translate one-for-one into 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 only cover a fraction of global emissions, and there is no global agreement in sight for at least 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 mean 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. However, as a regional policy can only sanction regional emissions, the second-best-efficient[3] 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;[4] coal reserves are often considered practically unlimited;[5] oil and gas are globally traded and exploitable in lim-

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

[4]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.

[5]See, e.g., van der Ploeg and Withagen (2011, 2012b) and Burniaux and Oliveira-Martins (2012). The

ited amounts at increasing costs; and locally or regionally consumed wood is, in 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. Therefore, this price is 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, an issue that has received scant attention in existing literature.

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, potentially, 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 the objective, according to political economics or ordinary people's preferences, 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. In this study 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

strong characteristic difference between oil and coal supply is also pointed out in Burniaux et al. (1992) and Golombek et al. (1995).

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, Golombek et al.'s 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. Clean backstops developed in the future is one example. Fuel transformation processes, such as coal-to-liquids (liquefaction), is another; they 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.[6] 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.

The present study follows Golombek et al. (1995) by focusing on the market for fuels. This seems to be a suitable approach as, for example, McKibbin and Wilcoxen (2008), Böhringer et al. (2010) and Kuik and Hofkes (2010) have shown that the trade of non-energy goods is of lesser importance for both leakage and terms-of-trade effects – these effects are dominated by the international trade in fuels.[7] 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 influence the time-path of the consumption of the various fossil fuels. These optimal time-paths are the central issue in studies by van der Ploeg and Withagen (2011, 2012b). Regarding the optimal carbon tax pattern, their analysis, on the one hand, is limited to a focus on *global* policies. 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

[6] 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 (BGR, 2009a).

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

by coal-derived grid electricity, with potential efficiency losses and overhead costs. This has important repercussions on the second-best time-paths of fuel consumption 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 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. Michielsen (2011) is related to the present study in that it also studies regional and intertemporal leakage for two imperfectly substitutable fuels. One of the fuels is supplied infinitely elastically (coal) and the other depletes (oil). This provides important insights about Green Paradox and leakage effects, as well as about sensible climate policies. Michielsen does not, however, explicitly study optimal *fuel-specific* carbon taxes, and restricts his attention to a stylized two-period model. Eichner and Pethig (2011) also study leakage and Green Paradox effects in a two-period model. They consider a single fuel and assume a limited elasticity of intertemporal substitution in demand, i.e., consumption in one period has a direct effect on the demand in the other period.

The (substantial) uncertainty about the long-term climate damage induced by carbon emissions is not directly considered here. 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) 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 the future just 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.[8] While Golosov et al. allow for emission discounting, they use a fuel reserve model that is more stylized 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 of limitless supply. Additionally, 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

[8]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).

used for electricity production and for some other immobile purposes, while particularly in the transport sector for 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 have been simultaneously consumed for 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 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 and the limited availability of oil, in the future this may lead to coal gasification or liquefaction (i.e., coal to oil transformation) as well as to 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. Others find values as low as around 5 % (e.g., OECD, 2009). 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. Overall, however, the bulk of the literature suggests very modest leakage rates. In an overview, Burniaux and Oliveira-Martins (2012) identify values ranging from 20 % to less than 5 %, and in Burniaux and Oliveira-Martins (2000) they conclude that "carbon leakages are likely to be small for the range of parameters most frequently quoted in the literature".

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 primarily for technical reasons. To see this, it is important to note that the models 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 this increase in ROW emissions 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. Correspondingly they do not capture that fuel consumption savings in one period may be offset 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 even applies 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 fossil fuels depletion.

Another strand 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 still do 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 early authors had already used dynamic models with at least partially endogenous fuel depletion mechanisms, for example Felder and Rutherford (1993) and Manne and Richels (1991). It should be noted that, however, the approach used in these two early works 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.[9] Thus, it seems that even in these studies the modest leakage rates could 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.[10] Thus, it appears that the most important reasons for which leakage in the long run may be substantially below 100 %, typically are not explicitly addressed in literature.[11] The proposed leakage rates are thus, *per se*, only of limited value for forward-looking, concerned societies or their policy makers. This seems especially clear as the primary reason for concern about climate change is that *future* global warming is anticipated today. If one were to exhibit an overly strong 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 (many) 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 additionally features fully endogenously depleting fossil fuel reserves.

Part I Theory of optimal unilateral tax and decomposition

3 Optimal Unilateral Tax

Since Pigou (1920), we know that in a simple framework a uniform unit tax on emissions, corresponding to the level of the marginal damage d, leads to the optimal level of consumption of a polluting good. Another simple case is that of a perfectly global pollutant in a situation where a tax is regionally constrained and a unitary pollution reduction within

[9] Manne and Richels (2000) explain that any judgment on a Kyoto policy crucially depends on what happens in the decades after the initial commitment period centered around 2010, and they 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.

[10] Some studies assumed coal to be of infinitely elastic supply without depletion and allowed for replacement of liquid fuels by coal. In the absence of time-discounting of emissions – as well as 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.

[11] A related point is made in Eichner and Pethig (2011, p. 768). They note that (from the perspective of the intertemporal theory of nonrenewable natural resources), "*the prevailing view on the effectiveness of demand-reducing policies is flawed because the public and academic discourse [...] has largely neglected the close link between the economics of global change and the economics of nonrenewable resources and has therefore failed to account for the supply side of the problem in an appropriate way*."

the tax region increases pollution in the remainder of the world by α units (α is called the leakage rate), and where, besides this pollution leakage, no additional relevant interaction between the regions takes place. As is understandable, and as Annex 1 shows, in this case the regionally optimal, unilateral tax level is reduced to $(1-\alpha)\cdot d$ (see Proposition 1 in Annex 1).

In general, this regional pollution tax calculation is, however, not pertinent. This notably because the channel through which the domestic emission choice generally affects the foreign emissions is through price effects, and the presence of these price effects warrants special consideration in the analysis of the optimal unilateral tax. When regional consumption affects prices of interregionally traded goods, such as the fossil fuels which are the basis for the vast majority of anthropogenic carbon dioxide emissions, a regional importer or exporter has incentives to influence the terms-of-trade by distorting its domestic consumption (and production) of the good. Consequently, this affects the optimal total level of the tax on the polluting good's consumption.

The remainder addresses the interrelatedness of the terms-of-trade component and the pollution component of the optimal unilateral fossil fuel (emissions) tax. We assume that the climate policy region is able to commit throughout time to a specific, initially announced future tax path. The case where a region is restricted to time-consistent fuel taxes is discussed, e.g., in Karp (1984) and, for the case including pollution, in Beermann (2012). Cf. Habermacher (2013) for a discussion of parts of the results in Karp (1984).

Model A fuel produces emissions at an intensity normalized to 1. Two consuming regions buy all their fossil fuel from external, decentralized producers at price p.[12] Regional welfare is given as $U_r = \int_T e^{-\rho t}\left[u_r(e_{r,t}) - e_{r,t}p_t - D_{r,t}\right]\mathrm{d}t$, where $T=[0,\infty]$ is the considered time-horizon, $u_r(e_t)$ is a utility flow concavely increasing in current fuel consumption $e_{r,t}$, p_t is the fuel price, and D_t is climate damage convex in cumulative emissions E_t. We assume the simple situation where the interest rate corresponds to the time-discount rate, ρ. Be $r=\{h,f\}$ the indexes for the domestic and the foreign region. For simplicity we abstract from foreign emission disutility;[13] that is, we set $D_{f,t}\equiv 0$, and call domestic damage $D_{h,t} = D_t = D\left(E_t\right)$, where $E_t \equiv \int_0^t e_{w,s}\mathrm{d}s$, with $e_w = e_h + e_f$, the worldwide fuel consumption. We call d_t the marginal instantaneous damage from marginal emissions at time t, $d_t = d(E_t) = D_t'(E_t)$. Assuming convex damage from cumulative emissions, we have $d'(E)>0$.

Foreign consumers are fully decentralized. We assume interior solutions, wherewith the

[12]This is a common setup used in the literature, e.g., in Eichner and Pethig (2011), and Karp (1984). As Karp suggests, for regions with domestic fuel production, the demand in this model may be considered as the regions' residual import-fuel demand.

[13]The extension to the case with foreign damage should be straightforward for most of what follows.

foreign consumption choice is thus governed by the FOC

$$u'_f(e_{f,t}) = p_t. \tag{.1}$$

Fuel producers extract fuels with increasing marginal cost $c_t = c(E_t)$, $c'(E) > 0$. Assuming a competitive market, dynamic programming shows that the maximization of the net present value of sales profits implies[14] a pricing according to

$$p_t = c_t + \int_t^\infty e^{-\rho(s-t)} \dot{c}_s \mathrm{d}s, \tag{.2}$$

where the second term on the RHS corresponds to the resource shadow value.

Unilateral Committed Policy We examine the case where the domestic region, h, considers to unilaterally tax fossil fuels, using a committed policy. The foreign region's consumption is governed by undistorted consumption decisions of decentralized fuel consumers.[15] In what follows, we often simplify the time index of variables, writing, e.g., e_t for $e(t)$. Additionally h is often omitted for the index of the *domestic* region, so e_t would stand for $e_h(t)$. Worldwide consumption is always indexed with w, i.e., we write e_w. Further, when we consider taxes, we always mean unit taxes.

The domestically optimal consumption rate is implicitly defined by the maximization problem

$$\max_{e_{h,T}} U = \int_T e^{-\rho t} \left[u(e_{h,t}) - e_{h,t} p_t - D_t\right] \mathrm{d}t,$$

where the paths p_T and $e_f(T)$ are functions of the choice variable path $e_{h,T}$ and implicitly defined by Eqs. (.1) and (.2).

Let e_h^* be the optimal domestic consumption path. The derivative of U for the FOC governing the optimal domestic consumption is

$$\frac{\mathrm{d}U(e_h^*)}{\mathrm{d}e_h(t)} = e^{-\rho t} u'(e_{h,t}) - e^{-\rho t} p_t - \int_0^\infty e^{-\rho s} e_{h,s} \frac{\mathrm{d}p_s}{\mathrm{d}e_{h,t}} \mathrm{d}s - \int_t^\infty e^{-\rho s} d_s \mathrm{d}s - \int_0^\infty e^{-\rho s} d_s \int_0^s \frac{\mathrm{d}e_{f,u}}{\mathrm{d}e_{h,t}} \mathrm{d}u \mathrm{d}s, \tag{.3}$$

where the last two terms are implied by $\frac{\mathrm{d}D_s}{\mathrm{d}e_{h,t}} = \underbrace{\frac{\partial D_s}{\partial E_s}}_{d_s} \frac{\mathrm{d}E_s}{\mathrm{d}e_{h,t}}$ and $\frac{\mathrm{d}E_s}{\mathrm{d}e_{h,t}} = \frac{\partial E_s}{\partial e_{h,t}} + \int_0^\infty \frac{\mathrm{d}e_{f,u}}{\mathrm{d}e_t} \frac{\partial E_s}{\partial e_{f,t}} \mathrm{d}u$, implying $\frac{\mathrm{d}E_{s<t}}{\mathrm{d}e_t} = \int_0^s \frac{\mathrm{d}e_{f,s}}{\mathrm{d}e_t} \mathrm{d}s$ and $\frac{\mathrm{d}E_{s\geq t}}{\mathrm{d}e_t} = \int_0^s \frac{\mathrm{d}e_{f,s}}{\mathrm{d}e_t} \mathrm{d}s + 1$, leading to $\int_0^\infty e^{-\rho s} \frac{\mathrm{d}D_s}{\mathrm{d}e_t} \mathrm{d}t =$

[14] By a simple variational argument: in equilibrium, if t is the optimal extraction period, we know that the time derivation of his NPV sales profit for extractions immediately before or after t must be zero, i.e., p_t must be such that for $C = c_t$ we have $\partial \frac{e^{-\rho t}(p_t - C)}{\partial t} \overset{!}{=} 0$. Solving for p_t yields Eq. (.2). Alternatively, the problem can be solved using a Hamiltonian as below, Eqs. (.13) through (.14); the second term on the RHS in Eq. (.2) corresponds to λ.

[15] The case where instead *both* consuming regions buy the exhaustible resource *strategically* from the competitive seller is treated in Karp and Newbery (1993); however, they do not take pollution into account.

$\int_t^\infty e^{-\rho s} d_s \mathrm{d}s + \int_0^\infty e^{-\rho s} d_s \int_0^s \frac{\mathrm{d}e_{f,u}}{\mathrm{d}e_{h,t}} \mathrm{d}u\mathrm{d}s$, and where the envelope theorem has allowed us to ignore the interdependence of the optimal *domestic* consumption rates from different time periods.

With decentralized consumers that equate private costs and benefits, and with a potential fuel or emissions tax τ_t, domestic consumption is governed by

$$u'(e_h(t)) = p_t + \tau_t,$$

which, for standard regularity conditions guaranteeing a single interior solution, provides an implicit one-to-one mapping between the tax τ_t and the domestic consumption $e_{h,t}$.

As the FOC requires $\frac{\mathrm{d}U}{\mathrm{d}e_{h,t}} = 0$, the tax path τ_T that sustains the optimal domestic consumption level $e_h(T)^*$ is thus defined by

$$\tau_t^* = \underbrace{\int_t^\infty e^{-\rho(s-t)} d_s \mathrm{d}s}_{\text{direct damage}} + \underbrace{\int_0^\infty e^{-\rho(s-t)} e_h(s) \frac{\mathrm{d}p_s}{\mathrm{d}e(t)} \mathrm{d}s}_{\text{terms-of-trade}} + \underbrace{\int_0^\infty e^{-\rho(s-t)} d_s \int_0^s \frac{\mathrm{d}e_{f,u}}{\mathrm{d}e_{h,t}} \mathrm{d}u\mathrm{d}s}_{\text{leakage}}. \quad (.4)$$

Partial derivatives are to be considered with domestic consumption in the other periods, $e_{h,v \neq t}$, held fixed, and the foreign consumption path, $e_{f,T}$, and the fuel price p_T adjusting according to Eqs. (.1) and (.2).

The optimal tax is thus governed by three distinct effects. The natural interpretation of the first is the direct pollution effect: the fuel consumption at time t directly increases cumulative emissions for all subsequent times, implying a climate cost d_s for all periods from t on, $s \geq t$. It corresponds to the optimal global tax, τ^*_{Pigou} from Eq. (.8). The consumption choice affects the price $p(s)$ paid for fuel imports $e(s)$, adding the second component, reflecting the terms-of-trade effect. Finally, the emissions in the foreign region, $e_f(s)$, are affected as well, leading to the third component, expressing the leakage effect.

4 Disentangling Climate and Terms-of-Trade Effect

The optimality condition Eq. (.4) for the tax defines the optimal carbon tax only implicitly, giving the optimal tax path τ_T^* as a function of variables that themselves also depend on the tax path itself (or on the domestic consumption path which is influenced by the tax). For non-trivial, empirically calibrated models, it cannot be presumed that the optimal tax path can be calculated analytically. For a numerical model, the optimal carbon tax path, however, can be calculated as the tax path τ_T^* (or its consumption counterpart e_T^*) that maximizes the overall domestic welfare U.

When goods producers exert market power, importing (and exporting) regions may resort to 'terms-of-trade' tariffs in order to change the equilibrium prices (the 'terms-of-trade') of the goods to their advantage and to thereby increase domestic welfare (Brander and Spencer, 1984; Pomfret, 2008). This holds in particular for fossil fuels, which are produced with decreasing returns overall and whose owners reap scarcity rents. Consuming regions can extract parts of the fuel scarcity rents with (positive) taxes on their domestic fuel consumption (Brander and Djajic, 1983). This may lead to global welfare losses. Therefore, such beggar-thy-neighbour policies are in the general case in conflict with free trade principles, and it is a major aim of the WTO to prevent such distorting policies. Nevertheless, for a fuel importing region, the terms-of-trade motive theoretically increases the regionally optimal emissions tax to a value beyond what would be justified for purely environmental reasons; in addition to the environmental damage related terms, the optimal tax contains a terms-of-trade component, as shown in Eq. (.4). For investigative, but also for policy purposes, it seems relevant to separate the environmental component of the optimal emissions tax from the terms-of-trade component, as it is widely acknowledged that taxes imposed genuinely for the protection of the global climate seem acceptable, whilst genuine terms-of-trade taxes, distorting trade at the expense of other parties, seem problematic. The remainder of this section analyzes how this separation can be implemented, and how the environmental-only component, which is used in the remainder of the paper, can be calculated. The next section shows that the optimal emissions tax that disregards terms-of-trade benefits is closely related to a net present damage value adjusted dynamic leakage rate.

Subtracting the Terms-of-Trade-only Tax The most straightforward attempt to split the numerically calculated optimal fuel consumption tax into a trade part τ^*_{tot} and a climate (or emissions) part τ^*_e would be to start by calculating the optimal fuel tax in absence of pollution damage. This would yield the optimal terms-of-trade tax τ^*_{tot}, and one could then use the difference between the optimal total tax with pollution, τ^*, and this trade-only tax, τ^*_{tot}, to define the climate component, or the optimal climate-only tax, as $\hat{\tau}_e \equiv \tau^* - \tau^*_{tot}$. However, this is not a very precise method as imposing the climate tax reduces domestic fuel consumption. Consequently, the optimal terms-of-trade tax, which, for fossil fuels offered with prices that increase in the demanded quantity, also decreases along with a reduction in the imported quantity. Annex 2 confirms this intuition with a simple analytical model for the case of the optimal tax in a static environment with an external fuel producer and a single importer. It shows that the pollution-only tax calculated with the proposed terms-of-trade subtraction method is always lower than the natural rate of the pollution-only tax, and that even for small pollution damages and correspondingly small environmental taxes, the bias of the pollution-only tax is non-marginal. Nevertheless, at least under certain circumstances, the approximation may still lead to results that are quite closely related to the truly optimal pollution-only tax τ_e^*, with, in the Annex example, the calculated tax $\hat{\tau}_e$ always deviating by less than a quarter from τ_e^* (cf. Proposition 2 in Annex 2).

Compensation Method An alternative way to neutralize terms-of-trade effects in the calculation of the optimal pollution tax is to hypothetically require the domestic region to compensate external actors for losses they incur due to the domestic consumption tax, ignoring, however, foreign damage from pollution. Taking this compensation into account, the domestic region no longer has a direct incentive to influence prices of the imported fuel. That this leads to the optimal pollution-only tax, corresponding to the level identified as optimal in the hypothetical presence of leakage in the absence of price-effects in section 1 in a static model with an external producer and a passive fringe consumer (and the corresponding carbon leakage) is shown in Annex 3, and corresponds largely to what Böhringer et al. (2010) have shown in their static framework with fuel consumption of industrial sectors.

The remainder of this section extends this result to the dynamic case with exhaustible fuels. It shows that compensation payments can be used to disentangle the terms-of-trade and the climate motive for the optimal unilateral fuel tax also in a dynamic framework with exhaustible fuels using a continuous time model with two fuel-consuming and one fuel-producing region (it is straightforward to extend the analysis to the case where fuel-production is distributed among the two consuming regions).

We use the same framework as in section 3, but with transfer payments. Thus, consider regional welfare as $U_r = z_r + \int_0^\infty e^{-\rho t} u_r(e_r(t)) - D_r(t)\mathrm{d}t$, where z is (present) consumption of a numeraire good, which, assuming perfect capital markets without borrowing constraints, can also be imagined as a shortcut for the NPV of a consumption path ζ_t, with $z = \int_0^\infty e^{-\rho t}\zeta_t \mathrm{d}t$; $u_r(e_r)$ as an instantaneous fuel consumption utility and D_r is the path of regional emission damages. For the domestic region, which may pay transfers Tr_f and Tr_e to the foreign region and the fuel producers, the budget constraint is $z_0 = z + Tr_f + Tr_e + \int_0^\infty e^{-\rho t} e(t) p_t \mathrm{d}t$. For the foreign region, potentially receiving the transfer Tr_f, it writes $z_{0f} + Tr_f = z_f + \int_0^\infty e^{-\rho t} e_f(t) p_t \mathrm{d}t$. The fuel producer's utility U_e is given as the level of consumption of a numeraire good, consisting of the NPV of fuel sales profits net of production costs plus a potential received transfer, Tr_e, $U_e = Tr_e + \int_0^\infty e^{-\rho t}\,(p_t - c_t)\, e_w(t)\mathrm{d}t$, with $e_w(t)$ the global fuel consumption, p_t the sales price, and c_t the extraction costs.

