Fossil Fuel Supply, Leakage and the Effectiveness of Border Measures in Climate Policy

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Abstract

Understanding fossil fuel supply behaviour is crucial for interpreting carbon leakage and assessing the potential effectiveness of border measures in climate policy. In most computable general equilibrium models, this fossil fuel supply is derived from a constant elasticity of substitution production function, in which a natural resource is treated as a fixed factor. We show that this leads to endogenously decreasing supply elasticities and sharply increasing marginal leakage rates for large coalitions that have ambitious emissions targets, particularly when fuel exporters participate in the coalition. We propose an alternative production function that has a constant elasticity of fuel supply, which results in more stable leakage rates and a different share of trade-related leakage. The role of this model variation for the assessment of border measures in climate policy turns out to be limited. In those cases where the model versions differ most (i.e. large coalition, ambitious targets), border measures have a small effect anyway.

Keywords: climate policy, carbon leakage, border measures, fossil fuel supply, constant elasticity of supply

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1 Introduction

Unilateral carbon policy in a coalition of countries may increase carbon emissions outside the coalition. This effect is called “carbon leakage”. Reducing carbon leakage is a concrete goal of border measures in climate policy. Although academic discussions may have centred on the question of whether border measures can reduce the “welfare” costs of climate policy, welfare is an elusive concept, and politicians prefer more tangible indicators. These two perspectives need not be in conflict, however. Supporters of border measures aim to reduce the welfare costs of climate policy *by* reducing leakage.

In any case, understanding the mechanisms of carbon leakage is crucial for an assessment of border measures in climate policy. However, this understanding is hindered by the interaction of two different channels of leakage. The first channel is leakage through the trade in emissions-intensive goods (*T-leakage* hereafter). Because of climate policy, the production of these goods partly shifts from coalition to non-coalition countries and the goods are then re-imported from there. This is the channel of leakage that border measures are designed to counteract. However, this is not the only mechanism at work. The second, interacting channel of leakage runs via the adjustment of fossil-fuel prices (*F-leakage* hereafter). Climate policy causes a reduction in fossil fuel demand, which translates into a fall in the world price level of fossil fuels. In regions outside the coalition, additional fuel use, and hence greater carbon leakage, is then triggered. This second channel of leakage cannot systematically be influenced by border measures.

The decomposition of leakage into T-leakage and F-leakage is therefore of particular importance for the assessment of border measures. If the trade channel turns out to be irrelevant, border measures have no role to play from the outset. If T-leakage can be shown to be relevant, so that a case for border measures remains, an informative assessment of the effectiveness of border measures should assess their effect (i.e. leakage reduction) in terms of reduction of T-leakage rather than of total leakage.

In computable general equilibrium (CGE) models, each of these two channels of leakage is connected to a crucial set of functional parameters. T-leakage is governed by “Armington elasticities”, which determine the substitutability between domestically produced and imported goods. The higher the Armington elasticity for energy-intensive goods, the larger is the relocation effect and thereby the larger is the leakage level. By contrast, the crucial parameters for F-leakage are the supply elasticities of fossil fuels.[1] The lower these elasticities, the more pronounced is the price reaction to a fall in fuel demand in coalition countries, and the higher is the F-leakage level in to non-coalition countries. This mechanism becomes clear under the extreme assumption of a supply elasticity of zero. In this case, the supply of fossil fuels is fixed and price adjustments would ensure that the global fuel use with climate policy is identical to that without. Leakage is thus necessarily 100 %.[2]

Understanding fuel supply behaviour is therefore crucial for interpreting the outcome of CGE simulations of climate policy.[3] Most CGE models treat fuel supply as a constant elasticity of substitution (CES) production function that has a natural resource, modelled as a fixed factor. In this paper, we show that a CES set-up leads to endogenously adjusting supply elasticities with potentially undesired consequences for leakage. To avoid this problem, we propose an alternative fuel supply module, namely a constant elasticity of fuel supply (CEFS) function. The differences between the two set-ups are highlighted by running identical scenarios[4] under both specifications and comparing the results.

In these comparative scenario runs, it turns out that the effect of the variation in supply modelling is context-dependent. With respect to leakage rates, the difference between the model versions is limited for small coalitions and moderate emissions reduction targets. However, for large coalitions that have ambitious targets, the difference can be substantial, especially if there are fuel exporters in the coalition.

Closer inspection shows that, with the CES specification, marginal leakage rates sharply increase when the target is tightened, whereas this is hardly the case with

[1]Fuel demand has a role to play as well. However, as climate policy can roughly be interpreted as a shift in fuel demand, this represents a movement on the fuel supply curve.

[2]See Burniaux and Oliveira Martins (2000) and Paltsev (2000) for a more general discussion of leakage in climate policy.

[3]This paper is motivated by the discussion about the comparative scenario runs in Round 24 of the Energy Modeling Forum (EMF). In this discussion, the decomposition of leakage took centre stage.

[4]We use the harmonised scenarios of EMF 24 for this purpose (see Balistreri et al., this volume).

the CEFS specification. This difference is the consequence of endogenously decreasing fossil fuel supply elasticities under CES. We cannot immediately dismiss this as counterfactual (because there are naturally no estimates of supply elasticities for a situation with a strict emissions target). Nevertheless, we see this as an undesirable model artifact.[5] Our preferred model specification is the CEFS function, which generates more stable leakage rates when reduction targets are tightened.

With respect to the effectiveness of border measures, the differences between the model versions turn out to be limited. Again, the case of large coalitions that have ambitious reduction targets is crucial. In this case, the share of F-leakage is significantly larger under the CES specification, which means that the contribution of border measures to reducing leakage is lower than that in the CEFS case. However, for large coalitions, border measures are hardly effective anyway, and thus this difference in the decomposition of leakage rates does not play a prominent role.

The remainder of this paper is structured as follows. Section 2 describes the CES method of modelling fossil fuel supply in CGE models and discusses its consequences and problems. Our modelling alternative, the CEFS function, is then presented in Section 3. In Sections 4 and 5, we perform the comparative simulations for the two modelling options and explain any differences. Section 6 concludes. The Appendix provides some analytical results used in the characterisation of the CES fuel supply specification.

2 CES Specification of Fossil Fuel Supply

In most of the CGE models used for the assessment of climate policy (including WorldScan, the model we adopted for the numerical simulations in Section 4), fossil fuel supply is modelled as a CES production function. At the uppermost nest of the CES function, production is split into the contribution of a natural resource (R) in fixed supply and an aggregate of all other variable inputs (V). For simplicity, we

[5] Empirical researchers are even struggling to pin down a single supply elasticity per fossil fuel (see our list of empirical studies in Section 4.1). As far as we know, no empirical study has addressed the question of whether supply elasticities vary systematically. After all, the implicit assumption underlying estimations of "the" supply elasticity is that this is a constant.

treat this aggregate of the rest as a homogeneous good with a constant price in the following.

Expressing the CES function in its "calibrated share form" (see Rutherford, 1998), the production function reads

$$Y(R,V) = \left[\theta_R \left(\frac{R}{\bar{R}}\right)^{\frac{\sigma-1}{\sigma}} + \theta_V \left(\frac{V}{\bar{V}}\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \tag{1}$$

where the θ_i's are the initial value shares, σ is the elasticity of substitution and an upper bar denotes an (exogenous) value of a variable in the initial situation. The production function yields the dual cost function

$$p_Y = \left[\theta_R \left(\frac{p_R}{\bar{p}_R}\right)^{1-\sigma} + \theta_V \left(\frac{p_V}{\bar{p}_V}\right)^{1-\sigma}\right]^{\frac{1}{1-\sigma}}$$

with prices p_i for good i, and the associated demand functions for $X = R, V$

$$\frac{X}{\bar{X}} = \frac{Y}{\bar{Y}} \left(\frac{p_Y \bar{p}_X}{p_X}\right)^{\sigma}$$

It can be shown (Babiker et al., 2001, reproduced for convenience in Appendix A.1) that the resulting elasticity of fuel supply, η^s, is

$$\eta^s = \frac{\partial \log Y}{\partial \log p_Y} = \sigma \frac{1 - s_R}{s_R} \tag{2}$$

where s_R is the value share of the fixed factor (identical to θ_R in the initial situation, but not in general). The usual procedure is to choose the unobservable σ so that, given the observable s_R, an exogenous estimate of η^s is reproduced. However, this calibration procedure, simple as it is, can still give rise to a number of follow-up complications. These are common knowledge among experienced modellers, but are hardly ever made explicit. For easier reference, list these complications in the following sub-sections.

