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Abstract

Future market developments determine the fate of fossil fuel carbon currently conserved unilaterally. Dynamic fuel depletion naturally suggests leakage rates approaching 100%. Reasons for lower leakage differ from what limits rates in previous studies. Discounting reduces present-value leakage as global emissions are delayed. Containing climate change requires future global political or technological breakthroughs to conserve some carbon forever. Early breakthroughs limit leakage but with late breakthroughs most unilateral emission reductions may be negated abroad. Future coal liquefaction suggests negative leakage rates for current mitigation, but a perfect backstop allows leakage above unity. Leakage rates and suggested taxes vary across fuels.

JEL-Code: Q540, Q410, H230, H210.

Keywords: unilateral climate policy, emission impulse response, fossil fuel depletion, dynamic carbon leakage, discounting, fuel specific carbon tax, coal liquefaction, backstop, OECD.

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1 Overview

> "[T]he 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."
> H. Hotelling, 1931 (pp. 138-139).

What Hotelling wrote 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 political developments – are of overwhelming importance. This question is: how severely is a unilateral effort to contain climate change by reducing regional carbon dioxide emissions undermined by offsetting foreign emission reactions; that is, by 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 more 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. 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 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 obvious reason why fuel consumption in the remainder of the world would stop before all of that fuel is extracted exists (cf., e.g., Habermacher, 2012). 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.

Nevertheless, unilateral policies need not be in vain. Fossil resources are so vast that unconstrained combustion could mean entering truly unknown territory in terms of global temperatures and the discussed, regionally limited climate measure may hopefully not be the last ever political or technological mitigating development (cf., e.g., Gerlagh, 2011).[1] Whether all initially, regionally spared fuel is consumed later on depends on whether future developments will, at some point, 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 with a delay of many decades,

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[1] This insight is also the basis for the currently emerging popular calls for 'carbon divestment' and the literature on carbon asset stranding (Ansar et al., 2013; Carbon Tracker/Grantham Institute, 2013).

depends on the time-discounting of emissions. Given the exhaustibility of 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. The aim of this paper is to provide 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, and what impact key drivers can have on the relevant leakage rates. The results suggest that the uncertainty about technological and political developments on the resource market over the course of the next decades and centuries makes it impossible to limit the range of plausible leakage rates for today's regional emission reductions to a narrow set of values. Besides relatively limited leakage percentages, not only very high but also negative, or potentially even above unity rates, can be possible, depending on, for example, the transformability of the fuels and characteristics of clean backstops.

The main text of this paper is separated into three sections. Section 3 emphasizes how central aspects of leakage are missed when focusing on a static fuel supply. A stylized, analytically tractable model with interregional carbon leakage through the two main effects, fuel channel and goods channel, is analyzed. Calculated leakage fractions are found small or modest when a static fuel supply is considered, but when supply dynamics is taken into account, they approach 100 % for a tax simulated in a business-as-usual baseline scenario. However, when the fuel emission era is limited because of global future climate measures or technologies, leakage for a current tax need not converge to 100 %; the tax can reduce total emissions until the end of the 'exogenously' limited fuel era. We further perform simulations with a calibrated computational general equilibrium (CGE) model closely following Burniaux and Oliveira Martins (2012). Based on an overview on the leakage literature and, especially, on their extensive CGE analysis, these authors conclude "*only rather implausible values of certain parameters [...] may generate high leakage rates. This also invalidates the argument that accompanying protectionist measures [...] would need to be implemented. The likelihood of small leakages favours in fact the formation of a worldwide coalition to stabilise climate change.*" (p. 488). Using the model parameters and the static fuel supply of their baseline calibration, we replicate the minor leakage fractions the authors find, of much below 10 %. Extending the analysis to a dynamic setup with depleting fuels, however, reveals a different picture, confirming the findings from our simple analytical model: leakage converges towards 100 % for an open fuel horizon. With restricted fuel horizons, leakage may be smaller. Besides the fuel era duration, the results point out the growth rate of fuel demand, as well as the amount of fuels assumed to be ultimately extractable, as crucial determinants of leakage. The rates appear much less sensitive on whether fuel supply is assumed myopic or forward-looking *à la* Hotelling.

Section 4 links the leakage of carbon to the theory of its optimal taxation in a dynamic framework. We provide a method to disentangle the intrinsically linked terms-of-trade and pollution components of the optimal tax within a Hotelling framework. Three leakage terms are proposed. The *Absolute* Leakage Rate (ALR) is the all-time foreign emission increases in response to a specific domestic emission reduction. The *Net Present Value* Leakage Rate (NLR) discounts emission changes according to the time of their occurrence. And the *Damage* Leakage Rate (DLR) weights emissions by their marginal impact on present value climate damage at the time of their occurrence. The DLR is found to be directly linked to the optimal unilateral tax rate path in presence of leakage. This is naturally the relevant measure when society values a delay of emissions, and it emphasizes the importance of systematically analyzing the lags with which foreign emissions 'responses' react to domestic mitigation 'impulses', as can hardly be seen in the applied leakage literature.

Section 5 uses a small calibrated fuel model with imperfectly substitutable fuels to explore several key sources of uncertainty around the magnitude of leakages according to the three leakage definitions from section 4, for OECD emission taxes. It investigates how optimal taxes could vary with specific assumptions about the fuel market. IEA extraction cost curves imply that oil, much scarcer in the medium-run, has larger leakage rates attached than emission reductions from more abundant coal in a simple scenario. However, when liquefied coal[2] provides a synthetic substitute for crude oil in future as soon as the conversion process becomes economic, negative oil leakage rates are found already for today's taxes. Saving oil delays the start of the dirty liquefaction process employed abroad and therewith reduces global emissions even beyond the amount saved domestically. This is reversed if a backstop fully replaces fossil fuels as soon as it becomes competitive: leakage from oil emission reductions can be above unity since sparing some units of scarce oil for the future can help keeping fossil fuels as an aggregate competitive for longer, leading to higher overall emissions.

Due to the foresight of fuel owners, leakage, as a response to an anticipated domestic tax at time t, tends to occur with a substantial spread across time centered around t: anticipating a future tax to reduce the profitability of future sales, fuel owners increase current sales. With substantial discount rates, this implies that the relevant DLRs can be well beyond unity for anticipated future taxes, leading to a Green Paradox (Sinn, 2008). Conversely, for an early tax, delayed leakage can imply that even when the domestic emission reductions are offset for the most part in the long run, the relevant DLRs rates may be low for today's taxes.

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[2] Chen et al. (2011) estimate that liquefaction could account for one-third of global liquid fuel supply in 2050. Felder and Rutherford (1993) have suggested negative leakage rates from a regional (not fuel-specific) tax during the years when liquefaction emerges. Besides the issues with the somewhat *ad hoc* representation of the fuel-extractions in their model (cf. section 2), they focused on *instantaneous* leakage rates rather than considering the (NPV) effect of *current* taxes on *future* emissions.

2 Motivation and literature

As a major impediment to unilateral climate protection, carbon leakage enjoys great attention in the theoretical and empirical literature. Leakage estimates found cover the full range of imaginable values. Böhringer et al. (2010) proposes leakage rates of 35–40 % for unilateral action by the EU, and 15–20 % for the US. Others find values as low as around 5 % (e.g., OECD, 2009). In Babiker (2005), industry dislocation and economies of scale imply leakage rates of up to 130 %. Di Maria and van der Werf (2008) model how directed technical change from the climate policy region may reduce rather than increase non-policy region emissions. 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 "*carbon leakages are likely to be small for the range of parameters most frequently quoted in the literature*" (p. 13).

Independent of their heterogeneity, the proposed leakage rates from most of these studies may *per se* be of limited value for a policy maker interested in the longer-run effects of unilateral action. The studies tend do not treat the time-dimension in detail, and miss major reasons why the leakage rates may be modest in reality. Instead, limited rates seem to be found primarily for technical reasons. The models typically neither discount future emissions, nor assume any major future technological or political climate relevant changes to drastically limit the scope for future emissions. Absent any technical or global political breakthrough in terms of climate protection, 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 negated 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, 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), Burniaux and Oliveira Martins (2012), Perroni and Rutherford (1993) and Babiker (2005) use static models. In such 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 Di Maria and van der Werf (2008) whose endogenous directed technological change model disregards the fuel-market channel of leakage and fossil fuels depletion.[3]

Another strand of the leakage literature uses dynamic models but simplifies 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. Consequently, their models 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.

Early studies had already used dynamic models with at least partially endogenous fuel depletion mechanisms, for example Felder and Rutherford (1993) and Manne and Richels (1991). The approach used in these two 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. 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 were longer. Thus, it appears that the most important reasons for leakage to potentially be substantially below 100 % are largely ignored in existing studies.[4] The leakage rates they propose are thus, *per se*, only of limited value for forward-looking policy guidance. This seems especially clear as the primary reason for concern about climate change is that *future* global warming is anticipated today; it seems obvious, that current policy evaluations should consider 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 features fully endogenously depleting fossil fuel reserves.

The fuel-specificity of carbon leakage has also received scant attention in literature.[5] The

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[3] Gerlagh and Kuik (2007) also propose negative leakage in a static model with technology spillovers.

[4] Eichner and Pethig (2011, p. 768) make a related point (from the perspective of the intertemporal theory of exhaustibles), "*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*." Habermacher (2012) discusses the same issue.

[5] Economic *sector*-specific leakage rates have been treated. Hoel (1996) analyzes the sector-specific

present treatment of this aspect of the optimal unilateral tax 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 of consumption of exhaustible fuels disregarding the issue of fuel-specific final energy demand. Golosov et al. (2011) and van der Ploeg and Withagen (2012) also study optimal global fuel policies, the former considering uncertainty about climate costs that is resolved only in future. Michielsen (2011) is related to the present study in that it also studies regional and intertemporal leakage for two imperfectly substitutable fuels. Coal is supplied infinitely elastically and oil depletes. This provides insights about Green Paradox and leakage effects. Michielsen's analysis is, however, restricted to a two-period model and does not explicitly study optimal *fuel-specific* tariffs. Eichner and Pethig (2011) also model leakage and Green Paradox effects in a two-period model. They consider a single fuel and assume an elasticity of intertemporal substitution in demand, i.e., consumption in one period directly influences the *demand* in the other period. Harstad (2012) addresses dynamic leakage in a two-period model with a climate damage that does not depend on when emissions occur. He shows that a first-best solution that prevents leakage can be implemented through an initial purchase of the marginal fuel reserves by the policy region. His result holds independently of whether the policy region can commit to future policies. Green Paradox effects in two-period models with international leakage are discussed in Long (2014).

3 The case for a dynamic viewpoint

3.1 Fuel and goods channel leakage: tractable statics and dynamics

This section considers a model of global fuel consumption capturing the two main leakage channels, fuel-price and goods-trade (cf. Felder and Rutherford, 1993). A highly stylized framework ensures analytical tractability. Two regions consume fuel directly as well as indirectly through a composite good derived from imperfectly substitutable regional intermediate goods. Fuels are produced externally by a third region. We analyze leakage effects in the short and in the medium and long run, in three fuel supply settings: perfectly elastic, price-dependent static, and with suppliers that dynamically optimize sales of fuels extractable at stock-dependent extraction costs. We compare a world with an open fuel

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differentiation of a unilateral CO_2 tax considering an aggregated fuel. Böhringer et al. (2010) introduced the compensation technique to distinguish between the efficiency-related leakage motive and the terms-of-trade reason for sector-differentiation of a unilateral 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.

extraction horizon, where only the increasing prices from the advancement of depletion in the case of dynamic fuel supply limit the long-run fuel consumption, to scenarios where alternative technologies or policies make expensive fossil fuels, or the associated emissions, redundant in the future.

Static Model

Let $i = \{a, n\}$ index the *a*bating (domestic) and the *n*on-abating (foreign) region, each endowed with an amount $z_{0,i}$ of a numeraire good. Utility is derived from numeraire good consumption, z_i, direct fuel consumption $e_{D,i}$, consumption of a composite good X_i, and disutility from climate damages, H_i. The composite good is a constant elasticity of substitution (CES) aggregate of imperfectly substitutable intermediate goods $x_{j,i}$ from all regions j,

$$X_i \equiv \left(\alpha x_{i,i}^{\frac{\sigma-1}{\sigma}} + (1-\alpha) x_{-i,i}^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}, \tag{1}$$

with α the share index for the domestic good, $0 < \alpha < 1$, σ the substitutability between the regional goods, $1 < \sigma < \infty$, and $-i$ the complement to region i, i.e. $x_{-i,i}$ is region i's foreign intermediate consumption. Fuel quantities e are expressed in emission-units, so damage from cumulative emissions, H_i, can be expressed as a function of global fuel consumption, $H_i(e)$, $H'(\cdot) > 0$, with e the sum of regional fuel consumptions e_i, consisting of direct (D) and indirect (I) fuel consumption,

$$e \equiv \sum_i e_i, \qquad e_i \equiv e_{D,i} + e_{I,i}. \tag{2}$$

Regional intermediate good production y_i has constant *m*anufacturing returns indirect fuel use $e_{I,i}$,

$$y_i \equiv m \cdot e_{I,i}, \tag{3}$$

The global market clearance for the regional intermediate y_i writes

$$y_i = x_{i,i} + x_{i,-i}. \tag{4}$$

Fuels are bought from global producers at the global market price p.[6] We assume the four utility components to be separable,

$$U_i \equiv z_i + u(e_{D,i}) + \nu(X_i) - H_i(e). \tag{5}$$

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[6] This setup with external, decentralized producers is common in the literature, cf. e.g., 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.

Denoting π_i the market price of the intermediate goods, the regional budget constraint is

$$z_i = z_{0,i} - pe_i + \pi_i \underbrace{(y_i - x_{i,i})}_{x_{i,-i}} - \pi_{-i} \underbrace{(y_{-i} - x_{-i,-i})}_{x_{-i,i}}, \tag{6}$$

and we consider logarithmic utility from fuel and aggregate goods,

$$u(e_{D,i}) \equiv \phi \log e_{D,i}, \qquad \nu(X_i) \equiv \theta \log X_i. \tag{7}$$

Whilst simple enough for analytical tractability, this structure incorporates the most basic fuel market effects underlying the leakage problematic: higher fuel prices tend to reduce direct fuel consumption, and a higher price on domestic final goods – e.g. due to domestic fuel taxes – tends to decrease domestic and foreign consumption of the domestic intermediate good (and vice versa), which is partly substituted by an increased consumption of the foreign good (and thus decreases domestic but increases foreign fuel consumption).

Cost minimizing intermediate demands and unit cost for the CES aggregation in (1) are

$$x_{i,i} = X_i \left(\frac{\alpha p_{X,i}}{\pi_i} \right)^{\sigma}, \qquad x_{-i,i} = X_i \left(\frac{(1-\alpha) p_{X,i}}{\pi_{-i}} \right)^{\sigma}, \tag{8}$$

$$p_{X,i} \quad = \quad \left(\alpha^{\sigma} \pi_i^{1-\sigma} + (1-\alpha)^{\sigma} \pi_{-i}^{1-\sigma} \right)^{\frac{1}{1-\sigma}}. \tag{9}$$

Before we discuss subtleties of welfare relevant leakage definitions in section 4, we here consider a simple notion of a leakage fraction (LF),

$$\text{LF} \equiv 1 - \frac{\Delta E}{\Delta E_a}, \tag{10}$$

with ΔE_a the domestic emission reduction during a period where the abating region imposes a climate tax, and ΔE the resulting total global (long-run) emission reduction.

Decentralized Equilibrium

Consider the decentralized equilibrium of the economy. Individuals choose consumption and production patterns that maximize their utilities in (5) subject to (6), ignoring climate and price externalities. Optimal intermediates production requires $\frac{p}{\pi_i} = \frac{\partial y_i}{\partial e_i} = m$, thus

$$\pi_i = \frac{p}{m}. \tag{11}$$

The first order condition (FOC) on direct fuel consumption yields

$$e_{D,i} = \frac{\phi}{p}. \tag{12}$$

For the composite good consumption the FOC implies $X_i = \frac{\theta}{p_{X,i}}$. So, with (8) the intermediates demand functions are

$$x_{i,i} = \left(\frac{\alpha}{\pi_i}\right)^{\sigma} \theta p_{X,i}^{\sigma-1}, \qquad x_{i,-i} = \left(\frac{1-\alpha}{\pi_i}\right)^{\sigma} \theta p_{X,-i}^{\sigma-1}. \tag{13}$$

Together with (11) and (9), we can now determine y_i and π_i contingent on a given fuel price: CES production yielding homotheticity of degree one, using (11) in (9) yields

$$p_{X,i} = \frac{p}{m}\left(\alpha^{\sigma} + (1-\alpha)^{\sigma}\right)^{\frac{1}{1-\sigma}}, \tag{14}$$

and (13) with (4) becomes

$$y_i = \frac{m\theta}{p}. \tag{15}$$

Attributing this intermediates output to regional consumption levels according to $x_{i,-i} = x_{i,i}\left(1-\alpha\right)^{\sigma}\alpha^{-\sigma}$ obtained from (13) and (14), and the market clearance (4), yield

$$x_{i,i} = \frac{\alpha^{\sigma}}{\alpha^{\sigma} + (1-\alpha)^{\sigma}}\frac{m\theta}{p}, \qquad x_{-i,i} = \frac{(1-\alpha)^{\sigma}}{\alpha^{\sigma} + (1-\alpha)^{\sigma}}\frac{m\theta}{p}. \tag{16}$$

With direct consumption $e_{D,i} = \frac{\phi}{p}$ from (12) and indirect fuel use $e_{I,i} = \frac{\theta}{p}$ from (15) in (3), total regional and global fuel consumptions are $e_i = \frac{\theta+\phi}{p}$ and $e = 2\frac{\theta+\phi}{p}$. Regional fuel consumption is thus proportional to the sum of the scaling factors for direct fuel utility, ϕ and for composite goods utility, θ, and inversely proportional to the fuel price.

