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Understanding Carbon Leakage

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Understanding carbon leakage

Christoph Böhringer and Knut Einar Rosendahl

Abstract:

Carbon leakage is a major concern in the design of *unilateral* climate policies aimed at reducing *global* emissions in a cost-effective manner. In order to assess the cost-effectiveness of anti-leakage measures, it is crucial to understand the fundamental mechanisms that contribute to leakage. We provide theoretical analysis of the two main channels of leakage: the fossil fuel market channel and the competitiveness channel. We show that the two channels reinforce each other. Furthermore, we find that whereas leakage via the fossil fuel market channel decreases with the fuel supply elasticity and increases with the fuel demand elasticity, the opposite is the case for the competitiveness channel. We show that the effectiveness of output-based allocation and border carbon adjustments to combat carbon leakage increases with the fuel supply elasticity and decreases with the fuel demand elasticity. We supplement the simplified theoretical analysis with numerical simulations using a more complex multi-sector, multi-region computable general equilibrium model of the global economy to quantify the implications of unilateral climate policy designs for the European Union. We find that leakage via the fossil fuel channel dominates leakage via the competitiveness channel unless fuel supply elasticities are quite high and fuel demand elasticities are quite low. Furthermore, we find that the lower the fossil fuel demand elasticity, the greater the gains in cost-effectiveness from implementing anti-leakage measures.

Keywords: carbon leakage, fossil fuel elasticities, output-based allocation, border carbon adjustments

JEL codes: D58, F18, H23, Q54

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1. Introduction

A major concern in the design of unilateral climate policy is the risk of carbon leakage, i.e., the extent to which domestic emissions abatement is offset by increased emissions abroad. This concern is particularly relevant for climate front-runners like the EU with significantly stricter emissions regulations than most other jurisdictions.¹

The theoretical literature on carbon leakage has identified two major intertwined leakage channels (for seminal contributions see Markusen (1975) and Hoel (1996)). Firstly, the fossil fuel market channel, where reduced demand for fossil fuels in regulated regions can lead to a decline in international fuel prices, thereby increasing demand for fossil fuels in unregulated regions.² Secondly, the so-called competitiveness channel, where higher domestic energy costs lead to a loss in competitiveness of emissions-intensive and trade-exposed (EITE) industries (e.g. steel, cement, chemicals) on domestic and export markets; as a consequence, domestic EITE production may relocate to countries with less stringent climate regulations thereby increasing emissions abroad (McKibbin and Wilcoxon (2008) and Burniaux and Oliveira Martins (2012)).³

The extent of leakage is strongly influenced by two sets of elasticities that reflect responsiveness of economic producers and consumers to emissions regulations. Leakage via the fossil fuel market channel depends crucially on supply and demand elasticities of fossil fuels. The lower the supply elasticities, the stronger the decrease in international fuel prices triggered by the reduction in fuel demand in the regulated countries, and the higher the leakage via the fossil fuel market channel.⁴ The higher the demand elasticities in unregulated countries, the stronger the increase in demand to lower fuel prices, and the higher the leakage. Leakage via the competitiveness channel is governed by trade elasticities, which determine the substitutability between domestically produced and imported goods. The more easily foreign and domestic products can be substituted for one another, the higher the leakage, as more expensive domestic products lose market shares both in the domestic market and foreign (export) markets.⁵

¹ <https://carbonpricingdashboard.worldbank.org/>

² The fossil fuel market channel is also referred to as energy market channel in the literature. Note that intertemporal leakage occurs if fossil fuel resource owners respond to future demand reductions by lowering current prices – the mere expectation of future stringent climate policies could incentivize fossil fuel owners to accelerate their extraction (the so-called “green paradox” – see Sinn (2008)). Our analysis is static and hence disregards this potential intertemporal leakage.

³ Other channels that are discussed less extensively in the literature and not examined further in this paper are: (i) the technology spillover channel: stricter climate policies can incentivize innovation in low-carbon technologies that may spread globally and thereby reduce emissions (see e.g. Gerlagh and Kuik (2014) and Di Maria and van der Werf (2008)), or (ii) the free-riding channel: in a game-theoretic setting, countries may benefit as free-riders from unilateral emissions abatement as a public good and then increase their own emissions as a strategic substitute (see e.g. Bohm (1993) and Barrett (1994)).

⁴ For the extreme case of fully inelastic fuel supply, i.e. a supply elasticity of zero, the leakage rate goes up to 100%. Empirical estimates of fossil fuel supply and demand elasticities vary considerably (see e.g. Prest et al. (2024)), which is due, among other things, to different time horizons or market structures underlying the respective estimates.

⁵ It should be noted that empirical estimates for both sets of elasticities partly reflect market structures. For example, highly competitive EITE markets imply that firms cannot easily pass through higher costs to users such that competitiveness losses for domestic firms due to unilateral emissions regulations will be more pronounced

Although important driving forces for leakage are well known, there are still knowledge gaps that we would like to fill in our analysis. Firstly, how do the two leakage channels interact - do they reinforce or counteract each other? Secondly, how do fossil fuel elasticities affect *overall* leakage, not only leakage in the fossil fuel market? Thirdly, which of the two leakage channels dominates total leakage? And last but not least, how does the (cost-)effectiveness of anti-leakage measures depend on the fossil fuel elasticities?