2.1 Calibration of the fossil fuel price

The calibration of the elasticity of substitution according to eq. (2) specifies the model in the base year. Extending the model over time ("baseline path") by time-varying productivity coefficients and/or endowments would produce an endogenous fuel supply curve that reflects the production function (1). Modellers are often required to calibrate the model so that it reproduces an exogenous scenario (e.g. the IEA "Energy Outlook") with a price/quantity combination that does not lie on the endogenous fossil fuel supply curve. This makes further adjustments necessary. For concreteness, let us assume that for an unchanged quantity a higher fossil fuel price is to be calibrated.[6]

At an unchanged quantity, a higher price translates one-to-one into a higher output value. The crucial calibration question is then what are the shares of the fixed factor and the variable input in this increased production value. Phrased in terms of economic mechanisms: to what extent is the increase in the prices caused by an increase in the costs (per-unit quantity of the variable input) and to what extent is it a pure inflation of rents? The answer to this question depends on our view of market developments in fossil fuel markets and thus it cannot be answered in general. The crucial point here is that calibration is not neutral in this respect.

A common procedure for targeting the exogenous fossil fuel price path is adjusting the amount of the fixed factor. This will lead to a change in the value share of the fixed factor according to[7]

$$\varepsilon_{s_R p_Y} = (1-\sigma)\,\frac{(1-s_R)}{s_R}$$

(See Appendix A.2 for the derivation.) In other words, for an elasticity of substitution below (above) one, the share will rise (fall) when a price is targeted that is above the endogenous supply curve. If the elasticity of substitution determined in eq. (2) is used in the calibration of the fuel price path, we thus have

$$\varepsilon_{s_R p_Y} = \frac{(1-s_R)}{s_R} - \eta^s$$

Apart from the requirement to find a consistent economic story behind such fuel price development, a technical restriction is also placed on the fuel price calibration. With an elasticity of substitution above one,[8] there is an upper bound for the price

[6]In an actual calibration exercise, we are faced with a price/quantity combination, which is calibrated by shifting both fuel supply (in the way described below) and fuel demand (by adjusting fuel efficiency).

[7]We use ε_{XY} as a shortcut for the elasticity $\frac{d \log X}{d \log Y}$.

[8]This situation can easily occur if you enter the calibration eq. (2) with a high supply elasticity and a high value share of the natural resource.

of the fuel that can be achieved by reducing the amount of the natural resource.[9] This upper bound is

$$\frac{p_Y^{max}}{\bar{p}_Y} = (1-\theta_R)^{\frac{1}{1-\sigma}}$$

Finally, we must pay attention to the supply elasticity in the course of the calibration to fuel prices. Higher fuel prices imply a change in the input value shares. At a constant σ (taken from the base-year calibration), this would mean that the elasticity of fuel supply adjusts according to eq. (2). As there is no systematic reason why the supply elasticity should be lower at higher fuel prices, it is reasonable to make σ a time-varying parameter,[10] adjusted to produce an exogenous supply elasticity according to eq. (2) in each period.

2.2 Fuel supply reaction to climate policy shocks

A climate policy shock shifts the fuel demand curve to the left; thus, fossil fuel producers can sell less at a constant producer price because of the emissions tax. This leads to a downward shift along the fuel supply curve, with a lower supply price, a lower rent to the natural resource and less use of the variable factor in fossil fuel production. It is not immediately clear, however, what happens to the value share of the natural resource. As before, this depends on the elasticity of substitution in fuel production. It can also be shown (see Appendix A.3) that the value share of the natural resource increases (decreases) in response to a negative demand shock if the elasticity of substitution is larger (smaller) than one.

The endogenous change in the value share of the natural resource, in turn, has repercussions on the supply elasticity. According to eq. (2), the supply elasticity falls with the value share of the natural resource (at a given elasticity of substitution). With an elasticity of substitution of larger (smaller) than one, a negative demand shock thus leads to a decrease (increase) in the supply elasticity.

[9] In order to avoid problems with this restriction, WorldScan uses a calibration procedure in which the elasticity of substitution is temporarily set to zero during the construction of the baseline path and switches back to the original elasticities only in the counterfactual simulations. The consequence is that additional value because of a price increase is completely absorbed by the natural resource rent.

[10] s_R is no longer free for adjustment, because it is needed to target the fuel price.

This raises questions of economic plausibility: is it reasonable that supply elasticities vary systematically with the level of output? (We return to this question in Section 3.) More fundamentally, an elasticity above one can easily cause numerical problems. In a CES function with $\sigma > 1$, the production factors are not essential, i.e. output can be produced by using only one factor. The quantity that may be produced with the natural resource alone forms therefore a lower bound for fossil fuel production:

$$\frac{Y^{min}}{\bar{Y}} = (\theta_R)^{\frac{\sigma}{\sigma-1}}$$

This lower bound is larger the larger the (initial) value share of the natural resource is, and the larger σ is.[11] A minimum quantity of fossil fuel production must then be considered to be an undesired model anomaly. Supply calibration to an exogenous, high price path (Section 2.1) turns out to be particularly unfortunate, because it increases the value share of the natural resource and – as a strategy of targeting the exogenously estimated fuel supply elasticities – increases the elasticity of substitution. Both effects add up to a higher minimum production quantity.

Further, a lower bound of fuel production causes numerical difficulties when scenarios with tight emissions targets are analysed, because emissions reduction basically means reducing the use, and hence the production, of fossil fuels. Unfortunately, these problems do not lend themselves to a straightforward treatment in a complementarity framework (Mathiesen, 1985). For a complementarity formulation, the desired behaviour of the supply function would be that the producer's price – and thus the rent of the natural resource – drops to zero once we reach the minimum quantity, so that this can be used as a complementarity condition for leaving a part of the natural resource unused. However, as the Inada conditions remain valid for CES functions with $\sigma > 1$, the marginal product of the variable factor will rise infinitely. Thus, a minuscule quantity of the variable factor will still be used, preventing the user price from dropping to zero. Unless special provision for this case is taken in the modelling code, the infinitely rising marginal productivity of the variable factor will lead to a breakdown of the numerical solving algorithm once climate policy is so severe that fossil fuel use must be suppressed below the level of

[11] As $\theta_R < 1$, a larger exponent means a reduction in the value. The exponent cannot become larger than one (for $\sigma > 1$), so θ_R is an upper bound for the minimum quantity.

minimum production.

2.3 Stabilising the fossil fuel supply price

When analysing leakage in climate policy, fossil fuel supply becomes crucial in yet another respect. In order to distinguish between trade-induced and fuel price-induced leakage, it is a useful diagnostic exercise to run scenarios where fossil fuel prices are fixed at their business-as-usual levels, so that only the trade channel for leakage remains.

A straightforward way of implementing fossil fuel price stabilisation is to let the quantity of the natural resource adjust precisely to the extent needed for a constant fossil fuel price. However, the economic interpretation of this adjustment is not immediately apparent. Adjusting the amount of the natural resource during policy simulations might lead to welfare consequences that can hardly be interpreted and are potentially unwanted. Let us therefore take a closer look at what happens during price stabilisation.

We need to analyse the response of the system of fuel supply and demand to a demand shock b:

$$R\theta_R^{\frac{1}{\sigma-1}}\left[1-(1-\theta_R)\,p_Y^{\sigma-1}\right]^{\frac{\sigma}{1-\sigma}}-Y=0$$

$$f(p_Y)-Y+b=0$$

where fuel output, Y, and resource input, R, are the endogenous variables and p_Y (output price stabilisation) is fixed. (σ and θ_R are parameters and $f(p_Y)$ is the fuel demand function.)