Planner's Choice without Pollution

Be fuel supplied competitively so that the fuel price p equals the marginal extraction cost, increasing in total fuel use, $p = C'(e)$, $C''(\cdot) > 0$, with $C(e)$ the total cost of extracting e units of fuel. Consider a planner maximizing the overall surplus absent pollution, $\max W \equiv \sum_i \left[u(e_{D,i}) + \nu(X_i)\right] - C(e)$, subject to the production and market clearing restrictions (1) through (4). Concavities in the utility and production functions ensure symmetry of the maximizing allocation across the two fuel consuming regions, with $x_{i,j} = x_{j,i}$. The solution for region i is therefore equivalent to that of the concise problem

$$\max_{x_{i,i}, x_{-i,i}, e_{D,i}} \hat{W}_i \;\; \equiv \;\; u(e_{D,i}) + \nu(X_i) - C(e)/2, \tag{17}$$

subject to (2), (1), (7) and $m \cdot e_{I,i} = x_{i,i} + x_{i,-i} = x_{i,i} + x_{-i,i}$, where the symmetry in the original problem allowed us to substitute $x_{i,-i}$ by $x_{-i,i}$. The last equation implies $e_{I,i} = \frac{x_{i,i}+x_{-i,i}}{m}$, and use in (17) yields $\hat{W}_i = \phi \log e_{D,i} + \frac{\sigma}{\sigma-1}\theta \log\left(\alpha x_{i,i}^{\frac{\sigma-1}{\sigma}} + (1-\alpha)x_{-i,i}^{\frac{\sigma-1}{\sigma}}\right) - \frac{1}{2}C\left(2\left(e_{D,i} + \frac{x_{i,i}+x_{-i,i}}{m}\right)\right)$. The FOCs for the three choice variables are

$$\frac{\partial \hat{W}_i}{\partial e_{D,i}} = 0: \qquad e_{D,i} = \frac{\phi}{C'(e)} \tag{18a}$$

$$\frac{\partial \hat{W}_i}{\partial x_{i,i}} = 0: \qquad \theta \frac{1}{\alpha x_{i,i}^{\frac{\sigma-1}{\sigma}} + (1-\alpha) x_{-i,i}^{\frac{\sigma-1}{\sigma}}} \alpha x_{i,i}^{-\frac{1}{\sigma}} = \frac{C'(e)}{m} \tag{18b}$$

$$\frac{\partial \hat{W}_i}{\partial x_{-i,i}} = 0: \qquad \theta \frac{1}{\alpha x_{i,i}^{\frac{\sigma-1}{\sigma}} + (1-\alpha) x_{-i,i}^{\frac{\sigma-1}{\sigma}}} (1-\alpha)\, x_{-i,i}^{-\frac{1}{\sigma}} = \frac{C'(e)}{m}. \tag{18c}$$

Combining (18b) and (18c) shows that $x_{-i,i} = x_{i,i}\,(1-\alpha)^{\sigma}\,\alpha^{-\sigma}$ holds, and substituting in either of the two FOCs gives the planner's solution,

$$x_{i,i} = \frac{\alpha^{\sigma}}{\alpha^{\sigma} + (1-\alpha)^{\sigma}} \frac{m\theta}{C'(e)}, \qquad x_{-i,i} = \frac{(1-\alpha)^{\sigma}}{\alpha^{\sigma} + (1-\alpha)^{\sigma}} \frac{m\theta}{C'(e)}. \tag{19}$$

The planner's allocation absent pollution (18a)-(19) corresponds to the decentralized equilibrium without tax given in (12) and (16) when fuel is priced competitively, $p = C'(e)$.

Planner's Choice with Pollution, and Optimal Global Tax

In presence of pollution, the planner maximizes $W \equiv \sum_i \left[u(e_{D,i}) + \nu(X_i) - H_i(e)\right] - C(e)$. The solution is symmetric, but for regional pollution damage. Therefore, the only change to the concise problem statement from the case without pollution (17) is the objective,

$$\max_{x_{i,i}, x_{-i,i}, f_{i,D}} \hat{W}_i \equiv u(e_{D,i}) + \nu(X_i) - pe_i - \frac{C(e) + H_i(e) + H_{-i}(e)}{2}.$$

The symmetry of the problem implies $e = 2e_i$. It is easy to verify that, because the marginal social cost of fuel consumption is increased by $\sum_i H_i'(e)$, in this case the planner's allocation is described by equations of a similar form as above,

$$e_{D,i} = \frac{\phi}{p^*}, \quad x_{i,i} = \tfrac{\alpha^{\sigma}}{\alpha^{\sigma} + (1-\alpha)^{\sigma}} \tfrac{m\theta}{p^*}, \quad x_{-i,i} = \frac{(1-\alpha)^{\sigma}}{\alpha^{\sigma} + (1-\alpha)^{\sigma}} \frac{m\theta}{p^*}, \tag{20}$$

where

$$p^* \equiv C'(e) + H_i'(e) + H_{-i}'(e). \tag{21}$$

With an emission tax τ, the price users pay for fuel becomes $p + \tau$. Further, (20)-(21) correspond to the decentralized equilibrium outcome when, with competitive fuel pricing, an emission tax at the level of the global marginal climate damage cost in the equilibrium,

$$\tau^* = H_i'(e) + H_{-i}'(e), \tag{22}$$

is imposed in both regions, increasing the gross fuel price perceived by individual consumers from p to the p^* from (21), i.e.,

$$p^* = p + \tau^*.$$

There is no surprise: this is the simple Pigouvian tax, internalizing pollution externalities.

Today, the optimal global carbon tax of (22) is politically infeasible. Instead, proactive regions are largely restricted to unilateral measures. The problem thus begs the question of the optimal regional carbon tax. Intrinsically related to this is the leakage question: which portion of potential domestic emission reductions may be offset by induced foreign emission increases? We save the question of the regionally optimal tax for section 4. The decreasing returns in external fuel production incites consuming regions with significant consumption shares to tax fuels even absent environmental damages, to improve import terms by depressing global fuel prices (cf. section 4.2). The remainder of this section focuses on carbon leakage, which we are interested in in terms of climate pollution rather than due to the terms-of-trade question.

Decentralized Equilibrium with Regional Tax

Following Sinn (2008), we consider an *ad valorem* sales tax τ_a, imposed by the abating region, and denote the associated tax factor $\upsilon \equiv 1 + \tau_a$, increasing the consumer fuel price in region a to the level υp, and equivalent to a unit tax $\tau = (\upsilon - 1)p$. Considering the add valorem tax factor simplifies notations. The FOCs for decentralized direct fuel consumption, and for intermediate production yield

$$\begin{aligned} e_{D,a} &= \frac{\phi}{\upsilon p}, \qquad e_{D,n} = \frac{\phi}{p}, \\ \pi_a &= \frac{\upsilon p}{m}, \qquad \pi_n = \frac{p}{m}, \end{aligned} \tag{23}$$

and substituting in in (13) gives

$$x_{a,a} = \frac{\alpha^\sigma}{\alpha^\sigma \upsilon + (1-\alpha)^\sigma \upsilon^\sigma} \frac{m\theta}{p}, \qquad x_{a,n} = \frac{(1-\alpha)^\sigma}{\alpha^\sigma \upsilon^\sigma + (1-\alpha)^\sigma \upsilon} \frac{m\theta}{p}, \tag{24a}$$

$$x_{n,a} = \frac{\upsilon^\sigma (1-\alpha)^\sigma}{\alpha^\sigma \upsilon + (1-\alpha)^\sigma \upsilon^\sigma} \frac{m\theta}{p}, \qquad x_{n,n} = \frac{\upsilon^\sigma \alpha^\sigma}{\alpha^\sigma \upsilon^\sigma + (1-\alpha)^\sigma \upsilon} \frac{m\theta}{p}. \tag{24b}$$

Comparative statics with the values (16) from the no-tax equilibrium of section 3.1, call them $x^0_{i,j}$, show that, for a fixed price p and for $\upsilon > 0$, we have

$$x_{a,i}|_p < x^0_{a,i}|_p, \qquad x_{n,i}|_p > x^0_{n,i}|_p. \tag{25}$$

That is, the tax decreases (increases) the consumption of the intermediate from the abating (non-abating) country in both regions. Eqs. (24a)-(24b) show the sum of the intermediates consumed in either region i decreases in the tax, $\partial \sum_j x_{j,i} / \partial \upsilon < 0$, and therewith also global indirect fuel consumption,

$$\partial e_I / \partial \upsilon < 0. \tag{26}$$

These partial derivatives all do not consider any possible reaction of the fuel price to the quantity of fuel consumed, and would correspond to an equilibrium outcome only with an infinitely elastic fuel supply. Let the leakage fraction given such an infinitely elastic fuel supply be called the goods channel leakage fraction LF_g,

$$\mathrm{LF}_g \equiv 1 - \frac{e(p,\upsilon) - e(p,0)}{e_a(p,\upsilon) - e_a(p,0)},$$

where $e(p,\upsilon)$ and $e_i(p,\upsilon)$ the global and regional fuel consumption as a function of the fuel price p and a's tax υ. As $e = e_a + e_n$, this can also be written $\mathrm{LF}_g = -\frac{e_n(p,\upsilon)-e_n(p,0)}{e_a(p,\upsilon)-e_a(p,0)}$. Defining $\omega \equiv \alpha^\sigma (1-\alpha)^{-\sigma}$, some algebra based on (24a)-(24b) and (23) shows

$$\mathrm{LF}_g = \left\{1 + \frac{\upsilon - 1}{\upsilon^\sigma - \upsilon^{2-\sigma}} \left[\omega + \omega^{-1} + \left(1 + \frac{\upsilon^{\sigma-1}}{\omega}\right)\left(1 + \frac{\upsilon^{1-\sigma}}{\omega}\right)\frac{\phi}{\theta}p\right]\right\}^{-1} \begin{cases} > 0 \\ < 1. \end{cases} \tag{27}$$

That a positive fraction strictly lower than 100 % of domestic emission reductions is offset abroad, could be anticipated from (25), (26), and (23): the tax reduces domestic indirect fuel consumption and increases it – by less – abroad, and it decreases domestic direct consumption.

For small taxes, L'Hôpital's rule yields

$$\lim_{\upsilon \to 1^+} \mathrm{LF}_g = \left\{1 + \frac{1}{2(\sigma-1)} \left[\omega + \frac{1}{\omega} + \left(1 + \frac{1}{\omega}\right)^2 \frac{\phi}{\theta}p\right]\right\}^{-1}.$$

Naturally, a relatively larger direct fuel consumption compared to intermediates consumption, $\frac{\phi}{\theta}$, lowers the goods-channel leakage fraction, as a tax affects direct consumption only domestically, when the fuel price is fixed. For approximately a unit-elasticity of substitution, $\sigma \to 1^+$, the goods-channel leakage fraction approaches zero; foreign intermediate production becomes insensitive to the tax, $\lim_{\sigma \to 1^+} \frac{\partial y_n}{\partial \upsilon} = 0$, indicated in (24b). Further, the leakage would become negative if the intermediates were complements, $\sigma < 1$. This is unlikely to be the empirically relevant case for general (fuel intensive) internationally traded goods so we do not further elaborate on that point.

Next, we allow fuel supply to increase in the fuel price,

$$e'(p) \quad > \quad 0. \tag{28}$$

Eqs. (24a) and (24b) show that, for a given tax υ, a *ceteribus paribus* increase of the fuel price reduces all intermediates consumption,

$$\left.\frac{\partial x_{i,j}}{\partial p}\right|_{\upsilon} < 0. \tag{29}$$

How does the fuel-price channel impact the leakage fraction? Annex A shows that the tax reduces the market fuel price p, but it increases the domestic consumption price, υp,

$$p < p^0 < \upsilon p. \tag{30}$$

Intuitively, as a direct effect, the tax tends to reduce global consumption, but a lower consumption reduces the fuel supply price, partially offsetting the gross price increase in the abating region – partially only, since, if the fuel consumption price would increase even in the abating region, global consumption would increase.

With upward sloping supply (28) the reduced equilibrium fuel price according to (30) shows that the tax reduces *global* fuel consumption. *Foreign* emissions increase, however, due to intermediates substitution arising from the higher fuel consumption price in region a, and the falling global fuel price, (24b) and (23). This implies that the overall leakage fraction remains strictly between 0 and 1 in this static model with fuel-price effect. This overall leakage fraction, LF, which accounts for the fuel channel and the goods channel, necessarily exceeds LF_g which hypothetically assumes a fixed fuel supply price. This is a necessary consequence of the decrease in the fuel price relative to the case with a fixed p, increasing in each region both the direct fuel consumption (23), as well as the indirect fuel consumption (24a) and (24b), showing $\partial x_{i,j}/\partial p < 0 \forall i, j$ and implying $\partial y_i/\partial p < 0$. By lowering the domestic emission savings while increasing the foreign emission increase, the fuel channel thus increases the overall leakage fraction.

For an isoelastic fuel supply $e(p) = e_0 p^{\psi}$, the proportionality of all fuel demand components to p in (23)-(24b) allows to pin down the leakage fraction LF for a given tax,

$$\mathrm{LF}(\upsilon) = \frac{(1 + \mathrm{LF}_g(\upsilon))\xi(\upsilon)}{\xi(\upsilon) - 1 + (1 + \xi(\upsilon)(\mathrm{LF}_g(\upsilon) - 1)/2)^{1/(1+\psi)}} - 1, \tag{31}$$

with LF_g from (27) and $\xi \equiv 1 - \frac{e_i(p_0,\upsilon)}{e_i(p_0,0)}$, where p_0 denotes the equilibrium fuel price in the situation without tax. Lemma 1 summarizes and emphasizes key properties of the leakage fraction according to (31):

Lemma 1. *For a smoothly increasing fuel supply, $0 < e'(p) < \infty$, the leakage fraction exceeds the goods channel-only fraction,*

$$0 < LF_g < LF < 1.$$

For an isoelastic fuel supply with elasticity ψ, the leakage fraction is given in (31), implying

$$\lim_{\psi\to 0} LF = 1, \qquad \lim_{\psi\to\infty} LF = LF_g.$$

Which channel dominates the leakage fraction? If fuel supply is sufficiently price elastic, we are close to the world in which the fuel-price channel is absent, and the trade channel dominates. The less elastic the fuel supply, and the larger the share of fuels consumed directly, the more likely the fuel price channel dominates leakage. Fuel supply is relatively inelastic at least in the shorter run, and a sectoral split of emissions reveals that less than a third of global greenhouse gas emissions stem from industrial processes (UNEP/GRIDA, 2008), which are the most likely to relocate. The fuel price channel seems thus likely to dominate the overall leakage in the shorter run. This is also what a number of studies that try to disentangle the two channels seem to imply.[7]

Given the long-term nature of the climate problem, it seems unlikely that efforts towards its solution are motivated by short-run benefits. Instead, the longer-run implications of measures are crucial. As supplies of fossil fuels across time all feed on the same, initially available overall stock of fuels, consumption in one period has direct effects on the fuel availability in other periods. This warrants a dynamic viewpoint, accounting how taxes in some (or all) periods affect fuel consumption *throughout time*.

Leakage with dynamic supply

Consider a continuous, open horizon $t = [0, \infty]$. To ease tractability while preserving the main characteristics of the model we assume equal share parameters for domestic and foreign goods, $\alpha = 1 - \alpha = 0.5$. Eqs. (24a) and (24b) yield $x_{a,i} = \frac{1}{p}\frac{m\theta}{\upsilon+\upsilon^\sigma}$, $x_{n,i} = \frac{\upsilon^\sigma}{p}\frac{m\theta}{\upsilon+\upsilon^\sigma} = \upsilon^\sigma x_{a,j}$, $\forall i, j$, and

$$y_a = \frac{2}{p}\frac{m\theta}{\upsilon+\upsilon^\sigma}, \qquad y_n = \frac{2\upsilon^\sigma}{p}\frac{m\theta}{\upsilon+\upsilon^\sigma}, \tag{32}$$

$$e = \frac{y_a + y_n}{m} + e_{D,a} + e_{D,n} = \frac{1}{p}\left[2\theta\frac{1+\upsilon^\sigma}{\upsilon+\upsilon^\sigma} + \phi\left(1+\frac{1}{\upsilon}\right)\right]. \tag{33}$$

Business-as-usual as baseline. Each marginal fuel unit has a unique extraction cost. At each point in time it is economic to exploit the cheapest resources first (Herfindahl, 1967). In equilibrium, this implies a stock-dependent extraction cost curve c strictly increasing with the amount A of fuel extracted, $c_t = c(A_t)$, $c'(A_t) > 0$, where $A_t \equiv \int_0^t e_s \mathrm{d}s$.

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[7] McKibbin and Wilcoxen (2008), Böhringer et al. (2010) and Kuik and Hofkes (2010) have shown that direct fossil fuel market effects dominate leakage, the trade of non-energy goods being of lesser importance. Simulation results of Fischer and Fox (2011) suggest the same. Oliveira Martins (1995) and Burniaux and Oliveira Martins (2012) find that the leakage effects are primarily determined by the fuel market, with trade characteristics of consumer goods being less important.

We assume a finite total amount of fuel $\bar{A}$ extractable,

$$\int_0^\infty e_t \mathrm{d}t \leq \bar{A}, \tag{34}$$

at a cost that is finite when a non-marginal amount of fuel remains exploitable, $\forall \varepsilon > 0, \exists \delta < \infty$ s.t. $c(\bar{A} - \varepsilon) \leq \delta$, but diverges to infinity, $\lim_{A \to \bar{A}} c(A) = \infty$.

Competitive supply, and the optimality condition for interior supply solutions require supplier's indifference between a marginal delay of extraction, yielding (Hotelling, 1931) $p_t = c_t + \lambda_t$ and $\dot{\lambda}_t = \lambda_t \rho - \dot{c}_t$, with λ_t the current value resource rent at time t. Integration allows to express λ_t as the present value of summed extraction cost increases up to a future time $\bar{t}$ plus the future resource rent, $\lambda_t = \mathrm{e}^{\rho(t-\bar{t})}\lambda_{\bar{t}} + \int_t^{\bar{t}} \mathrm{e}^{\rho(t-s)}\dot{c}_s \mathrm{d}s$. As the present value of resources not exploited for an infinite time is zero, we have $\lim_{t\to\infty} e^{-\rho t}\lambda_t = 0$. With an open fuel sales horizon the price is therefore

$$p_t = c_t + \int_t^\infty \mathrm{e}^{\rho(t-s)}\dot{c}_s \mathrm{d}s. \tag{35}$$

In a business as usual scenario without tax, $\upsilon_t = 1$, (33) thus implies the equilibrium extraction path condition

$$e_t = 2\frac{\theta + \phi}{c_t + \int_t^\infty \mathrm{e}^{\rho(t-s)}\dot{c}_s \mathrm{d}s}, \tag{36}$$

with $c_t = c(A_t) = c(\int_0^t e_t \mathrm{d}t)$. Full exhaustion occurs in finite time or asymptotically in the infinite future,

$$\lim_{t\to\infty} A_t = \bar{A}. \tag{37}$$

This is easily proven by contradiction: Assume instead $\lim_{t\to\infty} A_t \leq \bar{A} - \varepsilon$ for a non-marginal $\varepsilon > 0$. The extraction cost would remain finite throughout time and (36) implied a non-marginally positive extraction rate in each period. This would imply, in the long-run, an infinitely high cumulative extraction, $\lim_{t\to\infty} A_t = \infty$, a contradiction. ■

With such a business as usual baseline, full exhaustion occurs even with a unilateral tax: with a path of weakly positive taxes, $\upsilon_t \geq 0$, (33) yields an extraction rate

$$e'_t = \frac{1}{c_t + \int_t^\infty \mathrm{e}^{\rho(t-s)}\dot{c}_s \mathrm{d}s}\left[2\theta\frac{1+\upsilon_t^\sigma}{\upsilon_t + \upsilon_t^\sigma} + \phi\left(1 + \frac{1}{\upsilon_t}\right)\right], \tag{38}$$

for which the just used proof by contradiction that shows (37) applies, implying

$$\lim_{t\to\infty} A'_t = \bar{A}, \tag{39}$$

for $A'_t \equiv \int_0^t e'_t \mathrm{d}t$. Global emissions thus remain constant. With a decrease of direct and indirect fuel use in the abating region relative to the non-abating region (23) and (32) this implies that the tax induces domestic emission reductions that are fully offset by foreign increases in the long run; a leakage fraction of 100 %. Annex B shows this also holds when a demand choke price, equivalent to a given clean backstop technology, prevents parts of the fuel from being extracted. Because the tax fails to curb foreign demand, fuels continue to be used abroad until 'all' are consumed, independently of the tax.