A more thorough understanding of carbon leakage mechanisms is needed, not least because there is an apparent discrepancy between the extent of leakage identified in empirical ex-post studies and that identified in numerical ex-ante studies. Ex-post analysis of leakage is sparse and finds only very limited evidence of carbon leakage. Venmans et al. (2020) as well as Verde (2020) review the econometric literature on the impacts of carbon pricing in OECD and G20 countries, where a larger part of econometric assessments focuses on the EU Emissions Trading System (EU ETS). Most of these assessments conclude that there is no statistically significant effect of carbon pricing on leakage. The reviews cite several reasons for this. One intuitive explanation is that energy costs play an inferior role compared to other direct and indirect cost components of many EITE producers. Another reason is that empirical analyses have examined time periods when carbon prices were low (e.g., the price of emissions allowances in the EU ETS during 2012-2018 on average was less than \$10/tCO₂). Another important explanation is supplementary policy measures to protect EITE industries that are at risk of carbon leakage, such as generous free allowances allocated more or less proportional to firms' (recent) production levels – often referred to as output-based allocation.⁶

The lack of empirical evidence for carbon leakage stands in stark contrast to the bulk of ex-ante simulations, which are predominantly based on computable general equilibrium (CGE) models of the global economy and on average predict significant leakage rates induced by unilateral carbon pricing.⁷ Most simulation studies conclude that the leakage rate of a unilateral carbon price is in the range of 5–30%, i.e., a reduction of 100 units of CO₂ in the regulating countries leads to an increase of 5–30 units of CO₂ in non-regulating countries (see, e.g., the model cross-comparison by Böhringer et al. (2012) or reviews by Zhang (2012), Branger and Quirion (2014), or Carbone and Rivers (2017)).⁸ Leakage estimates derived from CGE simulations include leakage through both the competitiveness channel as well as the fossil fuel market channel, where a few previous studies have indicated that the latter tends to dominate

and leakage rates tend to be higher (for the implications of alternative trade structures see e.g. Balistreri and Rutherford (2012) or Balistreri et al. (2018)). Likewise, imperfect competition on fossil fuel markets can affect leakage through the fossil fuel market channel: When fuel supply is controlled by a dominant producer such as OPEC, leakage rates via the fossil fuel market become lower as the dominant producer cuts fuel supply to keep fuel prices high (Böhringer et al. (2014a); see also the theoretical contribution by Baccianti and Schenker (2022)).

⁶ Two more recent studies are Dechezleprêtre et al. (2022) and Wang and Kuusi (2024), where the former finds no evidence of leakage while the latter finds moderate leakage.

⁷ CGE models rely on microeconomic theory to explain complex market interactions. Due to the lack of comprehensive data series, they are typically not econometrically estimated in a comprehensive manner. Instead, technological options and preferences that determine the responses of economic agents are calibrated to empirical base-year observations (such as input-output data) and econometric estimates for elasticities. CGE models can then be conveniently used to run controlled policy experiments and come up with ex-ante predictions on economic responses (see Section 3).

⁸ There are, however, a few outliers with negative leakage (Elliott and Fullerton (2014)) or leakage rates above 100% (Babiker (2005)), adopting less conventional assumptions on international factor mobility or market power.

(Burniaux and Oliveira Martins (2012), Böhringer et al. (2012)). This may provide another – often overlooked – explanation why ex-post empirical estimates that typically focus on leakage via the competitiveness channel might be much lower than ex-ante estimates based on CGE simulations. The competitiveness channel is narrower than the fossil fuel market, as it primarily affects EITE industries, which account for a relatively small share of the economy; note that leakage through the fossil fuel market channel would occur even if no goods other than fossil fuels were traded internationally.

Given widespread policy concern about counterproductive carbon leakage, there is a large body of literature on second-best regulatory designs, i.e., how unilateral emissions pricing can be adjusted or supplemented to reduce leakage and foster the effectiveness of unilateral action. Mirroring the prevailing policy debate on adverse competitiveness effects for EITE industries, the literature focuses almost exclusively on measures to reduce leakage through the competitiveness channel. Early theoretical contributions date back to Markusen (1975) and Hoel (1996), who derive second-best combinations of domestic emissions taxes and trade taxes, i.e., import duties and export rebates based on the carbon content of traded goods. Such border carbon adjustments (BCA) are intensively discussed in the design of current climate policy (see Böhringer et al. (2022) or Fontagné and Schubert (2023) for more recent reviews) and already enshrined in law (at least with regards to imports), as in the forthcoming EU Carbon Border Adjustment Mechanism (CBAM). As an alternative to second-best trade measures, the theoretical literature proposes output-based allocation (OBA - likewise referred to as output-based rebating, OBR), in which EITE firms receive free allowances or offsets in proportion to their production (for early analytical contributions see Fischer (2001) or Böhringer and Lange (2005)). These rebates operate as implicit subsidies to domestic EITE production, thereby attenuating the relocation of output and emissions abroad.⁹ Quantitative impact assessments of anti-leakage measures such as OBR or BCA are largely based on ex-ante CGE simulation analysis confirming the theoretical potential for cost-effectiveness gains (e.g., Böhringer et al. (2014b))

Both the theoretical and applied literature on carbon leakage and potential anti-leakage measures have focused on the competitiveness channel, mirroring the political economy of climate policy. However, this focus has to a large degree neglected the important role of leakage through the fossil fuel market and not least the interactions between the two intertwined channels.

To gain deeper insights into the key mechanisms that drive carbon leakage and the potential effectiveness of anti-leakage measures, we combine theoretical and numerical analysis. In the theoretical part, we set up a stylized analytical model capturing the main economic drivers for leakage via the two channels. We then adopt three alternative trade assumptions (fossil fuel goods and/or EITE goods can be traded) to investigate how the two leakage channels perform separately and how they interact. We analytically show that the two channels reinforce each other, that is, the total leakage exceeds the sum of leakage via the two channels separately. Moreover, we show that the fuel supply elasticity and the fuel demand elasticity have opposite effects on leakage when considering the two

⁹ A more recent strand in the theoretical literature (Böhringer et al., 2017a, 2025) shows that output-based rebates combined with consumption taxes is more cost-effective than output-based rebates stand-alone and can be equivalent to border carbon adjustment as a second-best alternative to avoid trade conflicts. Furthermore, Böhringer et al. (2023, 2026) compare output-based rebates with other rebating schemes such as abatement-based or intensity-based rebating of revenues from emissions pricing regarding their impacts on leakage, EITE production, and cost-effectiveness of regulation.

channels separately. Finally, we find that the effectiveness of both OBR and BCA, as the most widespread and discussed policy instruments to address leakage through the competitiveness channel, increases with the supply elasticity and decreases with the demand elasticity of fossil fuels.