It can be shown (see Appendix A.4) that

$$\frac{d\log R}{d\log Y} = \frac{\varepsilon_{Yb}}{\varepsilon_{Rb}} = 1$$

In other words, the quantity of the fixed factor is adjusted exactly in proportion with the output. This means that the value share of the fixed factor remains constant (quantities move in proportion and prices remain constant).[12]

[12] At closer inspection, this is almost trivial. With output price and one input price fixed (and a given CES production function), the other input price must also remain constant. This means that both input quantities move exactly in proportion with output.

In numerical terms, the adjustment of the amount of the natural resource has the advantage that the amount of the output can be controlled smoothly (and without running into problems with minimum fuel production), simply by varying the amount of the fixed factor proportionally. As a consequence, the value share of the natural resource remains constant. Although this is reassuring, it is not without problems. After all, the behaviour of the inputs to fossil fuel production is not consistent with what has been established as the desired fossil fuel supply behaviour in the calibration.[13] Therefore, it is reasonable to think about an alternative approach to fuel price stabilisation.

This alternative way is price stabilisation through a compensatory output tax on the fossil fuel (leaving the stock of the natural resource untouched and thus remaining on the calibrated fuel supply function). In this case the relevant system of equations is

$$R\theta_R^{\frac{1}{\sigma-1}}\left[1-(1-\theta_R)\left(\frac{1+t}{\tilde{p}_Y}\right)^{1-\sigma}\right]^{\frac{\sigma}{1-\sigma}} - Y = 0$$

$$f(\tilde{p}_Y) - Y + b = 0$$

where t is the output tax and $\tilde{p}_Y = (1+t)p_Y$ is the buyers' price to be stabilised. We thus analyse a system of two equations in the variables Y and t. Again, the change in the value share of the natural resource is of crucial interest. Working with an output tax introduces an additional complication, however. We must now be precise: do we talk about the share of the natural resource in the production value, about the share of the natural resource in the buyers' value (including taxes) or about the residuum of the buyer's value over variable production costs?[14]

The share of the natural resource in production costs evolves according to

$$\varepsilon_{s_R b} = \frac{\sigma-1}{\sigma}$$

(see Appendix A.4), which is positive (negative) if $\sigma < 1$ ($\sigma > 1$).

[13] The calibration has been set up precisely to produce an *elastic* fuel supply, i.e. increasing marginal costs. In other words, a *more than proportional* increase in the variable factor for producing additional units of output.

[14] The latter seems to be the most relevant. We want to know what share of the gross-of-tax revenue goes to purchasing inputs and what share remains as rent, whether tax or natural resource rent.

The share of the variable factor in the buyer's value, $\hat{s}_V$, always decreases with a negative demand shock ($b < 0$):

$$\varepsilon_{\hat{s}_V b} \;=\; \frac{\theta_R}{1-\theta_R} > 0$$

While the adjustment through taxes captures our intuition that price stabilisation at falling quantities must increase the share of rents, the CES set-up again runs into problems with minimum quantities when $\sigma > 1$. If the demand shock b (which at a buyer's price stabilised by construction comes down to a quantity shock) is larger than the difference with the minimum quantity,

$$\frac{Y^{min}}{\bar{Y}} \;=\; (\theta_R)^{\frac{\sigma}{\sigma-1}}$$

the model fails.

3 Constant Elasticity of Fuel Supply

As we have shown in Section 2, modelling fossil fuel supply as a CES function that has a fixed factor (natural resource) can lead to problems, particularly if the elasticity of substitution that results from the calibration to exogenous fuel supply elasticities has a value above one.

- The elasticity of fuel supply changes with the quantity supplied, and therefore in the course of policy simulations.
- There is a minimum quantity of fossil fuel supply, which makes the model break down when ambitious climate policy goals are to be simulated (if $\sigma > 1$).
- Fuel price stabilisation through an adjustment of the fixed factor is possible, but this negates the income consequences of an upward-sloping supply function.
- Fuel price stabilisation through the introduction of an output tax is more informative about the cost/rent split, but runs into problems with the minimum production quantity (if $\sigma > 1$).

These problems motivated us to design an alternative specification of fossil fuel supply in WorldScan. Our core criterion is that we do not want the elasticity of fuel supply to change endogenously. The straightforward way of achieving this goal is by constant elasticity of supply function:[15]

$$\frac{p_Y}{\bar{p}_Y} = \left(\frac{Y}{\bar{Y}}\right)^{\frac{1}{\eta^s}}$$

In the implementation in WorldScan, we assume that fossil fuels are produced from their variable inputs in fixed proportions (Leontief production). The fixed factor is thus eliminated from the production function. The input of the natural resource is added to the capital and the aggregate is treated as homogeneous.

Total costs are calculated as the integral over marginal costs:

$$C(Y) = \int_0^Y p_Y(x)dx \quad = \bar{p} \int_0^Y \left(\frac{x}{\bar{Y}}\right)^{\frac{1}{\eta^s}} dx = \quad \frac{1}{\frac{1}{\eta^s}+1} Y p_Y$$

i.e. costs and rents (as the residual) are constant shares of revenue. The share of rents is larger as the supply elasticity rises. As this share does not tend to match the social accounting matrix data, we introduce a lump-sum transfer to account for the difference.

The consequences of this alternative fossil fuel supply specification for the four points listed at the beginning of this section are:

- The elasticity of supply remains constant by construction.
- There is no minimum quantity of production. The construction of the curve implies that supply can be reduced smoothly to approach zero with a decreasing price.[16]
- Fuel price stabilisation through the adjustment of the fixed factor is no longer possible because there is no fixed factor.

[15] A similar formulation has recently be introduced by Dong and Whalley (2012) in a model used for the analysis of OPEC monopoly rents in the course of climate policy.

[16] It would be possible to adjust the set-up so that the first unit produced has a positive price, but this would interfere with the property of constant elasticity.

- Fuel price stabilisation through an output tax remains possible and this is also relieved of the numerical problems that result from its minimum production quantity. Because the share of inputs (which are now all variable) in the net-of-tax production value is constant, the share of the inputs in the buyer's value apparently falls in the level of the adjusting tax.

4 Comparative Simulations

4.1 Scenarios

The common trait of all the scenarios used for the comparative simulations in this section is a 20 % reduction in business-as-usual emissions in coalition countries by 2020. These scenarios differ in three dimensions: types of border measures, size of the coalition and allocation of tax returns.[17] For reference, Table 1 provides a condensed overview.

BAU	Business as usual (no policy)
REF	Reference policy (no border measures)
tariff	Tariffs on embodied carbon
btax	Full border adjustment (tariff and export subsidy)
ffp	Fixed fuel prices (combined with REF, tariff and btax)
EUR	EUR only
A1xR	EUR + RA1 + USA (Annex 1 except Russia)
A1+C	A1xR + CHN (Annex 1 except Russia plus China)
Importer	Import tariff of the importing region
Exporter	Export tariff of the exporting region (voluntary export restriction)

Table 1: Scenarios in EMF 24

WorldScan, the model used in this paper, is a multi-region, multi-sector, recursively dynamic CGE model based on the GTAP 7 data set (Badri and Walmsley,

[17]We use the coordinated scenarios of the EMF 24 model comparison study. See Balistreri et al. (this volume) for a more extensive discussion.

2008) with a base year of 2004. The model is described in detail in Lejour et al. (2006). We use an aggregation to nine regions (Table 2) and 13 sectors (Table 3). The electricity sector has a bottom-up structure that contains several generation technologies, as described in Boeters and Koornneef (2011).

EUR	EU plus EFTA	USA	USA
RUS	Russia	CHN	China (incl. Hong Kong)
IND	India	RA1	Other Annex 1
EEX	Energy-exporting countries	MIC	Other middle-income countries
LIC	Other low-income countries		

Table 2: Regions in WorldScan (EMF 24)

Coal	Petroleum and coal products
Crude oil	Natural gas
Electricity	Non-ferrous metals
Iron and steel	Non-metallic minerals
Chemical products	Air transport
Water transport	Other transport
All other goods	

Table 3: Sectors in WorldScan (EMF 24)

The normal set-up of WorldScan is the analysis of deviations from a baseline (i.e. the business-as-usual) path. This path is not generated by WorldScan itself, but calibrated on the Reference Scenario of the World Energy Outlook (WEO) 2009 as implemented in the GAINS model (IEA, 2009; Amann and Wagner, 2009). The basic inputs for the baseline calibration are time series for population and GDP by region, energy use by region and energy carrier, and world fossil fuel prices by energy carrier. These are accommodated in the model by adjusting labour endowments, total factor productivity and energy efficiency. Fossil fuel supply is calibrated by the procedure explained in Section 2.1.