To calculate the climate effect separate from the terms-of-trade (t-o-t) effect, we switch off the t-o-t effect by requiring the domestic region to provide transfer payments that set off losses or gains the foreign region and the fuel producer would otherwise experience from the domestic fuel consumption (or emission) policy. The transfers compensate for changes in non-green welfare; that is, for a given policy, climate damage is not directly considered in the calculation of the compensation transfers.

We know that, absent any externality concerns, undistorted, decentralized consumption and production maximizes non-green overall output in terms of total present-discounted net output ignoring climate damages, derived from exhaustible resources. That is, social non-green surplus, $\int_0^\infty e^{-\rho t}\left[\underbrace{u(e(t))+u_f(e_f(t))}_{\text{consumption value}}-\underbrace{(e(t)+e_f(t))\,c_t}_{\text{production costs}}\right]\mathrm{d}t$, is maximized without any policy influencing the regional consumers or distorting the fuel producer's behavior (Hotelling, 1931). The maximization problem for the domestic region implicitly accounting for the imposed transfers can thus be written as the problem of maximizing the sum of domestic and non-green foreign and producers' welfare normalized for the level of the transfer payments, denoted U^*. The fuel price p_t, paid by the consumers but received by the fuel producers, cancels out and only the extraction costs, c_t, as well as the climate costs for the domestic region, D_t, are overall subtracted from the regional consumption utilities: $\max_{e_{h,T}} U^* = \int_T e^{-\rho t}\left[u_h(e_h(t))+u_f(e_f(t))-e_{w,t}c_t-D_t\right]\mathrm{d}t$, where both, the marginal extraction costs and the instantaneous damage defined as (increasing) functions of cumulative emissions, $c_t \equiv c\left(\int_0^t e_{w,s}\mathrm{d}s\right)$, $D_t \equiv D\left(\int_0^t e_{w,s}\mathrm{d}s\right)$, with e_f implicitly defined by Eqs. (.1) and (.2).

Assuming a single internal solution to obtain, the solution must satisfy the standard FOC. We thus develop

$$\begin{aligned}\frac{\mathrm{d}U^*}{\mathrm{d}e_h(t)} &= e^{-\rho t}u'(e_h(t))+\int_0^\infty e^{-\rho s}u_f'(e_f(s))\frac{\mathrm{d}e_f(s)}{\mathrm{d}e(t)}\mathrm{d}s-e^{-\rho t}c_t\\ &\quad-\int_0^\infty e^{-\rho s}\left[\frac{\mathrm{d}e_f(s)}{\mathrm{d}e_h(t)}c_s+e_{w,s}\frac{\mathrm{d}c_s}{\mathrm{d}e(t)}\right]\mathrm{d}s-\int_t^\infty e^{-\rho s}d_s\mathrm{d}s-\int_0^\infty e^{-\rho s}d_s\int_0^s\frac{\mathrm{d}e_{f,u}}{\mathrm{d}e_{h,t}}\mathrm{d}u\mathrm{d}s.\end{aligned}$$

From Eqs. (.1) and (.2) we have $u_f'(e_f(t)) = c_t+\int_t^\infty e^{-\rho(s-t)}\dot{c}_s\mathrm{d}s$. This implies

$$\begin{aligned}\frac{\mathrm{d}U^*}{\mathrm{d}e_h(t)} &= e^{-\rho t}u'(e_h(t))+\underbrace{\int_0^\infty e^{-\rho s}\left[\int_s^\infty e^{-\rho(u-s)}\dot{c}_u\mathrm{d}u\right]\frac{\mathrm{d}e_f(s)}{\mathrm{d}e(t)}\mathrm{d}s}_{I_1}-e^{-\rho t}c_t\\ &\quad\underbrace{-\int_0^\infty e^{-\rho s}e_{w,s}\frac{\mathrm{d}c_s}{\mathrm{d}e(t)}\mathrm{d}s}_{I_2}-\int_t^\infty e^{-\rho s}d_s\mathrm{d}s-\int_0^\infty e^{-\rho s}d_s\int_0^s\frac{\mathrm{d}e_{f,u}}{\mathrm{d}e_{h,t}}\mathrm{d}u\mathrm{d}s.\end{aligned}$$

We now show that terms I_1 and I_2 in Eq. (.3) cancel out, yielding Eq. (.5). From the definition of the extraction costs we have $\frac{\mathrm{d}c_s}{\mathrm{d}e_h(t)} = c_s'\cdot\left[\{1 \text{ if } s\geq t \text{ else } 0\}+\int_0^s\frac{\mathrm{d}e_f(u)}{\mathrm{d}e_t}\mathrm{d}u\right]$. Therewith, I_2 rewrites $\int_t^\infty e^{-\rho s}e_{w,s}\left[c_s'\cdot 1\right]\mathrm{d}s+\int_0^\infty e^{-\rho s}e_{w,s}\left[c_s'\cdot\int_0^s\frac{\mathrm{d}e_f(u)}{\mathrm{d}e_h(t)}\mathrm{d}u\right]\mathrm{d}s$. Noting that $c_t\equiv c\left(\int_0^t e_w(t)\mathrm{d}t\right)$ implies $\dot{c}_t = c_t'\cdot e_w(t)$, I_2 simplifies to $\int_t^\infty e^{-\rho s}\dot{c}_s\mathrm{d}s+\int_0^\infty e^{-\rho s}\dot{c}_s\cdot\int_0^s\frac{\mathrm{d}e_f(u)}{\mathrm{d}e_h(t)}\mathrm{d}u\mathrm{d}s$. Seeing further that $\int_0^\infty e^{-\rho s}\dot{c}_s\cdot\int_0^s\frac{\mathrm{d}e_f(u)}{\mathrm{d}e_t}\mathrm{d}u\mathrm{d}s$ is a simple double integral over the open 'area' defined by $u \leq s$, we know $\int_0^\infty e^{-\rho s}\dot{c}_s \cdot \int_0^s \frac{\mathrm{d}e_f(u)}{\mathrm{d}e_t}\mathrm{d}u\mathrm{d}s = \int_0^\infty \int_u^\infty e^{-\rho s}\dot{c}_s \frac{\mathrm{d}e_f(u)}{\mathrm{d}e_t}\mathrm{d}s\mathrm{d}u$, which, switching u and s yields the same as I_1. Terms I_1 and I_2 thus cancel out in Eq. (.3) and we get

$$\begin{aligned} \frac{\mathrm{d}U^*}{\mathrm{d}e(t)} &= e^{-\rho t}u'(e_h(t)) - e^{-\rho t}c_t - \int_t^\infty e^{-\rho s}\dot{c}_s\mathrm{d}s - \int_t^\infty e^{-\rho s}d_s\mathrm{d}s \\ &\quad - \int_0^\infty e^{-\rho s}d_s \int_0^s \frac{\mathrm{d}e_{f,u}}{\mathrm{d}e_{h,t}}\mathrm{d}u\mathrm{d}s. \end{aligned} \tag{.5}$$

The FOC of the maximization problem thus yields, with a multiplication by $e^{-\rho t}$ to switch from a present to current value expression,

$$\begin{aligned} u'(e_h(t)) &= c_t + \int_t^\infty e^{-\rho(s-t)}\dot{c}_s\mathrm{d}s + \int_t^\infty e^{-\rho(s-t)}d_s\mathrm{d}s \\ &\quad + \int_0^\infty e^{-\rho(s-t)}d_s \int_0^s \frac{\mathrm{d}e_{f,u}}{\mathrm{d}e_{h,t}}\mathrm{d}u\mathrm{d}s. \end{aligned} \tag{.6}$$

With a tax of rate τ_t, the decentralized consumer decisions are governed by the private FOC, equating private benefits and costs,

$$u_h'(e(t)) \stackrel{!}{=} p_t + \tau_t.$$

Recall from Eq. (.2) that the competitive suppliers set $p_t = c_t + \int_t^\infty e^{-\rho(s-t)}\dot{c}_s\mathrm{d}s$. For the tax τ_t to sustain the optimal consumption level according to Eq. (.6), we thus require

$$\tau_t^* = \underbrace{\int_t^\infty e^{-\rho(s-t)}d_s\mathrm{d}s}_{\text{direct damage}} + \underbrace{\int_0^\infty e^{-\rho(s-t)}d_s \int_0^s \frac{\mathrm{d}e_{f,u}}{\mathrm{d}e_{h,t}}\mathrm{d}u\mathrm{d}s}_{\text{leakage}}. \tag{.7}$$

The first term on the RHS in Eq. (.7) is the direct domestic pollution component as the net current value[16] of the response of the damage in all periods from time t on to the change of cumulative emissions from increased domestic emissions at t, which also equals the optimal global tax, τ^*_{Pigou} from Eq. (.8). The second term is the leakage component. Precisely, it is the net current value of all damage changes throughout time as a response to the cumulative change of foreign emissions in reaction to the domestic consumption change at time t. These direct pollution and leakage components, which were present also in the optimal unilateral tax without compensation, Eq. (.4), together determine the optimal unilateral 'climate-only' tax level. Terms-of-trade effects are absent; as conceived, the hypothetical compensation payment has neutralized them.

[16]See section 5 for a definition of the net *current* value.

Optimal Global Policy From its construction through the hypothetical compensation mechanism, which ensures that all agents' welfares are fully accounted for, it is clear that τ_t^* in Eq. (.7) in the absence of leakage must correspond to the optimal worldwide pollution tax. That is, the optimal global policy is

$$\tau^*_{\text{Pigou},t} = \int_t^\infty e^{-\rho(s-t)} d_s \mathrm{d}s > 0. \tag{.8}$$

Indeed, Edenhofer and Kalkuhl (2010) show that this corresponds to the social planner's choice, equalizing the competitive and the normative extraction and emission path. Intuitively, the level of the optimal global tax at time t equals the net current value of all future marginal damages from a unit of emission added, d_t. Competition or climate-independent resource conservation effects do not enter the optimal tax because pricing issues only correspond to a shift of rents between the buyers and sellers without changing the overall rent, and the supplier's dynamic pricing behavior leads to the optimal conservation of the resource in absence of externalities.

Given that for convex damages we have $\dot{d}_s > 0$ during the fuel consumption phase, the tax is strictly growing, $\dot{\tau}^*_{Pigou} > 0$. Also, Eq. (.7) implies that the tax grows at less than the interest rate (cf. also van der Ploeg, forthcoming): we have $\dot{\tau}^*_{Pigou,t} = \rho\tau^*_{Pigou,t} - d_t$, implying that $\tau^*_{Pigou,t}$ grows at a rate $g_{Pigou,t} = \rho - \underbrace{d_t/\tau^*_{Pigou,t}}_{>0} < \rho$. We thus emphasize:

Proposition 3a. Absent leakage effects, and given convex damages from cumulative emissions, the tax of the optimal pollution policy, τ^*_{Pigou}, is positive and strictly rising, growing at a rate $g_{\tau,Pigou}$ below the interest rate ρ,

$$\tau^*_{Pigou} > 0 \quad \text{and} \quad 0 < g_{\tau,Pigou} < \rho.$$

5 Definition of Leakage Rates and Terminology

The previous sections have shown that the tax rates of the optimal, green-only unilateral tax path are described in terms of the damage effect of (i) current domestic consumption, and (ii) the response of *foreign* consumption *at every period* to *current domestic* consumption changes (Eqs. (.4) and (.7)). That is, the optimal tax at time t does not directly depend on the response of *domestic* emissions at other periods, $e_{h,v \neq t}$, to changes in current emissions at time t, $e_{h,t}$.[17] Correspondingly, we here focus on leakage rates expressing the foreign offsetting of instantaneous domestic emission reductions when other

[17] This is not necessarily a surprise given that the domestic taxes in the other periods are assumed to be optimal as well. From the point of view that leakage generally implies that the optimal taxes here fall short of the perfectly internalizing Pigouvian, this result may, however, still not necessarily have been expected. It is nevertheless intuitive in the sense that the optimal tax path is directly derived from the optimal domestic consumption path for which we know that the envelope theorem implies that derivatives

domestic emissions are held constant. Given the results from the previous sections, these will be the leakage rates that are relevant for the optimal unilateral tax path.

First, as a concept that is probably the most compatible with both the existing literature on emission leakage as well as with a very casual interpretation of emission leakage, we define the absolute leakage rate (ALR), as the total fraction of some (anticipated) instantaneous emission savings that is offset by foreign emission changes,

$$\text{Absolute leakage rate: } \mathrm{ALR}_t \equiv \int_T \frac{-\mathrm{d}e_{f,v}}{\mathrm{d}e_{h,t}} \mathrm{d}v,$$

where the considered time horizon T starts at the period from which tax t is anticipated, and, theoretically, lasts until infinity. In the numerical simulations below, which focus on committed policies, we will generally assume T to start at the present date (expressed as $t = 0$, i.e., $T = (0, \infty)$). This has the advantage of providing results both for unanticipated taxes (as the leakage rate for the initial period) as well as for anticipated taxes (as leakage rates for later taxes that are anticipated from now on).

Expressing the standard in climate economics to discount future emissions, we define the NPV leakage rate, NLR, as the fraction of domestic emission reductions offset abroad in terms of the NPV value of emissions,

$$\text{NPV leakage rate: } \mathrm{NLR}_t \equiv \int_T e^{-\rho(v-t)} \frac{-\mathrm{d}e_{f,v}}{\mathrm{d}e_{h,t}} \mathrm{d}v, \tag{.9}$$

with ρ the corresponding present-discount rate for the emissions.

Finally, the form of leakage that is truly relevant for welfare concerns and directly related to the optimal unilateral overall or green-only carbon tax, is what we here name the damage leakage rate (DLR). DLR is defined as the fraction, in NPV terms, of the direct damage reduction related to a domestic emission cut that is offset by damage increases implied by the response of foreign emissions throughout the considered time horizon,

$$\begin{aligned} \text{Damage leakage rate: } \mathrm{DLR}_t \quad &\equiv \quad \frac{\int_0^\infty \frac{-\mathrm{d}e_{f,u}}{\mathrm{d}e_{h,t}} \cdot \int_0^\infty e^{-\rho s} \frac{\partial D(s)}{\partial e_{f,u}} \mathrm{d}s \mathrm{d}u}{\int_0^\infty e^{-\rho u} \frac{\partial D(u)}{\partial e_{h,t}} \mathrm{d}u} \\ &= \quad \frac{\int_0^\infty e^{-\rho(s-t)} d_s \int_0^s \frac{-\mathrm{d}e_{f,u}}{\mathrm{d}e_{h,t}} \mathrm{d}u \mathrm{d}s}{\int_t^\infty e^{-\rho(s-t)} d_s \mathrm{d}s}, \end{aligned} \tag{.10}$$

where it is important to note that $\frac{\partial D}{\partial e_{r,t}}$ is the partial derivative (as opposed to the total derivatives $\frac{\mathrm{d}(\cdot)}{\mathrm{d}(\cdot)}$ taken elsewhere) of damage D with respect to emissions of region r at time t, $e_{r,t}$, holding emissions elsewhere (and in other periods) constant.[18] The second equality

of choice variables, from other time periods with respect to current choice variables, become irrelevant in the optimality condition.

[18]The derivative $\frac{\partial D}{\partial e_{r,t}}$ does not depend on r.

follows from what we noted for the FOC in the section on the unilateral committed policy in section 3 (Eq. (.3)). With this definition of the DLR, the optimal pollution-only tax from the committed policy, Eq. (.7) can be rewritten as

$$\tau^* = \underbrace{\int_t^\infty e^{-\rho(s-t)} d_s \mathrm{d}s}_{\text{direct damage}} \cdot (1 - \mathrm{DLR}_t) = \tau^*_{Pigou} \cdot (1 - \mathrm{DLR}_t)\,, \tag{.11}$$

confirming that DLR_t is the welfare relevant dynamic equivalent of the simple leakage rate of a static model (cf. Annex 1). We thus see, in combination with Proposition 3a, that

Proposition 3b. The tax of the optimal pollution policy, τ^*_t, is increasing over time when DLR_t decreases, and it can only be decreasing when DLR_t increases. The tax is negative when $\mathrm{DLR}_t > 1$:

$$\dot{\mathrm{DLR}}_t < 0 \implies \dot{\tau}^*_t > 0 \qquad \dot{\tau}^*_t < 0 \implies \dot{\mathrm{DLR}}_t > 0 \qquad \mathrm{DLR}_t > 1 \implies \tau^*_t < 0.$$

Note that for a linear damage, that is, for constant marginal damage d, Eq. (.10) simplifies to $\mathrm{DLR}_t = \rho e^{\rho t} \int_0^\infty e^{-\rho s} \int_0^s \frac{\mathrm{d}e_{f,u}}{\mathrm{d}e_{h,t}} \mathrm{d}u \mathrm{d}s = \rho e^{\rho t} \int_0^\infty e^{-\rho s} \frac{\mathrm{d}e_{f,s}}{\mathrm{d}e_{h,t}} / \rho \mathrm{d}s$, which is equivalent to Eq. (.9). For a linear damage function, we thus have NLR = DLR.

Further terminology used throughout the paper:

The terminology ‘optimal’ tax as used in this paper can be somewhat confusing. We essentially consider unilateral taxes which per se are economically inefficient compared to global taxes. When we write about the optimal tax, we typically simply mean the best among the unilateral taxes.

We use the term ‘*current*’ for a specific time t as the value seen *from time t* on, i.e., opposed to the concept of *‘present’* values which means that future values are expressed in their value seen *from today’s time, time ‘zero’*. To express it analytically, we have, for a utility or monetary real value V_s occurring at time s, a today’s ($t = 0$) net present value $e^{-\rho s} V_s$ but a net current value at time t of $e^{-\rho(s-t)} V_s$.

To not complicate the descriptions unnecessarily, with a slight impreciseness we will usually use expressions such as a region’s ‘oil reduction’. This is always used as a shortcut to mean a regional reduction of the *consumption* of that fuel. Along the same line, we will in some cases use shortcuts such as ‘oil leakage’ when we mean the *overall emission* offsetting reactions in the remainder of the world as a reaction to the domestic reduction of *oil* consumption. That is, the term is not to be interpreted as concerning only the change in foreign *oil* consumption (emissions), but in the induced total foreign fuel consumption emission change as an equilibrium response to the domestic *oil* consumption change.

Part II Dynamic numerical model

This part analyzes optimal unilateral (OECD) carbon taxes, or the green component thereof, using a calibrated dynamic numerical fuel market model, accounting for the two dominant, and very distinct, fossil fuels – oil and coal. Sections 6 and 7 describe and illustrate the model, section 8 illustrates the results from the theory in Part 1. Finally, section 9 uses the model in a sequence of setups to examine the effect of various crucial elements of the model in order to provide an understanding of the mechanisms that drive the fuel-channel leakage rates and the optimal taxes. It also works to provide quantitative estimates of magnitudes of the leakage rate and the corresponding taxes for specific scenarios.

6 Model

Setup 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 consider emission taxes while the remainder of the world abstains and consumes in a decentralized fashion. The two fuels considered are oil and coal, indexed by $i = \{1, 2\}$.

A few words on the restriction to oil and coal as the two fossil fuels considered may be in order. First, the simulation results will already prove to be complex when we restrict the attention to the oil and coal. The interpretability would presumably be further complicated if gas were taken into account as well, and it is not clear whether relevant further insights would be gained. Additionally, currently 80 % of energy supply carbon emissions[19] stem from burning coal (43 %) and oil (36 %), and only 20 % from gas. Moreover, whilst gas is occasionally considered as the fuel of the future, in reality more than 50 % of the current growth of total global carbon dioxide emissions is attributable to coal, and 2/3 to coal and oil, with the remainder attributable to other sources, including gas. Furthermore, in the faster growing non-industrialized world the share of coal and oil in the growth of all CO_2 emissions exceeds 75 % (IEA, 2012). Finally, because gas has many features similar to oil, especially in terms of the exhaustibility and the convertibility of coal through gasification or liquefaction, to a certain degree one may interpret 'oil' in our model as representative of the ensemble of oil and gas, an approach also used by van der Ploeg and Withagen (2011).[20] The Discussion (section 11) speculates on how gas, and notably the currently increasing production of shale gas, could influence the model results.

[19]Energy supply is responsible for 83 % of all anthropogenic GHG emissions (IEA, 2012).

[20]In a similar fashion, climate and energy CGE models tend to treat oil and gas as a separate constant elasticity of substitution (CES) sub-aggregate, nested under another CES where the oil-gas sub-aggregate figures parallel to coal or even to different types of coal, see, e.g., Böhringer and Löschel (2004) and Böhringer et al. (2008).