In the numerical part, we apply a multi-region, multi-sector CGE model of the global economy to quantify the policy relevance of our theoretical insights in a more complex setting based on empirical data. Our simulations focus on the EU as front-runner in unilateral carbon pricing where leakage is a major concern and anti-leakage measures such as OBR and BCA have already been implemented or are currently being implemented. The simulation results confirm that the two leakage channels are indeed reinforcing each other. Further, we find that leakage through the fossil fuel market channel is dominant unless fossil fuel supply elasticities are quite high *and* demand elasticities are quite low. Consequently, while anti-leakage measures reduce leakage and can promote global cost-effectiveness of unilateral carbon pricing, they mainly address leakage through the competitiveness channel, and hence have only a limited effect on overall leakage. In line with the analytical results, we find that the higher the fossil fuel supply elasticity and the lower the fossil fuel demand elasticity, the more effective the measures against leakage are. The lower the elasticity of demand for fossil fuels, the higher are the cost-effectiveness gains from additional OBR or BCA measures. The results are somewhat mixed when it comes to supply elasticity, however in most cases, cost savings increase with this elasticity. In terms of the ranking of OBR and BCA, our numerical simulations confirm earlier findings from the literature that BCA enables greater cost savings than OBR. The difference is more pronounced when the supply elasticity is high. The ranking is more mixed though if the BCA only includes import tariffs (TRF) as OBR outperforms TRF if fuel supply is highly inelastic.

Our analysis fills the gap in theoretical and applied research on the interactions between the two major channels for carbon leakage, as well as the implications of fossil fuel market responsiveness for the extent of leakage of unilateral carbon pricing, and for the global cost-effectiveness of anti-leakage measures. While ex-ante CGE simulations in the past have already addressed the prominent role of fossil fuel supply and demand elasticities for leakage (see in particular the contribution by Burniaux and Oliveira Martins (2012)), there has been no theoretical analysis to substantiate the numerical results. Furthermore, to the best of our knowledge, a systematic analysis on how leakage through the fossil fuel market and the competitiveness channel interact and might affect both leakage and cost-effectiveness ranking of anti-leakage measures such as OBR and BCA is missing.

The remainder of the paper is organized as follows. In Section 2, we present our basic theoretical model; we derive analytical results on how fuel supply and demand elasticities affect leakage through the fossil fuel market and the competitiveness channels and how the two channels interact with each other. In Section 3, we briefly summarize the CGE model used for the simulation analysis. In Section 4, we describe the scenarios for unilateral climate policies in the EU and discuss the simulation results. In Section 5, we conclude.

2. Theoretical analysis

We consider two symmetric regions $i = 1, 2$, where “symmetric” means that quantities are the same across regions if prices are the same. Supply of fossil fuels in region i is denoted S_i , and is a function of the market price p_i in region i : $S_i = S(p_i)$. We assume a constant supply elasticity $\gamma > 0$:

$$(1) \quad S_i = s(p_i)^\gamma.$$

Demand for fossil fuels in region i depends on the end-user price in region i , which is the sum of the market price and a potential economy-wide CO₂ price τ_i : $p_i + \tau_i$. Fossil fuel demand takes place in two sectors in each region, one trade-exposed (t) and one non-tradable sector (n). The trade-exposed sector can be thought of as a composite of emissions-intensive and trade-exposed (manufacturing) industries, whereas the non-tradable sector can be thought of as mostly transport and electricity. For the non-tradable sector, we consider a simple demand function with constant demand elasticity $-\delta$:

$$D_i^n = d^n (p_i + \tau_i)^{-\delta} \text{ with } \delta > 0.$$

The trade-exposed sector in region i produces the good y_i , using fossil fuels. Let e_i denote fuel (emissions) intensity of production, so that fossil fuel use in region i is $D_i^t = e_i y_i$. There is a cost involved in reducing fuel intensity below a level e_{Free} , where e_{Free} would be chosen if fuel use were free of charge ($p_i + \tau_i = 0$). For this cost, we choose a functional form implying that for a fixed output level y_i , the fuel demand elasticity is constant (see below). Finally, costs of other inputs are assumed to be a quadratic function of output. The profit function is then:

$$\pi_i = p_i^y y_i - (p_i + \tau_i) e_i y_i - (e_i^{-\hat{\varepsilon}} - \bar{e}) y - \frac{c}{2} y_i^2$$

where $\hat{\varepsilon} > 0$ and $\bar{e} = e_{\text{Free}}^{-\hat{\varepsilon}}$. This gives the following first-order conditions for optimal output and fuel intensity:

$$(2) \quad y_i = \frac{p_i^y - (p_i + \tau_i) e_i - (e_i^{-\hat{\varepsilon}} - \bar{e})}{c}$$

$$(3) \quad e_i = \hat{\varepsilon}^\varepsilon (p_i + \tau_i)^{-\varepsilon}$$

where $\varepsilon = \frac{1}{\hat{\varepsilon} + 1} > 0$. Hence, for a given output level y_i , we see that the demand elasticity in the trade-exposed sector is constant and equal to $-\varepsilon$.¹⁰ Total fossil fuel demand in region i can then be written:

$$(4) \quad D_i = D_i^n + D_i^t = d^n (p_i + \tau_i)^{-\delta} + \hat{\varepsilon}^\varepsilon (p_i + \tau_i)^{-\varepsilon} \frac{p_i^y - (p_i + \tau_i) e_i - (e_i^{-\hat{\varepsilon}} - \bar{e})}{c}$$

To simplify the analysis, we assume that consumption of the trade-exposed good is exogenous and equal in the two regions: \bar{Y} .¹¹

¹⁰ Note that this elasticity ($-\varepsilon$) is strictly between 0 and -1, since we must have $\hat{\varepsilon} > 0$.

¹¹ Changes in demand of the trade-exposed good is of second order, as demand for manufacturing goods in aggregate is fairly inelastic. In the CGE model analysis, demand for all goods is endogenous and will respond to implementation of a CO₂ price.

In this model, leakage can occur via trade in fossil fuels and/or the trade-exposed good. If there were no trade in either of these, there would be no leakage. That is, a CO₂ price in region 1 can only affect emissions in region 2 if trade is allowed for at least one of these goods. Hence, to examine the two leakage channels, both individually and how they interact, we consider either no trade or unrestricted trade for both fossil fuels and the trade-exposed good, see the three alternative trade assumptions in Table 1. Since there is no leakage in the absence of any trade, we do not consider that alternative.