Of particular interest for the present study are the parameters of the fossil fuel production functions. The empirical estimates of fuel supply elasticities exist in a wide range. Our reading of the literature[18] is that values of one for oil and gas and four for coal are reasonable. The WEO baseline projects fossil fuel price increases of 120 % for oil, 83 % for coal and 76 % for gas between 2004 and 2020. Together with the value shares derived from the GTAP 7 data set, and by applying the calibration procedure described in Section 2.1, this results in substitution elasticities for the production function.

	2004		2020	
	s_R	σ	s_R	σ
EUR	0.24	1.23	0.54	5.22
USA	0.23	1.17	0.59	5.88
RUS	0.21	1.04	0.52	4.47
CHN	0.22	1.15	0.59	5.69
IND	0.25	1.35	0.68	8.41
RA1	0.24	1.30	0.60	6.08
EEX	0.27	1.48	0.67	8.07
MIC	0.23	1.19	0.59	6.03
LIC	0.23	1.18	0.64	7.16

Table 4: Coal supply parameters in WorldScan (EMF 24)

Table 4 shows the value shares for the natural resource (s_R) and elasticities of substitution (σ) for coal, because coal turns out to be the main driver of leakage (see Section 5). Owing to the calibration to higher coal prices over time, the value shares of the resource – and hence the elasticities of substitution – are considerably higher in 2020 than they are in 2004.

[18] Beck et al. (1990), Klijn and Nguyen (1993), Dahl and Duggan (1996), Graham et al. (1999), Krichene (2002) and Ringlund et al. (2008). The literature on the estimation of fuel supply elasticities is scarce, and there are hardly any recent empirical studies.

4.2 Comparing CES and CEFS

We run the EMF scenarios from Table 1 twice: once with the original set-up for fossil fuel supply, as described in Section 2, and once with a CEFS function (Section 3). Let us first take a tour through the results in order to identify those aspects in which this difference between the model variants turns out to be significant. We focus on the 2020 scenarios for two reasons. First, in 2020, the WorldScan results are less in line with the results of the other models (Balistreri et al., this volume) and more challenging to explain. The alternative approach to fuel supply may contribute here. Second, in 2020 the effects of a calibration to higher fuel prices (Table 4) are present, which have been identified as one of the causes of problems with the CES set-up.

	CES			CEFS		
	EUR	A1xR	A1+C	EUR	A1xR	A1+C
REF	33.1	24.3	27.8	30.5	17.9	10.0
tariff-importer	29.1	20.9	26.5	26.9	15.1	9.3
tariff-exporter	28.9	20.7	26.5	26.7	14.9	9.3
btax-importer	27.0	19.7	26.0	24.9	14.1	8.9
btax-exporter	26.8	19.5	26.0	24.6	13.9	8.9
REF-ffp	-1.0	0.4	5.7	2.3	-0.6	1.9
tariff-ffp-importer	-7.6	-4.0	4.6	-7.6	-4.9	1.1
tariff-ffp-exporter	-7.8	-3.6	4.8	-7.8	-4.5	1.2
btax-ffp-importer	-10.5	-6.5	3.8	-10.3	-7.0	0.7
btax-ffp-exporter	-10.8	-6.0	3.9	-10.5	-6.5	0.8

Table 5: Leakage rates (per cent)

Because the leakage rates in Table 5 are central to the whole exercise, we start our tour here. The two main hypotheses underlying the comparative scenarios are:

- Leakage rates decrease with coalition size.
- The trade channel is less important than the fossil fuel channel for leakage.

Related questions to be answered are:

- To what extent can border measures contribute to reducing leakage?
- What is the relative importance of import tariffs and export subsidies?
- Does it matter whether the revenue derived from border measures is collected by the importer or exporter?

The standard results from WorldScan (CES specification, left-hand side of Table 5) – against the background of these hypotheses and questions – are:

- It is not generally the case that leakage decreases with coalition size. In particular, the largest coalition (including China) has a higher leakage rate compared with the Annex 1 coalition.
- The fossil fuel channel dominates in terms of generating leakage. When fuel prices are stabilised, leakage is small (for the largest coalition) or even negligible (for smaller coalitions).
- Border measures can reduce leakage by a few percentage points, but not significantly. Their effect is stronger the smaller the coalition is.
- The contribution of import tariffs to leakage reduction is larger than that of export subsidies.
- The allocation of revenues – importer versus exporter – hardly matters at all.

The right-hand side of Table 5 provides the simulation results for the alternative WorldScan version with CEFS functions. the comparison of the two panels of Table 5 leads to the following results:

- Strikingly, under the CEFS specification, the inverse relationship between coalition size and leakage rate holds, as hypothesised. The difference between the two model versions is small for the EU-only case, but intriguingly large for the coalition including China.

- Leakage rates with fuel price stabilisation differ little between the two model versions. The difference in the overall leakage rates is thus caused by the fuel price channel. This is plausible, given that the model variation is in fuel supply.
- With overall smaller leakage rates in the CEFS case (particularly for the largest coalition), the effect of border measures is further reduced.
- The relative importance of tariffs and subsidies as well as the insignificance of revenue allocation is not affected by the modelling of fuel supply.

These results point clearly in the direction of a closer analysis of the relationship between coalition size and leakage rate (see Section 5). However, let us first round off our tour through the results. Table 6 summarises the emissions prices across scenarios.

	CES			CEFS		
	EUR	A1xR	A1+C	EUR	A1xR	A1+C
REF	29.0	23.4	39.9	25.8	19.3	22.0
tariff-importer	27.1	22.5	38.7	24.7	18.8	21.8
tariff-exporter	26.9	22.4	38.7	24.5	18.8	21.8
btax-importer	26.8	22.3	38.5	24.5	18.7	21.8
btax-exporter	26.6	22.2	38.5	24.3	18.7	21.8
REF-ffp	15.3	13.8	20.2	15.8	13.0	16.9
tariff-ffp-importer	14.6	13.3	20.1	14.4	12.6	16.8
tariff-ffp-exporter	14.5	13.4	20.2	14.3	12.6	16.8
btax-ffp-importer	14.8	13.2	20.0	14.6	12.4	16.8
btax-ffp-exporter	14.7	13.2	20.1	14.5	12.5	16.8

Table 6: Emissions prices (\$(2004)/tCO_2)

In general, there is a close connection with Table 5, namely emissions prices are higher the higher leakage rates are. This is in part a consequence of the construction of the scenarios. The coalition is required to compensate for leakage, i.e. to adjust the domestic emissions target so that global emissions are kept at a constant level.

Thus, the higher leakage, the stricter the domestic reduction target is and the higher is therefore the required emissions price. This means:

- Emissions prices decline with coalition size, except for the anomaly of the largest coalition.
- Emissions prices are significantly lower in the scenarios with fuel price stabilisation.
- Border measures reduce emissions prices, but only slightly.

The most significant effect of the change in fossil fuel supply modelling (right vs. left panels of Table 6) is again the coalition size effect. In the CES specification, the emissions price in the largest coalition rises sharply, whereas it is only slightly higher than in the "A1xR" coalition in the CEFS specification.