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 energy consumption Y, $u_r(Y_r)$, (ii) the total regional costs for energy provision $c_r(Y_r)$, and (iii) the regionally perceived environmental costs D_r, which we model as a function of cumulative global emissions, $D_r(E)$, where $E_t = \int_0^t e_s \mathrm{d}s$, with e_t global emissions at time t:[21]

$$W_r = u_r(Y_r) - c_r(Y_r) - D_r(E). \qquad (.12)$$

Each of the variables in Eq. (.12) 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:

$$\mathbb{W} = \int_T e^{-\rho_u \cdot t} W_{r,t} \mathrm{d}t,$$

where $\rho_u < 1$ is the time discount rate of the consuming regions.

The fuel consumers' energy consumption utility is isoelastic in the consumption of energy Y, $u_r = \frac{1}{1-\alpha} \xi Y^{1-\alpha}$, $\alpha > 0$, implying an isoelastic demand for energy Y, with elasticity $\varepsilon = -\frac{1}{\alpha} < 0$. Section 9.6 extends the model to a growing regional demand. Energy Y is the sum of a constant elasticity of substitution (CES) aggregation of oil and coal consumption, $F(x_1, x_2) = \left(a x_1^\delta + (1-a) x_2^\delta\right)^{1/\delta}$, implying an elasticity of substitution $\sigma = 1/(1-\delta)$ plus, if allowed for, the consumption of a clean backstop B, $Y = F + B$. The backstop may be provided at any given demand rate (infinite elasticity) for an exogenous price which may vary over time.

As a property of the CES aggregation function, the unitary fuel aggregate cost, c_F, is $c_F(p_{x_1}, p_{x_2}) = \left(a^\sigma p_{x_1}^{1-\sigma} + (1-a)^\sigma p_{x_2}^{1-\sigma}\right)^{\frac{1}{1-\sigma}}$, and, for a specific aggregate fuel consumption F, oil and coal consumption becomes $x_1 = F \cdot \left(\frac{a c_F}{p_{x_1}}\right)^\sigma$, $x_2 = F \cdot \left(\frac{(1-a) c_F}{p_{x_2}}\right)^\sigma$. Supply of both the aggregate fuel and (if not idled) the clean backstop is readily modeled with a complementary slackness condition with respect to the weakly positive difference of their cost to the overall energy price p_Y,

$$\begin{aligned} F \geq 0 \quad &\perp \quad p_F - p_Y \geq 0 \\ B \geq 0 \quad &\perp \quad p_B - p_Y \geq 0. \end{aligned}$$

Because the regional calibration of the demand structure to today's regional oil and coal consumption rates implies regional share parameters a in the CES fuel aggregation function, the *aggregate* fuel energy price will in general differ across the regions, wherewith also the time of the introduction of the backstop will not exactly coincide in the two

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

regions.

The model allows for an endogenous production of synthetic oil from coal by liquefaction as soon as the relative fuel prices make the process economic, given a specified overhead process cost and conversion efficiency, again implemented by a corresponding complementarity slackness condition.

An alternative way to model fuel consumption utility would be to consider a utility described by a polynomial quadratic in fuel consumption as Golombek et al. (1995) did when discussing fuel-specific leakage rates in their static model.[22] Here, our approach based on the CES fuel aggregate has two distinct advantages. First, it allows us to choose any desired value for each elasticity parameter when we calibrate the model to current fuel consumption/price pairs. Golombek et al. could only choose values for half of the (cross or direct price) elasticity parameters, and the observed consumption/price pairs implicitly defined the other half of the parameters. Second, and most importantly, the isoelastic fuel demand and the CES aggregation ensure that the imposed elasticities are valid also for fuel prices that are (far) away from the region of the original calibration point. As the progressive depletion of the fuels substantially increases fuel prices in the long run, this seems to be a crucial feature for our dynamic model.

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.[23] Given this standard rule, and assuming the resource owners discount their net revenues with a 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:

$$\begin{aligned} \mathcal{H} &= r_t \cdot (p_t(r_t) - c(A_t)) - \lambda_t r_t \\ &\text{s.t.} \quad \dot{A}_t = r_t \text{ and } A_0 = 0, \text{ i.e. } A_t = \int_0^t r_s \mathrm{d}s, \end{aligned} \tag{.13}$$

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 $t = 0$, $c(A)$ is the marginal extraction cost after the extraction of the A units of fuel that could be extracted

[22]See Habermacher (2011) for a dynamic application using also a quadratic utility function.

[23]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.

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 also depend on the amount of the other fuel supplied at time t).

The FOCs of the Hamiltonian in Eq. (.13) yield the following stationary condition and canonical equation:

$$\begin{aligned} \frac{\partial \mathcal{H}}{\partial r_t} = 0: \quad & p_t(r_t) \stackrel{!}{=} c(A_t) + \lambda_t \\ \dot{\lambda}_t = \rho_{\text{res}}\lambda_t + \frac{\partial \mathcal{H}}{\partial A_t}: \quad & \dot{\lambda}_t \stackrel{!}{=} \lambda_t \rho_{\text{res}} - \dot{c}_t, \end{aligned} \tag{.14}$$

where we define $c_t \equiv c(A_t)$,[24] and at time t λ_t is the shadow value for a marginal unit of resource stock after the cumulative extraction of A_t previous units. As the stationary condition (Eq. (.14)) 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.

Calibration The fuel demand (or utility) parameters are calibrated according to the current regional consumption of oil and coal at current prices in the OECD and the Non-OECD region (see Annex 4) and to the desired direct- and cross-price elasticities of the demand.[25] Interestingly, whilst oil consumption is 15 % lower in the ROW than in the OECD, coal consumption in the ROW is almost twice that of the OECD. Similarly to Golombek et al. (1995), in the main calibration we choose an elasticity slightly below unity and a weak substitutability of the fuels, setting $\varepsilon = -0.9$ and $\sigma = 1.1$. The weak substitutability between oil and coal mainly expresses the difficulty of replacing oil, in its major applications, by the solid fuel coal. (Note, as oil reserves are much more restricted than coal reserves, throughout our model simulations it will essentially be oil whose scarcity becomes relatively stronger over time, implying that the possibility of substitution of oil by coal is of relevance rather than the inverse).[26] The possibility of deriving synthetic oil from coal liquefaction (also called the coal-to-liquids, CTL, process) will be modeled as a separate process.

The curve of the extraction cost for oil as a function of cumulative extractions is implicitly defined through its inverse, the function giving the cumulative extraction A for a specific

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

[25] The clean backstop is considered as absent or prohibitively expensive at this stage.

[26] 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 used cross-price elasticities of 0.1, on average. Here, the larger demand elasticity (in absolute terms) 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. In an overview, Michielsen (2011) lists cross-price elasticities from various empirical studies, averaging 0.06 from oil (and gas) to coal and 0.12 from coal to oil.

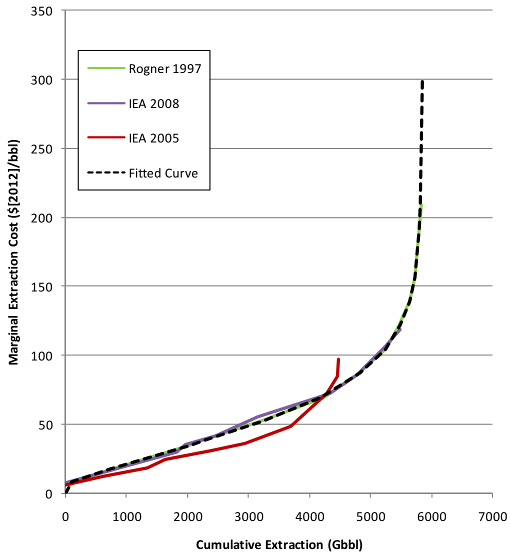

Figure 1: Oil extraction cost curves

marginal cost, $A(c)$. The following functional form appears to allow a very good fit to the extraction cost curve by Rogner (1997),

$$A(c) = p_3/(1 + \exp((c - p_1)/p_2)) + p_4 \exp((c - 45)/p_5).$$

We thus calibrated the parameters p_1 through p_5 to the extraction cost curve by Rogner (1997). As Fig. 1 shows, this fit provides an almost perfect correspondence to the Rogner curve. Moreover, there is a very good correspondence between the more recent IEA (2008) and an acceptable correspondence to the IEA (2005) projections.[27]

Indicating extraction costs for up to 1740 Gt coal, the coal cost curve in Rogner (1997) covers only a relatively modest fraction of the totally estimated resources of 16 000 Gt coal (DERA, 2012). Moreover, as Rogner notes, he models coal reserves in less detail than oil, which likely is a reason for the roughness of his estimated cost curve, replicated in Fig. 2. Given that historically coal prices were relatively low, around 30 \$/t in 2000, and today they fluctuate around 100 \$/t (DERA, 2012; EIA, 2013a), with a relevant fraction of the currently rather high prices probably explained by the unprecedented growth of worldwide coal consumption in the current millennium[28] rather than by a genuine long-term extraction cost increase, it was here decided to consider an actual coal extraction cost of 50 \$/t, and to assume an exponentially increasing extraction cost curve that matches the extraction 'cost and cumulative amount'-data pair for the largest quantity considered in Rogner (marginal cost of 286 \$/t after 1740 Gt extracted); that is, the curve given by

[27] All curves are inflation adjusted to \$2012.

[28] Worldwide coal consumption used to stagnate before the beginning of this millennium, with annual growth rates averaging -0.3 %. The dash for coal, notably in Asia, has lead to an average coal consumption growth rate of 4.6 % per year from 2000 through 2011 (own calculations based on EIA, 2013a).

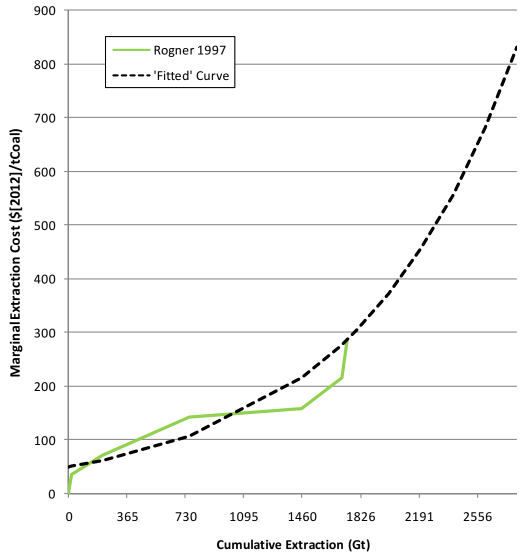

Figure 2: Coal extraction cost curves

$c = 50\,\$/\mathrm{t}\, e^{A/996\,\mathrm{Gt}}$. Fig. 2 shows how this curve provides a compromise between the general idea of a smooth, convex extraction cost curve, and the data points from the rough, convex and concave projection of Rogner (1997).

We generally consider two discounting schemes. Scheme 1 consists of equal discount rates for the fuel consumers and for the fuel producer, $\rho_u = \rho = 3\,\%$, as an attempted compromise between the in reality probably often rather large discount rates of fuel extractors and the potentially limited impatience of a regional planner in the fuel consuming regions.[29] Scheme 2 assumes a discount rate of only $\rho_u = 0.5\,\%$ in the consuming region and a higher fuel owner discount rate $\rho = 5\,\%$.[30] The emission intensity is $0.43\,\mathrm{tCO_2/bbl}$ for genuine oil and $2.8\,\mathrm{tCO_2}$ per ton for coal.

In the scenarios that consider liquefaction, the process is assumed to require 1 ton of coal per 2 barrels of synthetic oil produced (DOE/NETL, 2006; Bartis et al., 2008).[31] Whilst the final product, the synthetic oil, has the same emission intensity at its final consumption as genuine oil (that is, in the domestic use, direct emissions are the same), the use of half a ton of coal per barrel of oil produced implies excess emissions occurring during the

[29]Recall that the compensation method for disentangling the pollution and the terms-of-trade component of the optimal unilateral fuel tax described in Part 1 assumes equal discount rates for all involved actors.

[30]In the application of the model, the *consumers'* discount rate will essentially matter for the NPV calculation of future climate damages. At least for the case without growth, the modest 5 ‰ discount rate can be seen as a compromise between different, prominent views on climate discounting. Nordhaus (2008) suggests a pure-time discount factor for the emission damages of 1.5 % and Stern (2007) suggests 1 ‰. 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 exploratory rather than to provide precise quantitative results.

[31]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 slightly lower for subbituminous coal, about 1.8 (Bartis et al., 2008).

production (and thus, abroad) that exceed the final consumption emissions. Consequently, overall synthetic fuel is more than twice as emission intensive. 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 on a value of c_l=15 \$/bbl (of produced synthetic oil) 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.

When the clean backstop is considered, its price is assumed to approach an oil price equivalent of 200 \$/bbl-eq., with an initial price starting at 500 \$/bbl-eq., and the difference decaying exponentially at an annual rate of 2 %. To cover the period for which the considered processes imply an interesting dynamics, the simulation period stretches up to over 400 years. Shorter horizons are used in the cases where the clean backstop outcompetes all fuel sales earlier.

For the most part, we will restrict our attention to the case without growth in the energy demand, but we do treat an extended model with a demand growth roughly following IEA projections in the model extension in section 9.6. That section also treats the case of convex damages, whilst the NPV emission leakage rates examined in other sections can also be thought of as damage leakage rates under the implicit assumption of a linear damage function (cf. section 5).

7 Illustration of Model Results

Fig. 3 illustrates the model behavior in a standard setup with demand growth and the endogenous regional emergence of the backstop, as well as endogenous liquefaction (Annex 5 illustrates the outcome with constant demand and without liquefaction).

Plot 1 shows the fuel and backstop consumption paths. Blue denotes domestic (i.e., OECD) and foreign (ROW) oil consumption, o_d and o_f. Green refers to coal consumption c_d and c_f, and black regional backstop consumption, B_d and B_f. Red is the production of synthetic liquid fuel through liquefaction, o_{liq}. Plot 2 shows the corresponding prices and extraction costs: blue and green are for oil and coal respectively, the market prices p_o and p_c, and extraction cost c_o and c_c. Profits λ_o and λ_c correspond to the difference between prices and costs. Magenta shows the corresponding regional aggregate fossil energy prices $p_{EN,d}$ and $p_{EN,f}$, and the black line gives the exogenous backstop price, p_B.

Oil and coal consumption declines over time in the OECD. However, due to the large demand growth they increase initially in the ROW, peaking at around 50 years. With the relatively steep increase of the oil price compared to the more modest coal prices,

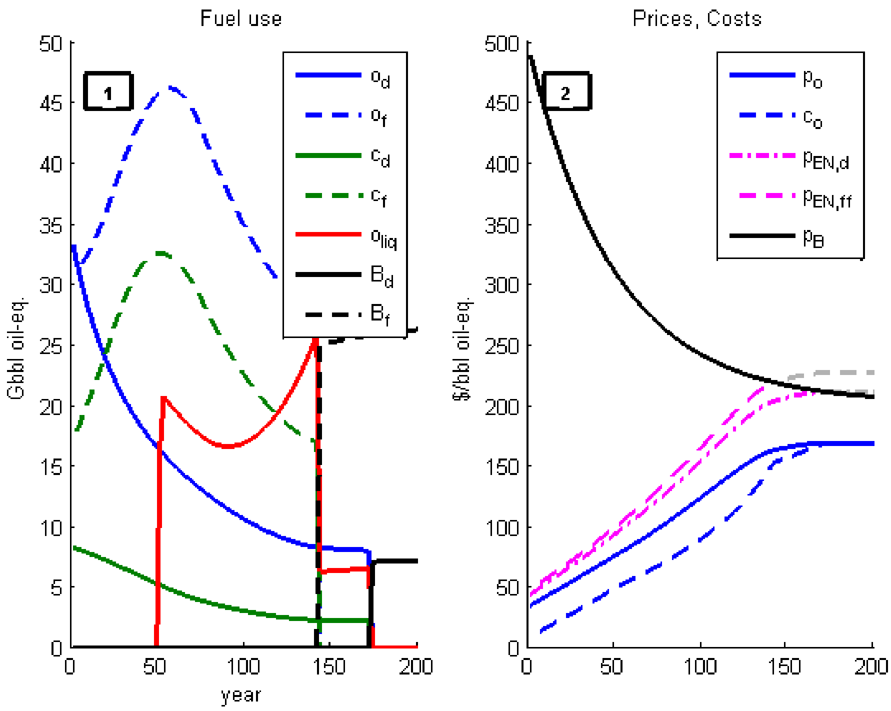

Figure 3: Simulation results with growth, backstop and liquefaction

liquefaction emerges in around year 50.[32] Because with coal the input to the CLT process is itself also exhaustible, crude and synthetic oil are thereafter used in parallel. When the regional aggregate fuel prices, $p_{EN,d}$ and $p_{EN,f}$, meet the backstop price p_B, in 140 years in ROW and in 170 years in the OECD, the regional fuel consumption stops and is replaced by the backstop. As the ROW dominates global consumption, resource rents already become very low by the time ROW fuel consumption stops, and they converge to zero by the time fossils also become redundant in the OECD. The slightly earlier switch from fossils to the backstop in ROW compared to the OECD is the natural consequence of the CES calibration to the current regional fuel consumption ratios, with the relatively larger coal consumption in the ROW. To see this, first note that oil represents the overwhelming share of fuel expenses today (in the OECD 90 % of total oil and coal costs, in the ROW 80 %, cf. Annex 4). In this case, the oil-share parameter approaches 1 in the CES function, and the closer to one the lesser coal is consumed in the benchmark for which the calibration is made. In parallel, the unitary aggregate energy cost becomes closer to the oil price, the fewer coal is consumed in the benchmark. In the price region for which the CES demand structure is calibrated in the model, modest increases of the amount of coal use in the benchmark (as is the case for the ROW compared to the OECD) do thus primarily increase the amount of coal used per unit of aggregate energy produced, and increase the unitary

[32] The (quasi) coincidence with the peak of ROW fuel consumption is pure chance; varying the overhead costs of the liquefaction process, c_l, to values different from the here assumed 15 \$/bbl directly shifts the time of the liquefaction start-up whilst changing the ROW consumption peak only slightly.

cost of aggregate energy, rather than to increase the implicit benchmark aggregate fuel energy consumption. This can make economic sense here if we believe that the relatively high coal consumption in the less developed ROW is partly explained by a less efficient use of coal rather than a higher overall need for final energy services. Given that the liquefaction process here prevents the oil price from diverging too far away from the lower coal price, the aggregate final energy costs in the OECD (which relies relatively more on oil) remain lower than those in the ROW (cf. plot 2 in Fig. 3). This explains that the switch to the backstop in the OECD occurs later than in the ROW. This is inverted in the case without liquefaction (Fig. A.1 in Annex 5). Without the synthetic oil supply, the rapidly depleting oil becomes so expensive over time that the higher reliance of the OECD on oil makes its fossil energy aggregate pricier than in the ROW, implying that the OECD switches first to the clean backstop even in absence of a tax.

8 Illustration of Tax Decomposition Method

Before we examine leakage rates in different scenarios in section 9, this section uses the numerical model to illustrate the main results of the theoretical findings from Part 1. For this purpose, consider Fig. 4, where the plot 1 (left) provides tax rate estimates, and plot 2 (right) shows leakage rates.

For simplicity we abstract from demand growth, from liquefaction or the backstop, and focus on a situation where damage is linear in cumulative emissions (implying, for the constant discount rate, that the calculated DLRs are equivalent to the NPV leakage rates, NLRs). We restrict the simulation horizon to 100 years assuming extractions to stop and cumulative emissions to remain constant thereafter. We consider discount scheme 1, i.e, $\rho_u = \rho = 3\,\%$. We assume an instantaneous marginal damage of $d = \rho \cdot 40\,\$/\text{tCO2}$, such that the current value of the future damage from a unit of emissions at time t is $\int_0^\infty e^{-\rho v} d\mathrm{d}v = 40\,\$/\text{tCO2}$.

In the left plot, τ^{all}_{max} and τ^{t-o-t}_{max} (solid blue and green) indicate the OECD tax rates numerically calculated as those which maximize OECD utility with (index 'all') and without (index 't-o-t', for terms-of-trade-only) pollution. Solid magenta shows $\hat{\tau}^{poll}_{max} \equiv \tau^{all}_{max} - \tau^{t-o-t}_{max}$, the crude approximation of the pollution-only tax described in section 2. Dashed blue, green, and magenta, show $\tau^{all}_{max,c}$,$\tau^{t-o-t}_{max,c}$, and the corresponding difference, $\hat{\tau}^{poll}_{max,c}$, are the analogs for the case when the region hypothetically is forced to compensate the fringe consumers and the producers (cf. section 2).[33]

In the right plot, DLR_{max} (blue solid) and $\text{DLR}_{\text{max,c}}$ (blue dashed) give the implicit leakage

[33]It is calculated with sequential maximization for different ts, using two iterations (the simulations showed that the convergence is very rapid with differences between utility-maximizing tax values calculated starting from $\tau_0 = 0$ or by starting from the values after the first iteration being tiny already).