Table 1. Three alternative trade assumptions

		Fossil fuels	
		Trade	No trade
Trade-exposed good	Trade	Alternative I (Trade ; Trade)	Alternative II (Trade ; No trade)
	No trade	Alternative III (No trade ; Trade)	

We thus consider leakage in Alternative II as leakage via the competitiveness channel alone and leakage in Alternative III as leakage via the fossil fuel channel alone.¹² The three Alternatives I-III in Table 1 are characterized as follows:

- I. $\sum_i S_i = \sum_i D_i, \sum_i y_i = 2\bar{Y};$ with $p_1 = p_2 = p, p_1^y = p_2^y = p^y$
- II. $S_i = D_i, \sum_i y_i = 2\bar{Y}$; with $p_1^y = p_2^y = p^y$
- III. $\sum_i S_i = \sum_i D_i, y_i = \bar{Y}$; with $p_1 = p_2 = p$

In addition to these equations, we have the eight equations (1)-(4) above. In Alternative I we thus have ten equations and ten variables ($S_i, D_i, y_i, e_i, p_y, p$), whereas in Alternatives II and III we have eleven equations and variables.

We now want to investigate the impacts on fossil fuel use (and thus CO₂ emissions) in region 2 when increasing the CO₂ price unilaterally in region 1 from $\tau_1 = 0$, and see how the impacts vary across the alternatives. Since the regions are symmetric, we have initially $e_1 = e_2 \equiv e_0, D_1^t = D_2^t \equiv D^t, D_1^n = D_2^n \equiv D^n$ and $y_1 = y_2 \equiv y_0$.

¹² In the Energy Modeling Forum Study 29 (EMF29; Böhringer et al., 2022), the two leakage channels were examined numerically in a different way. Leakage via the competitiveness channel was examined by holding the fossil fuel price fixed, and then leakage via the fossil fuel channel was determined as the residual leakage (i.e., subtracting leakage via the competitiveness channel from total leakage). Thus, leakage via the fossil fuel channel was defined as leakage via the fossil fuel *price*, whereas in our analysis it is defined via fossil fuel *trade*. The two approaches differ since increased production of the trade-exposed good in region 2 affects prices of fuels (and other input factors) in region 2, even in the absence of trade in fuels. Moreover, the approach in EMF29 implies by construction that total leakage equals the sum of leakage via the two channels. We believe that our approach is better capturing the essence of the two leakage channels, as it is trade that lies at the heart of this leakage.

In order to simplify the expressions, and without loss of generality, we make the following normalization of initial values of the variables: $S_i = 1$, $p_i = 1$ and $p_i^\gamma = 1$.

In Appendix A we derive reduced-form expressions for the effects on prices and quantities of increasing the CO₂ price (from zero) in Alternatives I-III in Table 1. The leakage rate L is defined as the increase in emissions in the unregulated region 2 as a share of the decrease in emissions in the regulated region 1. Since emissions are proportional to fossil fuel use in our analytical model, we have $L = -\Delta D_2 / \Delta D_1$. Plugging in the derived quantities, we obtain the following leakage rates for the three alternative trade assumptions:

$$(5) \quad L^I = \frac{c\lambda^2 + e_0^2(\lambda + \gamma)}{c\lambda(\lambda + 2\gamma) + e_0^2(\lambda + \gamma)} \quad (\text{trade in both goods})$$

$$(6) \quad L^{II} = \frac{\gamma e_0^2}{2c\lambda(\lambda + \gamma) + e_0^2(2\lambda + \gamma)} \quad (\text{trade only in the trade-exposed good})$$

$$(7) \quad L^{III} = \frac{\lambda}{\lambda + 2\gamma} \quad (\text{trade only in fossil fuels})$$

where $\lambda = \delta D^n + \varepsilon D^f$ is the weighted demand elasticity (with D^n and D^f as weights). We immediately see that the leakage rates are strictly between 0 and 1 in all three alternatives (as long as the elasticities are finite and not zero, and – in Alternative II – there is some fossil fuel use in the trade-exposed sector).

Leakage via the fossil fuel market (L^{III}) only depends on the fuel supply and (weighted) demand elasticities, and we notice that if supply and demand are equally elastic, this leakage rate is one third. On the other hand, if supply is twice as elastic as demand, leakage via this channel drops to one fifth, whereas if demand is twice as elastic as supply, leakage becomes one half. These results are intuitive and qualitatively well known.

Next, leakage via the competitiveness channel (L^{II}) highly depends on the fuel intensity in the trade-exposed sector (e_0), but also on the different elasticities (see analysis and discussion below).

Total leakage (L^I) looks like a combination of leakage via the two channels (L^{II} and L^{III}), but as we shall see below it is not simply the sum of leakage via these two channels ($L^I \neq L^{II} + L^{III}$).

We are interested in how the leakage rates vary with the supply and demand elasticities, and start with Alternative III, where there is only trade in fossil fuels. We see immediately from (7):

$$\frac{dL^{III}}{d\gamma} < 0$$

$$\frac{dL^{III}}{d\delta}, \frac{dL^{III}}{d\varepsilon} > 0$$

Leakage decreases with the supply elasticity γ . The reason is that the fossil fuel price reduction caused by lower fuel use in region 1 leads to a bigger reduction in fossil fuel supply the higher is γ . This dampens

the price reduction and hence the fuel use increase in region 2. For the demand elasticities (δ and ε) it is the opposite. The more price-responsive fossil fuel demand is, the bigger the increase in fuel demand in region 2 of a given increase in the CO₂ price.¹³

Turning to Alternative II, where there is only trade in the trade-exposed good, we can show (see Appendix A):

$$\frac{dL^II}{d\gamma} > 0$$

$$\frac{dL^II}{d\delta}, \frac{dL^II}{d\varepsilon} < 0$$

We see that the effects of changing the fossil fuel elasticities have the opposite effects on leakage in this case. The effects on emissions abroad are now exclusively via the trade-exposed good market. When higher fuel costs in region 1 (due to the CO₂ price) shift output to region 2, fossil fuel use in region 2 increases. However, if the supply elasticity is low, increased fuel demand will to a large extent raise the fossil fuel price in that region, dampening the net increase in fuel use in region 2 (fuel use in the non-tradable sector will decline). Similarly, if fossil fuel demand is very price-responsive, the increase in fuel demand will be dampened in response to the higher fuel price in region 2.