Future developments in baseline. The scenario in the previous section overlooks an important element of reality. The worldwide fossil fuel reserves are so enormous that independent of a regionally limited tax, bringing all of the contained CO_2 into the atmosphere could have disastrous consequences for mankind, with many degrees of warming and unforeseeable consequences including possible warming-emission feedback loops. Therefore, any hope for an acceptable solution to the climate problem must lie in future technological or political developments to make a large fraction of the fossil fuels redundant or to prevent their CO_2 from warming the atmosphere. How does leakage look in a world where the long-run baseline scenario contains such measures?

We consider the example where, from a time T, a global policy makes the use of fuel redundant. This is a special, stylized case, and Annex D shows that the leakage effects are qualitatively similar in the case of a stringent and *gradually* tightening global cap on emissions introduced at some future time. Further, the numerical application below illustrates how the analysis extends to the case when instead of making fuels redundant, the future development prevents *only the emissions' effects* from fuels use, such as could be the case with carbon capture and storage or successful geo-engineering.

Assuming a tax υ during a short initial period $t = [0, \delta]$, simplifies the discussion. It is going to be clear that the results extend to a much broader set of tax paths. Competitive fuel pricing (35) implies

$$p_T = c_T, \qquad \lim_{t \to T} p_t = \lim_{t \to T} c_t = c_T.$$

For an infinitely late alternative development, $T \to \infty$, the contradiction, as used to show (37), between a non-marginal extraction rate (from (38)) sustained for an infinitely long duration, and a finite cumulative extraction, immediately shows that extraction approaches $\bar{A}$,

$$\lim_{T \to \infty} A_T \;=\; \bar{A}.$$

Supply pricing (35) implies that the price diverges as well, and demand (38) in turn implies an infinitesimal consumption rate,

$$\lim_{T\to\infty} p_T = \infty, \qquad \lim_{T\to\infty} e_T = 0.$$

These properties imply that the overall leakage fraction converges towards 100 % for an initial tax when the future development emerges at an arbitrarily late time T. Further, the leakage fraction LF from (10), with $\Delta E_a = \int_0^\delta e^0_{a,t} - e_{a,t}\mathrm{d}t$ and $\Delta E = \int_0^T e^0_t - e_t\mathrm{d}t$, is strictly limited to the goods-channel leakage fraction, and thus below unity, when the future development is imminent,

$$\lim_{T\to\infty} \mathrm{LF} = 1, \qquad \lim_{T\to\delta^+} \mathrm{LF} = \mathrm{LF}_g < 1, \tag{40a}$$

with LF_g the goods-channel only leakage fraction from (27). Annex C provides the proofs. Intuitively, when emerging late enough, the alternative measure becomes quantitatively irrelevant to the overall amount of fuel consumed, so that the effect of the tax becomes similar to that in the case with the open time horizon, with a tax unable to affect long-run emissions, c.f. (39). Behind the result of limited leakage for $T \to \delta$ in (40a) lies the observation that the imminent tax limits scarcity rents and the fuel price thus essentially consists of extraction cost and hence changes only marginally in reaction to the tax. This renders the fuel price channel effect marginal. Annex D shows that these results extend to the case of a cap that *gradually* fades out fuel use rather than abruptly prohibiting it.

In reality, to which degree, and especially at which point in time, a future fuel market development curbs the fuel use, is not known. A simple way to account for this uncertainty is to assume the future scheme to emerge stochastically with a certain probability at each point in time, rather than at a specific, anticipated or unanticipated, time. In this case, fuel owners take into account at each point in time that the measure may emerge (and *de facto* expropriate them) at the next point in time with a specific annual probability, say γ. They become less patient in their fuel sales, factoring in the probability γ to their revenue discount rate ρ (cf. Dasgupta and Heal, 1974). Scarcity rents evolve according to $\dot{\lambda}_t = \lambda_t\,(\rho + \gamma) - \dot{c}_t$, implying that the seller equilibrium price path still has the form

$$p_t = c_t + \int_t^{\bar{T}} \mathrm{e}^{\varrho(t-s)}\dot{c}_s \mathrm{d}s,$$

with an increased time discount factor $\varrho \equiv \rho + \gamma$, i.e., the revenue discount rate augmented by the annual probability of introduction of the future measure.[8] As the fuel consumers are unaffected until the future measure materializes, the analysis above remains unchanged except for the altered discount factor in the fuel owners' pricing. Key results from the

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[8] The measure's probability of emergence conditional that it has not emerged earlier, γ, may be time-varying. This leads to a time-varying discount index $\varrho_t = \rho + \gamma_t$ but does not change the result further.

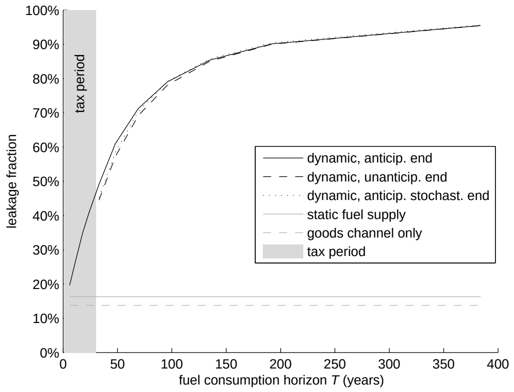

Figure 1: Leakage fraction for short and long fuel horizons T

deterministic case about the short term and the longer term leakage fractions thus extend to the case of a stochastic future measure: Leakage from a current tax is low if the future measure materializes early, and large if it emerges late, converging towards 1 for $T \to \infty$.

Numerical Illustration

Fig. 1 illustrates the results for the discussed deterministic and the stochastic case with results from numeric simulations of the fuel market model for a tax of 30 years, for fuel consumption horizons (corresponding to the value of T) of 30 to 400 years.[9] The figure also shows leakage fractions for the case where fuel suppliers do not anticipate the end of the fuel consumption horizon. This is equivalent to forward-looking supply in the situation where, rather than fuels becoming redundant, a cheap enough measure emerges that prevents harmful emissions from their combustion. The goods-only leakage fraction was calculated by replacing, in the calculations with the tax, the equilibrium fuel price path p_t from (35) with the calculated equilibrium value from the calculations without tax. For the static fuel supply run, cumulative extractions in each period were assumed to be only the within-period fuel use, and the fuel price set to the extraction cost of the marginal unit. The goods-substitutability was $\sigma = 1.5$, and the extraction costs the sum of a positive intercept and a function exponentially increasing in cumulative extractions.[10] The goods-only leakage fraction is small (14 % in the example). For short fuel consumption horizons, the dynamic leakage fraction is barely higher than the modest overall leakage fraction with static supply (16 %), but it rises rapidly for fuel consumption horizons of multiple decades and approaches unity if the fuel consumption horizon comprises one or several centuries. Trade characteristics, here the goods substitutability, have considerable importance for short-term leakage fractions – for example, the goods-trade leakage fraction is confirmed to

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[9] Simulations were run for up to 450 years to prevent significant end-of horizon effects in the case of the unanticipated end future measure.

[10] Demand for direct fuel consumption and aggregate goods was unitary-elastic, in line with the logarithmic utility assumption of the model. It was not calibrated to real-world demand. Parameter values available from the author.

be 0 % for $\sigma = 1$, and larger than 25 % for $\sigma = 2$. In the medium and longer term, the fuel-channel leakage dominates and is responsible for the overall leakage fraction to converge to 100 % relatively independently of the model parameters (for a horizon of 100 years it is 79 % in the plotted example, and 73 % and 82 % for $\sigma = 1$ and $\sigma = 2$). This convergence pattern proves very robust to other model configurations as well. Leakage fractions in the case where the end of the fuel horizon is unanticipated, or where it is assumed to be stochastic, plotted in Fig. 1, are almost indistinguishable of the leakage fractions for anticipated fuel horizon ends.[11] The relationship between these three setups is interesting: in the scenario with the unanticipated end-of-horizon, the patient suppliers exploit the fuels more slowly than suppliers that anticipate the deterministic or stochastic futures measure. Along with the least advanced extraction, this scenario shows the lowest leakage fraction for each value of T. The relationship between exploitation of deterministically and stochastically anticipating suppliers is ambiguous: if the future measure materializes early, the suppliers in the stochastic world would have attributed a high chance to it arriving later, and therefore would have sold less fuel than suppliers that would have anticipated the early end of the fuel period. This also leads to reduced leakage fractions in the stochastic scenario compared to the scenario with an anticipated early end. The contrary is the case if the future measure materializes late. In this case fuel owners in a stochastic world would have attributed a high chance for the measure to come earlier than it does, and thus will have sold already more fuel that would have been optimal ex-post. Along with a more advanced extraction, this leads to a higher leakage fraction in the stochastic world compared to the case of an anticipated late end of the fuel era.[12]

3.2 General equilibrium view with CGE model

Burniaux and Oliveira Martins (2012), BOM hereafter, provide a partial overview of the leakage literature and use a small, relatively flexible general equilibrium model to examine whether fears about leakage to undermine the effectiveness of unilateral climate measures would be justified. They find in general very small or small leakage rates and conclude

> "[T]he argument that unilateral carbon abatement action taken by a large group of countries [...] is flawed because its environmental effectiveness is undermined by large carbon leakages is not supported by our sensitivity analysis over a plausible range of parameters' values. According to our analysis, only rather implausible values of certain parameters [...] may generate high leakage rates. This also invalidates the argument

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[11] Stochastic case: $\gamma = 1.8\,\%$; plotted is the overall leakage fraction materializing for the given ending times, rather than ex-ante expectation values.

[12] The inversion happens later than at the median time of the implementation of the future measure in the stochastic case. The assumed annual probability implies a 50 % probability for the measure to materialize in the first 39 years, and an average time to materialization of 56 years. The leakage fraction in the stochastically anticipated measure exceeds its counterpart of the case of the deterministically anticipated measure only when arriving after more than 100 years.

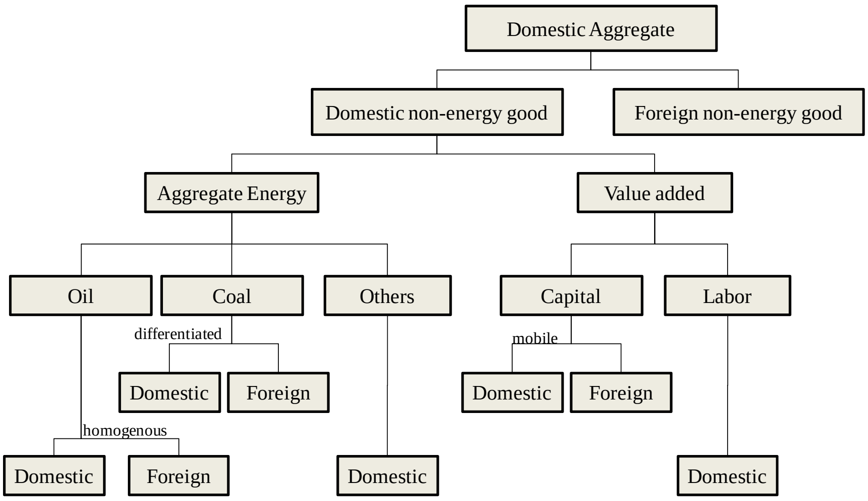

Figure 2: Regional CGE production structure

> that accompanying protectionist measures or tax exemptions to energy-intensive industries would need to be implemented. The likelihood of small leakages favours in fact the formation of a worldwide coalition to stabilise climate change.”
> J.-M. Burniaux and J. Oliveira Martins, 2012 (p. 488).

Besides on their literature review, the confidence the authors convey that leakage would be a minor problem is founded on a sensitivity analysis with a reasonably standard, calibrated single-period CGE model. Exogenous capital and labor inputs combine with price-responsive energy supplies over several stages of regional production functions and interregional trades and aggregations to ultimately yield regional final consumption. For their central scenarios the authors find leakage rates that are indeed small enough for, if realistic and the only thing that is to be said about the magnitude of carbon leakage, one could happily stop reading right here. For a carbon constraint implemented in a large coalition of countries the rates amount to a mere 2 %. This low value is notably a result of the assumption of a very high coal supply elasticity of 20. BOM contains a sensitivity analysis showing that the resulting leakage rate remains low or modest even for substantially lower coal supply elasticities, a result that our replication confirms.

BOM do not provide a dynamic analysis. Their results change dramatically when one extends the model to a dynamic framework. To see this, we implemented a dynamic general equilibrium model that uses the same economic structure as the one used by BOM, represented in Fig. 2, but with a dynamic supply of the considered, depleting fuels: coal, oil and other energies. The model was calibrated to available actual data for the OECD and the rest of the world for the abating and the non-abating region, respectively. In order to match the BOM analysis as closely as possible except for the dynamics we introduce, we adopt their functional forms considering Armington trade and constant elasticity of substitution production forms, as well as the parameters values they report.[13]

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[13] Trade substitution elasticity ‘other’ energies 4; elasticity of transformation for capital mobility 0 (i.e.

We consider a tax of \$10/tCO_2, imposed on fuel consumption emissions in the OECD, from now until the long-run future,[14] and the simple leakage fraction as defined in (10) equals the ratio of the induced increase of total foreign emissions over the total reduction of domestic emissions. When adopting the static fuel supply assumptions of BOM, our calibration to recent data on a regional level of fuel production, trade and consumption, capital and labor use and remuneration, as well as energy and non-energy value added, yields the same low leakage fractions as in BOM's central scenario, of less than 4 %.

We extend the model with a dynamic fuel supply similarly to the case discussed in section 3.1. We consider regional fuel availabilities from DERA (2012), in terms of proven reserves and the larger estimated recoverable resources of coal, oil, and gas. Although we here simplify the fuel extraction cost curve relative to the calibration in section 5, assuming costs to increase proportionally with the reciprocal of the remaining fuel stock, we consider lower and upper limits along two crucial dimensions of fuel availability. First, we consider both, the situation where the fuel stocks are limited to the proven *reserves*, as well as the situation where the stocks correspond to all the *resources*.[15] Second, we consider fuel to be supplied either at the marginal extraction costs in each period – corresponding to perfectly myopic fuel suppliers and arguably an approximation to the case of very high discount rates on fuel extraction rents such as could emerge in a case of substantial uncertainty about future resource ownership –, or under a competitive Hotelling supply behavior as was assumed in section 3.1, i.e. long-term forward looking suppliers that time extractions such as to maximize present discounted profits.[16]

Fig. 3 plots the resulting leakage fractions, for different fuel horizons as discussed in section 3.1. The asymptotic result for long horizons can be interpreted as representing an open fuel horizon, for which the convergence of all plotted lines towards 1 indicates that carbon leakage would fully offset unilateral OECD fuel consumption reductions within a baseline scenario according to the BOM model adopted. As this paper emphasizes, though BOM and other leakage studies largely ignore it, there is, however, scope for future climate measures in form of technological or political progress that goes beyond the currently discussed unilateral tax, to reduce fuel consumption or emissions thereof, and to basically limit the fuel consumption horizon. The curves in Fig. 3 illustrate what such reduced fuel sales horizons mean for the leakage fraction from the studied unilateral measure. Even for relatively limited fuel horizons, cumulative leakage for the unilateral

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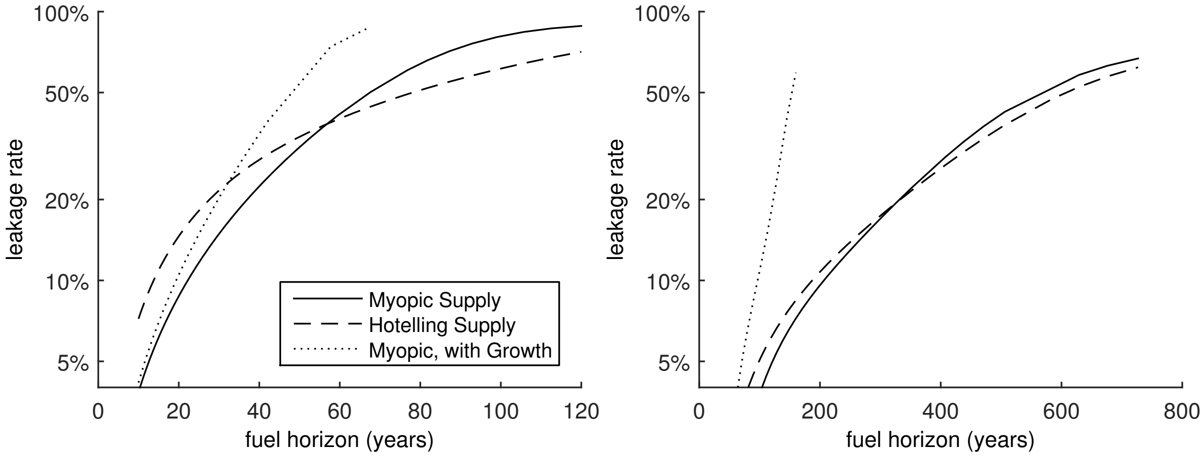
case where capital unresponsive to equilibrium interest rate); inter-fuel substitution elasticity 2; capital-labor substitution elasticity 0.4 (cf. Table 1 in BOM). Cf. Annex in BOM for the list of main equations; our numerical implementation is in levels rather than, as in BOM, log-linearized.