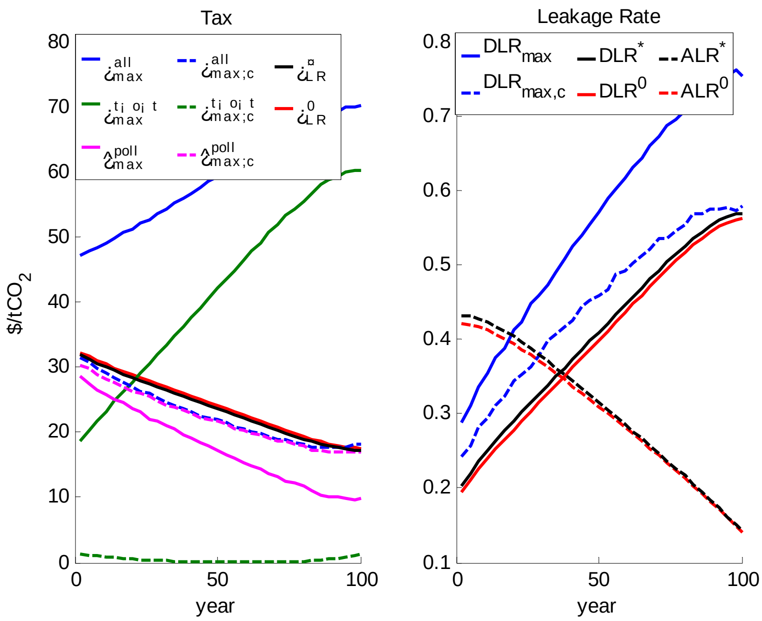

Figure 4: Illustrating the theory: taxes and leakage rates

rates defined by the approximations of the pollution-only tax, $\hat{\tau}^{poll}_{max}$ and $\hat{\tau}^{poll}_{max,c}$, calculated as DLR $= 1 - \hat{\tau}^{poll}/dam$ (cf. Eq. (.11)), where dam is the net current value of all future damages from current emissions at time t, which due to the linear damage assumption is constant at $40\,\$/\mathrm{tCO_2}$.

The right plot also shows DLR* (solid black) and DLR^0 (solid red), the directly calculated DLRs (here equivalent to the NLRs), based on the reaction of the foreign emission *path* to small variations of domestic emissions at t. DLR* is calculated from $\tau^{all}_{max,c}$, the utility-maximizing tax path for pollution damage and the hypothetical compensation, that is, implicitly on the optimal 'green-only' tax,[34] and DLR^0 for the tax path $\tau_t = 0$. We note that these two leakage rate paths are almost identical despite the substantial difference in the base tax paths under whose fuel-market equilibrium the leakages are calculated. ALR* (dashed black) and ALR^0 (dashed red) are the equivalents to DLR* and DLR^0, in terms of absolute emissions.

Finally, τ^*_{LR} (black) and τ^0_{LR} (red) in the left plot give the optimal green tax rates implicitly implied by the damage leakage rates DLR* and DLR^0, again according to Eq. (.11).

The graphs confirm several key points from the theoretical part of this paper. The crude approximation of the pollution-only tax from the simple subtraction method, $\hat{\tau}^{poll}_{max}$, is substantially lower than the optimal pollution-only tax rates approximated by both, the compensation scheme calculation (with the corresponding numerical approximations $\hat{\tau}^{poll}_{max,c}$ and $\tau^{all}_{max,c}$) or the leakage-rate based calculation (τ^*_{LR}). This confirms the theoretical result that the subtraction method leads to an understatement of the optimal pollution

[34] Note that in theory $\tau^{t-o-t}_{max,c}$ is zero, and thus $\tau^{all}_{max,c}$ equal to $\hat{\tau}^{poll}_{max,c}$.

tax (cf. section 4).[35] Further, that $\tau^{t-o-t}_{max,c}$ (no damage) is almost exactly zero confirms that the hypothetical compensation neutralizes terms-of-trade effects as we have derived analytically.[36] Finally, the tax rates indicated by the solid cyan and red in the left – calculated based on the emission damage *dam* augmented by the factor (1-DLR), where DLRs were calculated directly using small perturbations of domestic consumption (solid black and red on the right) – correspond very closely to the directly calculated overall welfare maximizing domestic taxes (dashed green on the left). This confirms the theoretical finding that the optimal regional pollution-only tax (or the optimal regional overall tax under the compensation scheme) corresponds to $dam \cdot (1 - \text{DLR})$ (cf. Eq. (.11)).

In the next section the form and values of the graphs are discussed along with the results from additional model setups.

9 OECD Leakage Rates

To ensure an understanding of the leakage rate paths in the more complex model, the following starts with a discussion of leakage rates in very basic setups, and sequentially adds complicating elements until, ultimately, models taking into account all the features described in section 6 are considered. Since the path of the foreign emission offset can best be understood when direct emission leakage, either in absolute or NPV terms, is considered, we start by considering solely ALR and NLR paths. The additional effect of the damage convexity by studying DLR rates is only taken into consideration at a later stage.

The various graphs of the model results in the following sections contain many details, each of which can stem from obvious or not so obvious effects in the modeled resource market. The aim here cannot be to fully describe all these details; instead, we try to focus on the most interesting aspects.

9.1 Single Fuels

We start by considering simplified variants of the model where only a single fuel is consumed, with constant demands and without liquefaction and backstop. In addition, we consider a variety of hypothetical extraction curves. In all other respects, the model corresponds to the original setup described above.

Fig. 5 shows NLR (solid) and ALR (dashed) leakage rate paths for five different single-fuel model setups, for discount schemes 1 and 2, the first four plots for oil, and plot 5 for coal.

[35] Correspondingly, the implicit leakage rate calculated based on $\hat{\tau}^{poll}_{max}$, DLR_{max}, is too high.

[36] We used a time-step duration of 1 year for the simulations.

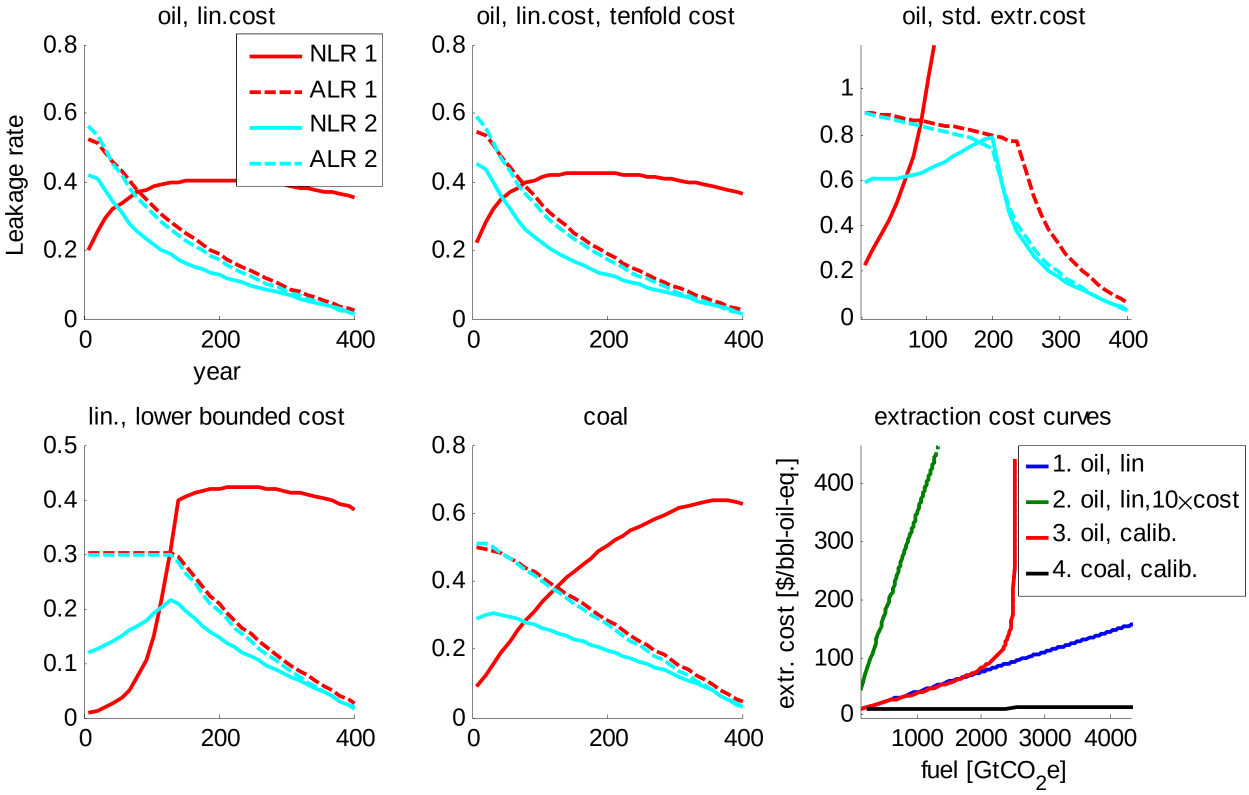

Figure 5: Leakage paths single fuels

Plot 1 is from a run where the highly convex oil cost curve is replaced by a linear cost curve constructed as the tangent to the initial slope of the original oil cost curve (plot 6 shows the cost curves: blue for the linear tangent curve and red for the original oil cost curve). Plot 2 is also based on a linear oil cost curve, but with oil made much scarcer, by multiplying by a factor 10 the costs from the first linear curve (green line in plot 6). Plot 3 considers the original cost curve, and plot 4 the first linear cost curve, but with all costs increased to minimally 70 $/bbl, resulting in a cost curve with a constant and a linearly increasing region. Finally, plot 5 is for the model with coal only, for standard coal extraction costs (black line in plot 6).

As already in Fig. 4, ALR paths are generally downward sloping. That is, an early domestic emission reduction leads to a larger overall foreign emission increase than a late domestic emission reduction of the same magnitude. The offset rates, ALRs, do not converge exactly to zero, but they become small as time approaches the end of the model horizon. This cannot simply be explained by the fuel owners' having, for early domestic reduction, more time to offset it abroad 'after' the time of that early reduction, because the model assumes perfect foresight (and commitment), that is, the fuel owners could per se react to *late* domestic emission reductions by increasing sales *prior* to the late reductions, symmetrically to their *future* reaction to *early* domestic emission reductions. Instead, the effect can be explained by the earlier fuel units being cheaper to extract.

Intuitively, providing the fuel owners with an 'additional' unit of a *cheap* fuel increases fuel sales within a specific time-horizon more than if they were given a more expensive additional unit of fuel; if we hypothetically consider a unit of very cheap fossil fuel to be added to the reserves, this tends to increase overall fuel sales (within a limited sales period) by more than the addition of a unit whose extraction costs are so large that it is barely profitable to extract the unit. That this, rather than the timing of the domestic perturbation per se, explains the downward trend of the leakage rates is confirmed in the fourth oil cost curve scenario considered here (plot 4 in Fig. 5): assuming a cost curve that is constant for a specific amount of fuel and rises only after this amount is extracted the leakage rate remains constant during the phase of constant extraction costs, and it starts to decrease only once the fuel extraction costs have started to increase. Similarly, in oil cost scenario 3, when taking into account the calibrated, quasi-kinked oil cost curve that yields a substantial amount of very cheaply extractable oil but very rapidly rising costs after a certain amount when only difficult to extract units are left (Fig. 1), we find that during the whole initial phase with the modest costs the absolute leakage rate remains rather stable, and it starts to drop rapidly[37] after around 200 years when the phase with the rapidly rising extraction cost is reached (plot 3 in Fig. 5).[38] Finally, besides in this specific pattern in the case of the quasi-kinked oil cost curve, that the decrease of the ALRs is not simply explained by the approaching of the artificial ending of the simulation horizon, is also confirmed by the case where the fuel-sales period ends endogenously with the relative competitiveness of a backstop technology (cf., e.g., Fig. 11, plot 2).

A few additional patterns deserve our attention: First, the influence of the fuel-owner discount rate on the ALRs seems very limited.[39] In most cases, the ALR paths for the two discount schemes (dashed lines) are hardly distinguishable in Fig. 5. The only notable difference occurs for the case of the quasi-kinked oil cost curve (plot 3) where the difference seems to essentially stem from the fact that the more impatient fuel owners (cyan, $\rho = 5\,\%$) sell fuel more rapidly and thus that the quasi-kink in the extraction rate – and the corresponding steeper downward trend of the ALR path – is reached earlier.

Second – and maybe most surprisingly –, a scaling down of the oil reserve sizes by a factor 10 hardly matters for the leakage rates, assuming linear oil extraction costs. All ALR and NLR paths are almost exactly identical between the corresponding plots 1 and 2, where scenario 2 was based on a 10 times increased cost curve. This reserve-scale invariance

[37]The very distinct kinks in the leakage rate paths are in reality slightly smoother if we use lower numerical time-steps for the calculation of the leakage rates; here we used leakage rate time-steps of 12 years duration.

[38]We omit the time-path of the extraction cost curve here. See, e.g., Figs. A.2 and 7 where, for the standard model with oil and coal a similar oil leakage rate pattern results, with the kink in the leakage rate path in Fig. 7 corresponding to the time of the oil cost quasi-kink in Fig. A.2 also a few decades after 200 years.

[39]The consumers here are acting non-strategically and so the consumer discount rate is irrelevant for absolute leakage.

was not necessarily expected since a more pronounced scarcity is generally thought of as tending to increase fuel-price channel leakage rates: if a fuel is abundant enough, regional savings tend to have a small impact on the worldwide price, thus implying limited leakage rates. In contrast, for scarce enough resources one may, put bluntly, assume that what is not bought by one party will simply be bought by the other; in other words, (at least absolute) leakage rates to approach 100 % even for limited time horizons. In the present case, that a scaling of the reserve size only has a marginal effect, considering solely oil and linear extraction costs, can be explained by the scale invariance of the demand function. To see this, first note that in plot 6 in Fig. 5 the linear oil cost curve (blue line) passes almost through the origin, evidencing that the fuel extraction costs are almost proportional to cumulative extractions. Intuitively, having an isoelastic demand, an γ-fold increase of the cost of the extraction of a specific amount of fuel, may in this case simply imply that the fuel extraction is reduced by a constant factor and the fuel price (and extraction costs) augmented by another constant factor, with nothing else changing in the (time) pattern of the problem's solution. In this case, because the extraction cost increase has only scaled all variables proportionally by specific, constant factors, but left the problem and its solution unchanged elsewise, the leakage reactions to small domestic perturbations also should exhibit the same pattern in both cases. This intuition about a pure scale-only effect of the cost-augmenting factor on the fuel market outcome is analytically confirmed in Annex 6.

Third, and related to the second point, the absolute leakage rate is almost one for the initial periods in the case of the empirically calibrated oil cost curve (plot 3), and it does not vary with the fuel-owner discount rate. In all three other cases, the absolute leakage rate starts 'only' at just below 0.6 in the initial periods and becomes lower later on. This stark difference confirms the importance of Green Paradox type effects: with the pronounced quasi-kink in the oil extraction costs for the calibrated oil cost curve, the situation corresponds almost to one with a fixed amount of fuel extractable (the amount corresponding roughly to the cumulative production possible before the extraction cost become rapidly very high just after the curve's kink) relatively cheaply, and only a very limited additional amount extractable for even quite high costs. In this case, sparing some of the cheap fuels in one place will mostly relocate this consumption to the other, passively consuming, region rather than yielding long-run global savings. Thus it will yield absolute leakage rates very close to unity. In this sense, and in relation to the previous observation about the resourse-scale-invariance of leakage rates, we note that in the basic dynamic resource exhaustion model the leakage rate pattern seems much more directly influenced by the curvature of the extraction cost curve than by the absolute amount of fossil fuels available (where the last point holds at least for linear costs with small intercepts[40]). The

[40]In later scenarios with interdependent demand for several fuels, we will generally find that with convex extraction costs a higher demand (and thus, higher relative scarcity) tends to increase leakage

various scenarios examined here therefore also clearly indicate that whilst oil is – in the case of the calibrated cost curve (plot 3) – subject to a much higher leakage rate than the more abundant coal (plot 5), this is, at least in the simple model considered in this section, less due to the general relative abundance of the fuels. Instead it appears to be mainly due to the special form of the oil extraction cost curve, implying that with the quasi-kink a quasi-fixed amount of oil will be available.

Fourth, the time-path for NPV leakage rates for anticipated taxes is highly non-monotonous and has a tendency to stretch over large ranges from very low up to values exceeding unity, especially in the case of the higher emission (consumer) discount rate (NLR_1, $\rho_u = 3\,\%$). The initial NPV leakage rates are below their absolute counterparts. This is the necessary consequence of the foreign emission reaction being spread across time and thus to be discounted, i.e., they are weighted relatively less than the initial domestic emission changes. This difference between the NPV and the absolute leakage paths tends to become smaller over time, as the domestic emission reductions themselves become more discounted, and as parts of the foreign reaction take place in times prior to the domestic reductions. For the NLR_1, this leads to discount rates that even rise over time as the domestic emission reduction is discounted ever more while parts of the foreign reaction continue to take place in the earlier periods. For the linear oil extraction costs (plots 1 and 2), and for low discount rates (NLR_2), this effect is reversed in later periods where the absolute amount of leakage becomes so small (dashed lines) that the additional timing effect is outweighed by the decrease in the fraction of the emissions offset overall. The third oil case, with the calibrated oil cost curve, is interesting. For early emission reductions, a part of the offsetting abroad occurs later on. This implies that, whilst the absolute offsetting fraction is close to 1, especially NLR_1 is low as the initial domestic reduction achieves at least a partial delay of global emissions. The inverse holds for periods later on but still before the extraction cost's quasi-kink: relatively late domestic emission reductions are weighted against foreign offsetting reactions earlier on. In the case of a strong enough discounting, this implies that the NPV leakage rate exceeds unity: we have a Green Paradox effect where the timing shift outweighs the (relatively small) overall emission reduction effect. Whilst plot 3 does not show the whole NLR_1 path, the path reaches very high levels above a factor of $\mathrm{NLR}_{1,t} = 10$. Similar effects drive the special shape of the NLR paths in plot 4. There, however, in a less accentuated form, as the slope of the cost curve after the kink is much less steep than in the calibrated oil cost curve, wherewith, the 'quasi-fixed reservoir' effect from the calibrated curve applies less strongly to case 4.

rates (cf., e.g., discussion of coal leakage rates in the basic case with interdependent fuels, section 9.2 and in that with liquefaction, section 9.3).

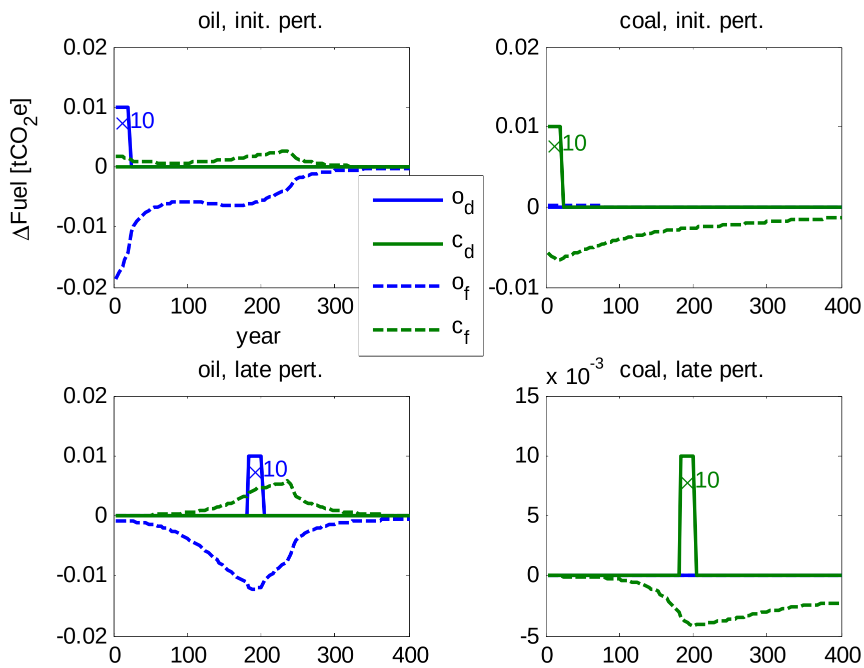

Figure 6: Emission reaction paths, basic setup

Foreign oil and coal consumption reactions (o_f, c_f) to domestic oil or coal (o_d or c_d) consumption changes, for weak substitutability ($\sigma = 1.1$) and discounting scheme 1 ($\rho = 3\,\%$). For visibility, domestic consumption changes are scaled down by a factor 10.