Finally, we turn to Alternative I (total leakage), which is characterized by trade in both fossil fuels as well as the trade-exposed good. Then we find (see Appendix A):

$$\frac{dL^I}{d\gamma} < 0$$

$$\frac{dL^I}{d\delta} < 0 \text{ if and only if } \frac{\delta^2}{\gamma} < \frac{e_0^2}{c},$$

where we in the latter case have assumed $\varepsilon = \delta$.¹⁴

We see that leakage decreases with the supply elasticity, that is, similar to the case in Alternative III (trade in fossil fuels only) but the opposite of the case in Alternative II (trade in the trade-exposed good only). Hence, the most important for this outcome is whether or not there is trade in fossil fuels.

For the demand elasticity the impact on leakage is ambiguous, depending on the initial size of the two elasticities, but also on fossil fuel use in the trade-exposed sector. The more fuel intensive the trade-exposed sector is, the more likely it is that the leakage rate *decreases* with the demand elasticity, i.e., similar to the case in Alternative II (trade in the trade-exposed good). The reason is that the output

¹³ Since high price elasticities imply bigger fuel demand response also in region 1, both the numerator and the denominator increase in (7). However, as long as γ is strictly positive, the price response via the supply side (see the last element in the denominator) becomes less and furthermore less important when the demand elasticity increases (in absolute value).

¹⁴ If we don't assume $\varepsilon = \delta$, we get a very similar condition when we differentiate with respect to either ε or δ , except that δ is replaced by $\delta D^n + \varepsilon D^I$.

shifting effect becomes relatively less important as the demand elasticity increases. However, the sign also depends on the two elasticities – we see that for δ sufficiently small, $\frac{dL}{d\delta} < 0$, whereas for δ sufficiently large, $\frac{dL}{d\delta} > 0$. Hence, the leakage rate will have a U-shape as we increase the demand elasticity.

We summarize our results in the following proposition:

Proposition 1. Consider a region implementing a unilateral CO₂ price, leading to carbon leakage via i) the fossil fuel channel and ii) the competitiveness channel. Then we have:

- a) The leakage rate via the fossil fuel channel decreases with the supply elasticity of fossil fuels and increases with the demand elasticity of fossil fuels.
- b) The leakage rate via the competitiveness channel increases with the supply elasticity and decreases with the demand elasticity.
- c) The total leakage rate decreases with the supply elasticity, whereas the effect of increasing the demand elasticity has a U-shape (decreasing if and only if $c\delta^2 < e_0^2\gamma$).

Proof: The proposition follows from the derivations above, including proofs in Appendix A.

A question discussed in the literature is whether leakage via the competitiveness channel is larger or smaller than leakage via the fossil fuel channel. Our stylized model cannot be used to conclude on that matter. However, it follows from the proposition that the higher is the fossil fuel supply elasticity and the lower is the demand elasticity, the more likely it is that leakage via the competitiveness channel is dominating.

Next, we are interested in the interactions between leakage via the two channels. We examine whether leakage via the two markets is counteracting or reinforcing each other. That is, we consider the sign of $L^I - (L^{II} + L^{III})$, using the expressions in (5)-(7). We can then show (after some tedious derivations, see Appendix A) that the sign is strictly positive, that is, $L^I > L^{II} + L^{III}$, irrespective of the parameters of the model. In words, total leakage when there is trade in both markets is higher than the sum of leakage via the respective markets (when there is no trade in the other market). Hence, we conclude that leakage in the two markets reinforces each other.

Proposition 2. Consider a region implementing a unilateral CO₂ price, leading to carbon leakage via i) the fossil fuel channel and ii) the competitiveness channel. Total leakage is then strictly higher than the sum of leakage via the two channels separately.

Proof: The proposition follows from the derivations above, including proofs in Appendix A.

Why does leakage via the two channels reinforce each other? The intuition is as follows. First, consider that there is no trade in fossil fuels – only in the trade-exposed good. Climate policy in region 1 then increases supply of the trade-exposed good in region 2, but the expansion is constrained by higher fuel prices caused by increased fuel demand from the trade-exposed sector. If the fossil fuel channel is

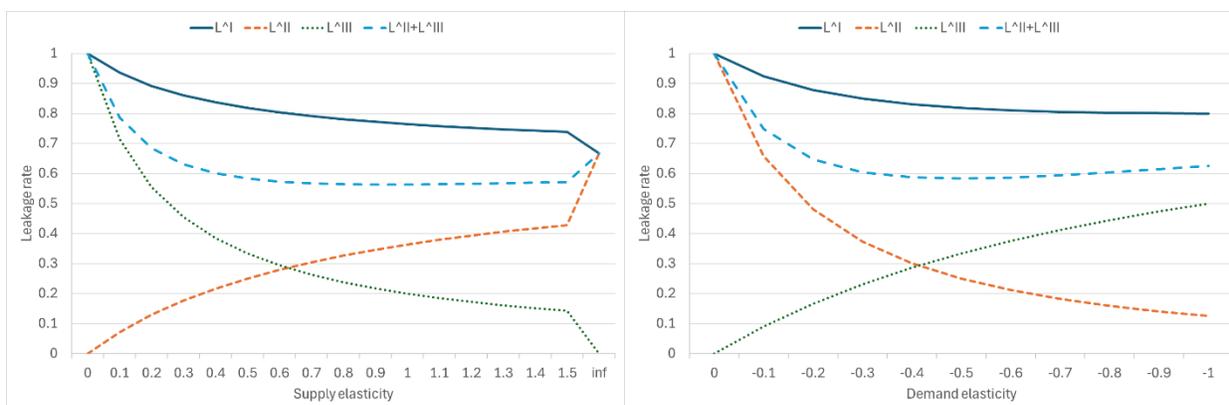
opened, the fuel price in region 2 is relieved, allowing for further expansion of the trade-exposed production. That is, region 2 can to a larger extent exploit its improved competitiveness in the trade-exposed sector when the fossil fuel channel is also open. Hence, the two leakage channels reinforce each other.