[14] The results are very robust to the level of the tax.

[15] There is a very substantial difference. At the current rate of consumption, coal, oil, and gas *reserves* last for roughly 130, 50 and 50 years, but *resources* for >2000, 150, and 200 years (DERA, 2012).

[16] To contrast this scenario to the case of myopic supply, we consider a relatively limited real discount rate of 3 %. Higher discount rates reduce the net present value of scarcity rents and bring us closer to the case of the myopic supply.



(a) Reserves ***(b)*** Resources

Figure 3: CGE results with dynamic fuel supply

Logarithmic y-axis

tax tend to be large or very large, especially in the case of the lower initial fuel stocks. Whether fuel owners are forward-looking or myopic is of secondary importance to the order of magnitude of the leakage fractions; for short fuel horizons the impact depends on the relative importance of fuel rents for the various fuels considered, but for longer horizons, the accelerated depletion in the case of myopic suppliers generally aggravates the leakage problem. Assuming the smaller fuel stocks, leakage fractions surpass 50 % even for relatively short fuel consumption horizons of a few decades (barely more than 50 years). With the large fuel stocks, high leakage fractions may arise with fuel horizons of several hundred years in the case of static fuel demand.

This supports the conclusion from the previous section that a key determinant for the expected magnitude of carbon leakage is whether, and when (and how) future measures mitigate the climate problem. A second such key determinant appears to be the baseline medium-term growth rate of fuel demand. In addition to the four scenarios discussed that assumed constant fuel demand, the dotted lines in Fig. 3 show the leakage fractions within scenarios with a modest annual demand growth of 1.5 %. With such a growing demand, increasing the speed at which the fuels deplete, the leakage fraction is very large even in the scenario with the abundant *resources* and fuel horizons of around 100 years, reversing the conclusion from the case of a static demand that large reserves would imply modest leakage fractions even if fuel was to be sold for several centuries to come.

The CGE model adopted here presents multiple steps towards the real world compared to the model from the previous section. It considers a variety of fuels, and regions-specific fuel stocks. Substantial trade costs exist, as the low-carbon energy, consisting of natural gas and other energies, is assumed not tradable at all, and the most energy intensive fuel, coal, is tradable only subject to moderate Armington elasticities, the costs attached to which can be thought of representing fuel transport costs and to potential heterogeneity within a same fuel category. Further, the various types of fuel are imperfect substitutes for each other and energy demand is modeled in a consistent general equilibrium framework.

The identified relation between the fuel horizon and the leakage fraction contains limited information about the time lags with which leakages occur. The time-path of leakage responses, along with implied welfare relevant leakage rates and and optimal taxes, is among the issues discussed in the remaining sections.

4 Theory of optimal unilateral tax and decomposition

4.1 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 h, 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 the tax region increases pollution in the remainder of the world by l units (l is called the leakage rate), and where, besides this pollution leakage, no additional relevant interaction between the regions takes place. In this case the regionally optimal, unilateral tax level is reduced to $(1 - l) \cdot h$ (shown with Lemma 2 in Annex E).

In general, this regional pollution tax calculation is not pertinent. It is through price effects that the domestic emission choice affects the foreign emissions, 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 representing 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 of this section addresses the interrelatedness of the terms-of-trade component and the pollution component of the optimal unilateral fossil fuel (emissions) tax. We assume the climate policy region is able to commit throughout time to a specific, initially announced tax path. The case where a region is restricted to time-consistent fuel taxes is discussed, e.g., in Karp (1984) and, with pollution, in Beermann (2012).[17]

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[17] Cf. Habermacher (2013a) for a discussion of parts of the results in Karp (1984).

Model

We adopt the framework from section 3.1, but focus on direct fuel consumption, denoted $e_{i,t}$, and call global consumption $e_t \equiv \Sigma_i e_{i,t}$. Regional welfare over the open horizon can be written as $W_i \equiv \int_0^\infty \mathrm{e}^{-\rho t} \left[u_i(e_{i,t}) - p_t e_{i,t} - H_i(E_t)\right] \mathrm{d}t$. We assume fuel utility $u_i(e_{i,t})$ to increase concavely in current time t fuel consumption. At this stage we assume the simple situation where the interest rate corresponds to the time-discount rate, ρ. For simplicity we abstract from foreign emission disutility;[18] that is, we set $H_n(\cdot) \equiv 0$, and call domestic damage $H_{a,t} = H_t = H(E_t)$, with $E_t \equiv \int_0^t e_s \mathrm{d}s$. Be h_t the marginal instantaneous damage from marginal emissions at time t, $h_t = h(E_t) \equiv H_t'(E_t)$. Assuming convex damage from cumulative emissions, we have $h'(E) > 0$. Supply is competitive and forward-looking, hence governed by (35), with the extraction cost curve $c_t = c(E_t)$, $c'(E) > 0$. Decentralized consumers equate private costs and benefits. Assuming interior solutions, potentially affected by a unit consumption tax $\tau_{i,t}$, demand in region i respects the FOC

$$u_i'(e_{i,t}) = p_t + \tau_{i,t}. \tag{41}$$

Optimal Global Policy

Edenhofer and Kalkuhl (2010) show that in this framework, the social planner's choice, equalizing the competitive extraction path and the surplus maximizing path, chooses, at any time t, a global tax equal to the net current value of all future marginal damages from a unit of emission added,

$$\tau_{Pigou,t} \equiv \int_t^\infty \mathrm{e}^{-\rho(s-t)} h_s \mathrm{d}s > 0, \tag{42}$$

the dynamic counterpart to the static tax in (22). Climate-independent resource conservation effects do not enter the optimal tax as the supplier's dynamic pricing behavior leads to optimal conservation of the resource in absence of externalities (Hotelling, 1931).

Given that for convex damages we have $\dot{h}_s > 0$ during the fuel consumption phase, the tax is strictly growing, $\dot{\tau}_{Pigou} > 0$. Also, (42) implies that the tax grows at less than the interest rate (cf. also van der Ploeg, 2013): we have $\dot{\tau}_{Pigou,t} = \rho \tau_{Pigou,t} - h_t$, implying that $\tau_{Pigou,t}$ grows at a rate $g_{\tau,Pigou,t} = \rho - \underbrace{h_t/\tau_{Pigou,t}}_{>0} < \rho$. We thus see that:

Proposition 1a. 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 $g_{\tau,Pigou}$ strictly below the interest rate ρ,

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

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

Unilateral Committed Policy

We assume the abating region, a, to commit to a unilateral fossil fuel tax path. As the foreign region's consumption is untaxed,[19] for the foreign region (41) simplifies to

$$u_n'(e_{n,t}) = p_t. \tag{43}$$

The domestically optimal consumption rate is implicitly defined by the problem

$$\max_{e_a} W_a \equiv \int_0^\infty \mathrm{e}^{-\rho t}\left[u_a(e_{a,t}) - e_{a,t}p_t - H_t\right]\mathrm{d}t,$$

where the paths p and e_n are functions of the choice variable path e_a and implicitly defined by (43) and (35).

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

$$\begin{aligned}\frac{\mathrm{d}W_a(e_a^*)}{\mathrm{d}e_{a,t}} &= \mathrm{e}^{-\rho t}u_a'(e_{a,t}) - \mathrm{e}^{-\rho t}p_t - \int_0^\infty \mathrm{e}^{-\rho s}e_{a,s}\frac{\mathrm{d}p_s}{\mathrm{d}e_{a,t}}\mathrm{d}s \\ &\quad - \int_t^\infty \mathrm{e}^{-\rho s}h_s\mathrm{d}s - \int_0^\infty \mathrm{e}^{-\rho s}h_s\int_0^s \frac{\mathrm{d}e_{n,w}}{\mathrm{d}e_{a,t}}\mathrm{d}w\mathrm{d}s,\end{aligned} \tag{44}$$

where the last two terms are implied by $\frac{\mathrm{d}H_s}{\mathrm{d}e_{a,t}} = \underbrace{\frac{\partial H_s}{\partial E_s}}_{h_s}\frac{\mathrm{d}E_s}{\mathrm{d}e_{a,t}}$ and $\frac{\mathrm{d}E_s}{\mathrm{d}e_{a,t}} = \frac{\partial E_s}{\partial e_{a,t}} + \int_0^\infty \frac{\mathrm{d}e_{n,w}}{\mathrm{d}e_{a,t}}\frac{\partial E_s}{\partial e_{n,t}}\mathrm{d}w$, implying $\frac{\mathrm{d}E_{s<t}}{\mathrm{d}e_{a,t}} = \int_0^s \frac{\mathrm{d}e_{n,s}}{\mathrm{d}e_{a,t}}\mathrm{d}s$ and $\frac{\mathrm{d}E_{s\geq t}}{\mathrm{d}e_{a,t}} = \int_0^s \frac{\mathrm{d}e_{n,s}}{\mathrm{d}e_{a,t}}\mathrm{d}s + 1$, leading to $\int_0^\infty \mathrm{e}^{-\rho s}\frac{\mathrm{d}H_s}{\mathrm{d}e_{a,t}}\mathrm{d}s = \int_t^\infty \mathrm{e}^{-\rho s}h_s\mathrm{d}s + \int_0^\infty \mathrm{e}^{-\rho s}h_s\int_0^s \frac{\mathrm{d}e_{n,w}}{\mathrm{d}e_{a,t}}\mathrm{d}w\mathrm{d}s$, and where the envelope theorem has allowed us to ignore the interdependence of the optimal *domestic* consumption rates from different time periods. For standard regularity conditions warranting a unique interior solution, we have an implicit one-to-one mapping between the tax τ_t and domestic consumption $e_{a,t}$ according to (41). As the FOC requires $\frac{\mathrm{d}W_a}{\mathrm{d}e_{a,t}} = 0$, the tax path that sustains the optimal domestic consumption level e_a^* is thus defined by

$$\bar{\tau}_t^* = \underbrace{\int_t^\infty \mathrm{e}^{-\rho(s-t)}h_s\mathrm{d}s}_{\text{direct damage}} + \underbrace{\int_0^\infty \mathrm{e}^{-\rho(s-t)}e_{a,s}\frac{\mathrm{d}p_s}{\mathrm{d}e_{a,t}}\mathrm{d}s}_{\text{terms-of-trade}} + \underbrace{\int_0^\infty \mathrm{e}^{-\rho(s-t)}h_s\int_0^s \frac{\mathrm{d}e_{n,w}}{\mathrm{d}e_{a,t}}\mathrm{d}w\mathrm{d}s.}_{\text{leakage}} \tag{45}$$

Partial derivatives are to be considered with domestic consumption from the other periods, $e_{a,s\neq t}$, held fixed, and the foreign consumption path, e_n, as well as the fuel price path, p, adjusting according to (43) and (35).

The optimal tax (45) is governed by three distinct effects. The first is the direct pollution

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[19] *Both* consuming regions buy the exhaustible resource *strategically* from the competitive seller in Karp and Newbery (1993). They abstract from 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 (42). The consumption choice affects the price p_s paid for fuel imports $e_{a,s}$, adding the second, the terms-of-trade effect. The third, the emission component, expresses that foreign emission, $e_{n,s}$, are affected as well.

4.2 Disentangling climate and terms-of-trade effect

As is found in (45), when goods producers exert market power, importing (and exporting) regions may resort to 'terms-of-trade' import tariffs with levels above what purely environmental reasons justified, in order to change equilibrium prices 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). In a simple world such beggar-thy-neighbor policies reduce welfare, and they are in general in conflict with free trade principles notably within the WTO. 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; taxes imposed genuinely for the protection of the global climate may be accepted when genuine terms-of-trade taxes, aimed at distorting trade at the expense of other parties, are not. The remainder of this section analyzes how this separation can be implemented, and how the environmental-only component, used in the remainder of the paper, can be calculated. The next section shows that the optimal emissions tax disregarding terms-of-trade benefits is directly related to a net present damage adjusted dynamic leakage rate.

For complex extraction cost and demand curves, explicitly calculating the optimal regional tax according to (45) may be tedious, potentially infeasible analytically. Conveniently, the numerical calculation of the tax that maximizes the domestic utility can, however, provide the numerical values of that regionally optimal tax path $\bar{\tau}_t^*$. This could be done with or without taking environmental damages into account, and the difference between the two resulting taxes could be thought as a first approximation of the optimal environmental-only tax. But, as is visible in (45), the terms-of-trade effect on the optimal tax is proportional to the domestic fuel consumption, e_a, and is therefore directly affected by the level of (the environmental component of) the tax. Approximating the environmental-only tax as the difference between the tax levels that maximize the regional utility with climate damage and without introduces therefore a first-order bias and would therefore, as Habermacher (2013b) shows for the static case, tend to underestimate the environmental-only tax. As the next subsection shows, a simple compensation method allows the calculation of the terms-of-trade disregarding, environmental-only tax component, as a utility-maximizing tax path.

Compensation Method

To neutralize terms-of-trade effects in the calculation of the optimal pollution tax, we 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 optimal in the hypothetical presence of leakage in the absence of price-effects in a static model with an external producer and a passive fringe consumer (and the corresponding carbon leakage) is shown in Habermacher (2013b).[20]

Here we extend this result, showing 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.[21] We use the same framework as in section 4.1, but with transfer payments. Regional welfare is $W_i \equiv z_i + \int_0^\infty \mathrm{e}^{-\rho t} u_i(e_{i,t}) - H_{i,t} \mathrm{d}t$, where z is (present) consumption of a numeraire good, which, assuming perfect capital markets, can also be interpreted as a shortcut for the NPV of a consumption path $\zeta_{i,t}$ with $z_i = \int_0^\infty \mathrm{e}^{-\rho t} \zeta_{i,t} \mathrm{d}t$. For the domestic region, which may pay transfers Tr_n and Tr_e to the foreign region n and the fuel producers indexed e, the budget constraint is $z_{0,a} = z_a + Tr_n + Tr_e + \int_0^\infty \mathrm{e}^{-\rho t} e_{a,t} p_t \mathrm{d}t$. For the foreign region, potentially receiving the transfer Tr_n, it writes $z_{0,n} + Tr_n = z_n + \int_0^\infty \mathrm{e}^{-\rho t} e_{n,t} p_t \mathrm{d}t$. Producer welfare W_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, $W_e \equiv Tr_e + \int_0^\infty \mathrm{e}^{-\rho t} (p_t - c_t) e_t \mathrm{d}t$, with e_t the global fuel consumption, p_t the sales price, and c_t the extraction costs.

To separate climate from the terms-of-trade effects, we switch off the latter by requiring the domestic region to provide transfer payments that set off losses or gains the other two parties would otherwise experience from the domestic policy. The transfers compensate for changes in non-green welfares; that is, for a given policy, climate damage does not enter 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, $\int_0^\infty \mathrm{e}^{-\rho t} [\underbrace{u_a(e_{a,t}) + u_n(e_{n,t})}_{\text{consumption value}} - \underbrace{(e_{a,t} + e_{n,t})\, c_t}_{\text{production costs}}] \mathrm{d}t$, is maximized without

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[20] This result is closely related to what Böhringer et al. (2010) have shown in their static framework, with fuel consumption by industrial sectors.

[21] The extension to fuel-production distributed among the two consuming regions is straightforward.

any policy influencing the regional consumers or distorting the fuel producers' 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 $\hat{W}$. 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, H_t, are overall subtracted from the regional consumption utilities: $\max_{e_a} \hat{W} = \int_0^\infty \mathrm{e}^{-\rho t} \left[u_a(e_{a,t}) + u_n(e_{n,t}) - e_t c_t - H_t\right] \mathrm{d}t$, with both, the marginal extraction costs and the instantaneous damage (increasing) functions of cumulative emissions, $c_t = c\left(\int_0^t e_s \mathrm{d}s\right)$, $H_t = H\left(\int_0^t e_s \mathrm{d}s\right)$, with e_n implicitly defined by (43) and (35).

Assuming a unique internal solution to obtain, the standard FOC must hold. We develop

$$\begin{aligned}\frac{\mathrm{d}\hat{W}}{\mathrm{d}e_{a,t}} &= \mathrm{e}^{-\rho t} u_a'(e_{a,t}) + \int_0^\infty \mathrm{e}^{-\rho s} u_n'(e_{n,s}) \frac{\mathrm{d}e_{n,s}}{\mathrm{d}e_{a,t}} \mathrm{d}s - \mathrm{e}^{-\rho t} c_t \\ &\quad - \int_0^\infty \mathrm{e}^{-\rho s} \left[\frac{\mathrm{d}e_{n,s}}{\mathrm{d}e_{a,t}} c_s + e_s \frac{\mathrm{d}c_s}{\mathrm{d}e_{a,t}}\right] \mathrm{d}s - \int_t^\infty \mathrm{e}^{-\rho s} h_s \mathrm{d}s \\ &\quad - \int_0^\infty \mathrm{e}^{-\rho s} h_s \int_0^s \frac{\mathrm{d}e_{n,w}}{\mathrm{d}e_{a,t}} \mathrm{d}w \mathrm{d}s.\end{aligned}$$

From (43) and (35) we have $u_n'(e_{n,t}) = c_t + \int_t^\infty \mathrm{e}^{-\rho(s-t)} \dot{c}_s \mathrm{d}s$. This implies

$$\begin{aligned}\frac{\mathrm{d}\hat{W}}{\mathrm{d}e_{a,t}} &= \mathrm{e}^{-\rho t} u_a'(e_{a,t}) + \underbrace{\int_0^\infty \mathrm{e}^{-\rho s} \left[\int_s^\infty \mathrm{e}^{-\rho(w-s)} \dot{c}_w \mathrm{d}w\right] \frac{\mathrm{d}e_{n,s}}{\mathrm{d}e_{a,t}} \mathrm{d}s}_{I_1} - \mathrm{e}^{-\rho t} c_t \\ &\quad \underbrace{- \int_0^\infty \mathrm{e}^{-\rho s} e_s \frac{\mathrm{d}c_s}{\mathrm{d}e_{a,t}} \mathrm{d}s}_{I_2} - \int_t^\infty \mathrm{e}^{-\rho s} h_s \mathrm{d}s - \int_0^\infty \mathrm{e}^{-\rho s} h_s \int_0^s \frac{\mathrm{d}e_{n,w}}{\mathrm{d}e_{a,t}} \mathrm{d}w \mathrm{d}s.\end{aligned} \tag{46}$$

Annex F shows that terms I_1 and I_2 in (46) cancel out, yielding (47).

$$\frac{\mathrm{d}\hat{W}}{\mathrm{d}e_{a,t}} = \mathrm{e}^{-\rho t} \left[u_a'(e_{a,t}) - c_t\right] - \int_t^\infty \mathrm{e}^{-\rho s} \left[\dot{c}_s + h_s \left(1 + \int_0^s \frac{\mathrm{d}e_{n,w}}{\mathrm{d}e_{a,t}} \mathrm{d}w\right)\right] \mathrm{d}s. \tag{47}$$

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

$$u_a'(e_{a,t}) = c_t + \int_t^\infty \mathrm{e}^{-\rho(s-t)} \left[\dot{c}_s + h_s \left(1 + \int_0^s \frac{\mathrm{d}e_{n,w}}{\mathrm{d}e_{a,t}} \mathrm{d}w\right)\right] \mathrm{d}s. \tag{48}$$

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

$$u_a'(e_{a,t}) = p_t + \tau_t.$$

Recall from (35) that the competitive suppliers set $p_t = c_t + \int_t^\infty \mathrm{e}^{-\rho(s-t)} \dot{c}_s \mathrm{d}s$. For the tax τ_t to sustain the optimal consumption level according to (48), we thus find

$$\tau_t^* = \underbrace{\int_t^\infty \mathrm{e}^{-\rho(s-t)} h_s \mathrm{d}s}_{\text{direct damage}} + \underbrace{\int_0^\infty \mathrm{e}^{-\rho(s-t)} h_s \int_0^s \frac{\mathrm{d}e_{n,w}}{\mathrm{d}e_{a,t}} \mathrm{d}w \mathrm{d}s}_{\text{leakage}}. \tag{49}$$

As conceived, the hypothetical compensation payment has neutralized the terms-of-trade effect from (45). Only the direct domestic pollution component, equal to the optimal global tax τ_{Pigou} from (42) (abstracting from foreign emission damage), and the leakage component, remain in the optimal unilateral 'climate-only' tax (49). The leakage component 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 together determine the optimal unilateral 'climate-only' tax level.