9.2 Basic Joint-Fuel Setup

We consider the model with joint fuel demand (substitution elasticity $\sigma = 1.1$), without growth, in the absence of liquefaction and backstop. Fig. A.1 in Annex 7 provides the detailed model results. As the understanding of the leakage rate paths requires some insight in the foreign (cross-)fuel reactions to domestic consumption changes, we first illustrate and interpret the paths of foreign emission reactions to initial and later domestic fuel consumption reactions, plotted in Fig. 6.

Analysis The bars (exogenous increase of domestic consumption) always imply an opposite reaction of the dashed same-colored curves. They are spread in general over the whole time horizon (negative response of foreign consumption of the same fuel, as a direct price effect) with the reaction typically being strongest during the period of the exogenous perturbation, and in most cases they monotonously decrease in both time-directions. Foreign consumption of the other fuel – dashed, other-colored curve – reacts in the direction of the exogenous domestic perturbation. This is a consequence of the (weak) substitutability of the two fuels ($\sigma > 1$): if one fuel becomes more expensive on the marked and less consumed (due to the increase in foreign consumption of it), the other fuel is consumed more. This cross-fuel reaction is accentuated for larger substitutability σ, and reverted when the fuels are complements ($\sigma < 1$), as shown in Annex 7.

We note some further qualitative features of the reaction paths. First, the relative reaction of coal-to-coal is somewhat smaller than the oil-to-oil reaction.[41]

Second, whilst there is substantial coal-to-oil reaction (green dashed on left), the absolute oil-to-coal (blue dashed on right) appears to be small (this pattern persists, less accentuated, for the cases with σ further away from unity, cf. Figs. A.3 and A.4 in Annex 7). This may be a surprise given that the order of magnitude of absolute (foreign) emissions is the same for the two fuels, and we use a demand system based on a CES function with a single substitutability parameter σ for both fuels. An analysis of the properties of the CES demand system offers an answer. As a mathematical property, as the price of a fuel x becomes large, the relative reaction of the other fuel y to changes in the price p_x, $\partial y/\partial p_x$, becomes large relative to the direct price reaction $\partial x/\partial p_x$. Given the scarcity of oil and its much higher price (per unit of energy as well as per unit of emissions), the secondary reaction of coal to oil can thus be relatively large, whilst the more abundant coal can be replaced more easily by only a smaller amount of oil. This also offers an explanation for why the relative reaction of coal to oil becomes even smaller for the case of the late perturbation (plot 4) when the rapid depletion of oil has even further increased the relative scarcity of oil compared to coal.[42] Moreover, it explains why the coal-to-oil reaction is relatively larger for the later oil-perturbation (plot 3) than for the initial oil-perturbation (plot 1), and why the absolute magnitude of the coal-to-oil reaction peaks later than the oil-to-oil reaction itself (both, in plot 1 and plot 3).[43]

Leakage rate paths Fig. 7 shows NLR (solid lines) and ALR paths (dashed lines) implied by the emission reactions illustrated in Fig. 6. Blue lines are for discounting scheme 1 ($\rho = \rho_u = 3\,\%$), green for scheme 2 ($\rho = 5\,\%$, $\rho_u = 0.5\,\%$).

Analysis Introducing fuel-interdependence (cf. Fig. 7) qualitatively changes things relatively little compared to the cases with single fuels (plots 3 and 5 in Fig. 5). For oil, LRs are slightly reduced (early and later, except for the NLR for discount scheme 1, which is hardly affected) as, given the (weak) substitutability, foreign coal emissions are somewhat reduced when domestic oil reduction increases foreign oil availability and consumption. We even find negative oil leakage for very late periods when the strong relative scarcity

[41] Whilst the spread of the reaction over time is overall more or less comparable, with the same scaling applied in all graphs for coal the maximal amplitude of the reaction is always smaller than a tenth of the original perturbation whilst for oil the corresponding maximum is always larger than a tenth.

[42] This pattern persists in the results for $\sigma = 1.7$ and $\sigma = 0.3$, Figs. A.3 and A.4, Annex 7.

[43] The magnitude of the oil-to-coal reaction is further reduced relative to that of the coal-to-oil reaction by the relative emission intensities of the fuels: coal is more emission intensive than oil, and in terms of the relative magnitude of the coal-to-oil vs. oil-to-coal effect ratios, and the relative size of the two cross-fuel emission changes is proportional even to the squared factor of the relative emission intensities.

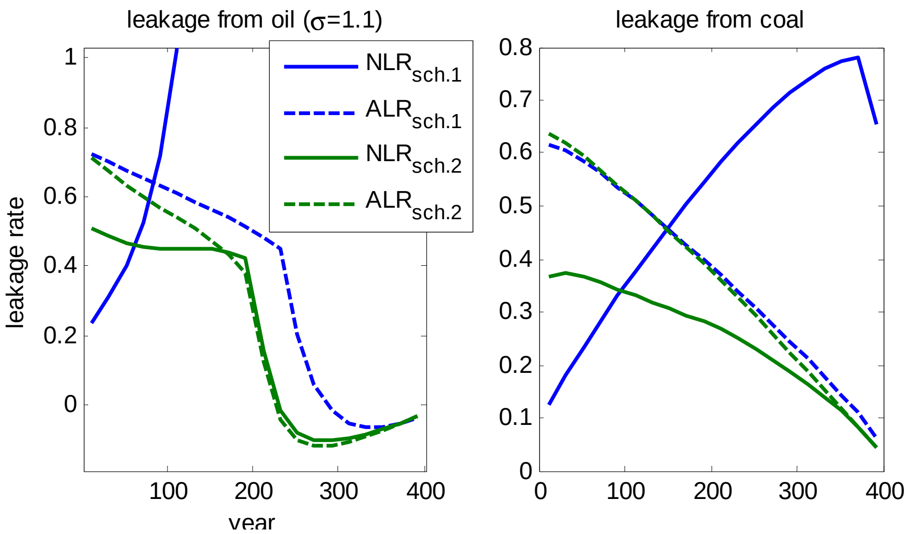

Figure 7: Leakage paths basic setup

of oil implies that increased oil availability reduces coal consumption strongly, such that the oil-to-coal substitution dominates the original foreign oil emission increase (see the analysis to Fig. 6 for a detailed description of this mechanism). For coal, in contrast, LRs are increased, early and later. This seems to be readily explained as follows: with the fuels as substitutes, and oil becoming very scarce over time, the demand for coal increases relatively strongly over time compared to the single-fuel case where coal is modeled separately. Therefore, compared to coal modeled as single fuel, future coal becomes relatively scarcer when the two fuels are modeled together. The higher relative scarcity of coal, increasing notably over time as oil becomes more and more rare and demand for coal increases progressively, in turn tends to increase the leakage rate for domestic coal reductions (note, coal extraction costs are exponential, not linear). As Fig. 6 shows, secondary coal-to-oil effects are small in terms of emissions and do not revert this result.

9.3 Liquefaction

We allow the endogenous emergence of coal liquefaction. As plot 1 in Fig. 8 shows, this provision of synthetic oil supplementing crude oil supply ramps up after around 60 years, to provide a substantial part of the overall oil consumption (sum of blue lines). The corresponding increase of coal consumption increases the coal cost and price (plot 2) compared to the case without liquefaction (Fig. A.2 in Annex 7), whilst flattening and limiting the cost of (crude) oil. Fig. A.5 in Annex 8 gives a zoomed view on the curves of plot 2 during the transition phase to the liquefaction process. It reveals that extraction cost and profit curves are kinked. The coal (oil) cost curve rises more (less) rapidly after the CTL onset, and the oil shadow value decreases rapidly as CTL is imminent, as was to be expected.

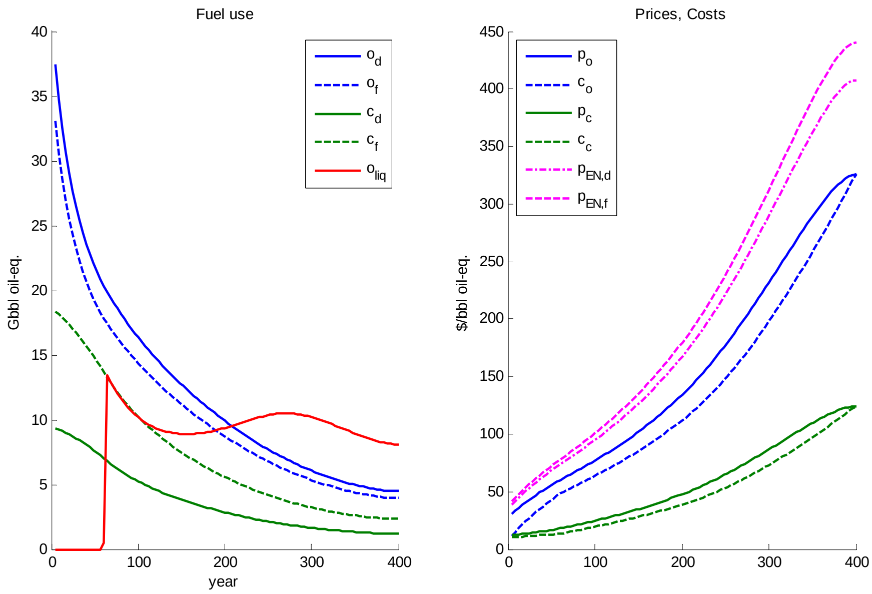

Figure 8: Simulation details with liquefaction

Fig. 9 shows the leakage rates, analogous to Fig. 6, for the case when the endogenous liquefaction production is allowed for.

The introduction of the liquefaction process has further increased the LRs for coal, compared to the case without liquefaction (cf. plots 2 in Figs. 9 vs. 7). Again, this is readily explained by coal (with convex extraction costs) becoming somewhat scarcer when its use, for the purpose of liquefaction, is increased – especially during the future periods after the initiation of the CTL process. For oil, LRs become much lower, and relatively soon even become negative, converging to below -1 in the longer run. This is explained as follows: with liquefaction and scarce crude oil and abundant coal domestic oil savings primarily lead to lower (or later) CTL globally; as synthetic oil is *more than twice* as emission intensive as genuine oil this implies strongly negative leakage rates, of up to *below -1*,[44] when fuel end-consumption leakage by itself is small. The latter is the case (i) especially during late periods (cf. section 9.1), but (ii) to a limited extent already earlier, given the abundance of coal and the corresponding abundance of the dirty, liquid backstop synthetic oil.

However, both, absolute and NPV LRs are at least slightly positive for initial domestic oil reductions. This is explained by the fact that over the long time horizon considered even though coal is abundant it is still a depleting resource[45] with corresponding increases in foreign coal and synthetic oil consumption following a domestic oil reduction, offsetting the CTL-related negative leakage in part or even fully. It is the general decrease of this

[44]Recall that the synthetic and genuine oil have similar emissions during their final consumption, but the production (abroad) of the synthetic fuel adds more than these emissions (section 6)

[45]And its depletion is here non-negligible especially due to the large amount of coal used for liquefaction.

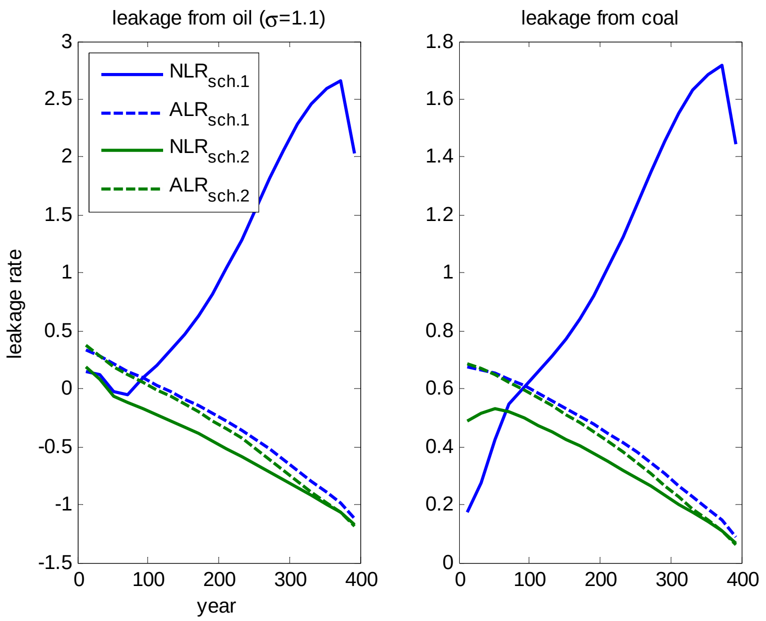

Figure 9: Leakage paths with liquefaction

offsetting over time (again, cf. explanations section 9.1) which explains the downward slope of the leakage rates in general (the exception of the mainly increasing NLR for the strong time-discounting being, as usual, explained by later domestic emission changes implying *earlier* and thus relatively more weighted foreign reactions), as fuel-end consumption leakage decreases over time and the 'negative leakage' CTL-effect becomes more and more dominant. A negative NLR for initial oil savings results if overhead costs are small enough (shown in Fig. A.8, Annex 8, for $c_l = 0$). Emission reaction paths, with details on the response of foreign fuel consumption to domestic changes and with liquefaction, are given in Annex 8 (Fig. A.6 and, for cumulative changes, Fig. A.7).

9.4 Clean Backstop

We allow the endogenous emergence of a clean backstop that replaces the fossils as soon as it is competitive in the different regions. Here, we consider the case in absence of liquefaction; section 9.5 allows also for liquefaction. As plot 1 in Fig. 10 shows, this alternative energy technology replaces the fossil fuel aggregate towards year 200, first in the OECD and soon thereafter in the ROW. Naturally, fuel profits (plot 2, difference between market prices, p, and extraction costs, c) converge to zero up to the time when the backstop fully replaces the fossil fuels. The backstop alters the problem in the sense that the stopping time of the fuel sales and emissions is no longer exogenously given by the end of the simulation horizon, but it is endogenous and dependent on domestic fuel emission changes.

Fig. 11 shows the leakage rates, analogous to Fig. 6, for the case when the backstop is

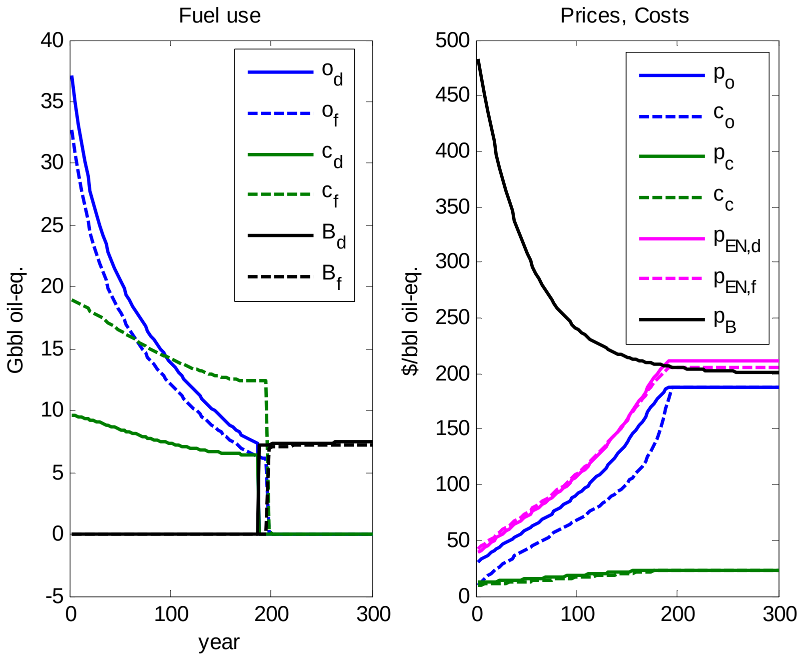

Figure 10: Simulation details with backstop

considered.

In presence of the clean backstop for the fossil fuel aggregate, domestic *savings* of the scarcer and more rapidly depleting resource – oil – strongly *increase* the absolute amount of total emissions (plot 1, ALRs > 1).[46] This in stark contrast to the case without clean backstop, where absolute leakage rates are always below unity when the fuels are substitutes ($\sigma > 1$). Moreover, it also goes against the general predictions of the implications of a clean backstop for the effect of climate mitigation policies, where the backstop is typically found to limit leakage or Green Paradox effects, as the backstop facilitates the reduction of total fuel consumption (e.g., van der Ploeg, forthcoming; Essay 1 in this dissertation; Hoel, 2010[47]). The evolution of *cumulative* foreign emission changes in response to a domestic oil perturbation (Fig. A.10, plot 1, Annex 9) helps to explain the above-unity leakage rate found here. The oil is scarce enough for a large fraction (almost 1 Gbbl) of the early domestic savings (of 1.5 Gbbl) to be offset abroad before the phasing in of the endogenous backstop, and the induced delay of the emergence of the backstop increases this fraction to almost exactly 100 %, the foreign oil offset reaching almost 1.5 Gbbl. What pushes the overall leakage rate to above 1 is the additional coal used during the additional time during which the fossil fuel aggregate is consumed. That is, by stretching the time during which the fossil-fuel aggregate is competitive against the clean backstop, an increased supply of the *scarcer* fuel tends to imply an overall emissions

[46] Fig. A.11 in Annex 9 confirms that this holds even for the case of where the resources are stronger substitutes or strong complements.

[47] The finite choke price in Hoel (2010) can readily be thought of as a backstop price.

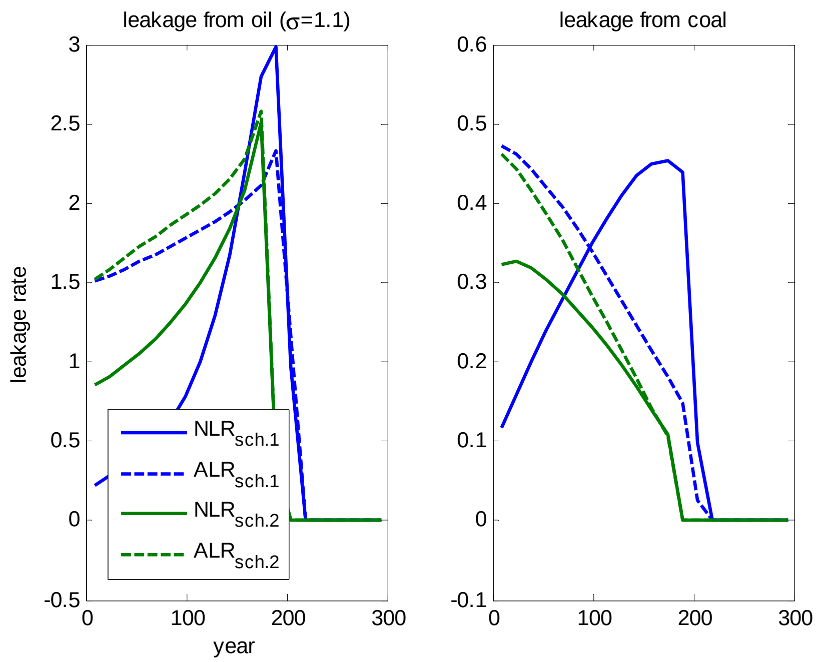

Figure 11: Leakage paths with backstop

increase that exceeds the emissions of the additional amount of the scarce resource itself. The extra coal burn during the additional phase of fossil fuel use is large. This is again related to the relative scarcity of oil during these late periods: as oil is scarce (expensive) during that final period, the substitutability of the fuels implies that a unit of aggregate fossil energy to a larger degree consists of coal than, e.g., in the initial periods when the price of oil is not yet so much higher than that of coal. With the assumed weak substitutability, $\sigma = 1.1$, this effect is limited here and would conceivably be even stronger for a higher σ.

A very different picture results for coal leakage rates: domestic savings of the more abundant resource – coal – strongly reduce global emissions (Fig. 11, plot 2), with LRs < 0.5 for all variants and times. This corresponds to standard expectations for a relatively abundant[48] fuel in the presence of a clean backstop: given that the fuel is not too rapidly depleting and price effects of regional savings imply only relatively moderate (that is, 'slow') reactions of foreign emissions as well as only a limited delay of the phasing in of the backstop, a relevant fraction of the domestic savings is carried on until the phase-out of the fossils by the clean backstop. In fact, a comparison with the effect of an additional supply of oil confirms that it is mostly due to the depletion of oil that the backstop becomes competitive (Figs. A.10 and A.9, Annex 9). The additional supply of coal has a

[48] At first sight it may appear somewhat contradictory to the findings in section 9.1, where the importance of the absolute abundance of the fuel was qualified. Recall that this was the case for a setting with linear extraction costs and, importantly, single fuels. As we observe and explain here, when different fuels are consumed as substitutes (and especially in presence of a backstop), a higher scarcity of a fuel seems to imply a larger leakage rate for domestic savings of that fuel.