Figures 1a. and 1b. illustrate how the leakage rates vary with the supply and demand elasticities, respectively. In the benchmark case, we set both elasticities equal to 0.5. The share of fossil fuel use in the non-tradable sector is set equal to one half ($D^n = D^t = 0.5$), and $c = 0.5$.

The figures reflect the two propositions above; the sum of leakage in Alternatives II and III is below the leakage rate in Alternative I (as long as both elasticities are finite and strictly positive in absolute value), and for the most part significantly below. When it comes to the U-shape for $dL^I/d\delta$, we see that the leakage rate is markedly decreasing with the demand elasticity at low levels of the elasticity, but flattens out around $\delta = 1$, which is also consistent with the condition stated above (for the chosen parameter values).¹⁵

Figure 1. Impacts of the supply and demand elasticities on the leakage rates

a. Leakage rate as a function of the supply elasticity b. Leakage rate as a function of the demand elasticity



Note: The two demand elasticities ε and δ are held equal.

A common measure to mitigate carbon leakage via the competitiveness channel is output-based allocation (of allowances). If we introduce an OBR scheme where all revenues from the emissions payments from the trade-exposed sectors are channeled back to the sector as a production subsidy σ_i , we have $y_i \sigma_i = e_i y_i \tau_i$. It follows that $d\sigma_i = e_i d\tau_i$. Consider now the case with trade in both fossil fuels and the trade-exposed good. It is then straightforward to show that the leakage rate L^{OBR} is simply equal to L^{III} , i.e., the leakage rate without OBR but with no trade in the trade-exposed sector (see Appendix A):

¹⁵ Holding ε and δ equal, we cannot consider demand elasticities lower than -1, see footnote 10. The expression for L^I increases with δ for $\delta > 1$. If the share D^t is below 0.5 (which seems more plausible, see also the CGE analysis), the leakage rate has a minimum below 1 (see Proposition 1c).

$$(8) \quad L^{OBR} = L^{III} = \frac{\lambda}{\lambda + 2\gamma}$$

The intuition is that the OBR scheme in this case exactly levels the playing field, that is, production of the trade-exposed good is unchanged in the two regions ($y_1 = y_2 = y_0$).¹⁶ Hence, we are left with leakage via the fossil fuel channel.

Next, we examine the *reduction* in leakage by introducing the OBR scheme. Subtracting L^{OBR} from L^I , we get:

$$(9) \quad L^I - L^{OBR} = \frac{2\gamma e_0^2 (\gamma + \lambda)}{\left[c\lambda(2\gamma + \lambda) + e_0^2 (\gamma + \lambda) \right] (2\gamma + \lambda)}$$

Differentiating this expression with respect to γ , we find (see Appendix A):

$$\frac{d(L^I - L^{OBR})}{d\gamma} > 0$$

Furthermore, we find (see Appendix A):

$$\frac{d(L^I - L^{OBR})}{d\delta}, \frac{d(L^I - L^{OBR})}{d\varepsilon} < 0$$

In other words, the effects on leakage of implementing an OBR scheme do not only depend on characteristics of the trade-exposed sectors, but also on the supply and demand responsiveness in the fossil fuel market. The more price-responsive fossil fuel supply is, the *more* effective the OBR scheme is in reducing leakage. Conversely, the more price-responsive fossil fuel demand is, the *less* effective the OBR scheme is in reducing leakage. These findings reflect the results in Proposition 1b, i.e., that leakage via the competitiveness channel increases with the supply elasticity and decreases with the demand elasticity.¹⁷

Another measure to mitigate leakage is border carbon adjustments (BCA), consisting of a carbon tariff and possibly an export rebate. Thus, we consider the effects of implementing BCA instead of OBR, with a tariff t_1 on imports of y_2 into region 1, combined with an export rebate r_1 to exports of y_1 from region 1 to region 2. Both the tariff and the rebate are set equal to the emissions intensity in region 1 multiplied by the emissions price in region 1, i.e. $t_1 = r_1 = e_1 \tau_1$.¹⁸ It then follows that producers in the two regions

¹⁶ Note that we assumed fixed demand of the trade-exposed good, so that OBR (or any other policies) could only alter the distribution of production across regions, not the total volume. In the CGE analysis below, this is no longer the case.

¹⁷ These results are not directly following from Proposition 1b, however, even though $L^{OBR} = L^{III}$, as we know from Proposition 2 that $L^I > L^{II} + L^{III}$. That is, there are interactions between the two leakage channels which also have to be taken into account.

¹⁸ In the economics literature, different tariff designs have been considered, including the one used here (see e.g. Böhringer et al., 2017b). Note also that since $e_1 = e_2$ initially, we would get the same result if the tariff was based on

are indifferent between selling in region 1 or 2 if and only if $p_1^y - p_2^y = e_1 \tau_1$. If this condition is not fulfilled, both producers would only sell in one and the same region, which would not hold in equilibrium. Hence, the condition must hold in this model with homogenous y goods and no transport costs.

Consider again the case with trade in both fossil fuels and the trade-exposed good. We then find that the leakage rate L^{BCA} is identical to L^{OBR} , i.e., the leakage rate with OBR (see Appendix A):¹⁹

$$(10) \quad L^{BCA} = L^{OBR} = \frac{\lambda}{\lambda + 2\gamma}$$

Proposition 3. Consider a region implementing a unilateral CO₂ price. The effects on carbon leakage of adding either OBR or BCA are more pronounced the higher is the fossil fuel supply elasticity and the lower is the fossil fuel demand elasticity.

Proof: The proposition follows from the derivations above, including proofs in Appendix A.

3. Numerical analysis

The theoretical analysis has identified the drivers and channels which are fundamental to understanding carbon leakage. However, to keep analytical tractability and clarity, the theoretical exposition neglected various real-world features that are potentially relevant for drawing viable policy conclusions. The stylized theoretical model focused on two goods and two regions in a symmetric setting whereas the global economy is characterized by multiple heterogeneous regions that trade a variety of goods and services. In the theoretical analysis, traded goods are assumed to be homogeneous across regions which may lead to over-specialization and does not reflect empirical evidence of trade in geographically differentiated products where countries import and export the same good (so-called cross-hauling of data). Demand for the trade-exposed good has been fixed in the analytical model, while in reality it will endogenously respond to changes in relative prices. And last but not least, the theoretical analysis builds on simplistic partial equilibrium representations of supply and demand whereas more comprehensive economic adjustment is driven by a variety of substitution, output, and income effects that stem from more complex production technologies and preferences.