4.3 Definition of leakage rates

The previous sections have shown that the tax rates of the optimal, climate-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 (45) and (49). That is, the optimal tax at time t does not directly depend on the response of *domestic* emissions at other periods, $e_{a,s\neq t}$, to changes in current emissions at time t, $e_{a,t}$.[22] Correspondingly, the remainder focuses on leakage rates expressing the foreign offsetting of instantaneous domestic emission reductions when other domestic emissions are held constant, i.e. the impulse-response of foreign emissions to domestic emission changes. These are the welfare relevant leakage rates, to which the optimal unilateral 'climate-only' is proportional according to (49).

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

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[22] 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. Technically, it may be 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 of choice variables, from other time periods with respect to current choice variables, become irrelevant in the optimality condition. Even if leakage will make the policymaker set the tax in a different period s below the Pigouvian, the tax τ_s per se allows the policymaker to freely choose the consumption level during this period s.

$$\text{Absolute leakage rate: } \mathrm{ALR}_t \equiv \int_0^\infty \frac{-\mathrm{d}e_{n,s}}{\mathrm{d}e_{a,t}} \mathrm{d}s,$$

where the time-horizon is normalized so that it starts at the period from which the tax from period t is anticipated, and, theoretically, lasts until infinity. In the numerical simulations below we focus on taxes at the beginning of the simulation horizon, $t = 0$, thought of as today.[23]

We define the NPV leakage rate, NLR, as the fraction of domestic emission reductions offset abroad in terms of the NPV value of emissions,

$$\text{NPV leakage rate: } \mathrm{NLR}_t \equiv \int_0^\infty \mathrm{e}^{-\rho(s-t)} \frac{-\mathrm{d}e_{n,s}}{\mathrm{d}e_{a,t}} \mathrm{d}s, \tag{50}$$

with ρ the corresponding discount rate for the emissions.

We call damage leakage rate (DLR) the rate which is directly related to the optimal unilateral overall or climate-only carbon tax. It is the fraction, in NPV terms, of the direct damage reduction related to a domestic emission cut offset by damage increases implied by the response of foreign emissions throughout the considered time horizon,

$$\begin{aligned} \text{Damage leakage rate: } \mathrm{DLR}_t &\equiv \frac{\int_0^\infty \frac{-\mathrm{d}e_{n,w}}{\mathrm{d}e_{a,t}} \int_0^\infty \mathrm{e}^{-\rho s} \frac{\partial H_s}{\partial e_{n,w}} \mathrm{d}s\mathrm{d}w}{\int_0^\infty \mathrm{e}^{-\rho w} \frac{\partial H_w}{\partial e_{a,t}} \mathrm{d}w} \\ &= \frac{\int_0^\infty \mathrm{e}^{-\rho(s-t)} h_s \int_0^s \frac{-\mathrm{d}e_{n,w}}{\mathrm{d}e_{a,t}} \mathrm{d}w\mathrm{d}s}{\int_t^\infty \mathrm{e}^{-\rho(s-t)} h_s \mathrm{d}s}, \end{aligned} \tag{51}$$

where it is important to note that $\frac{\partial H}{\partial e_{i,t}}$ is the partial derivative (as opposed to the total derivatives $\frac{\mathrm{d}(\cdot)}{\mathrm{d}(\cdot)}$ taken elsewhere) of damage H with respect to emissions of region i at time t, $e_{i,t}$, holding emissions elsewhere (and in other periods) constant.[24] The second equality follows from what we noted for the FOC in section 4.1 on the unilateral committed policy, cf. (44). With this definition of the DLR, the optimal pollution-only tax from the committed policy (49) can be rewritten as

$$\tau_t^* = \underbrace{\int_t^\infty \mathrm{e}^{-\rho(s-t)} h_s \mathrm{d}s}_{\text{direct damage}} \cdot (1 - \mathrm{DLR}_t) = \tau_{Pigou,t} \cdot (1 - \mathrm{DLR}_t), \tag{52}$$

confirming that DLR_t is the welfare relevant dynamic equivalent of the simple leakage rate of a static model (cf. Annex E). In combination with Proposition 1a we see that

Proposition 1b. 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

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[23] Habermacher (2013b) considers also anticipated future taxes from committed policies.

[24] The derivative $\frac{\partial H}{\partial e_{i,t}}$ does not depend on i.

negative when $\text{DLR}_t > 1$:

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

With a constant marginal damage h, (51) simplifies to $\text{DLR}_t = \rho \mathrm{e}^{\rho t} \int_0^\infty \mathrm{e}^{-\rho s} \int_0^s \frac{-\mathrm{d}e_{n,w}}{\mathrm{d}e_{a,t}} \mathrm{d}w \mathrm{d}s = \rho \mathrm{e}^{\rho t} \int_0^\infty \mathrm{e}^{-\rho s} \frac{-\mathrm{d}e_{n,s}}{\mathrm{d}e_{a,t}} / \rho \mathrm{d}s$. For a linear damage function $H(E)$ we thus have NLR = DLR.

5 Fuel supply dynamics as key determinant of leakage

To give a flavor of how the future evolution of the fuel market may impact medium- and longer-run carbon leakage, this section analyzes OECD carbon abatement, and the leakage thereof, using a calibrated dynamic numerical fuel market model. It accounts for the two dominant fossil fuels, oil and coal, for which we consider estimated long-run extraction cost curves. The model allows for substitution between fuels, for a clean backstop whose price declines over time and which endogenously replaces fuels in the future, as well as for coal liquefaction, complementing liquid fuel supply as soon as the scarcity of crude oil renders the liquefaction process economic. Sections 5.1 and 5.2 describe and illustrate the model, section 5.3 illustrates theoretical results from section 4, and section 5.4 estimates emission response functions and leakage rates within different setups. Absolute, as well as present discounted leakage rate magnitudes are very large. They are highly sensitive to the assumptions about the future fuel market framework, allowing for both, negative leakage rates as well as for leakage rates above 100 % for oil emissions.

5.1 Model

Setup

The basic structure of the model from section 4.1 is extended to the case of two substitutable fuels, oil and coal, indexed by $f = \{\text{oil}, \text{coal}\}$. These fuels are today responsible for 80 % of energy supply carbon emissions.[25] Fuel demand may grow over time, and optionally a clean backstop, or coal liquefaction may emerge as soon as economical.

We start by abstracting from liquefaction. International fossil fuel prices are p_f, and the regional consumption rates, in emission equivalents, $e_{f,i}$. Energy Y is the sum of the consumption of a constant elasticity of substitution (CES) aggregate fuel aggregate, $F_{i,t} \equiv [\beta_i e_{\text{oil},i,t}^{\frac{\varsigma-1}{\varsigma}} + (1-\beta_i) e_{\text{coal},i,t}^{\frac{\varsigma-1}{\varsigma}}]^{\frac{\varsigma}{\varsigma-1}}$, and, if allowed for, a clean backstop B_i, $Y_i \equiv F_i + B_i$. The backstop may be provided at any given demand rate (infinite elasticity) for an exogenous

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[25] Cf. IEA (2012). Annex G gives more detailed explanation for the focus on oil and coal.

price which varies over time, $p_{B,t}$. Supply of both the aggregate fuel and (if not idled) the clean backstop is readily modeled with complementary slackness conditions with respect to the weakly positive difference of their prices to the overall energy price $p_{Y,i}$,

$$\begin{aligned} F_i \geq 0 \quad &\perp \quad p_{F,i} - p_{Y,i} \geq 0 \\ B_i \geq 0 \quad &\perp \quad p_B - p_{Y,i} \geq 0. \end{aligned}$$

The global emission rate is the sum of fuel consumption rates across all regions and fuels, $e_t \equiv \Sigma_{f,i} e_{f,i,t}$. As the natural extension from the single-fuel setup in 4.1, and following Golombek et al. (1995), instantaneous regional utility $U_{i,t}$ contains the three linearly separable terms (i) energy consumption utility, $u_{i,t}(Y_{i,t})$, (ii) costs for aggregate energy provision $p_{Y,i,t} Y_{i,t}$, and (iii) regionally perceived environmental emission costs, $H_{i,t}$, which we model as a function of cumulative global emissions, $H_i(E_t)$, where $E_t \equiv \int_0^t e_s \mathrm{d}s$:

$$U_{i,t} \equiv u_{i,t}(Y_{i,t}) - p_{Y,i,t} Y_{i,t} - H_i(E_t).$$

Denoting ρ the consumer time discount rate, the total regional welfare is the present value sum of instantaneous utilities, $W_i \equiv \int_0^T \mathrm{e}^{-\rho t} U_{i,t} \mathrm{d}t$.

Fuel consumption utility is $u_{i,t} \equiv \frac{1}{1+1/\eta} \xi_t Y_{i,t}^{1+1/\eta}$, with a negative demand elasticity parameter $\eta < 0$, so the FOC for decentralized consumption yields $Y_{i,t} = (\xi_t / p_{Y,i,t})^{-\eta}$. The CES aggregation implies the unitary fuel aggregate cost $p_{F,i} = [\beta_i^{\varsigma} (p_{\text{oil}} + \tau_{\text{oil},i})^{1-\varsigma} + (1 - \beta_i)^{\varsigma} (p_{\text{coal}} + \tau_{\text{coal},i})^{1-\varsigma}]^{\frac{1}{1-\varsigma}}$, with $\tau_{f,i}$ the regional fuel specific taxes. The cost-minimizing factor demands for a specific aggregate fuel consumption level F_i are $e_{\text{oil},i} = F_i \cdot \left(\frac{\beta_i p_{F,i}}{p_{\text{oil}} + \tau_{\text{oil},i}} \right)^{\varsigma}$ and $e_{\text{coal},i} = F_i \cdot \left(\frac{(1-\beta_i) p_{F,i}}{p_{\text{coal}} + \tau_{\text{coal},i}} \right)^{\varsigma}$.

An extension of 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. Similarly to the emergence of the clean backstop, the model implementation of the process uses a complementary slackness condition: the synthetic oil representing a perfect substitute for genuine oil, and the overall costs of the process per unit of synthetic liquid fuel produced represent an upper bound for the oil sales price such that demand that cannot be met by genuine oil supply for that price will be met by synthetic fuel from coal-liquefaction. As the price for the input into the process, coal, rises over time, both types of liquid fuel may be consumed simultaneously over an indefinite time period. In the end-use the synthetic liquid has the same emission intensity as oil. But the additional carbon content of the coal used for the process is released during the conversion that takes place outside of the abating region.

Similarly as in section 3.1, suppliers sell their fuels on the international market under perfect competition. In addition to the stock-dependent basic extraction cost curve, the model optionally allows accounting for an extraction *rate* dependent cost component κ_f that increases both, in the extraction rate, $e_f \equiv \Sigma_i e_{f,i}$, and in the difficulty of the access to the reserves, indexed by the overall progress of extraction, A_f: $\kappa_f(e_f, A_f) \geq 0$, $\partial\kappa_f(e, A)/\partial e > 0$, $\partial\kappa_f(e, A)/\partial A > 0$. The current-value Hamiltonian for the profit maximization problem for the fuel owners reads

$$\begin{aligned} \mathcal{H}_f \quad &\equiv \quad e_{f,t} \cdot [p_{f,t}(e_{f,t}) - c_f(A_{f,t}) - \kappa_f(e_{f,t}, A_{f,t})] - \lambda_{f,t} e_{f,t} \\ &\text{s.t.} \quad \dot{A}_{f,t} = e_{f,t} \,\text{and}\, A_{f,0} \equiv 0, \text{ i.e. } A_{f,t} = \int_0^t e_{f,s} \mathrm{d}s, \end{aligned} \tag{53}$$

with $c_f(A_f)$ the marginal extraction cost, and $p_{f,t}(e_f)$ the inverse demand for the considered fuel at time t: the price $p_{f,t}$ resulting on the international fuel market according to the demand described above for a supply at rate e_f.[26] As we will see, the rate-dependent costs will not affect the core results with respect to the judgment on the relevance of the leakage, but this additional cost component can reconcile modeled extraction with the currently observed fuel consumption rates and prices.

The Hamiltonian yields the stationary condition and canonical equation

$$\begin{aligned} \frac{\partial\mathcal{H}_f}{\partial e_{f,t}} = 0 : \quad & p_{f,t}(e_{f,t}) = c_f(A_{f,t}) + \kappa_f(e_{f,t}, A_{f,t}) + \lambda_{f,t} \\ \dot{\lambda}_{f,t} = \rho_r \lambda_{f,t} + \frac{\partial\mathcal{H}_f}{\partial A_{f,t}} : \quad & \dot{\lambda}_{f,t} = \lambda_{f,t}\rho_r - \dot{c}_{f,t} - e_{f,t}\partial\kappa_f(e_{f,t}, A_{f,t})/\partial A, \end{aligned} \tag{54}$$

where we use $c_{f,t} \equiv c_f(A_{f,t})$,[27] and $\rho_r > 0$ is the revenue discount rate. Strictly speaking, the representation of rate-dependent extraction extra-costs, and their expression in (54), is consistent for the case of multiple, heterogeneous reserves offered competitively only in the sense of an additional cost that depends on the *global* extraction rate, which could be thought of as, e.g., higher prices of globally supplied, extraction related capital or services. More simply it may, however, be considered an approximation to the case of geology-based, field-specific extra costs.

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 rest of the world (ROW) (see Annex H), and to the desired direct- and cross-price elasticities of the demand.[28] 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 a fuel demand elasticity slightly below unity, $\eta =$

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[26] With non-zero cross-price elasticities of fuel demand, $p_{f,t}$ may also depend on the amount of the other fuel supplied at time t.

[27] Note that as $e_{f,t} = \frac{\partial A_{f,t}}{\partial t}$, we have $\dot{c}_{f,t} \equiv \frac{\partial c_f(A_{f,t})}{\partial t} = \frac{\partial A_{f,t}}{\partial t}\frac{\partial c_f(A_{f,t})}{\partial A_{f,t}} = e_{f,t}\frac{\partial c_f(A_{f,t})}{\partial A_{f,t}}$.

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

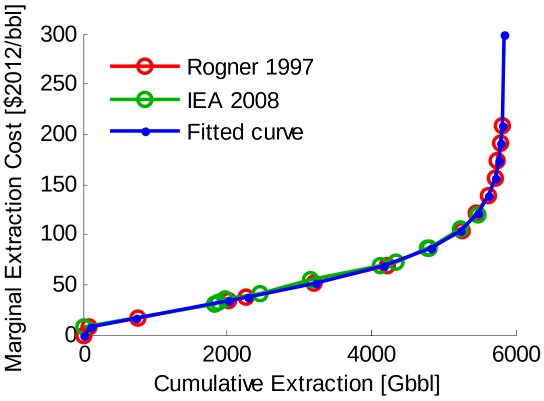

Figure 4: Oil extraction cost curves

-0.9, and a weak substitutability of the fuels, $\varsigma = 1.1$. In line with literature, the weak substitutability between oil and coal mainly expresses the difficulty of replacing oil, in its major applications, by the solid fuel coal (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).[29] The possibility of deriving synthetic oil from coal liquefaction is modeled as a separate process.

For oil, which depletes faster than coal, the form of the extraction cost curve is relevant. It is defined through the inverse function, the curve giving the cumulative extraction $A_{\text{oil},t}$ corresponding to a given marginal cost, $A_{\text{oil}}(c_{\text{oil},t})$. The functional form $A_{\text{oil}}(c_{\text{oil}}) = \mu_1/(1 + \mu_2 \mathrm{e}^{\mu_3 c_{\text{oil}}} + \mu_4 \mathrm{e}^{\mu_5 c_{\text{oil}}})$ proved to allow a very close fit to the extraction cost curve by Rogner (1997), cf. Fig. 4. The figure also shows the good correspondence to the more recent IEA (2008) data. Annex H describes the coal cost curve.

To explore qualitatively different scenarios, we consider two discounting schemes. The heterogeneous discounting scheme consists of a modest discount rate for emissions, $\rho = 0.5\,\%$, and a higher fuel owner discount rate, $\rho_r = 5\,\%$.[30] The homogeneous discounting scheme consists of equal discount rates for the fuel consumers and for the fuel producer, $\rho = \rho_r = 3\,\%$, as an attempted compromise between the in reality probably often rather

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[29] Golombek et al. (1995) used -0.9 for the direct fuel consumption price elasticities in the OECD and -0.75 in the ROW, and cross-price elasticities of 0.1, on average. Here, the larger demand elasticity (in absolute terms) in the ROW 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.