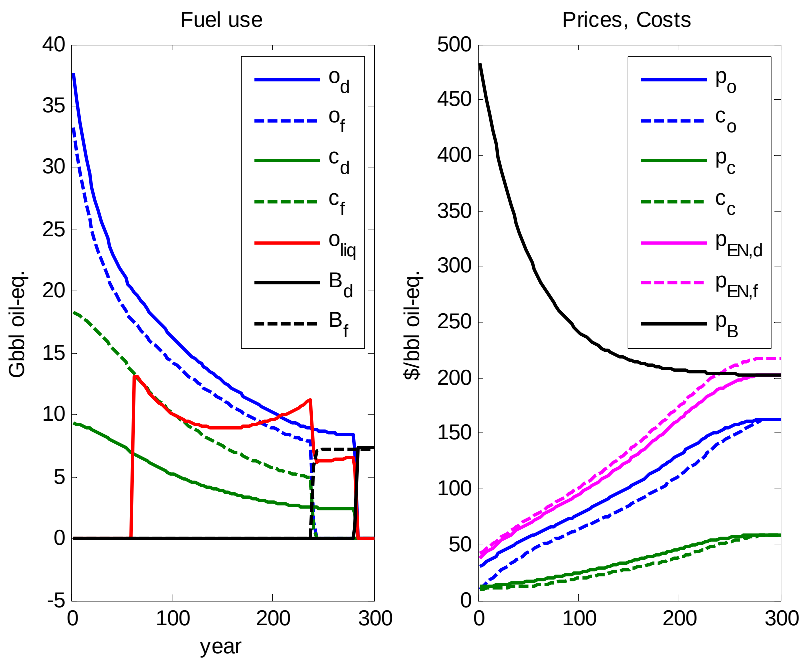

Figure 12: Simulation details with backstop and CTL

much more negligible effect on the time the backstop replaces the fossil fuels and on the cumulative emission changes.

9.5 Clean Backstop with Liquefaction

Liquefaction is added to the model variant with the backstop from the previous section. Fig. 12 shows the detailed simulation results. Supplementing the supply of liquid fossil fuel, liquefaction stretches substantially the period during which the fossils outcompete the backstop, from just below 200 years for the case without liquefaction (Fig. 10) to almost 300 years here.[49] Given what we noted in the last section, this is no surprise: without CTL, it was essentially the rapidly depleting oil which allowed the backstop to replace the fossils, but here synthetic oil allows a sustained production of liquid fuel.

Fig. 13 shows the leakage rates, analogous to Fig. A.9, for the case with liquefaction in addition to the backstop.

Besides prolonging the fossil fuel use, and therewith the path of non-zero leakage rates, liquefaction does not alter the main conclusions about the fuel-specific leakage rates in presence of the clean backstop. For oil, absolute leakage rates are still above unity, around 1.5 or even higher. CTL, as a relatively inefficient conversion and having overhead costs, leaves oil still as the relatively more scarce resource, implying that more oil significantly prolongates the fossil-fuel era. In addition, the initial 'negative' leakage (related to foreign

[49]Due to the mechanism described in section 7, liquefaction implies that the backstop replaces fossils first in the ROW and only later in the OECD.

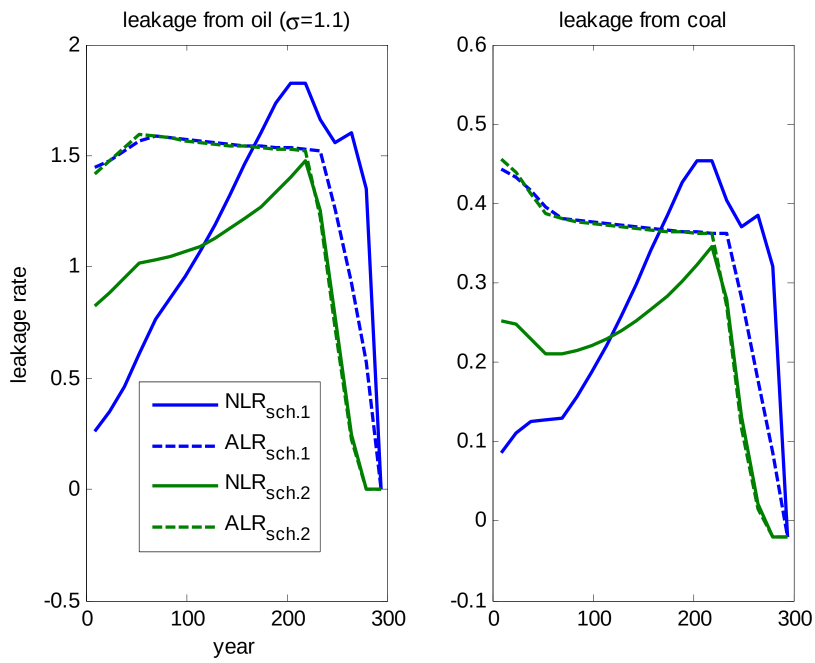

Figure 13: Leakage paths with backstop and CTL

emission savings if less synthetic oil is produced) is offset during the end phase of the fossil fuel era where CTL lasts slightly longer due to the initially saved coal from the initial CTL delay. Thus, overall CTL has a modest effect on initial ALRs. Also the NPV leakage is high, especially for the low emission discount rate, and NRL_1 is almost unity. Qualitatively also the coal leakage rates remain comparable to those from the case of the backstop without liquefaction with rates that are always below 50 %.

9.6 Extension

Here we consider the case where fuel demand is growing and where climate damages are convex in cumulative emissions.

Demand growth

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 after the first 25 years, as the ROW economies are maturing, their energy demand *growth rates* slowly decline by 0.05 % p.a. This ends when 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 zero.[50]

[50] 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

Quadratic damages

Whilst it also seems natural to address the question of carbon emission leakage in terms of the absolute fraction of emission offsetting in the rest of the world, it is clear that for the welfare impact of the leakage, if future utility flows are generally present-discounted, emissions should be weighted according to the time they occur, as we have done above for the NPV leakage rates. In addition, it is, however, also the case that marginal emissions at different points in time and in different scenarios can have very different utility impacts on the populations concerned. Indeed, it is generally assumed that the marginal damages from emissions can rise rapidly as cumulative emissions increase, that is, climate damage is considered strongly convex in cumulative emissions. The formulas we derived for the optimal 'green-only' policies, strictly speaking, support the definition of the optimal tax based on leakage estimates only if either we assume damages to be indeed linear in cumulative emissions, or if we use a new definition of the leakage rate that expresses a sort of a rate of leakage of the *damages* from (leaked) emissions rather than emissions directly. Accordingly, we calculate here what we defined in section 5 the 'damage leakage rate', DLR, defined as the fraction by which the foreign emission offsetting reduces the overall impact of the domestic emission change on present-discounted future climate damage. Since climate damage is often approximated as quadratic in emissions, we assume an instantaneous damage function which is proportional to the square of cumulative emissions.[51] Accounting for the approximately half a trillion tons of (anthropogenic) carbon (TtC), or 1835 $GtCO_2$ that have been emitted until today (Allen et al., 2009), the damages $D(E)$ after the cumulative emission E from today on are thus proportional[52]

consumption changes during the same period in a fuel market simulation 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 across 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 smaller in the medium-run than what the cited numbers suggest on first sight: OECD consumption in the World Energy Outlook is assumed to slightly decrease only until 2015, and from then on the projected consumption change is already approximately zero until 2030.

[51] This has the further advantage that (except for today's historic cumulative emissions) we do not need to define any additional parameter.

[52] Roughly half of the emitted carbon is absorbed quite rapidly and the other half stays in the atmosphere for hundreds of years. As this applies equally to the 0.5 TtC of historic emissions as to future emissions E, the proportionality is not affected by this factor of one half. Our formulation does, however, neglect that future emissions contain, besides those from oil and coal, additional carbon emissions from, e.g., gas and land use change, which also contribute a significant proportion. This is the case even though oil and coal contributes 80 % of manmade energy related emissions, cf. section 6.

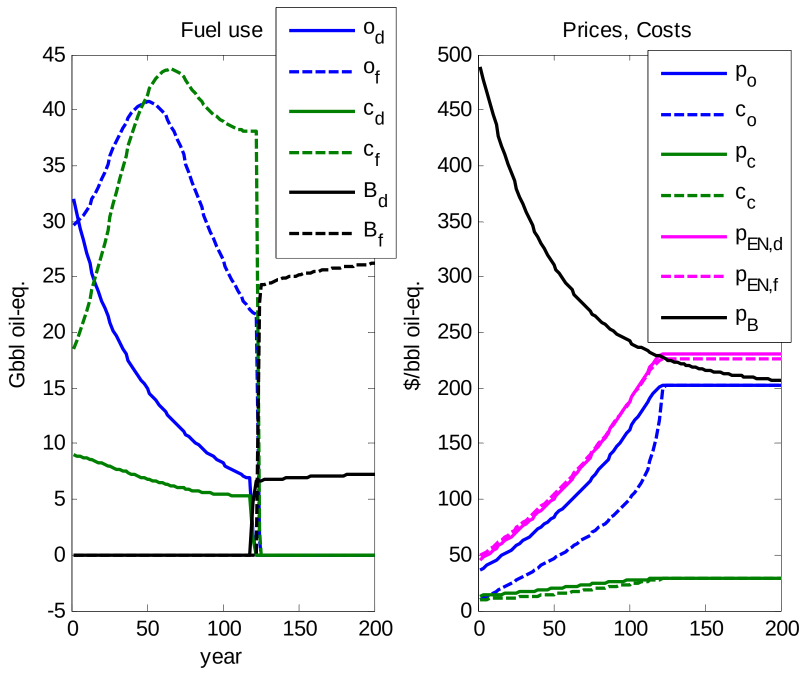

Figure 14: Simulation details with growth and backstop

to $D(E) \propto (0.5\,\mathrm{TtC} + E_{TtC})^2$ and thus[53] $D'(E) \propto 2\,(1835\,\mathrm{GtCO2} + E_{GtCO2})$. With the numerical simulation ending at time T, and cumulative emissions taken into account up to that point, cumulative emissions, and therewith marginal damage, during the time beyond T is implicitly assumed constant, wherewith, for a discount rate ρ_u the cumulative emissions up to time T, $E(T)$ create, for the time after T, a NPV damage of $E(T) \cdot \int_0^\infty e^{-s+T} \mathrm{d}s = E(T)\frac{1}{\rho_u}e^{-\rho_u T}$.

Results

In the following we present the usual emission leakage graphs (ALR and NLR paths) as well as the damage leakage rate (DLR) paths, taking demand growth into account. Whilst we consider the endogenous emergence of the backstop, we rule out liquefaction, thereby implicitly assuming that the international pressure prevents the non-climate coalition countries (ROW) from expanding the dirty CTL process.

Fig. 14 shows the simulation outcome details. The increased demand speeds up the depletion of the fuels and brings the switch to the backstop nearer, to around year 135. As a consequence of its relatively rapid initial growth, the ROW dominates global consumption quickly.

Leakage rate paths, including DLRs, are given in Fig. 15. Emission leakage rate paths (ALR and NLR) remain qualitatively very similar to cases with constant demand. However, the paths are 'squeezed' along the time-axis. This can be explained by the more rapid advancement of the depletion of the fuels due to the increased demand. Oil leak-

[53] CO_2's molar mass is 3.67 times carbon's atomic mass.

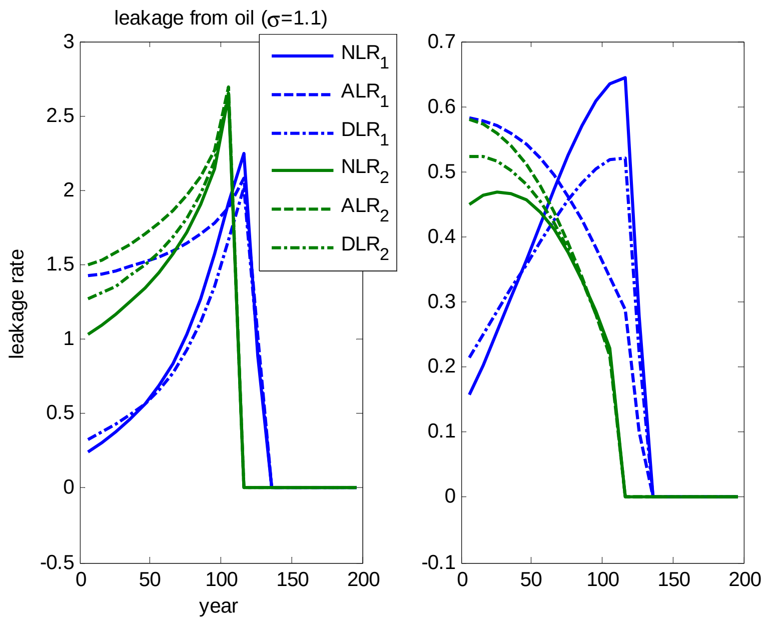

Figure 15: Leakage paths with growth and backstop

age remains typically above 1 (for discounting scheme 2, even the initial NLR exceeds unity, warranting a negative oil tax), and coal leakage is limited to values not much larger than 0.5. Interestingly, however, oil leakage has slightly decreased whilst coal leakage has slightly increased compared to the case without demand growth (section 9.4; Fig. 11). Given the higher scarcity of oil and the very steep increase of the oil cost curve and the higher demand and thus accentuated scarcity effects, one might have expected oil leakage to increase relatively more compared to coal leakage. That this is not the case seems explained by the fact that the ROW relies relatively more on coal than the OECD (cf. plot 1 in Fig. 14), implying that the concentration of demand growth to the ROW tends to increase the global demand (and thus the scarcity) for coal more than for oil.[54]

Adding the damage convexity affects leakage rates only moderately. DLRs are slightly higher than the NLRs for early domestic perturbations but slightly lower for later ones. This is readily explained by earlier emissions being weighted relatively less and later ones relatively more, and the foreign reactions being spread across time. Of course, this modest effect on the leakage *rates* does not imply that the convexity would, per se, be unimportant for the climate policy; in fact, the convexity has itself a strong effect of increasing overall damage, and thus optimal taxes, relative to the case where marginal damages would remain constant at their present level.[55]

[54]This is confirmed by the ratio of the final coal extraction costs to increase by a higher fraction than for coal, when demand growth is added to the model.

[55]If we compare the NPV direct damage from present emissions in the case where marginal damages remain constant at today's level, to the case when this marginal damage increases over time according to the quadratic damage function and the historic emissions, the convexity increases the damage by a factor 1.7 or 3.1 in the situations with discount scheme 1 or 2, respectively (considering the case with growth and the clean backstop, illustrated in Fig. 14).

10 Optimal Tax Structure

Tax base for the evaluation

Part 1 discussed the relationship between the leakage rates and the optimal tax structure, with Eq. (.11) relating the DLRs and the willingness to pay for global emission reductions to the optimal regional tax. The DLRs calculated in section 9 would thus allow the calculation of optimal tax paths, except for a general damage intensity (or global emission disutility) factor, which is exogenous to our analysis. The leakage rates were hitherto calculated, however, based on zero tax rates. Imposing substantial taxes could theoretically change the leakage rates and consequently the optimal tax values, even though the corresponding results from section 8 suggest that the influence on the leakage rates, and thus of the optimal taxes, will be very small.

To calculate the optimal tax path more precisely, we ran the simulations iteratively, calculating the leakage rates for an initial (zero) tax path, and derived the optimal tax path according to Eq. (.11) and a damage factor that yields – for today's level of cumulative emissions (hypothetically held constant throughout time) – a marginal long-run damage of $50\,\$/tCO_2$. In the absence of leakage this would imply in the model an optimal tax of more than $50\,\$/tCO_2$ that would rise over time; the increase would take place since additional emissions boost the marginal damage from (cumulative) emissions given that we consider a convex damage curve. In the next step, leakage rates were recalculated, starting from the just calculated tax path. We repeated this until convergence, which, as in section 8, was almost immediate; we thus stopped after four iterations where no notable changes were found anymore. Moreover, the differences between the leakage rates evaluated starting from zero tax rates and those from the optimal tax path hardly differ at all, confirming again what we found in section 8. Fig. 16 illustrates this with the example of the scenario without liquefaction and backstop (results for other scenarios show similarly small differences) for which we plot (the convergence of) DLRs and the corresponding optimal tax paths, shown for the first 100 years.

Optimal Tax

We spare a description or plot of the optimal tax paths for all the scenarios analyzed in section 9. Instead we recall that the optimal regional tax rate is, at each point in time t, proportional to $1 - \mathrm{DLR}_t$, but, as given in Eq. (.11), also to the net current value sum of all future marginal damages from point t on, which for the convex damage function increases over time as long as global emissions are not zero. As we have observed, in general the leakage rates given seem to be valid approximations for the leakage rates in the case where the OECD sets the regionally optimal tax rate.

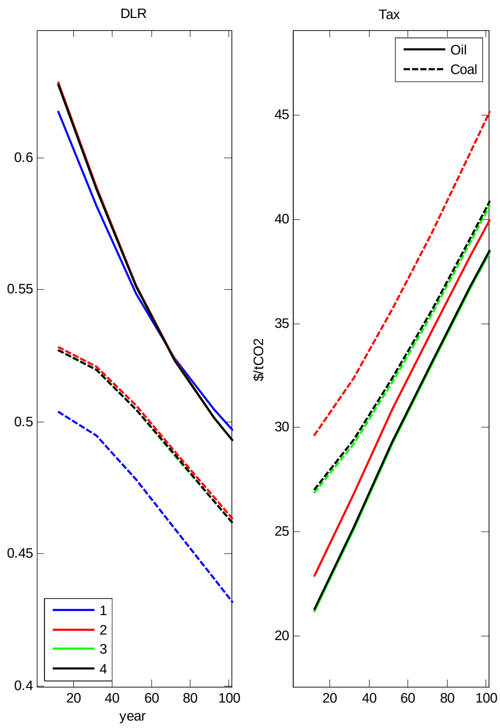

Figure 16: Convergence of tax path

The line colors 1-4 indicate the first through the fourth iteration.

11 Discussion

The results of the dynamic analysis show how emission leakage rates can have large magnitudes, how they strongly depend on the time spans (discounting) considered, how they vary dramatically with the exact scenario considered (assumptions about extraction cost curves, substitutabilities, presence of liquefaction or clean backstop), and how they can strongly differ across fuels. Whilst several key findings, some of which seem surprising even though they can be explained, are discussed above, admittedly, without strong assumptions on the exact fuel market setup of the future, it seems very hard to suggest a narrow range for realistic leakage rates, in relevant NPV (damage) terms. That is, if there is one overarching conclusion of the study, this may best be described as the uncomfortable implication that a more or less precise estimation of welfare-relevant leakage rates will require not only 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, consequently, the fuel demand pattern) or political developments (e.g., global climate treaties) concerning greenhouse gas emissions. Equally inconvenient is that any policy relevant leakage index will strongly depend on the controversial time-discounting of future greenhouse gas emissions. Explicitly making and stating assumptions about such parameters and about future developments, along with any proposed leakage rate, seems to be the only viable option. Nothing is gained from neglecting uncertainties and 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 though controversial probability, large-scale liquefaction will emerge in the future and if, in this case domestic oil savings could – as the present analysis suggests – be subject to a negative leakage rate, and if, without that liquefaction, domestic oil savings would be subject to a large positive leakage rate of around 50 %, potentially even above 100 % – as also suggested in our model –, then economic models should, at least insofar as they aim at estimating the truly relevant leakage rates, take these 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 skepticism expressed in this article against the traditional leakage literature may be rephrased as follows: many will agree that one cannot be sure whether a major fraction of the realistically exploitable 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, at least if fuel is imported from a clearly globalized worldwide market, as it exists today for case of oil but increasingly also for the other fossil fuels.[56] 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. In some cases it may indeed make some sense to assume limited horizons, rather than quasi-infinite ones, as one may attach a value to know that emissions be at least delayed for a couple of decades. This is a preference that may also be funded in the belief that technological or political progress hopefully will prevent the emissions from a certain point in time on. The judgment 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 and ideally tested for deviations from these assumptions. 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 (utility) system with parameter values calibrated to fit current fuel consumption and prices, and some elasticity values inspired by the literature. Although a sensitivity anal-

[56] See also Habermacher (2012b) for a discussion of this possibility.

ysis in a study closely related to the present one, using a slightly different model,[57] has found model results to be rather 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 – within a more detailed model in 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 (cf., 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). For example, instead of the here considered clean backstop that directly replaces the fossil fuel *aggregate*, a more detailed characterization of different alternative energy technologies could make the model more realistic, potentially also qualifying some of the present findings. 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 in this paper (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). However, clearly this should not come at the price of giving up the here specifically considered supply aspects with forward-looking resource owners.