In our numerical analysis, we relax the restrictive assumption of the theoretical model by adopting a multi-region multi-sector computable general equilibrium (CGE) model which considers market interactions and income-expenditure cycles of economic agents in a comprehensive manner. The breakdown of macroeconomic production, consumption, and trade activities across multiple regions and sectors based on empirical input-output data makes it possible to track policy-induced structural change in more detail and to avoid potential aggregation biases.

the emissions intensity abroad. Finally, note that EU's CBAM is somewhat different as it depends on the emissions intensity of the importing firm.

¹⁹ The identical leakage rates with OBR and BCA crucially hinge on the assumption of exogenous demand for the y good. In the CGE analysis below, this assumption is relaxed, and leakage rates are no longer identical. The qualitative results in Proposition 3 still hold though.

The quantitative CGE analysis based on empirical data not only allows for a robustness check of the theoretical propositions, but also provides policy-relevant information on the cost-effectiveness gains of anti-leakage measures.

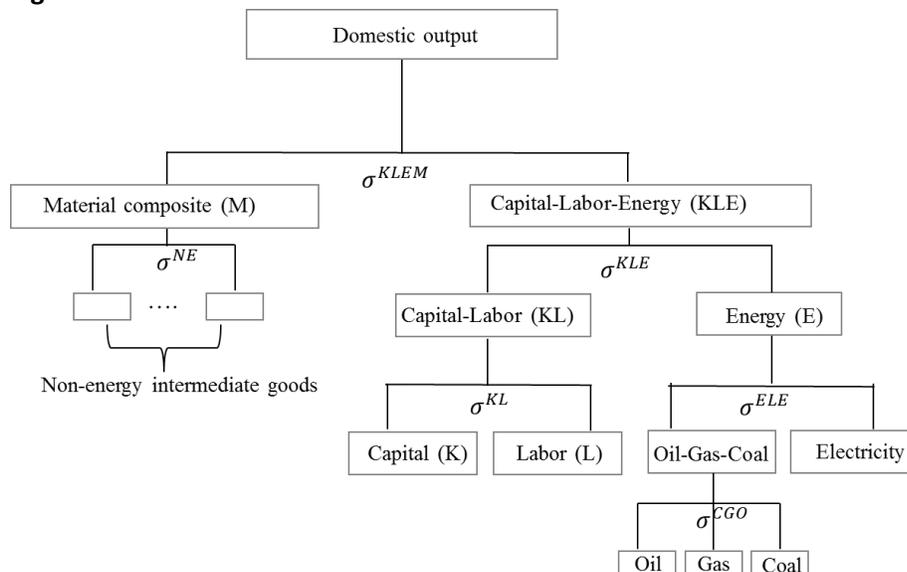
The numerical analysis is organized in three subsections. In the first subsection, we summarize the basic features of the CGE model and the data sources for model parameterization. In the second subsection, we lay out our policy scenarios and interpret the central case simulation results. In the third part, we provide additional sensitivity analysis.

3.1 CGE model summary and data

We apply a generic static multi-sector multi-region CGE model for the world economy, which is designed for the macroeconomic impacts analysis of carbon emissions pricing (see e.g. Böhringer et al. (2017a, 2025)). The brief non-technical summary focuses on key structural assumptions while a more detailed algebraic model description is provided in e.g. Appendix E in Böhringer et al. (2025).

In production, we distinguish labor and capital as well as natural resources that enter the supply of fossil fuels (crude oil, coal and natural gas). Labor and capital are mobile across sectors while natural resources are specific to the respective fossil fuel sectors. Goods (except for fossil fuels) are produced according to a four-level nested constant-elasticity-of-substitution (CES) cost function combining inputs of capital (K), labor (L), energy (E), and material (M) – see Figure 2. Of particular importance for our analysis are the substitution possibilities between energy and the value-added composite (σ^{KLE}) and between electricity and fossil fuels (σ^{ELE}). Thus, when we examine the effects of price-responsiveness of fossil fuel demand on carbon leakage, we will vary these two elasticities in tandem. Fossil fuel production is represented by a CES cost function, where the demand for the natural resource trades off with a Leontief composite of all other inputs. The substitution elasticity is calibrated to match an exogenous supply elasticity, which we will vary in our simulations to highlight its crucial role for leakage, as derived in the theoretical analysis.

Figure 2. Production structure in the CGE model



Note: The parameters σ^j denote substitution elasticities between the stated input factors/composites

As is customary in static CGE analysis, investment and government demand are kept exogenous at the base-year level. Assuming separability, welfare analysis can then focus on policy-induced changes of household consumption which in this case is identical to the Hicksian equivalent variation of income as the common welfare metric.

Trade between regions is modeled following Armington's differentiated goods approach (Armington, 1969), where domestic and foreign goods are distinguished by origin. By varying the (Armington) substitution elasticity, we can effectively vary the trade exposure of the EITE goods, which is particularly relevant for leakage via the competitiveness channel. A balance of payment constraint incorporates the base-year trade deficit or surplus for each region.

CO₂ emissions are proportional to the use of coal, refined oil and natural gas, with CO₂ coefficients differentiated by fuel and sector. Pricing of CO₂ emissions is assumed to be economy-wide, either via taxes or auctioning of emission allowances, with the price endogenously determined to reach a certain emissions target. Reduction of CO₂ emissions can take place via switching between energy goods and via energy savings (i.e., switching between energy and non-energy goods and/or scaling down production and final consumption activities).

The free parameters of functional forms that characterize production technologies (cost functions) and consumer preferences (expenditure functions) are calibrated using cost and expenditure shares from empirical multi-region multi-sector input output data which provide a coherent observation of economic transactions for a particular base-year. For the calibration we use most recent input-output tables from the Global Trade Analysis Project (GTAP version 11, Aguiar et al., 2022), with detailed balanced accounts of production, consumption, bilateral trade flows as well as data on physical energy consumption and CO₂ emissions for the base-year 2017.