	CES			CEFS		
	EUR	A1xR	A1+C	EUR	A1xR	A1+C
REF	-0.90	-0.52	-1.04	-0.88	-0.54	-0.79
tariff-importer	-0.81	-0.48	-0.98	-0.81	-0.50	-0.77
tariff-exporter	-0.90	-0.53	-1.03	-0.89	-0.55	-0.80
btax-importer	-0.80	-0.48	-0.99	-0.80	-0.50	-0.77
btax-exporter	-0.89	-0.53	-1.04	-0.88	-0.55	-0.80
REF-ffp	-0.57	-0.48	-0.77	-0.60	-0.49	-0.79
tariff-ffp-importer	-0.50	-0.44	-0.74	-0.52	-0.46	-0.78
tariff-ffp-exporter	-0.60	-0.49	-0.79	-0.60	-0.51	-0.80
btax-ffp-importer	-0.51	-0.44	-0.75	-0.52	-0.46	-0.78
btax-ffp-exporter	-0.60	-0.50	-0.79	-0.60	-0.51	-0.81

Table 7: Welfare change in the coalition (EV as a percentage of GDP)

Next, we turn to the welfare effect (expressed as equivalent variation (EV) as a percentage of GDP) for the coalition and for the world as a whole (Tables 7 and 8). There is a close relationship between EV in the coalition and the figures for leakage (Table 5) and emissions prices (Figure 6). This is not surprising, as any effect that

	CES			CEFS		
	EUR	A1xR	A1+C	EUR	A1xR	A1+C
REF	-0.28	-0.44	-0.90	-0.29	-0.47	-0.73
tariff-importer	-0.27	-0.43	-0.88	-0.28	-0.46	-0.73
tariff-exporter	-0.27	-0.43	-0.88	-0.28	-0.46	-0.73
btax-importer	-0.25	-0.41	-0.86	-0.27	-0.45	-0.72
btax-exporter	-0.25	-0.41	-0.86	-0.27	-0.45	-0.73
REF-ffp	-0.26	-0.54	-0.89	-0.22	-0.45	-0.77
tariff-ffp-importer	-0.25	-0.52	-0.89	-0.21	-0.44	-0.77
tariff-ffp-exporter	-0.25	-0.52	-0.89	-0.21	-0.44	-0.77
btax-ffp-importer	-0.23	-0.51	-0.87	-0.20	-0.42	-0.76
btax-ffp-exporter	-0.24	-0.51	-0.87	-0.20	-0.43	-0.76

Table 8: World welfare change (EV as a percentage of GDP)

leads to higher leakage, and therefore to a tighter reduction target in the coalition, should be expected to raise the emissions price and reduce welfare. Broadly, this is what we see in Table 7.

- Welfare losses do not vary monotonously with coalition size, but are rather lowest for the medium-sized coalition.[19]
- Border measures reduce costs for the coalition, but the effect is limited.[20]
- This is the only point where the allocation of revenues matters. Obviously, it is disadvantageous for the coalition if tariff revenues are given to the exporter. In this case, climate policy with border measures can easily be more costly than without these measures.

The world welfare change (Table 8) is informative of the overall efficiency of climate

[19] This is driven by the strictness of the reduction target; see the discussion in Section 5.

[20] Interestingly, border measures can reduce the loss for the coalition even if there is no leakage to start with (in the scenarios with fuel-price stabilisation). This is a clear indication that the welfare effect of border measures is largely an effect of strategic trade policy, rather than an efficiency gain in climate policy.

policy. We see that across all coalition sizes, fuel price stabilisation and different specifications of fuel supply, there is an efficiency gain through border measures – but it is tiny. The order of magnitude is one hundredth of a percent of GDP, which must be weighted against the cost of setting up an administrative apparatus that implements these measures. Even if we express efficiency gains as a percentage of climate policy costs, we remain in the range of no more than 10 %.

Summing up, the differences between the two model versions of WorldScan – CES and CEFS modelling of fuel supply – are predominantly driven by the large difference in the leakage rates for the largest coalition. In the next section, we further analyse and explain this difference.

5 Coalition size and leakage

The first point to realise when analysing the relationship between coalition size and leakage rate in the EMF scenarios for 2020 is the construction of the 2020 emissions reduction targets. The targets for 2020 are defined as a reduction to 80% of the base year emissions (2004), corrected for leakage.[21] As always with these kinds of scenario exercises, the projected business-as-usual development of emissions is crucial. The higher the projected emissions growth at the business-as-usual level, the more stringent is the reduction target. As China has a particularly high emissions growth, the relative reduction target (even before any correction for leakage) is the most ambitious in the largest coalition (including China). Relative to the baseline 2020 emissions, the reduction targets in the three different coalitions are 19.7 % (EUR), 20.3 % (A1xR) and 33.6 % (A1+C).

The second element in the analysis is the relationship between the reduction target and leakage rate. Figure 1 shows the marginal (dotted lines) and average (solid lines) leakage rates for the three coalitions and an increasingly strict target.[22]

For any given relative reduction target, average leakage rates decrease with coalition size. This is simply the basic effect that one would expect given that the

[21] In other words, global emissions are reduced by the difference between baseline emissions and 80% of base year emissions in the coalition.

[22] The points marked by symbols correspond to the leakage rates in Table 5.

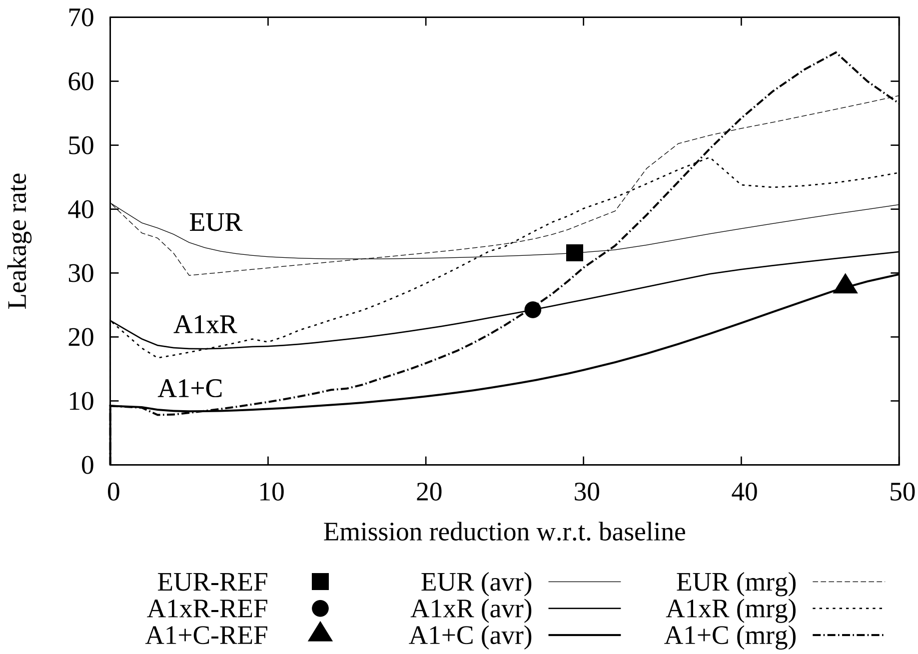

Figure 1: Leakage rates with increasing target stringency (CES)

part of the world where leakage can take place is shrinking. However, for all three coalitions, the marginal leakage rates are increasing along with the strictness of the target. For the largest coalition, this effect is the strongest. At a target intensity of approximately 40 %, the marginal leakage rate of the largest coalition even overtakes those of smaller coalitions. As domestic reduction (which is on the x-axis) must be compensated for leakage, we arrive at compensated reduction targets of 29.4 % (EUR), 26.8 % (A1xR) and 46.4 % (A1+C). The large leakage rate of the largest coalition is thus the combined effect of an ambitious initial (uncompensated) target and a steeply increasing marginal leakage rate.

Figure 2 shows the same relationship in the CEFS specification, and the difference with the CES case is striking. For small reduction targets, the curves are almost identical.[23] However, for ambitious reduction targets, there is no longer a sharp increase in marginal leakage rates (with the exception of EUR above 35 %). In particular, the marginal leakage rate for the largest coalition now remains stable and below the leakage rates of smaller coalitions. As a consequence, the leakage-adjusted

[23]This is not surprising given that both sets of functions have been calibrated to the same local fuel supply elasticities.