[30] A time-discount rate of 5 ‰ 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 ‰. Growth of the economy can lift the social discount rate to values above the pure-time rate, but may lower it if the intertemporal elasticity of consumption does not exceed one, or if part of growth is due to population increases. An extended discussion of the reasons for higher and lower values for the controversial discount factor is beyond the aim of the present study whose purpose is exploratory rather than to provide precise quantitative results. E.g. Schelling (1995) explains why market interest rates may have little to do with appropriate emission discount rates.

large discount rates of fuel extractors and the potentially limited impatience of a regional planner in the fuel consuming regions.[31] Fuel emission intensities are 0.43 $\mathrm{tCO_2}$/bbl for crude oil and 2.8 $\mathrm{tCO_2}$/tonne for coal.

Liquefaction requires 1 tonne of coal per 2 barrels of synthetic oil produced (DOE/NETL, 2006; Bartis et al., 2008).[32] 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 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 subject to a constant transformation cost for each barrel of synthetic fuel produced, c_{liq}=\$10/bbl.

The clean backstop price is assumed to approach a level of \$200 per bbl-eq. of aggregate fossil energy substituted, 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, we consider simulation horizons of up to 400 years. Transitions to the backstop, and the emergence of liquefaction, take place much earlier, so the standard setup considers a horizon limited to 200 years, implicitly assuming an external political measure, as discussed in section 3, to displace fossil fuels at the end of that period.

Regional energy demand may initially grow, but we assume the growth rates to approach zero in the long run, decaying at 3 % per year. The initial demand growth rates are 0 % in the OECD and 3 % in the ROW in the main setup, as is roughly in line with IEA scenario data (cf. Habermacher, 2013c). An alternative calibration considers constant demand.

A proportionality factor k_f was calibrated for both fuels such that using a rate dependent cost component $\kappa_f(e_{f,t}, A_{f,t}) \equiv k_f \frac{e_{f,t}}{S_f - 0.8 A_{f,t}}$ roughly reconciled initial fuel prices in the model and today's fuel prices (Fig. 5), when S_f is the initial stock of resources.[33]

Only the DLRs require specification of the damage function H, and only up to a certain proportionality factor. Climate damages are widely considered strongly convex in cumulative emissions. Since calibrated climate damage functions are often approximated as quadratic in emissions, we assume an instantaneous damage function which is proportional to the square of cumulative emissions.[34] Accounting for the approximately half a trillion

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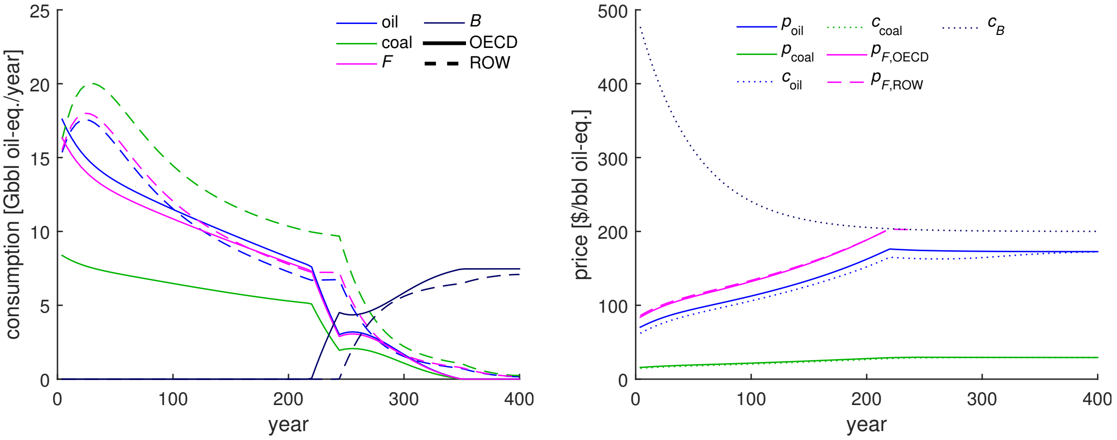
[31] The compensation method for disentangling the pollution and the terms-of-trade component of the optimal unilateral fuel tax described in section 4 assumes equal discount rates for all involved actors.

[32] 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 bbl/tonne (Bartis et al., 2008).

[33] Specifically, we used S_{oil}=6000 Gbbl, S_{coal}=15 000 Gt and reached initial prices of \$70/bbl and \$79/tCoal.

[34] This is also convenient as, except for today's historic cumulative emissions, no additional parameter needs to be specified.



(a) Consumption ***(b)*** Prices

Figure 5: Simulation results with growth, backstop, and rate-dependent extraction costs
Resource owner discount rate $\rho_r = 5\,\%$

tons of (anthropogenic) carbon, or 1835 GtCO$_2$ that have been emitted until today (Allen et al., 2009), the damages $H(E)$ after the cumulative emission E from today on are thus proportional[35] to $H(E) \propto (0.5\,\mathrm{TtC} + E_{\mathrm{TtC}})^2$ and thus $H'(E) \propto 2(1835\,\mathrm{GtCO_2} + E_{\mathrm{GtCO_2}})^2$. 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, the cumulative emissions up to time T, E_T create, for the time after T, a NPV damage of $H(E_T) \int_0^\infty \mathrm{e}^{-\rho(s+T)} \mathrm{d}s = H(E_T) \frac{1}{\rho} \mathrm{e}^{-\rho T}$.

5.2 Resource dynamics

Fig. 5 illustrates the model behavior in a setup with demand growth and the endogenous regional emergence of the backstop, as well as rate-dependent extraction costs (Annex I illustrates the outcome with the base setup without backstop). Left shows the regional fuel and backstop consumption paths. Owing its demand growth, the non-OECD world increases the consumption of both fuels during the first decades, before consumption eventually starts to fall towards the end of the first half of the century, due to the rising fuel prices, plotted right. After roughly two centuries, fuel extraction becomes so expensive that the resource rents (the difference between the fuel prices and the extraction costs) approach zero and fossil fuel eventually gives place to the backstop energy, at a roughly similar time in both regions. From then on, fuel consumption will slightly increase over

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[35] 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 neglects 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. Oil and coal contributes 80 % of manmade energy related emissions.

time despite the stable demand, as the backstop price keeps approaching its lower asymptotic level.

5.3 Optimal tax and decomposition application

The theoretical section 4 analyzed the regional utility-maximizing emissions tax and its decomposition into the terms-of-trade and the purely environmental components in a dynamic framework, as well as the relationship between the environmental tax and leakage rates. Before analyzing leakage rates in key scenarios in the next section, we briefly illustrate key insights from section 4 with results from simulations with the numerical model.

We run the model over a horizon of 165 years[36] without backstop and liquefaction, and assume extraction to stop at the end of that period. We use the homogeneous discount scheme, $\rho = \rho_r = 3\,\%$. The quadratic damage function is calibrated so that the annual emission damage at the beginning of the simulation horizon, i.e., at today's concentration levels, yields an annual damage of h_0=\$1/tonne, which in equilibrium will yield a social NPV cost of current carbon emissions rising from \$54/tonne at the beginning of the period to \$101/tonne in year 100. Considering an environmental-only emissions tax homogoenous across fuels for the same periods, the regionally optimal level estimated with the compensation method (section 4.2) rises from τ_1^*=\$43/tonne to τ_{100}^*=\$51/tonne. The reaction of foreign emissions to domestic fuel consumption changes with a marginal variation of the domestic tax around this regionally optimal level yield a damage leakage rate $\mathrm{DLR}_0 = 21\,\%$ at the beginning of the horizon, confirming (52), stating that the optimal regional environmental tax level τ_t^* is $1 - \mathrm{DLR}_t$ times the social emission cost of the same period, h_t.

Over the model horizon, the tax $\bar{\tau}_t^*$ which maximizes unilateral welfare, taking into account terms-of-trade gains, averages \$89/tonne when accounting for climate damages, and at \$54/tonne when ignoring these damages. As conjectured in section 4.2, an estimate of the optimal environmental-only tax as the difference of these two values, yielding \$36/tonne, would be an underestimation compared to the welfare relevant values τ_t^*, who average \$48/tonne.

The environmental-only OECD tax path τ_t^* is calculated as the tax which maximizes global surplus, denoted $\hat{W}$ in section 4.2. By setting the regional tax (homogeneous across fuels) to that regionally optimal environmental-only level τ_t^* that accounts for leakage, the OECD increases the global social surplus by \$306bn relative to the level that would be achieved if the tax was chosen such as to correspond to the social cost of carbon in

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[36] The numerical implementation uses 330 periods, and to achieve a high numerical precision we limit the time-step duration to 0.5 years.

equilibrium, ignoring leakage, $\tau_{Pigou,t}$.[37] Leakage rates, and accordingly the optimal taxes, differ across fuels. For example, corresponding to damage leakage rates of 73 % for oil and 37 % for coal, the optimal environmental-only taxes in year 100 are found \$27/tonne and \$63/tonne for emissions from these two fuels, with the social cost of global emissions at \$101/tonne at that time. The move from the unilateral homogeneous to the optimal unilateral fuel-specific tax path increases the social surplus, by \$41bn in the example.

The leakage rates appear very robust to whether they are calculated for marginal-only taxes or for marginal tax variations around the optimal pollution-only regional tax, or for the non-marginal tax change from zero to the optimal path's values.[38]

5.4 Emission impulse response and leakage from OECD tax

Section 3 emphasized that discount rates and future technological or political developments determining the fuel horizon, i.e. the time frame within which fossil fuels are going to be used, affect the relevant leakage rates significantly. To give a flavor of how the considered leakage rates could depend on additional future events, this section focuses on a number of specific developments that could plausibly affect the fuel supply dynamics and significantly affect the to be expected leakage rates from currently imposed unilateral climate measures. Even without altering the assumptions about the current fuel market framework, depending on which developments take place in the future, leakage rates for current fuel emission taxes may be negative, or strongly positive, and even above 100 %, for both discounting schemes.[39]

We consider taxes of a duration of 30 years. Section 4 indentified the welfare relevant leakage rate (DLR) for a tax at a specific point in time as an integral over the foreign emission impulse response function to the within-period domestic emission change induced by the tax, and the two alternative leakage measures, ALR and NLR, were defined as integrals over the same emission responses. The 'impulses', i.e. the domestic emission reductions, based on which the emission reactions and leakage rates are calculated, are

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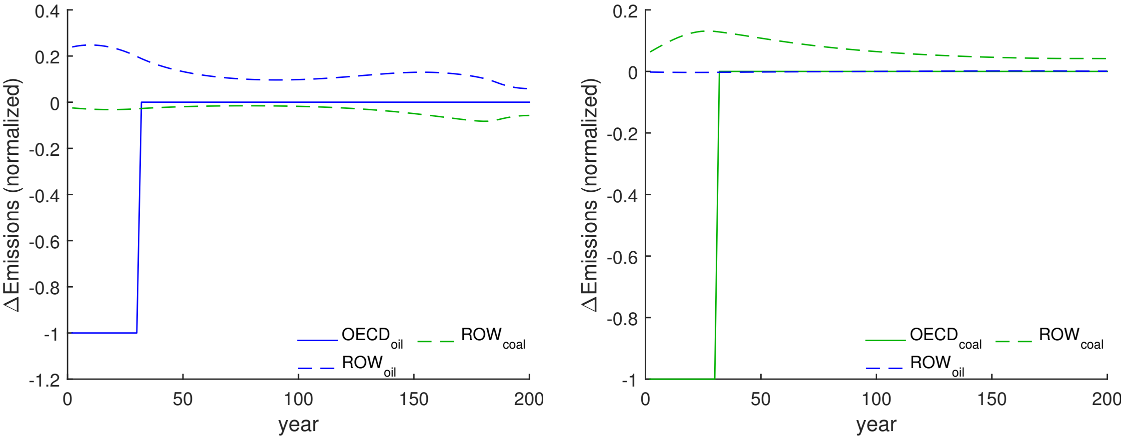
[37] Compared to the situation absent any taxes, the regional pollution-only tax τ_t^* increases global surplus by \$6065bn (NPV) in the simulation. If taxes are not restricted to the OECD, the regional fuel emission tax levels as maximands of global welfare in the model are, as expected, found to correspond to the social cost path, $\tau_{Pigou,t}$, in equilibrium for both regions and fuels. Global welfare would increase by \$22 558bn, substantially more than with the OECD-only taxes, emphasizing the losses incurred by regional constraints on the emission taxes.

[38] Habermacher (2013b) provides more details. For simulations conducted in a basic setup, a long-run emission damage of \$40/tCO$_2$ (and higher in current value for later emissions as cumulative emissions increase over time), the two leakage rates differ by around two percentage points (around 5 % in relative terms) over the following century. As damage leakage rates of roughly 50 %, the estimated corresponding tax rates differed by similar values.

[39] Habermacher (2013c) contains a detailed examination of leakage paths from a model similar to that used here, considering also effects in settings with a single fuel and different supply cost curves as well as various additional sensitivities, with dynamic emission impulse response functions for both, current as well as (anticipated) future taxes.



(a) Oil ***(b)*** Coal

Figure 6: Emission impulse response, base setup

Normalized ROW emission impulse response functions to OECD oil consumption reduction (-2.9 Gbbl oil during first 30 years, left plot), and OECD coal consumption reduction (-3.7 Gbbl-eq. coal, right plot). Resource owner discount rate $\rho_r = 5\,\%$

2.9 Gbbl/year for oil, and 3.7 Gbbl-eq./year for coal, roughly corresponding to the impact of \$40/tCO$_2$ taxes on the respective fuel sustained for 30 years.[40] The emission response functions are very stable over different magnitudes of domestic emission reductions, and thus over the level of the implicit 30-year tax.[41]

Base setup

In the basic setup we use a model horizon of 200 years to look at longer-term leakage from a unilateral emission reduction during the first 30 years, in a scenario with growing fuel demand and where neither a clean backstop, nor liquefaction disrupts the business-as-usual fuel market framework. Fig. 11 in Annex I provides the energy consumption and price dynamics for this scenario. Fig. 6 plots the welfare relevant foreign emission impulse response functions to the unilateral emission reduction for the initial OECD fuel consumption reduction measures during the first 30 years, for the heterogeneous discounting scheme (5 % fuel-owner discount rate).

The impulse responses show that a relevant fraction of emissions is offset simultaneously during the tax period. A further, substantive fraction of the initial reduction is offset during the remainder of the model horizon, especially for oil, which depletes relatively faster. The substitutability of the fuels implies that as a reaction to the domestic consumption reduction in one fuel, the foreign consumption of the *other* fuel tends to be reduced as well. The relatively limited substitutability moderates this reaction. Simulations for the

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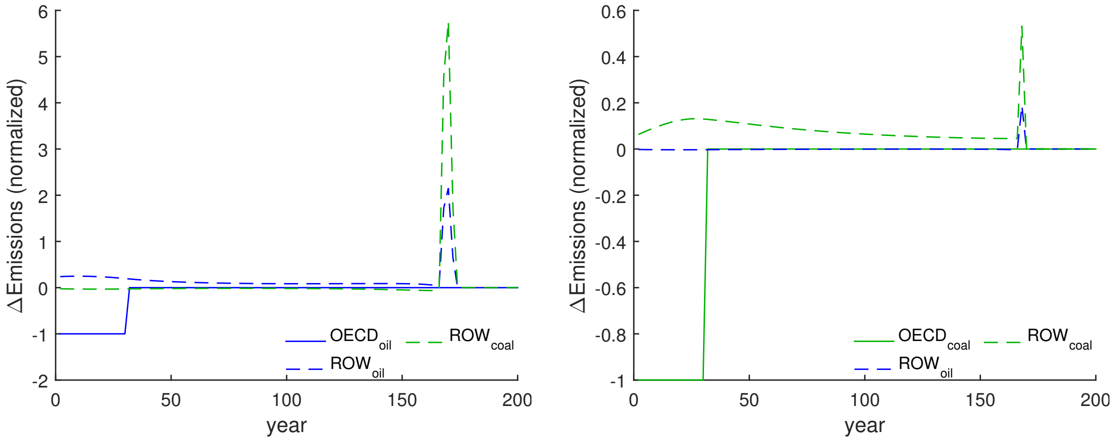
[40] These values corresponds to the average impact of a \$40/tCO$_2$ emission tax on the respective fuels in a simulation with a backstop and a long fuel-horizon as well as the extra extraction costs calibrated such as to result for initial consumption rates corresponding to today's fuel consumption rates.

[41] E.g., overlaid long-run impulse-response functions for domestic emission reductions between 0.4 Gbbl/year and 10 Gbbl/year, sustained for 30 years, are practically indistinguishable.



(a) Oil ***(b)*** Coal

Figure 7: Emission impulse response, backstop

Heterogeneous discounting scheme

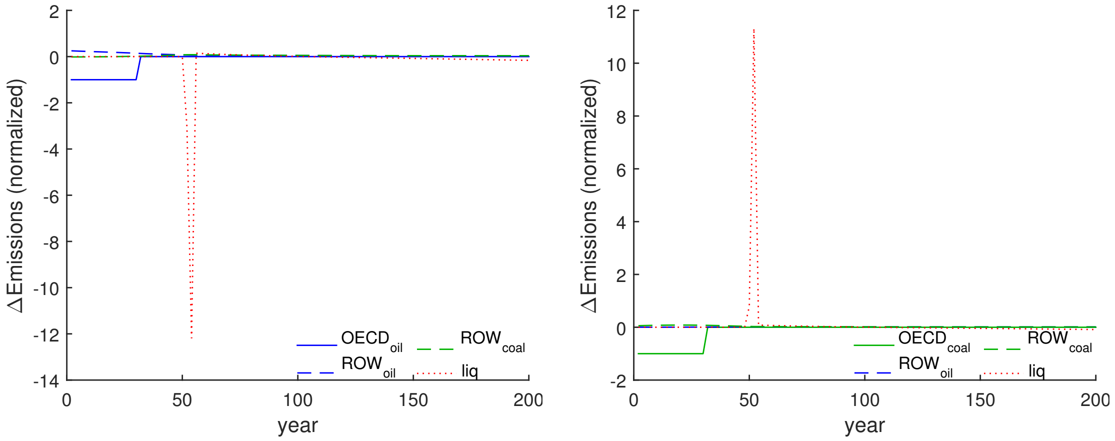
case of the homogeneous discounting scheme yield very similarly looking response functions. Habermacher (2013b) shows emission response functions for future taxes. In this case, fuel supply anticipates future taxes, increasing worldwide early emissions (Green Paradox effect).