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

The present analysis does not explicitly take natural gas into account, and therewith ignores a fossil fuel which contributes 20 % of the carbon emissions from energy supply worldwide. No obvious reason as to why the main results of the present analysis should be fundamentally altered when natural gas is modeled as well exists. Nevertheless, taking into account this third most important fossil fuel in terms of current consumption may still have a significant effect on the response of the energy market and emissions to a unilateral policy. First, gas may be a better substitute to both, oil and coal, than those two fuels are between themselves: Gas is widely used to feed power stations, which are also the most important consumers of coal, but much less of oil.[58] And gas is also a relatively good

[57] Habermacher (2011), conducted the study using a dynamic model to calculate optimal constant tax rates based on some simplifying assumptions and a calibrated utility quadratic in oil and coal, largely analogous to Golombek et al. (1995).

[58] Coal, natural gas, and oil contribute 41 %, 21 %, and 5 % of worldwide power generation (OECD, 2012). Some see (shale) gas as an important step to reduce the emission intensity of the energy system, notably due to substitution of coal (e.g., Helm, 2012). This view is supported by the strong decrease of US energy related carbon emissions 2007-2012 which seems at least partly due to the substitution of coal

substitute for oil in major applications such as domestic heating and transport, where the direct use of solid coal is less trivial. Accounting for gas would thus not only add a fuel to the model which could be substituted easily for one of the other fuels, but it could indirectly increase also substitutability between oil and coal, as changing the use of one of these two major fuels would affect the demand for gas which in turn would affect the demand for the other major fuel. An increased substitutability between the fuels can narrow the gap between the leakage rates across the different fuels. At the same time, it would not directly reduce the overall leakage rate for a general emissions tax. Second, gas is relatively expensive to transport. Pipeline transportation is much more costly for gas than for oil. Both oil and coal can be shipped over short and long distances much more cheaply than gas, which requires capital and energy intensive liquefied natural gas (LNG) fascilities. This seems to be a main reason why the shale gas 'revolution' in the US leads to very low current prices for natural gas in the US compared to overseas, with a current production of shale gas in the US (and worldwide) that remains limited (less than 200 bcm in 2010) compared to worldwide gas production (more than 3000 bcm).[59] From a medium or long-run perspective, the current US gas price anomaly and the significant transportation costs are, however, not indicating a true segregation of the global gas market: Even though LNG-transportation costs are substantial compared to current energy prices, they are not prohibitive for an interregional gas trade when large and sustained price differentials are foreseeable.[60] A third point concerns the greenhouse-gas intensity of the increasingly important unconventional gas resources. A first study that included methane emissions suggested that shale gas may even be much more emission intensive than coal (Howarth et al., 2011). The study has been widely criticized, and more recent peer-reviewed studies conclude, on the contrary, that the overall emission-intensity of unconventional gas hardly exceeds that from conventional natural gas, and that shale gas powered electricity is substantially more climate friendly than coal power (e.g., Hultman et al., 2011, and Jiang et al., 2011). The controversy[61] is far from settled, and it is thus unclear what the differential in the emission intensity between conventional and unconventional gas could imply for the leakage rate. Overall, it seems plausible that an increased availability of gas in the medium and longer-term – the inclusion of shale-gas has increased the technically recoverable worldwide resources by 47 % according to EIA (2013b), a number which is, however, subject to very high uncertainty[62] – affects the

by gas in power production.

[59]In total, unconventionals (shale gas, tight gas and coal bed methane) have a share of around 12 % in global gas production (IEA, 2010).

[60]As is evidenced, for example, by LNG exports from South-East Asia, the Middle East, Africa and South America to Europe and Japan, and, at least until recently, to the US.

[61]See Stevens (2012) for an overview of the debate.

[62]Stevens (2012) provides a brief overview on the uncertainties attached with estimates of technically recoverable shale gas. For example, in 2012 Poland reduced it's estimate of technically recoverable resources to around one-tenth of the initially indicated figure.

quantitative results to a non-negligible degree, but it cannot be said *a priori* in which direction.

12 Conclusion

We provide a method to disentangle the terms-of-trade and the pollution part of an optimal regional climate policy in a dynamic framework with an exhaustible fuel, and define a welfare relevant leakage rate related to it.

We calculate fuel-specific leakage rates for current and anticipated future taxes, in a stylized, calibrated model of the dynamic market for major fossil fuels. The model considers an exogenous, downward sloping demand for energy, which can be provided as a constant elasticity of substitution aggregate of weakly substitutable oil and coal, or, potentially, by a clean backstop with infinite supply elasticity and a cost that diminishes over time. The fuel demand is split between the OECD and the rest of the world, and calibrated according to current demand and worldwide prices; held constant over time in the main setup, demand is allowed to grow in an extension of the model. We exclude non-fuel trade between the two fuel consuming regions and focus only on the fuel channel of leakage. The fossil fuels are extracted for marginal costs that increase with cumulative extraction according to empirical estimates, and they are offered by forward-looking competitive suppliers, corresponding to a standard Hotelling framework with an exogenous discount rate. We find that leakage rates for OECD fuel emission reductions may vary strongly in magnitude, and even sign, across fuels and as a function of the considered scenarios. For example, when coal-liquefaction supplements the supply of liquid fuel, domestic oil savings can be subject to negative leakage rates: increasing the availability of oil on the global market delays the use of the very emission intensive liquefaction process and therewith implies that even foreign emissions are reduced when less domestic oil is consumed; this can imply negative leakage rates even for oil reductions during times before liquefaction has become economically viable. In the same scenarios with liquefaction, coal emission leakage rates remain positive, as more coal available on the global market implies more foreign coal consumption, both for direct use and for use as an input to liquefaction. The variations across scenarios are so large that it would seem questionable to indicate here a specific guess for the exact value of the real expected leakage rate for an emission tax. Depending on the scenario considered, they may be as low as 10 % for a fuel, such as found for coal taxed in early periods in the setups without liquefaction: the relative abundance of coal compared to the more 'limiting' factor oil implies that a bit more coal hardly changes the rate (and, in the presence of the backstop technology emerging in future, duration) of aggregate fossil energy use, so that a domestic reduction implies only a small foreign increase in coal use and emissions. As in addition, the foreign emission reaction is spread over time, the NPV leakage rate becomes especially low for early domestic coal reductions, starting at around 10 % for immediate reductions. In other cases, the leakage rates may exceed unity, as found for oil in presence of the clean backstop and without liquefaction: given that oil depletes very fast, it becomes essentially the limiting factor among the two fuels aggregated with a relatively weak substitutability to overall fossil energy. Increasing the availability of oil thus prolongates the time that the fossil-fuel aggregate remains competitive against the clean backstop technology, and because relatively much coal is burned per unit of oil used for the aggregate fossil energy provision, this extension of the fossil fuel use implies a lot of additional foreign emissions per unit of oil-emissions saved at home, overall leading to a leakage rate that tends to exceed unity, especially for ALR, where the emissions from the additional use of the fossil aggregate are not discounted. The time dimension of the problem appears to be of overwhelming importance; the rates depend very strongly on discount rates and on future developments in the fuel market, such as the emergence of liquefaction processes or a clean backstop replacing the fossils.

The fact that the leakage rates depend so strongly on future developments qualifies numerous semi-empirical estimates provided in the literature without any explicitly stated (or discussed) 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. Contrary to what most leakage studies, often focused on a static fuel demand, suggest, leakage may offset an overwhelming fraction of domestic emission reductions.

13 Annex

Annex 1 Optimal Pollution Tax, Partial Equilibrium

Consider a numeraire good z and a polluting good x that costs p and whose global consumption leads to a proportional pollution damage, for the avoidance of which the home region has a marginal WTP d.

Consider a domestic (h) and a foreign (f) region, two regions $r = \{h, f\}$, with domestic utility $U_h = z + \log x_h - d \cdot X$, subject to the budget constraint $z = z_0 - p \cdot x_h$, with global consumption $X = x_h + x_f$, and some leakage, which can be written as $x_f = x_{f0} - \alpha x_h$, where α is the leakage rate.

The domestic planner's FOC for domestic consumption x_h writes

$$p \stackrel{!}{=} \frac{1}{x_h} - d(1-\alpha). \tag{A.1}$$

Domestic decentralized consumption decisions, subject to a potential tax τ_h imposed by the domestic government, are given by the FOC which takes into account that private consumption has a negligible effect on the regional consumption level (as well as on the redistributed tax proceeds), that is, the direct marginal consumption utility must equal the private costs, $\frac{1}{x_h} \stackrel{!}{=} p + \tau$. In this simple setup, the optimal level of domestic consumption implicitly given by Eq. (A.1) can thus be sustained in a decentralized market by imposing a domestic pollution tax of the level

$$\tau_h^* = d(1-\alpha).$$

Proposition 1. *At constant prices, if only global pollution matters and if foreign consumption of a polluting good increases proportionally at rate α when domestic consumption is reduced, i.e., we have a leakage rate of α, the regionally optimal level of the unilateral pollution tax τ_h^* is $\tau_h^* = d(1-\alpha)$, where d is the domestic WTP for global pollution reductions.*

Whilst it surely makes quite some intuitive sense that the optimal tax may be proportional to 1 minus the leakage rate α, as the region has a WTP for global emission reductions and those emission reductions, after all, are $1-\alpha$ per unit of domestic pollution avoided, the proposition is based on the assumption of fixed prices. The inconvenient truth about this assumption is that leakage naturally occurs exactly via price effects – it is just, e.g., by affecting the global price of fuels (or of that traded goods) that domestic demand changes affect foreign fuel consumption.

Annex 2 Optimal Pollution Tax and Terms-of-Trade Effects

Assume decreasing returns in production of a good X, supplied by external supplier for a price equaling marginal costs,

$$p \equiv a + bX \quad \text{with } a, b > 0. \tag{A.2}$$

Be domestic utility U^* linearly separable in the consumption of the fuel, with

$$U^* \equiv z + \log X, \tag{A.3}$$

implying the budget constraint being $z = z_0 - pX = z_0 - aX - bX^2$. We define $U \equiv U^* - z_0$, implying $U = \log X - aX - bX^2$, and maximizing U is equivalent to maximizing U^*.

The regional planner's FOC is $\frac{1}{X} \stackrel{!}{=} a + 2bX$, implying $X^* = \frac{-a+\sqrt{a^2+8b}}{4b}$. In contrast, the decentralized consumer takes the fuel price as a given and chooses according to the decentralized FOC for $U = \log X - pX$, namely $\frac{1}{X} \stackrel{!}{=} p$, which, in equilibrium, implies $\frac{1}{X} \stackrel{!}{=} a + bX$, yielding the (suboptimally high) free market consumption $X_m = \frac{-a+\sqrt{a^2+4b}}{2b} > X^*$.

A correcting (unit) tax τ ensures that even the market outcome yields the optimal consumption level X^*: With the tax, the decentralized FOC implies $\frac{1}{X} \stackrel{!}{=} a + bX + \tau$ and thus $X_{m,\tau} = \frac{-(a+\tau)+\sqrt{(a+\tau)^2+4b}}{2b}$. Requiring the tax to bring the consumption level to the optimum, we have τ implicitly defined by $\frac{-(a+\tau)+\sqrt{(a+\tau)^2+4b}}{2b} \stackrel{!}{=} \frac{-a+\sqrt{a^2+8b}}{4b}$, yielding $\tau^* = \frac{1}{4}\left(\sqrt{a^2+8b} - a\right) > 0$, which is increasing in b and decreasing in a.

Adding external pollution damage, d, we have $U = \log X - aX - bX^2 - dX$. By analogy to the case without damage, it is trivial to see that this yields the regionally optimal level $X_d^* = \frac{-(a+d)+\sqrt{(a+d)^2+8b}}{4b} < X^*$. As the decentralized actors ignore the damage their consumption induces when choosing X, the market consumption is still $X_{m,\tau}$ from above, and the optimal tax is thus implicitly given by $X_{m,\tau} \stackrel{!}{=} X_d^*$, i.e., $\frac{-(a+\tau)+\sqrt{(a+\tau)^2+4b}}{2b} \stackrel{!}{=} \frac{-(a+d)+\sqrt{(a+d)^2+8b}}{4b}$, yielding

$$\tau_d^* = \frac{1}{4}\left(\sqrt{a^2+8b+2ad+d^2} - a + 3d\right). \tag{A.4}$$

Recognizing that $\frac{\partial}{\partial d}\sqrt{a^2+8b+2ad+d^2} = \frac{1}{\sqrt{1+\frac{8b}{a+d}}} \in (0,1)$, we see that Eq. (A.4) implies

$$\tau^* + \frac{3}{4}d < \tau_d^* < \tau^* + d,$$

that is, the optimal overall tax rises less rapidly in presence of a pollution externality than the pollution externality itself, with a rate that is smaller the larger the slope of the price, b, is compared to both, the level of the price (a) and the externality (d). We emphasize this result in the proposition 2. The increase of the overall tax does, however, in this framework amount to more than $\frac{3}{4}$ of the pollution externality.

Proposition 2. *Consider a good offered and consumed according to Eqs.* (A.2) *and* (A.3)*. A specific level of marginal pollution-externality attached to the consumption of that good increases the optimal tax levied by the region on that good by less than the level of the marginal pollution-externality. The difference between the level of the externality level and the optimal environmental tax level is of first order degree, i.e., the ratio* $d/(\tau_d^* - \tau)$ *is non-marginally above 1 even for an asymptotically small environmental externality level* d*, when* τ_d^* *is the optimal buyer tax with, and* τ^* *that without pollution.*

Proof: given above.

An intuition for this result is as follows: In absence of pollution, the region optimally levies a tax τ^* on the consumption that corrects for the distortion arising from that fact that an individual consumer takes into account only the direct price she pays for her individual consumption but ignores the price-increasing effect of her purchase on the price the others pay for their consumption. As we see in the expression for the optimal tax without environmental damage, this correction is stronger when a lower a yields a larger amount of consumption (more consumers suffer from the price-increasing effect of additional consumption by an individual), and when the price-increase by a marginal quantity consumed is larger, i.e., when b is larger). Given that with environmental damage, and the corresponding additional climate tax component, the amount of the good purchased overall is reduced, the price-increase-effect of marginal consumption by an individual harms less other consumers, i.e., the optimal import tariff component is reduced. As the optimal import tariff component is thus reduced as the environmental damage increases, the optimal overall tax level rises less rapidly than the environmental externality level.

If terms-of-trade effects imply positive optimal unilateral taxes even in the absence of pollution, it can thus be non-trivial to disentangle the non-pollution and the pollution component of an optimal overall tax. As we have the inequality $\tau_d^* < \tau^* + d$ for the case of zero leakage, we can not expect $\tau_d^* = \tau^* + d(1 - \alpha)$ to hold either. In fact, from the first-order deviation, without further investigation that at least for low enough leakage rates we know that we have $\tau_d^* < \tau^* + d(1 - \alpha)$: note that for an arbitrarily small foreign country and thus an arbitrarily small leakage rate, the optimal overall home tax is arbitrarily close to the above τ_d^*, and in the case without pollution it would be arbitrarily close to τ^*. Thus, for small enough α, in this case we know that the optimal overall tax falls short of the sum of the optimal tax in the absence of pollution and $1 - \alpha$ times the externality rate.

Annex 3 Compensation in Static Framework

Consider regional welfare functions of the form $U = z_0 - p(E) \cdot e + u(e) - D(E)$, where z_0 is regional numeraire good consumption, e and E regional and global fuel consumption, $p(E)$ the fuel price as a function of the global consumption $E = e_h + e_f$, $u(e)$ is the fuel consumption utility and $D(E)$ the damage from global emissions.

For decentralized decisions of foreign consumers we know $u'_f(e_f) = p(E)$. Knowing the domestic region compensates the foreigners for the tax induced changes (ignoring environmental damage), we can directly take the foreign consumption and the fuel producers' profit (U_p) into account in our maximization and omit to write the transfer, $U^* \equiv U + U_f + U_p$. The maximization problem writes $\max_e U^{**} = z_0 - C(E) + u(e) - D(E) + u_f(e_f)$, s.t. $u'_f(e_f) = c(E)$, and $E = e + e_f$ and with $C(E) = \int_0^E c(E)\mathrm{d}E$, yielding $C'(E) > 0$ and $C''(E) > 0$, i.e. marginal costs of extraction increase as $c'(E) > 0$.[63] Similarly, we write total damage $D(E) = \int_0^E d(E)\mathrm{d}E$. As usual we assume $p(E)$ to be increasing: $p'(E) > 0$.

The FOC writes

$$\begin{aligned}
\frac{\partial C(E)}{\partial e} + \frac{\partial D(E)}{\partial e} &= u'(e) + \frac{\partial u_f(e_f)}{\partial e} \\
c(E)\frac{\partial E}{\partial e} + d(E)\frac{\partial E}{\partial e} &= u'(e) + u'_f(e_f)\frac{\partial e_f}{\partial e} \\
c(E)\frac{\partial E}{\partial e} + d(E)\frac{\partial E}{\partial e} &= u'(e) + c(E)\frac{\partial e_f}{\partial e} \\
c(E)\left(1 + \frac{\partial e_f}{\partial e}\right) + d(E)\left(1 + \frac{\partial e_f}{\partial e}\right) &= u'(e) + c(E)\frac{\partial e_f}{\partial e} \\
c(E) + d(E)\underbrace{\left(1 + \frac{\partial e_f}{\partial e}\right)}_{\text{leak.adj.emiss.}} &\overset{!}{=} u'(e). \qquad \text{(A.5)}
\end{aligned}$$

Thus, the marginal utility of energy consumption is to equate marginal social costs of energy: extraction cost plus damage with emission factor adjusted for the relative impact of own emissions on foreign emissions (the leakage rate).

Decentralized domestic consumption under a tax is given by the FOC

$$p(E) + \tau \overset{!}{=} u'(e), \qquad \text{(A.6)}$$

where we know $p(E) = c(E)$, wherewith Eq. (A.6) shows that, according to Eq. (A.5), for the tax to sustain the optimal level of consumption with compensating transfers to the

[63]Note the fuel owners' profit canceled out since, as a transfer it does not affect the sum of welfare overal all actors.

producer and to the other region, the tax required is

$$\tau^* = \underbrace{d(E)\left(1 + \frac{\partial e_f}{\partial e}\right)}_{\text{leak.adj.emiss.}},$$

that is, it is fully independent of the terms-of-trade effects which would depend on the *change* of the price (and thus the *change* of the marginal extraction cost) induced by consumption changes. We thus have confirmed that the compensation of both, the producer and the foreign consuming country, allows, in this setting, to isolate the optimal emissions tax from any terms-of-trade tax component. This corresponds to what Böhringer et al. (2010) have shown in their static framework for the analysis of sector-specific leakage.

Annex 4 Details Numeric Calibration

Current Prices and Regional Consumption of Fuels for Calibration are given in Table A.1.

Table A.1: 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)

Annex 5 Model Run Basic Setup

Fig. A.1 shows the model results for a basic setup, with a backstop but without liquefaction and with constant demand.