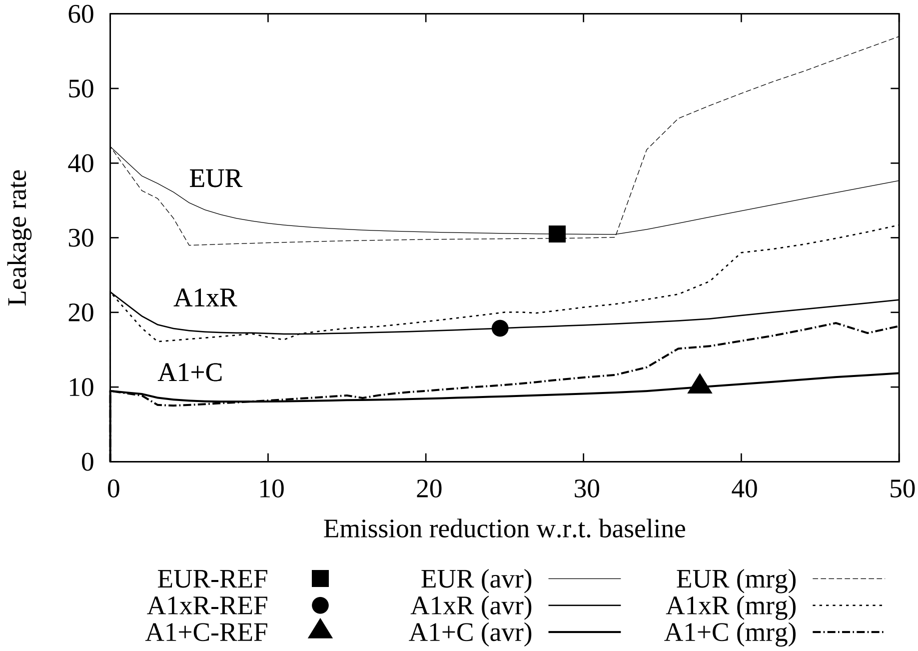

Figure 2: Leakage rates with increasing target stringency (CEFS)

target is now considerably less stringent compared with the CES case: 37.4 % leakage in A1+C, whereas there is little change for smaller coalitions (28.3 % and 24.7 % for EUR and A1xR, respectively).

Let us now focus on the most intriguing case: the steeply increasing marginal leakage rate for the large coalition in the CES specification. Figure 3 shows the marginal leakage by (non-coalition) region, expressed as a multiple of the leakage at a 0 % target (to correct for the size of regions). Here, we see that while all regions contribute to the increase in leakage, they react asymmetrically. India (IND) is at the extreme, with a leakage rate peaking at almost 14 times the initial value, followed by the energy exporters (EEX) and low-income countries (LIC).[24]

A closer analysis of the developments in India shows that the leakage can almost exclusively be attributed to coal use in electricity generation (with both a substitution towards coal and an increase in total electricity generation). The predominance of coal in the leakage is illustrated in Figure 4.

[24] It should be noted, however, that in absolute numbers, the contribution of middle-income countries (MIC) is the largest, simply because here we have the largest amount of emissions to start with.

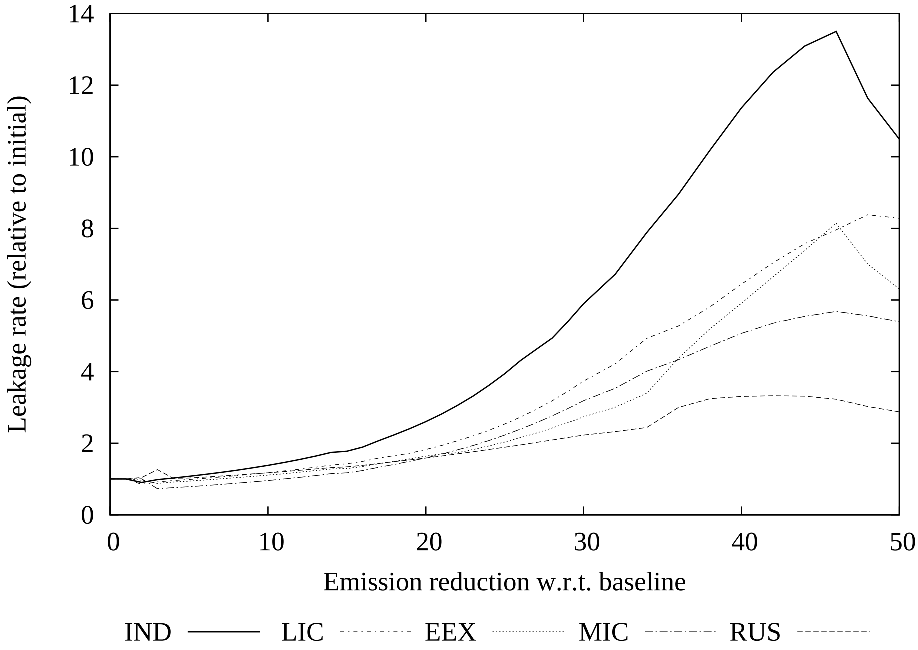

Figure 3: Relative regional leakage (large coalition, CES)

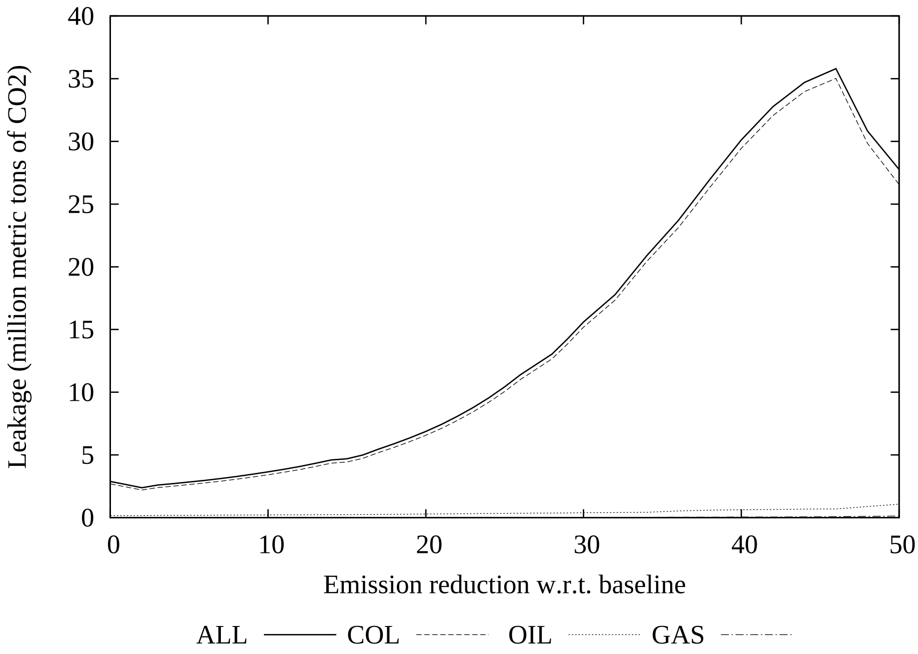

Figure 4: Leakage in India (large coalition, CES)

The sharp increase in coal use in India, in turn, is driven by large and increasing imports of cheap coal from coalition countries, most importantly China and the USA. Figure 5 shows total coal use in India by source region as function of increasing stringency of the abatement target in the coalition. Until a reduction target of approximately 30 %, the changes are small, but beyond that level, a rapid substitution process towards imported coal is taking off.[25]