Corresponding to the substantial offsetting, the leakage rates for the taxes, or for the unilateral emission reductions, tend to be very high. Absolute leakage rates are $\mathrm{ALR}_{\mathrm{oil}}^{Base} = 64\,\%$ and $\mathrm{ALR}_{\mathrm{coal}}^{Base} = 48\,\%$. Because of the time-delay, the welfare-relevant damage leakage rates that discount future emission damages, are lower, but they remain very substantial,$\mathrm{DLR}_{\mathrm{oil}}^{Base} = 57\,\%$ and $\mathrm{DLR}_{\mathrm{coal}}^{Base} = 42\,\%$. Considering instead the homogeneous discounting scheme (indexed with a "*"), does not greatly impact the magnitudes of the absolute leakage rates ($\mathrm{ALR}_{\mathrm{oil}}^{*Base} = 72\,\%$ and $\mathrm{ALR}_{\mathrm{coal}}^{*Base} = 46\,\%$), but the higher emission discount rate reduces the damage leakage rates ($\mathrm{DLR}_{\mathrm{oil}}^{*base} = 30\,\%$ and $\mathrm{DLR}_{\mathrm{coal}}^{*Base} = 19\,\%$). Tab. 2 in Annex I summarizes and reports NLR leakage rates.

Backstop

With a clean backstop whose price decreases over time and that replaces the fossil fuel aggregate as soon as as competitive, the leakage rates for oil can become larger than 100 % with either discounting scheme. We find $\mathrm{ALR}_{\mathrm{oil}}^{BS} = 163\,\%$ and $\mathrm{DLR}_{\mathrm{oil}}^{BS} = 125\,\%$. The impulse response plots in Fig. 7 illustrate the reason: saving oil in the OECD during the first 30 years means sparing some oil for future years and delays the time by which oil becomes so scarce that the backstop outcompetes the fossil fuel aggregate. As during the transition phase towards the backstop energy, the fossil fuel aggregate is very coal intensive (oil depletes much faster, so the aggregate becomes increasingly coal intensive), delaying the transition to the backstop technology increases emissions a lot.

For the much more abundant resource coal, this effect appears much less important; a bit



(a) Oil ***(b)*** Coal

Figure 8: Emission impulse response, liquefaction

Heterogeneous discounting scheme

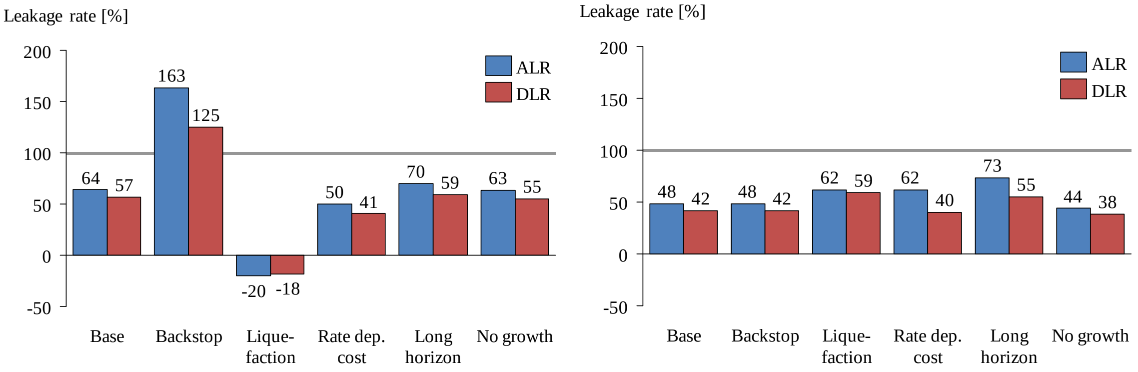
more coal underground changes the longer-run fossil aggregate price much less. Hence, the leakage rates remain substantially below unity, $\mathrm{ALR}^{BS}_{\mathrm{coal}} = 48\,\%$ and $\mathrm{DLR}^{BS}_{\mathrm{coal}} = 42\,\%$. Additional leakage rates are reported in Tab. 2 in Annex I.

Liquefaction

Fig. 12 in Annex I illustrates the resource dynamics liquefied coal emerges as a widespread supplement for the more rapidly depleting crude oil, as soon as the liquefaction process becomes economic, after a bit more than 50 years. In this scenario, a tax on oil emissions in the OECD, sparing some oil for the future, delays the time at which oil becomes so scarce that liquefaction emerges as a supplementary source for liquid fuel, as seen in the impulse response functions, Fig. 8. As it delays the emergence of the very emission intensive liquefaction process, the unilateral oil emissions tax thus reduces not only domestic emissions, but also longer-run global emission reductions, hence oil leakage rates may be negative, which we find for both discounting schemes. For heterogeneous discounting we find $\mathrm{ALR}^{Liq}_{\mathrm{oil}} = -20\,\%$ and $\mathrm{DLR}^{Liq}_{\mathrm{oil}} = -18\,\%$. The process has an opposite impact on leakage rates from coal emissions. Due to the additional use for liquefaction, coal depletes faster than in the base setup, in the long-run. Saving some coal early on delays coal exhaustion and thus leads to a faster emergence of liquefaction, increasing thus the overall pace at which domestic coal emission reductions are offset abroad. Coal leakage rates are thus higher than in the base setup without leakage, $\mathrm{ALR}^{Liq}_{\mathrm{coal}} = 62\,\%$ and $\mathrm{DLR}^{Liq}_{\mathrm{coal}} = 59\,\%$.

Further sensitivities

The summary table Tab. 2 in Annex I also lists leakage rates for a scenario with a model horizon increased to 400 years, as well as for a scenario, with the same extended model horizon, with the calibrated rate dependent extraction costs (cf. Fig. 5 for a simulation outcome with these extra costs). With the 400 year model horizon, end-of-horizon effects



(a) Oil *(b)* Coal

Figure 9: Leakage rates
Heterogeneous discounting scheme

become negligible for the welfare relevant leakage rates even in the case of the low emission discount rate. In line with the theoretical and numerical results from section 3, the extension of the fuel horizon tends to increase the leakage rates beyond those in the base setup, with absolute rates exceeding 70 %. An additional sensitivity considers a hypothetical world in which fuel demand in the non-OECD world would not grow over time. This appears to reduce leakage rates only to a minor extent. Fig. 9 gives an overview of the rates for the heterogeneous discounting scheme.

6 Discussion

This analysis can be interpreted as an attempt to reconcile a resource economics view, prominently expressed, e.g., in Sinn (2012), that unilateral abatement would be rather fruitless as it failed to curb global emissions from fossil fuels drawn from a global stock to be ultimately exhausted in any case, and the leakage literature, synthesized by Burniaux and Oliveira Martins (2012), focusing on trade and goods production elasticities to find modest leakage from unilateral action. The present results show a more nuanced picture, and suggest that both views may be too extreme.

The analytical and numerical results, based on dynamic fuel market models accounting for the fuel price and the goods trade channel of leakage, find emission leakage rates for current climate measures to strongly depend on the time spans (discounting) considered, and to vary dramatically with details assumed about the future energy market structure. Assumptions about extraction cost curves, about future economic growth, and about the emergence of liquefaction, or of an affordable clean backstop energy, are key determinants of the emission leakage to be expected for current fossil fuel savings. Without imposing very strong assumptions about the future fuel market framework, it appears impossible to indicate a narrow range for realistic leakage rates, in relevant NPV terms, even if a specific discount rate, relevant to aggregate the future emission reactions to a present value index, were agreed upon. Thus, if the present study has one overarching conclusion, this may best be described as the uncomfortable result 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 future, technical or political developments related to 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.

The skepticism expressed in this article against studies proposing low leakage rates mainly because they restrict attention to a rather static viewpoint, 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, in many situations, regional emission savings during the next few decades would ultimately be subject to a leakage of close to 100 % in terms of undiscounted emissions, at least if fuel is imported from a strongly globalized worldwide market, such as we have it today for oil but increasingly also for the other fossil fuels. The surveyed literature hardly provides substantive economic reasons why such a scenario should be impossible.

The analytical and numerical models employed here range from very stylized single-fuel models up to a calibrated small-scale CGE model with several substitutable, regional fuels and goods, in a dynamic supply setting. We generally assume the fuel extractors as forward-looking rational agents in our main scenarios. Nevertheless, we confirm the key findings also within scenarios with fully myopic fuel suppliers, and when we depart from the simple Hotelling extraction model by considering rate-dependent costs in addition to the basic stock-dependent extraction costs. Although a sensitivity analysis in a study closely related to the model in section 5, using a slightly different model,[42] 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 the present study – 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 CGE analysis than the one we here adopted from the literature. The models used abstract from influence of the energy sector on the general economic development, assuming, e.g., exogenous capital stocks and demand growth. Specifically, including an extended energy bottom-up module, and considering endogenous technological change could have a significant effect on the results. As Lanz and Rausch (2011) show, the inclusion of bottom-up elements in general equilibrium models allows to more closely follow the development of the electricity

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[42] Cf. Habermacher (2011), a 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 a dynamic version of the study by Golombek et al. (1995).

sector and fuel 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 increase the accuracy of the predictions. Thus, complementing a multisectoral top-down model with bottom-up elements concerning the (non-constant) 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 considered supply aspects with forward-looking resource owners.

Whilst the study considers the endogenous deployment of alternative energy supplies, it considers their development as exogenous. It also assumes future and foreign policy to be exogenous. Both simplifications are not harmless. The direction of the effect on leakage rates of the endogeneity of both, developments of alternative technologies and further policies, is ambiguous. Higher fuel emission taxes can on one hand be a substitute for (government) support for alternative technologies, but on the other hand the higher consumer prices can aid their development. On a policy level, unilateral action can make freeriding by the remainder of the world even more lucrative on one hand, but on the other hand there is widespread belief that leading regional policy examples would be incentives *per se* for other regions to join a coalition, and it cannot be excluded that bandwagon effects are indeed relevant. Hence, taking technology and policy endogeneity into account could even widen the range of possible leakage rates.

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. Properly accounting for such leakage effects, also by considering differentiating the regional tax rates across the fuels – warranted by the heterogeneity of leakage rates we identified across the major fuels – may not only imply an efficiency gain but specifically increase the political acceptance of unilateral action.

7 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 exhaustible fuels, and define a welfare relevant leakage rate related to it. We analyze leakage rates analytically, and in numerical fuel market models calibrated for the simulation of OECD emission reductions. In stark contrast to the bulk of the applied leakage literature, we find that leakage rates may be very large in magnitude, well above 50 % in many scenarios. Even detailed information about the economic structure of the current global economy is not sufficient to pin down leakage rates for emissions from major fossil fuels to a narrow range of possible values. Instead, the rates depend on unknown future developments. This conclusion emerges from the adoption of a dynamic viewpoint: on one hand, we take into account that rather than the simultaneous increase in foreign emissions as a response to a considered unilateral emission reduction measure, the aggregate of short-, medium- and longer-term emission reactions – the foreign 'emission response function' to the domestic emission (change) impulse – determine to which degree one considers the effectiveness of unilateral climate policies to be impaired by offsetting in other places. We define the leakage rates accordingly as the net present value of induced emission responses to a unilateral fuel consumption reduction. On the other hand, we take into account that at each point in time the forward-looking (Hotelling) fossil fuel suppliers are restricted to draw on the same initial fuel resource stock found in the earth's crust. Hence, fuel not consumed by a region in one time, may be consumed elsewhere not only simultaneously but also in later periods. Nevertheless, the case for unilateral emission reduction policies may not be as bleak as has been suggested within the resource economic literature. There is no good reason to believe that currently discussed climate policies will remain the only protection measures throughout time. If the horizon within which fossil fuel consumption is economically and politically unrestricted, is relatively limited, it may not be economic for fuel owners to increase sales in other places and times one-to-one in response to unilateral fuel consumption reductions. Hence, under the right circumstances, a substantial fraction of the spared fuel may indeed be left underground forever. Further, we find that a significant fraction of the overall emission response occurs with substantial delay. If time-preferences strongly favor emission delays, leakage rates expressed in NPV damage equivalents may be limited to values much below unity, maybe as low as 30 % for a damage discount rate of 3 % – though values may be substantially higher for more modest discount rates.

Further key determinants of carbon leakage include demand growth and the amount of fuel extractable, as well as the way how a clean backstop may at some point replace the fossil fuels. In some cases, such a backstop may even imply that oil consumption reductions within the OECD, delaying the time when the scarcity of oil renders the backstop economic, could lead to larger overall emissions, i.e., a leakage of more than 100 %. In this case, the optimal regional tax on emissions from coal exceeds the optimal tax on emissions from oil. This is, however, reversed, if in future liquefaction emerges as a globally relevant supplement to traditional liquid fuel. In this case, leakage from oil savings could be negative, warranting a high regional tax: reducing today's consumption of crude oil could delay the time when the emission intensive liquefaction process emerges.

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Annex

A Tax increases domestic but reduces foreign consumption price

Let “^{0}” index variables in the equilibrium without tax. With $e_I = \sum_{i,j} x_{i,j}/m$, (29) and (23) imply that, absent a tax, global fuel consumption, $e \equiv e_D + e_I$, is strictly decreasing in the fuel price, $\partial e^0/\partial p < 0$. Further, (23) and (26) imply that global fuel consumption strictly decreases in the tax, $\partial e/\partial \tau < 0$. For any hypothetical situation, indexed “$\tilde{}$” we thus have

$$p \lesseqgtr \tilde{p} \cap \tau \lesseqgtr 0 \cap \tilde{\tau} = 0 \implies e \gtreqless \tilde{e}. \tag{A.1}$$

This allows to show with two contradictions that $p < p^0 < p + \tau$, for a strictly positive tax $\tau > 0$:

Assume, as a first alternative, $p \geq p^0$. This implies

$$p \geq p^0 \implies p + \tau > p^0 \cap p > p^0 \overset{\text{(A.1)}}{\implies} e < e^0,$$

but simultaneous occurrence of the first and the last relation is in immediate contradiction with an upward sloping fuel supply.

Assume the second possible alternative, $p + \tau \leq p^0$. Given the symmetry of the problem, for the demand the situation under the tax would be equivalent to a hypothetical one with the negative of the tax $\tilde{\tau} = -\tau$, and a price $\tilde{p} = p + \tau \leq p^0$. Therefore, we have

$$p + \tau \leq p^0 \overset{\text{(A.1)}}{\implies} e > e^0,$$

again a contradiction with an upward sloping fuel supply. ■

B Long-run lekage with choke price

We consider the dynamic fuel market framework from section 3.1, but global demand drops to zero when the fuel market price p reaches a choke price b, interpretable as the price for an alternative clean technology. The fuel price still evolves according to (35), but fuel consumption with a regional tax is

$$e_t = \begin{cases} \frac{1}{p_t}\left[2\theta\frac{1+\upsilon_t^s}{\upsilon_t+\upsilon_t^s} + \phi\left(1+\frac{1}{\upsilon_t}\right)\right] & \text{if} \quad p_t < b \\ 0 & \phantom{\text{if}} \quad p_t \geq b. \end{cases} \tag{B.2}$$

No fuel with extraction costs above b can be economically exploited, hence (35) implies $p_t \leq b \forall t$. With this finite fuel price, e_t is nonmarginally positive throughout the fuel extraction horizon, independently of the regional fuel tax υ_t. Eq. (35) also implies that the fuel price p_t remains weakly below the cost of the most expensive resource ever to be extracted. According to (B.2), resource extraction thus continues until at some time T the extraction costs reach b,

$$\int_0^T e_t \mathrm{d}t = A^{-1}(b).$$

Global long-run emissions are unaffected but the tax still reduces the abating region's emissions, cf. (23) and (32)), and thus is subject to a leakage fraction of 100%. ■

C Leakage in limit with short and long fuel horizon

Complete leakage for sufficiently distant future measure, $T \to \infty$

We start by noting that a hypothetical marginal decrease of T cannot reduce cumulative emissions, $A_T \equiv \int_0^T e_t \mathrm{d}t$, at a rate higher than the final extraction rate,[43]

$$\frac{\mathrm{d}A_T}{\mathrm{d}T} \leq \lim_{t \to T^-} e_t. \tag{C.3}$$

Because suppliers are free to time their offer within the fuel consumption era, a change in demand during an infinitesimally short period can change the scarcity rents λ_t only marginally. Competitive pricing (35) thus implies that during the initial, short period where the tax applies, the tax has an infinitesimal influence on the price, $p'_0 \approx p_0$, where the apostrophe ' indexes equilibrium variables in the situation with the tax. The results from the static analysis with a fixed fuel price therefore apply; only the goods-channel is relevant for the regional fuel consumption reactions to the tax, with a limited within-period leakage fraction, lf, strictly between 0 and 1, that is, if the tax reduces the within-period domestic fuel consumption rate by Δ, the foreign consumption rate increases by $\Delta \cdot \text{lf}$ with $0 < \text{lf} < 1$. The remainder of the domestic within-period emission reduction, $\delta\Delta\,(1 - \text{lf})$, increases the stock of resources at the end of the short tax period. From time δ on, it takes $\varepsilon = \delta\Delta \frac{1-\text{lf}}{e'_{t\to\delta+}}$ units of time until this additional stock of resources is used and cumulative extraction attains the original value at the end of the tax period,

$$A'_{\delta+\varepsilon} = A_\delta. \tag{C.4}$$

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[43] Consider a hypothetical situation, indexed by quotes ", with a baseline T" reduced by a marginal $\varepsilon > 0$ to $T" \equiv T - \varepsilon$. If pre-$T$" sales remained unchanged, this implied a new final total consumption $A"_{T"} = A_{T"} = A_T - \varepsilon e_{t\to T}$. In this case (35) would imply a lower fuel supply price throughout time, $p"_t < p_t \forall t < T"$, which in turn would increase the demanded fuel quantity at each point in time. The equilibrium requires a fraction of fuel originally sold between T" and T to be sold before T" in the situation of the shortened sales horizon: $\lim_{\varepsilon\to 0} A"_{T"} \geq A_T - \varepsilon \cdot e_{t\to T^-}$.