Annex 6 Scale-Invariability for Linear Costs and Isoelastic Demand

The supplier's price their fuel on the market according to

$$p_t = c_t + \int_t^\infty e^{-\rho(s-t)} \dot{c}_s \mathrm{d}s. \tag{A.7}$$

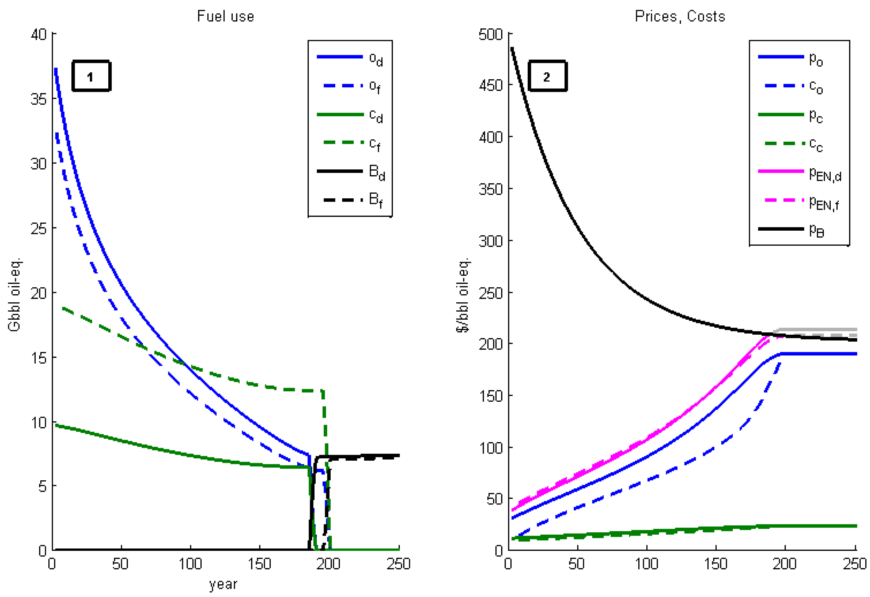

Figure A.1: Simulation results basic setup

We have an isoelastic demand,[64]

$$x_t = \xi p_t^{\varepsilon}, \tag{A.8}$$

and extraction cost proportional to cumulative extractions, $c_t = b \int_0^t x_s \mathrm{d}s$.

Consider an γ-fold increase of the extraction costs, i.e., $c_t^* = \gamma b \int_0^t x_s \mathrm{d}s$. Assume this increases the resulting cost path by a constant factor α, that is,

$$c_t^* = \alpha c_t \, \forall t.$$

This respects the extraction cost curve when we have

$$x_t^* = \frac{\alpha}{\gamma} x_t. \tag{A.9}$$

The supplier's pricing equation, Eq. (A.7), remains respected if we have

$$p_t^* = \alpha p_t. \tag{A.10}$$

The remaining condition which must be fulfilled is the demand equation, Eq. (A.8). With Eqs. (A.9) and (A.10) this implies $\frac{\alpha}{\gamma} = \alpha^{\varepsilon}$, which holds *iif* $\alpha = \gamma^{1/(1-\varepsilon)}$.

In the linear oil-cost curve models in section 9.1, we have $\varepsilon = -0.9$ and, neglecting the relatively small intercept in the extraction cost curve, an inverse reserve-scaling factor $\gamma = 10$, implying that p_t and c_t increase by a factor $\alpha = 10^{1/1.9} = 3.4$ and extraction

[64]In the leakage model, we have two regions demanding the fuel. This can readily be accounted for by assuming the here used ξ to be the sum of the corresponding regional demand parameters, $\xi = \xi_d + \xi_f$, not affecting the remainder of the analysis here.

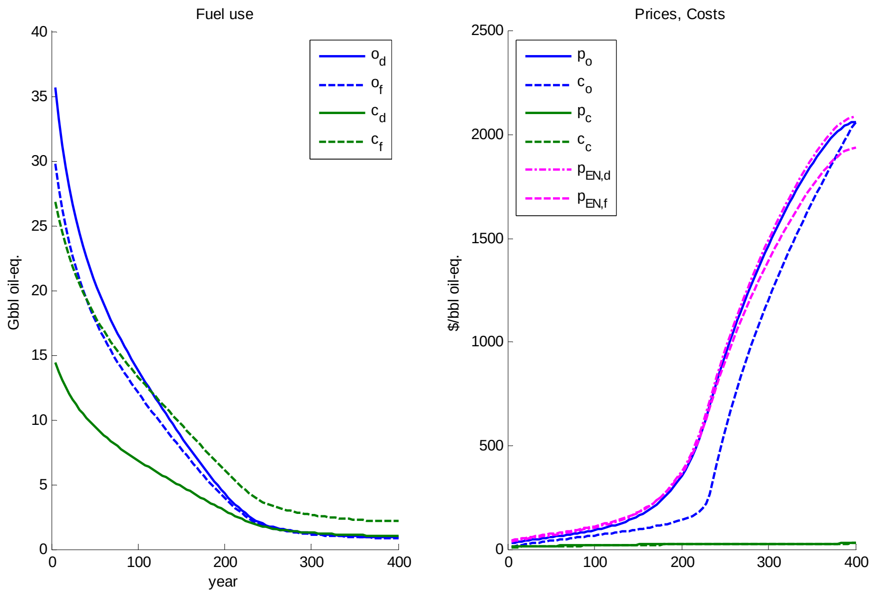

Figure A.2: Simulation results basic setup

Scenario with constant demand, no backstop and no liquefaction. Discounting scheme 1.

is reduced by the factor $\frac{\gamma}{\alpha} = 2.98$. Despite the not perfectly negligible intercept of the extraction cost curve, this approximates extremely well what happens in the simulation, where the price and the extraction costs increase by a factor 3.34 and extractions are reduced by the factor 2.90 (values calculated for the last simulated period; plots omitted here have shown these values to remain almost perfectly constant also in other periods).

Annex 7 Supplementary Graphs Basic Setup

Simulation results for the basic setup: constant demand, no liquefaction, no backstop, considering discounting scheme 1.

Figs. A.2 through A.4 give detailed simulation results, for unperturbed domestic equilibrium consumption.

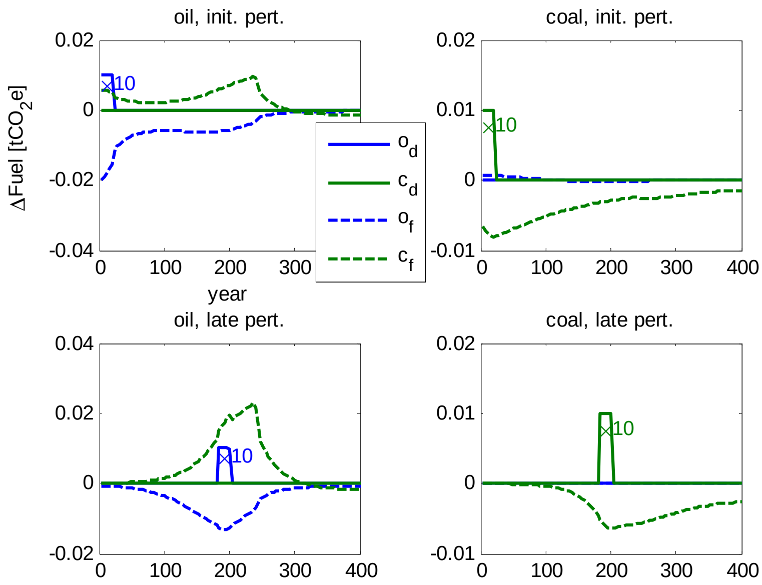

Figure A.3: Emission reaction, basic setup, stronger substitutability
Scenario with constant demand, no backstop and no liquefaction. Substitutability increased to $\sigma = 1.7$. Discounting scheme 1.

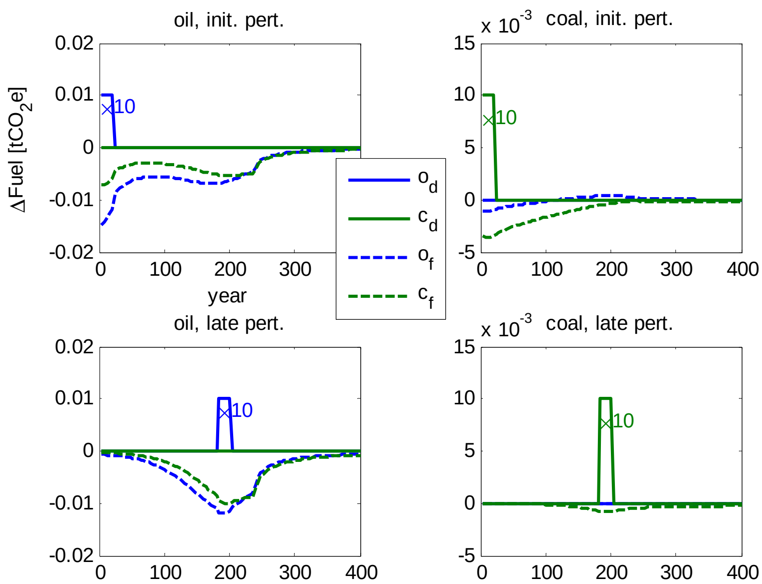

Figure A.4: Emission reaction, basic setup, strong complementarity
Scenario with constant demand, no backstop and no liquefaction. Complementary fuels, $\sigma = 0.3$. Discounting scheme 1.

Annex 8 Supplementary Graphs Liquefaction

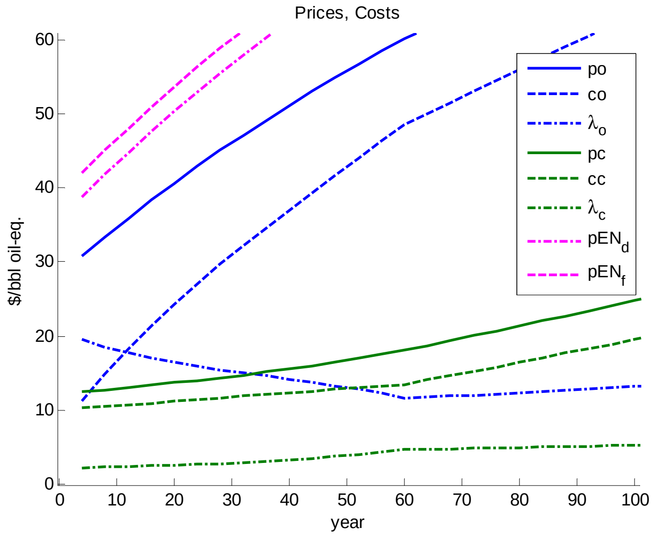

Figure A.5: Zoom, simulation details with liquefaction

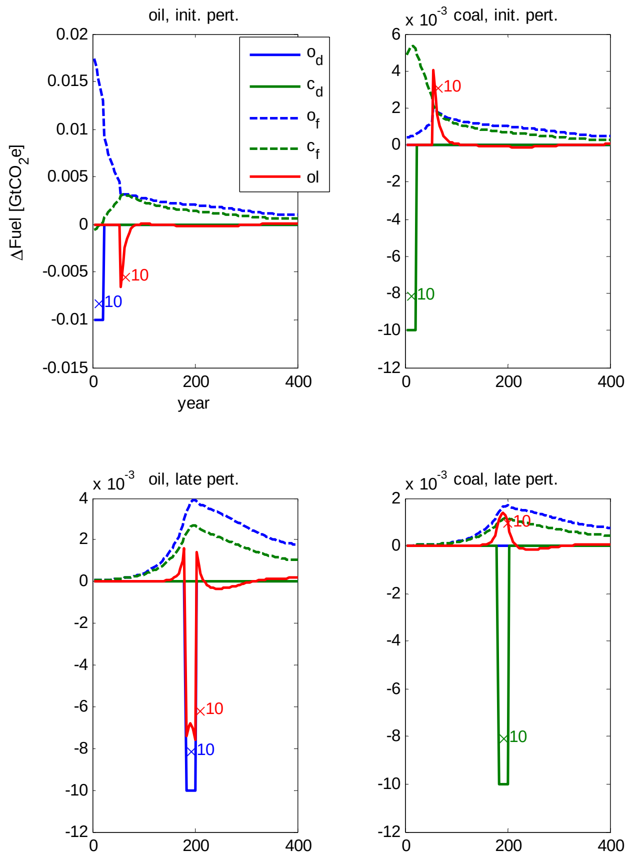

Figure A.6: Emission reaction paths, liquefaction

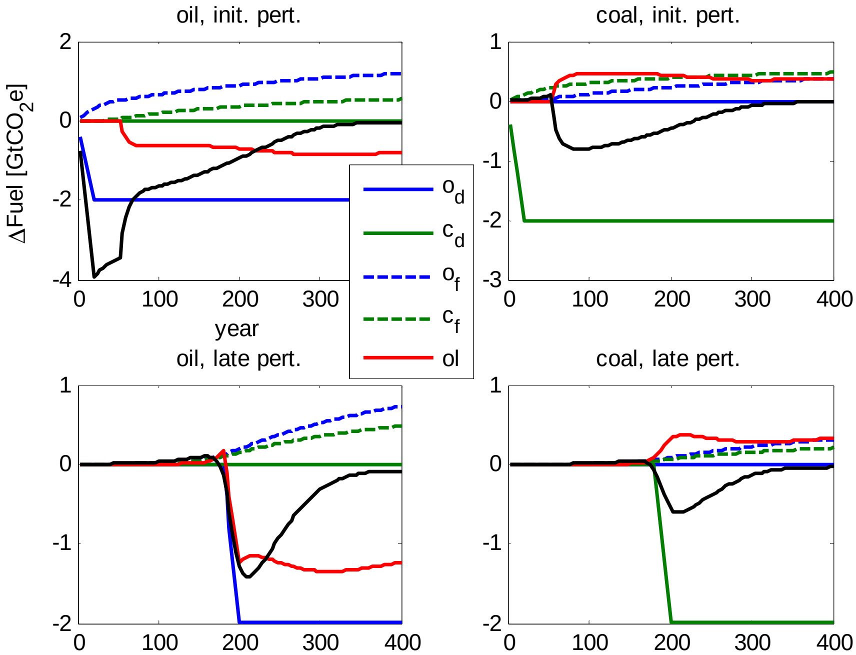

Figure A.7: Cumulative emission reactions, liquefaction

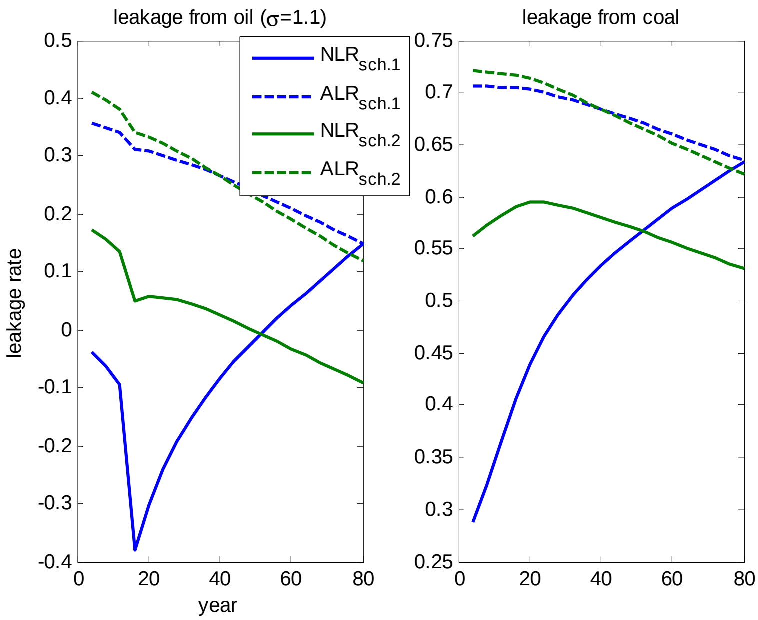

Figure A.8: Leakage paths with liquefaction, for c_l=0 \$/bbl

Annex 9 Supplementary Graphs Backstop

Figs. A.9 through A.11 plot instantaneous and cumulative emission reactions for domestic medium-term consumption reductions, as well as leakage rate paths for stronger and weaker than standard fuel substitutabilities.

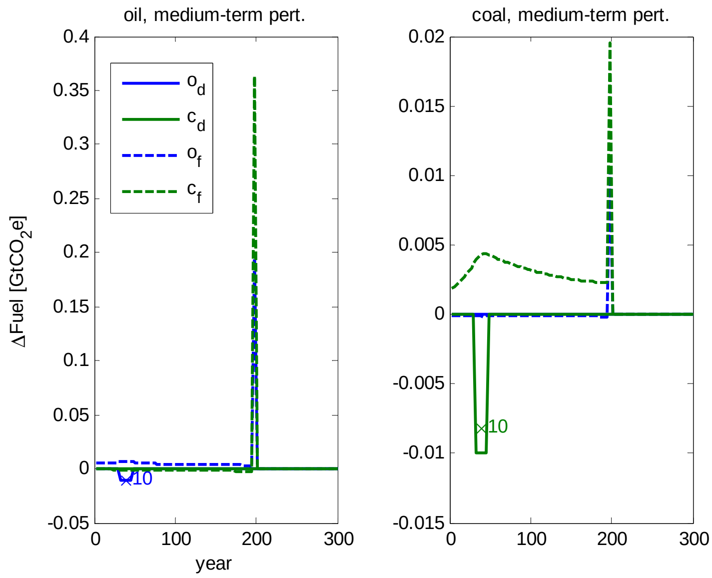

Figure A.9: Emission reaction paths, backstop

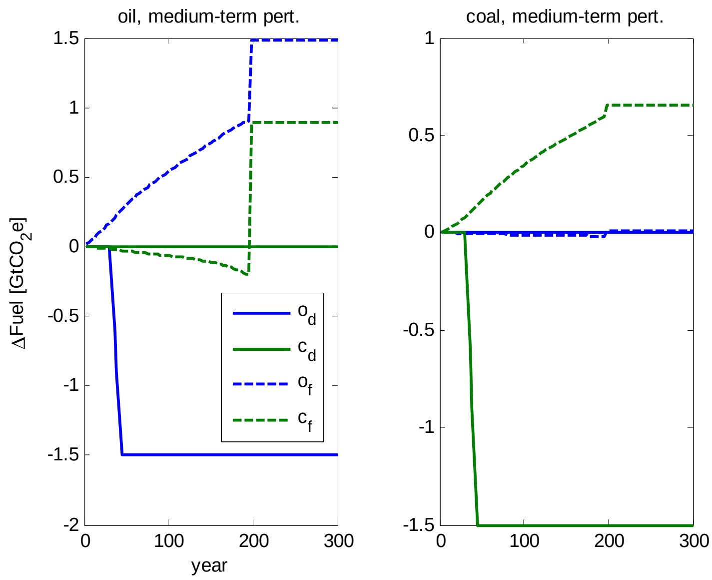

Figure A.10: Cumulative emission reactions, backstop

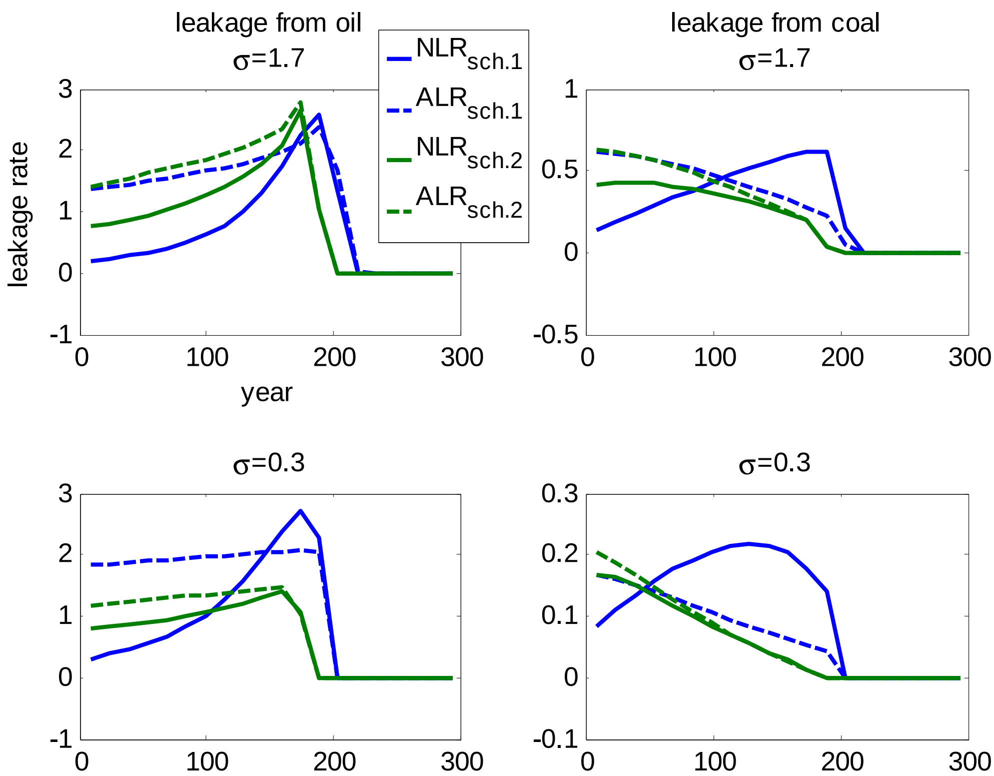

Figure A.11: Leakage paths with backstop, alternative substitution elasticities σ

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