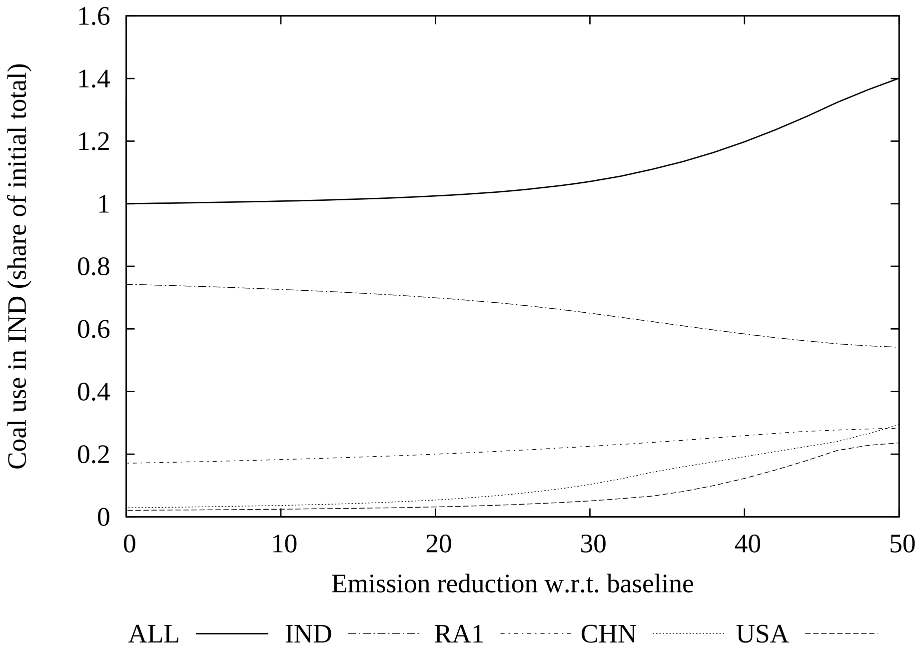

Figure 5: Coal use in India by source (large coalition, CES)

The last step in our exploration of the energy markets in WorldScan links these developments back to the modelling of fossil fuel supply. The reason for the shifts in fossil fuel trade patterns is the sharply decreasing fossil fuel prices in coalition countries. This, in turn, is a consequence of the endogenously adjusting fossil fuel supply elasticities discussed in Section 2.2. Figure 6 shows the general equilibrium supply elasticities in coalition countries for coal; this elasticity is actually declining rapidly, almost reaching zero in EUR, USA[26] and CHN.[27] In the scenarios with the

[25]Similar graphs could be presented for EEX (where substitution is mostly towards coal imported from the USA) and LIC (where imports are predominantly from CHN).

[26]We cannot explain the strange hiccup at the level of 15 % emissions reduction.

[27]For comparison purposes, we have included the elasticity in the non-coalition region MIC, which is declining as well, but not as rapidly as seen in coalition countries.

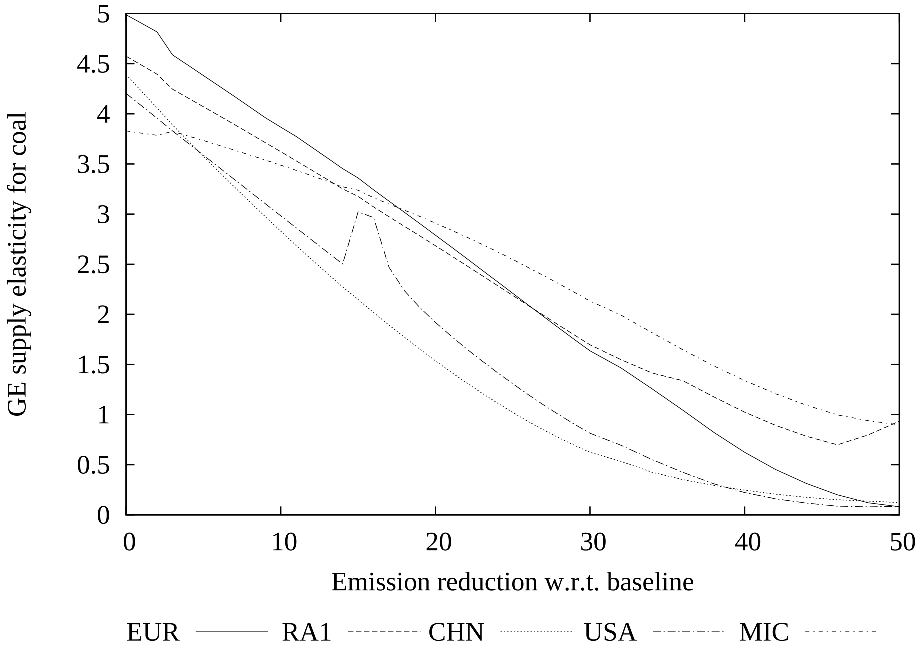

Figure 6: Coal supply elasticities (large coalition, CES)

CEFS modelling of fuel supply, this effect is suppressed, preventing the sharp rise in leakage featured in the CES scenarios.

6 Conclusions

Most of the CGE models used for the evaluation of climate policy represent fossil fuel supply by CES functions that have a fixed factor (natural resource). This model specification needs a closer look in two respects. First, while in a CES function the elasticity of substitution is constant, the elasticity of supply is not. This leads to large changes in supply behaviour and, as a consequence, in leakage rates when reduction targets of the coalition are ambitious. Second, when scenarios are run with fuel price stabilisation, the adjustments made for this aim (adjustment of the natural resource stock) may interfere with the economic effects to be analysed. To explore these potential problems, we set up an alternative specification of fossil fuel supply in WorldScan (i.e. constant elasticity of fuel supply, CEFS) and compare the outcomes of the EMF scenarios for these two specifications.

The effect of the variation in supply modelling depends on the settings of the scenario analysed. For small coalitions and moderate emissions reduction targets, the difference in leakage rates between the two model versions is limited. This difference can be substantial, however, for large coalitions that have ambitious targets, especially if there are fuel exporters in the coalition.

The consequences of these model differences for the assessment of border measures turn out to be limited. In the case of large coalitions that have ambitious reduction targets, where the versions differ most, border measures are hardly effective anyway. The difference in the decomposition of leakage rates therefore plays no prominent role.

In somewhat more detail, the most prominent outcomes of the model comparison – CES versus CEFS – are the following:

- In the CES specification, leakage does not decrease with coalition size. In particular, the largest coalition (including China) has a higher leakage rate than the Annex 1 coalition. In the CEFS specification, by contrast, the inverse relationship between coalition size and leakage rate is re-established.
- The fossil fuel channel (F-leakage) dominates in terms of generating leakage in both model specifications. With fuel price stabilisation, leakage is small (for the largest coalition) or even negligible (for smaller coalitions). The difference in leakage between the two model specifications is attributable to the fossil fuel channel. Therefore, the relative importance of F-leakage is larger in the CES specification.
- In both specifications, border measures can reduce leakage by a few percentage points, but their impact is small and there are no quantitatively significant differences. Qualitatively, their effects are stronger the smaller the coalition and relatively larger under the CEFS specification.

A deeper analysis of the two model specifications shows that there are sharply increasing leakage rates with stricter reduction targets in the largest coalition under CES fuel supply. Actually, endogenously decreasing supply elasticities in the CES specification drive the model results.

- Through calibration to a relatively high fossil fuel price path in the baseline, the CES specification results in high elasticities of substitution (above one for coal in all regions) if the given elasticities of supply are reproduced.

- This results in a minimum production quantity for fossil fuels. Once the emissions reduction target in the coalition becomes so strict that it reduces fossil fuel use towards this minimum production quantity, fuel supply elasticities fall to zero. This results in an accelerated fall of fossil fuel producer prices in the coalition.

- As fossil fuel use in the coalition is restricted through climate policy measures, the only remaining channel for selling the minimum production quantity is exports. According to the pre-existing Armington patterns of international trade, exports are allocated to non-coalition regions and thus they produce leakage there.

- Differences in (marginal) leakage rates are not so much a question of coalition *size*, but rather of whether the coalition includes fuel exporters.

These simulation results deserve qualification. Certainly, a climate policy coalition could implement measures to prevent large-scale fossil fuel exports if this turns out to be a major cause of leakage in the course of tightening the emissions targets. However, rather than trying to introduce compensating measures in the CES model setup, we view varying supply elasticities as an artifact that should be avoided. The CEFS approach achieves this while remaining relatively simple to implement in a CGE framework. We have thus made it the preferred specification in WorldScan.