Since after δ the tax rate is zero in both scenarios, (C.4) implies that for a hypothetical introduction of the future measure at $\tilde{T}' \equiv T + \varepsilon$, the extraction paths coincide except for a time-shift by ε, $\tilde{e}'_{t+\varepsilon} = e_t \forall t \in [\delta, T]$, and therefore $\tilde{A}'_{T+\varepsilon} = A_T$. Rather than shifted by ε, we consider a measure whose implementation time is not directly impacted by the initial tax choice, that is, we consider the case of $T' \equiv T$. This is identical to the hypothetical situation with the measure emergence at $\tilde{T}'$, except for the measure to arrive ε units of time earlier. With (C.3) this implies $A_T - A'_T \leq e_T \varepsilon$. But $\lim_{T\to\infty} e_T = 0$, so the difference of total emissions with and without the tax vanishes at a degree more rapidly than the initial domestic emission reduction. Therefore, due to the fuel-price channel, the fraction of the domestic emission reductions offset overall converges to 100%,[44]

$$\lim_{T\to\infty} \frac{\int_0^T e_t - e'_t \mathrm{d}t}{\int_0^\delta e_{a,t} - e'_{a,t} \mathrm{d}t} = 0.$$

■

Limited leakage for imminent future measure, $T \to \delta^+$

With T arbitrarily close to δ, $\lim T \to \delta^+$, (35) implies $p_t \approx c_0 \forall t \in [0, T)$, independent of v. The tax thus changes the post-δ extraction rates only marginally. The asymptotically fixed price also means that during the tax phase, $t = [0, \delta]$, both regions' emission rates change according to the static case with the non-marginal impact of the tax on the global within-period extraction rate, subject to a goods-channel only leakage fraction strictly lower than 1 as found in (27). For T approaching the marginal duration δ of the tax phase, the reaction of post-δ extraction rates thus becomes insignificant, $\frac{\int_\delta^T e_{i,t} - e'_{i,t} \mathrm{d}t}{\int_0^\delta e_{j,t} - e'_{j,t} \mathrm{d}t} = 0 \forall i, j$. Therefore, post-$\delta$ emission reactions to the initial tax v have a marginal effect on the overall leakage fraction which thus equals the goods channel-only leakage fraction as identified in the static case without fuel price response. ■

D Leakage with gradual cap

Assume a global fuel use cap, strictly binding from period T on and progressively fading out fuel use until a finite amount of time $\bar{\Delta} < \infty$ periods later. Let $\bar{T} \equiv T + \bar{\Delta}$, that is, $F_t = \Phi(t) \forall t \in [T, \bar{T}]$, with $\Phi'(t) < 0 \forall t \in [T, \bar{T}]$ and $\Phi(\bar{T}) = 0$. Strictly binding

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[44] Part of the emission reductions during the initial tax period are offset by *domestic* emission increases later on. Independent of whether one considers the here used definition of leakage fraction as the fraction of emissions offset either abroad, or domestically after the tax period, or defines it as the *total* emission increase abroad to the *total* domestic emission reduction throughout time induced by the (initial) tax, the leakage fraction converges to 100% in the present case. Having shown the former, the latter follows immediately from initial emission increases in the foreign country offsetting a non-marginal fraction of the initial domestic emission reductions, and the post-δ emission in both regions being the same independently of the pre-δ tax.

means that if the cap restriction was lifted during a specific time period $t \in [T, \bar{T}]$, the unrestricted global demand e_t^u would be above the cap, $\Phi(t) < e_t^u$, in all regional tax scenarios considered.

Complete leakage for sufficiently distant future measure, $T \to \infty$

The proof is largely analogous to the proof for the case of the non-gradual cap in Annex C. We start by noting that a hypothetical marginal decrease of T and $\bar{T}$ cannot reduce cumulative emissions, $A_{\bar{T}} \equiv \int_0^{\bar{T}} e_t \mathrm{d}t$, at a rate higher than the extraction rate immediately before the cap emergence,[45] i.e., (C.3) holds. Because suppliers are free to time their offer within the fuel consumption era, a change in demand during an infinitesimally short period can change the scarcity rents λ_t only marginally. Competitive pricing (35) thus implies that during the initial, short period where the tax applies, the tax has a negligible influence on the price, $p'_0 \approx p_0$, where the apostrophe ’ indexes equilibrium variables in the situation with the tax. During the tax period, $t \in [0, \delta]$, the results from the static analysis with a fixed fuel price therefore apply; only the goods-channel is relevant for regional fuel consumption reactions to the tax, with a limited within-period leakage fraction lf strictly between 0 and 1, that is, if the tax reduces the within-period domestic fuel consumption rate by Δ, the foreign consumption rate increases by $\Delta \cdot \mathrm{lf}$ with $0 < \mathrm{lf} < 1$. The net within-period emission reduction, $\delta\Delta\,(1 - \mathrm{lf})$, increases the stock of resources at the end of the short tax period. From time δ on, it takes $\varepsilon = \delta\Delta\frac{1-\mathrm{lf}}{e'_{t\to\delta+}}$ units of time until this additional stock of resources is used and cumulative extraction attains the original value at the end of the tax period, i.e. (C.4) holds. Since after δ the tax rate is zero in both scenarios, (C.4) implies that with a hypothetical introduction of the future measure at $\tilde{T}' \equiv T + \varepsilon$, the extraction paths coincide except for a time-shift by ε, $\tilde{e}'_{t+\varepsilon} = e_t \forall t \in [\delta, \bar{T}]$, and therefore $\tilde{A}'_{\bar{T}+\varepsilon} = A_{\bar{T}}$. Rather than shifted by ε, we consider a measure whose implementation is not directly impacted by the initial tax choice, that is, we consider the case of $T' \equiv T$. This is identical to the hypothetical situation with the measure emergence at $\tilde{T}'$, except by the measure to come ε units of time earlier, $T' = \tilde{T}' - \varepsilon$. With (C.3) this implies $A_T - A'_T \le e_T \varepsilon$. But $\lim_{T\to\infty} e_T = 0$, and the difference of total emissions with and without the tax vanishes at a degree more rapidly than the initial domestic emission reduction. Therefore, due to the fuel-price channel, the fraction of the domestic emission

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[45] Consider a hypothetical situation, indexed by quotes ", with a capping scheme Φ” marginally shifted, so that the fuels are faded out by $\varepsilon \to 0^+$ units of time earlier, so that $\Phi''(t - \varepsilon) = \Phi(t) \forall t \ge T$. Let $I \equiv \int_T^{\bar{T}} \Phi(t)\mathrm{d}t = \int_{T''}^{\bar{T}''} \Phi''(t)\mathrm{d}t$. If pre-$T''$ sales would not change, the shift would imply a new total consumption $A''_{\bar{T}''} = A_{\bar{T}} - \varepsilon e_{t\to T^-}$. In this case (35) would imply a lower fuel supply price throughout time, $p''_t < p_t \forall t < \bar{T}''$, which in turn would increase the demanded fuel quantity during the entire pre-cap phase. The equilibrium thus requires some of the fuel originally sold between T'' and T to be sold before T'' in the situation of the shortened sales horizon: $\lim_{\varepsilon\to 0} A''_{\bar{T}''} \ge A_{\bar{T}} - \varepsilon e_{t\to T^-}$.

reductions offset overall converges to 100%,

$$\lim_{T\to\infty} \frac{\int_0^{T+\bar{\Delta}} e_t - e'_t \mathrm{d}t}{\int_0^{\delta} e_{a,t} - e'_{a,t} \mathrm{d}t} = 0.$$

■

Limited leakage for imminent future measure, $T \to \delta^+$

With T arbitrarily close to δ, $\lim T \to \delta^+$, (35) implies $p'_t \approx p_t \forall t \in [0, \bar{T})$, independent of υ. The tax thus changes the post-δ extraction rates only marginally. The asymptotically fixed price also means that during the tax phase, $t = [0, \delta]$, both regions' emission rates change according to the static case with the non-marginal impact of the tax on the global within-period extraction rate, subject to a goods-channel only leakage fraction strictly lower than 1 as found in (27). For T approaching the marginal duration δ of the tax phase, the reaction of post-δextraction rates thus becomes insignificant, $\frac{\int_\delta^{T+\bar{\Delta}} e_{i,t} - e'_{i,t} \mathrm{d}t}{\int_0^{\delta} e_{j,t} - e'_{j,t} \mathrm{d}t} = 0 \forall i, j$. Therefore, post-$\delta$ emission reactions to the initial tax υ have a marginal effect on the overall leakage fraction which thus equals the goods channel-only leakage fraction as identified in the static case without fuel price response. ■

E 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 h.

Consider an *a*bating (domestic) and a *n*on-abating (foreign) region, $i = \{a, n\}$, with domestic utility $U_a \equiv z + u(x_a) - h \cdot X$, subject to the budget constraint $z = z_0 - p \cdot x_a$, with global consumption $X \equiv x_a + x_n$, and leakage at rate l, $x_n = x_{n0} - l x_a$.

The domestic planner's FOC for domestic consumption x_a writes

$$p = u'(x_a) - h(1 - l). \tag{E.5}$$

Domestic decentralized consumption decisions, subject to a potential domestic tax τ_a, 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 private costs, $u'(x_a) = p + \tau$. In this simple setup, the optimal level of domestic consumption implicitly given by (E.5) can thus be sustained in a decentralized market by imposing a domestic pollution tax of the level

$$\tau_a^* = h(1 - l).$$

Lemma 2. *At constant prices, if only global pollution matters and if foreign consumption of a polluting good increases proportionally at rate l when domestic consumption is reduced, i.e., we have a leakage rate of l, the regionally optimal level of the unilateral pollution tax τ_a^* is $\tau_a^* = h(1-l)$, where h is the domestic WTP for global pollution reductions.*

F Simplification

$I_1 \equiv \int_0^\infty \mathrm{e}^{-\rho s} \left[\int_s^\infty \mathrm{e}^{-\rho(w-s)} \dot{c}_w \mathrm{d}w\right] \frac{\mathrm{d}e_{n,s}}{\mathrm{d}e_{a,t}} \mathrm{d}s$, $I_2 \equiv \int_0^\infty \mathrm{e}^{-\rho s} e_s \frac{\mathrm{d}c_s}{\mathrm{d}e_{a,t}} \mathrm{d}s$. These terms take on the same value and therefore cancel each other out in (46):

From the definition of the extraction costs we have $\frac{\mathrm{d}c_s}{\mathrm{d}e_{a,t}} = c_s' \cdot \left[\{1 \text{ if } s \geq t \text{ else } 0\} + \int_0^s \frac{\mathrm{d}e_{n,w}}{\mathrm{d}e_{a,t}} \mathrm{d}w\right]$. Therewith, I_2 rewrites $\int_t^\infty \mathrm{e}^{-\rho s} e_s \left[c_s' \cdot 1\right] \mathrm{d}s + \int_0^\infty \mathrm{e}^{-\rho s} e_s \left[c_s' \int_0^s \frac{\mathrm{d}e_{n,w}}{\mathrm{d}e_{a,t}} \mathrm{d}w\right] \mathrm{d}s$. As $\dot{c}_t = c_t' e_t$, I_2 simplifies to $\int_t^\infty \mathrm{e}^{-\rho s} \dot{c}_s \mathrm{d}s + \int_0^\infty \mathrm{e}^{-\rho s} \dot{c}_s \int_0^s \frac{\mathrm{d}e_{n,w}}{\mathrm{d}e_{a,t}} \mathrm{d}w \mathrm{d}s$. Seeing further that $\int_0^\infty \mathrm{e}^{-\rho s} \dot{c}_s \int_0^s \frac{\mathrm{d}e_{n,w}}{\mathrm{d}e_{a,t}} \mathrm{d}w \mathrm{d}s$ is a simple double integral over the open 'area' defined by $w \leq s$, we know $\int_0^\infty \mathrm{e}^{-\rho s} \dot{c}_s \int_0^s \frac{\mathrm{d}e_{n,w}}{\mathrm{d}e_{a,t}} \mathrm{d}w \mathrm{d}s = \int_0^\infty \int_w^\infty \mathrm{e}^{-\rho s} \dot{c}_s \frac{\mathrm{d}e_{n,w}}{\mathrm{d}e_{a,t}} \mathrm{d}s \mathrm{d}w$, which, switching u and s, yields the same as I_1. Terms I_1 and I_2 are thus equivalent.

G Focus on oil and coal

Several factors suggest a focus on oil and coal as the two explicitly modeled fuels in this exploratory study. First, the simulation results will already prove to be complex when we restrict the attention to these two fuels. 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[46] 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 ⅔ 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 as well as 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).[47]

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

[47] 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).

H Details numeric calibration

Demand

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

Table 1: Current fuel consumption and prices

Region	*Oil* *Gbbl/yr*	*Coal* *Gt/yr*
OECD	16.4	1.16
Non-OECD	14.3	3.12
World	30.7	4.28

(a) Regional Fuel Consumption

Fuel	*Price* *US$[2010]*
Oil (bbl)	76
Coal (tonne)	83

(b) Fuel Prices

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

Coal supply cost curve

The approximate fit of the coal extraction cost curve to the data is given in Fig. 10. 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. 10. Given that historically coal prices were relatively low, around \$30/tonne in 2000, and today they fluctuate around \$100/tonne (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[48] rather than by a genuine long-term extraction cost increase, it was here decided to consider an actual coal extraction cost of \$50/tonne, 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/tonne after 1740 Gt extracted); that is, the curve given by $c(A_{\mathrm{coal}}) = \$50/t_{coal}\mathrm{e}^{A_{\mathrm{coal}}/996\,\mathrm{Gt\,coal}}$, with A_{coal} the amount of coal extracted. Fig. 10 shows how this curve provides a compromise between the general idea of a smooth, convex extraction cost curve, and the data points used from the rough, convex and concave projection of Rogner (1997).

I Additional results

Fig. 11 shows main model results for the basic setup.

Fig. 12 shows main model results for the scenario with liquefaction

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[48] Worldwide coal consumption used to stagnate before the beginning of this millennium, with annual

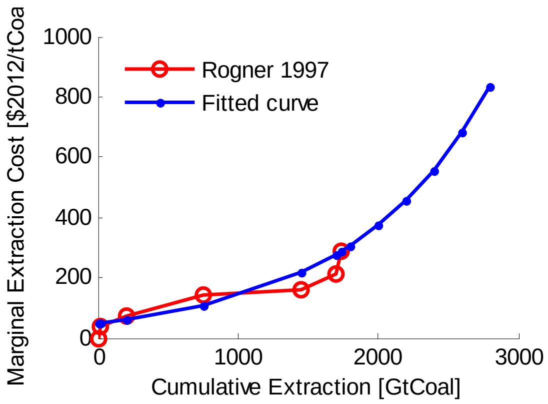
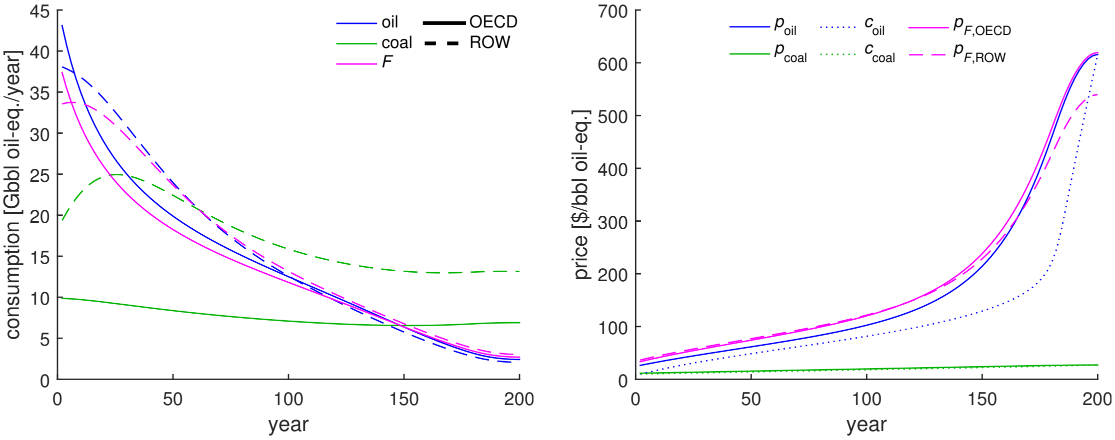


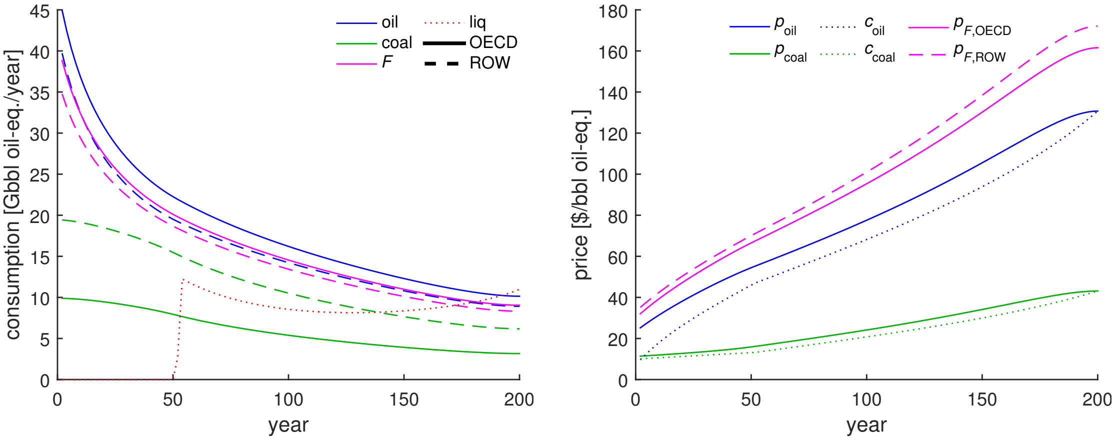
Figure 10: Coal extraction cost curves



(a) Consumption ***(b)*** Prices

Figure 11: Simulation results base setup

Heterogeneous discounting scheme



(a) Consumption ***(b)*** Prices

Figure 12: Simulation results with liquefaction

Heterogeneous discounting scheme

	Heterogenous Discounting			*Homogenous Discounting*		
Scenario	*ALR*	*NLR*	*DLR*	*ALR*	*NLR*	*DLR*
Base	64%	50%	57%	72%	27%	30%
Backstop	163%	95%	125%	161%	26%	30%
No Growth	63%	47%	55%	67%	24%	27%
Liquefaction	-20%	-15%	-18%	-19%	7%	2%
Long Horizon	70%	50%	59%	71%	26%	28%
Extra Extraction Costs	50%	30%	41%	63%	27%	29%

(a) Oil

	Heterogenous Discounting			*Homogenous Discounting*		
Scenario	*ALR*	*NLR*	*DLR*	*ALR*	*NLR*	*DLR*
Base	48%	36%	42%	46%	16%	19%
Backstop	48%	36%	42%	49%	16%	18%
No Growth	44%	32%	38%	43%	14%	16%
Liquefaction	62%	52%	59%	63%	22%	28%
Long Horizon	73%	41%	55%	72%	16%	18%
Extra Extraction Costs	62%	40%	52%	60%	25%	26%

(b) Coal

Table 2: Summary leakage rates

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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).