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Appendices

A.1 Fossil fuel supply with a fixed factor

In calibrated share form (Rutherford, 1998), the cost function derived from a one-level CES production function with output Y (fossil fuel) and inputs R (natural resource) and V (aggregate of variable inputs) reads:

$$p_Y = \left(\theta_R \tilde{p}_R^{1-\sigma} + (1-\theta_R)\,\tilde{p}_V^{1-\sigma}\right)^{\frac{1}{1-\sigma}} \tag{3}$$

where θ_R is the value share of the natural resource, σ is the elasticity of substitution and the variables with a tilde denote values relative to the initial (calibrated) value ($\tilde{x} = x/\bar{x}$). The resulting demand function for the fixed factor is:

$$\tilde{R} = \tilde{Y}\left(\frac{\tilde{p}_Y}{\tilde{p}_R}\right)^{\sigma}$$

As R is fixed at its initial value, we have $\tilde{R} \equiv 1$. Inverted for the unobservable price of the resource:

$$\tilde{p}_R = \tilde{p}_Y \tilde{Y}^{\frac{1}{\sigma}} \tag{4}$$

Substitution into the cost function (3):

$$\tilde{p}_Y^{1-\sigma} = \theta_R \tilde{p}_Y^{1-\sigma} \tilde{Y}^{\frac{1-\sigma}{\sigma}} + (1-\theta_R)\,\tilde{p}_V^{1-\sigma}$$

Solved for the output:

$$\tilde{Y} = \left[1 - (1-\theta_R)\left(\frac{\tilde{p}_V}{\tilde{p}_Y}\right)^{1-\sigma}\right]^{\frac{\sigma}{1-\sigma}} \tag{5}$$

This reproduces the calculations in footnote #6 in Babiker et al. (2001), except that in that paper the exponent after the square bracket in the last equation is missing.

In an environment that has stable prices for the variable factors ($\tilde{p}_V \equiv 1$), the elasticity of fuel supply is

$$\begin{aligned}
\eta^s &= \frac{\partial \log \tilde{Y}}{\partial \log \tilde{p}_Y} \\
&= \sigma\left[1 - (1-\theta_R)\,\tilde{p}_Y^{\sigma-1}\right]^{-1}(1-\theta_R)\,\tilde{p}_Y^{\sigma-1} \\
&= \sigma \frac{1-s_R}{s_R}
\end{aligned}$$

where s_R is the variable value share of the natural resource (whereas θ_R is the fixed value share at the initial point):

$$s_R = \theta_R \frac{\tilde{p}_R}{\tilde{p}_Y \tilde{Y}} = 1 - (1 - \theta_R)\, \tilde{p}_Y^{\sigma-1}$$

A.2 Calibration of the fossil fuel price

Starting from eq. (5), adjusted for variable R and fixed p_V ($\tilde{p}_V \equiv 1$),

$$\tilde{Y} = \tilde{R} \left[1 - (1 - \theta_R)\, \tilde{p}_Y^{\sigma-1}\right]^{\frac{\sigma}{1-\sigma}}$$

the change in the fixed factor necessary for a given output price change (and fixed output) can be calculated as

$$\varepsilon_{Rp_Y} = -\frac{\sigma\,(1 - s_R)}{s_R}$$

According to eq. (4), the change in the rent of the fixed factor is

$$\varepsilon_{p_R p_Y} = 1 - \frac{1}{\sigma}\varepsilon_{Rp_Y} = \frac{1}{s_R}$$

Finally, for the change in the value share, we get

$$\varepsilon_{s_R p_Y} = \varepsilon_{Rp_Y} + \varepsilon_{p_R p_Y} - 1 = (1 - \sigma)\, \frac{(1 - s_R)}{s_R}$$

If $\sigma > 1$, output can be produced with the variable factor alone. The amount of $\tilde{V}$ needed to produce $\tilde{Y}$ with $\tilde{V}$ alone is

$$\tilde{V}^{max} = \left(\frac{1}{1 - \theta_R}\right)^{\frac{\sigma}{\sigma-1}} \tilde{Y}$$

Using only $\tilde{V}$ for production gives at the same time the upper bound for the price

$$\tilde{p}_Y^{max} = \frac{\tilde{V}^{max} \bar{V} p_V}{\bar{V}\bar{p}_V + \bar{R}\bar{p}_R} = \left(\frac{1}{1 - \theta_R}\right)^{\frac{\sigma}{\sigma-1}} (1 - \theta_R) = (1 - \theta_R)^{\frac{1}{1-\sigma}}$$

A.3 Reaction to a climate policy shock

A negative policy shock to fuel demand ($b < 0$) must be analysed in the supply/demand system of equations:

$$\bar{R}\theta_R^{\frac{1}{\sigma-1}}\left[1-(1-\theta_R)\,p_Y^{1-\sigma}\right]^{\frac{\sigma}{1-\sigma}} - Y = 0$$

$$f(p_Y) - Y + b = 0$$

where $f(p_Y)$ is fuel demand, with elasticity

$$\eta^d = \frac{d\log f(p_Y)}{d\log p_Y} < 0$$

The reactions of the endogenous variables, Y and p_Y, to a demand shock b are

$$\begin{aligned}\varepsilon_{Yb} &= \frac{\eta^s}{\eta^s-\eta^d} > 0\\ \varepsilon_{p_Y b} &= \frac{1}{\eta^s} > 0\end{aligned}$$

where elasticities are defined as

$$\varepsilon_{xb} = \frac{Y\,d\log x}{db}$$

The rent of the fixed factor changes according to

$$\varepsilon_{p_R b} = \varepsilon_{p_Y b} + \frac{1}{\sigma}\varepsilon_{Yb}$$

and the change in the value share of the fixed factor can be calculated as

$$\begin{aligned}\varepsilon_{s_R b} &= \varepsilon_{p_R b} - \varepsilon_{Yb} - \varepsilon_{p_Y b}\\ &= \left(\frac{1-\sigma}{\sigma}\right)\frac{\eta^s}{\eta^s-\eta^d}\end{aligned}$$

A negative shock to fuel demand ($b < 0$) leads to an increase (decrease) of the share of the fixed factor if $\sigma > 1$ ($\sigma < 1$).

The minimum production level (with $\sigma > 1$) is calculated from the production function

$$\tilde{Y} = \left[\theta_R\left(\tilde{R}\right)^{\frac{\sigma-1}{\sigma}} + \theta_V\left(\tilde{V}\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}$$

by setting $\tilde{R} = 1$ and $\tilde{V} = 0$:

$$\tilde{Y}^{min} = (\theta_R)^{\frac{\sigma}{\sigma-1}}$$

A.4 Fuel price stabilisation

Fuel price stabilisation essentially eliminates the second equation from the supply/demand system

$$R\theta_R^{\frac{1}{\sigma-1}}\left[1-(1-\theta_R)\,p_Y^{\sigma-1}\right]^{\frac{\sigma}{1-\sigma}}-Y=0$$

$$f(p_Y)-Y+b=0$$

because $dp_Y=0$ by construction, and therefore $dY=db$. As with a constant p_Y, R and Y are proportional in the first equation. Thus, we have trivially

$$\frac{d\log R}{d\log Y} = 1$$

In the case with an output tax, we have

$$R\theta_R^{\frac{1}{\sigma-1}}\left[1-(1-\theta_R)\left(\frac{1+t}{\tilde{p}_e}\right)^{1-\sigma}\right]^{\frac{\sigma}{1-\sigma}}-Y=0$$

which results in

$$\varepsilon_{tY}=\frac{dt}{(1+t)d\log Y}=\frac{-s_R}{\sigma_e\,(1-s_R)}=-\frac{1}{\eta^s}$$

The rent of the fixed factor changes according to

$$\varepsilon_{p_RY}=-\varepsilon_{t_eY}+\frac{1}{\sigma_e}$$

This means for the share of the fixed factor in production value:

$$\varepsilon_{s_Rb}=\varepsilon_{p_Rb}-\varepsilon_{p_Yb}-\varepsilon_{Yb}=-\varepsilon_{tb}+\frac{1}{\sigma}+\varepsilon_{tb}-1=\frac{1-\sigma}{\sigma}$$

For the share of the variable factor in the buyers' value, $\hat{s}_V$, we have:

$$\begin{aligned}\hat{s}_V &= \frac{1-s_R}{(1+t)}\\ \varepsilon_{\hat{s}_Vb} &= -\frac{s_R}{1-s_R}\varepsilon_{s_Rb}-\varepsilon_{tb}\\ &= \frac{s_R}{1-s_R}>0\end{aligned}$$