The GTAP database covers 160 regions and 65 sectors which we have grouped into the 7 regions and 13 sectors listed in Table 2 for our model-based analysis. In terms of regional aggregation, we focus on the EU, together with a few other European countries, as the front-runner region undertaking unilateral emissions pricing together, and furthermore consider its main trading partners (USA, China, other OECD countries, India) together with a composite of oil-exporting countries and a residual Rest-of-World region. In terms of sectoral aggregation, we keep track of all primary energy carriers (Coal, Crude Oil, Natural Gas) and secondary energy carriers (Refined Oil, Electricity) to distinguish energy goods by CO₂ intensity and the degree of substitutability. In addition, we keep those GTAP sectors explicit in the aggregate dataset which are considered as emission-intensive and trade-exposed (EITE) industries, i.e., Chemical Products, Non-Metallic Minerals, Iron and Steel, and Non-Ferrous Metals. The remaining sectors are grouped into four broader categories: Transport, Other Manufacturing, Agriculture, and Services.

Base-year data together with exogenous elasticities determine the free parameters of the functional forms. Armington elasticities and factor substitution elasticities are provided by the GTAP database, but are also varied as explained above to test for sensitivity. The benchmark substitution elasticities between

energy and the value-added composite (σ^{KLE}) and between electricity and fossil fuels (σ^{ELE}) are both set to 0.5. The benchmark supply elasticities for fossil fuels are set to 0.75.²⁰

Table 2. Sectors and regions in the CGE model

<i>Sectors and commodities</i>	<i>Countries and regions</i>
<i>Primary energy</i>	EU – European Union*
Coal	United States of America
Crude Oil	China
Natural Gas	India
<i>Secondary energy</i>	Other OECD countries
Refined Oil	Oil-exporting countries
Electricity	Rest of World
<i>Emission-intensive and trade-exposed sectors (EITE)</i>	
Chemical Products	
Non-Metallic Minerals	
Iron and Steel	
Non-Ferrous Metals	
<i>Other sectors</i>	
Transport	
Other Manufacturing	
Agriculture	
Services	

* The composite EU region includes the United Kingdom and EFTA

3.2 Scenarios and simulation results

The simulation analysis departs from a reference scenario **REF** where the EU as a front-runner in climate policy undertakes unilateral economy-wide CO₂ pricing to achieve a 20% emissions reduction from its base-year emissions levels. To assess the cost-effectiveness of supplemental anti-leakage measures we consider three additional scenarios where the EU protects its EITE industries with i. freely allocated emissions allowances (**OBR**), ii. a carbon tariff levied on EITE imports (**TRF**), or iii. a full border carbon adjustment which in addition to carbon tariffs rebates embodied carbon payments to the EITE exports of the EU (**BCA**). Table 3 summarizes the unilateral climate policy regulations across the four scenarios.

For the three anti-leakage scenarios, the CO₂ price in the EU is adjusted endogenously so that global emissions remain unchanged compared to the REF scenario. This ensures a coherent global cost-effectiveness comparison as we refrain from assessing climate damages. All simulation results are reported in relation to the initial base-year situation to which the model has been calibrated.

²⁰ Prest et al. (2024) provide a survey of crude oil supply elasticities with an average value of 0.42. As coal supply is likely to be more price-responsive than oil (and gas) due to bigger reserves and more competitive markets, we apply a common benchmark supply elasticity of 0.75.

Table 3. Summary of unilateral climate policy scenarios

<i>Scenario acronym</i>	<i>Climate policy design in the EU</i>
REF	20% reduction in emissions of the EU via a uniform, economy-wide CO ₂ price
OBR	The CO ₂ price is combined with 100% output-based rebate to the EITE sectors. With a 100% rebate the number of free allowances given to each of the EITE sectors is equal to the (endogenous) emissions in each of these sectors.
TRF	The CO ₂ price is combined with a carbon tariff on imports of EITE goods to the unilaterally action region. The effective tariff is computed based on the emissions intensity (direct emissions plus indirect emissions from electricity use) of producing the given commodity in the non-regulated exporting region (multiplied with the prevailing emissions price in the EU).
BCA	The CO ₂ price is combined with full border carbon adjustment for EITE goods. In addition to the carbon tariffs as in scenario TRF, BCA includes an export rebate, acting like a subsidy per exported output of each of the EITE commodities, where the export rebates to an EITE sector equal the total payment for direct emissions used to produce the exports.

For each policy scenario, we vary the elasticities for fossil fuel supply and energy demand as key drivers for leakage through the fossil fuel market channel. Likewise, we consider different trade (Armington) elasticities, which are important for leakage through the competitiveness channel. Further sensitivity analysis considers alternative levels of stringency for the unilateral emissions reduction targets and implications of structural differences in emissions and trade intensities across regions (as we examine the effects of the policy region being the US instead of the EU).

To gain insights into the relative importance of the fossil fuel market channel and the competitiveness channel, we need to disentangle them. However, this is less straightforward than in the stylized partial equilibrium framework in Section 2. One reason is that we calibrate our model to a historic benchmark, where there is of course trade in both fossil fuels and EITE products. Hence, considering no trade in either fossil fuels or EITE products, as in Alternatives II and III in the theoretical analysis, is not possible without constructing a different, hypothetical benchmark. Another approach, which we apply here, is to keep trade flows fixed at the benchmark levels. Thus, we construct two variants of the CGE model that mimic Alternatives II-III, where we fix trade flows of respectively fossil fuels and EITE goods between the policy region and other regions at the benchmark level.²¹ This approach is not innocuous though, especially in the case of the EU which is a significant importer of fossil fuels. It is difficult, and at some point infeasible, to reduce CO₂ emissions significantly without reducing imports of fossil fuels. Thus, Alternative II (fixed trade in fossil fuels) can only be analyzed for moderate emissions reductions in the EU. Still, the advantage of this approach is that the markets in the non-policy regions are not affected by

²¹ Felder and Rutherford (1993) take a similar approach when decomposing the two leakage channels in their CGE model. They construct an alternative model where trade in basic materials (i.e., EITE products) is maintained at the baseline level. However, they do not construct a second alternative model where trade in fossil fuels is maintained.

changes in fuel trade with the policy region (in Alternative II), and thus the derived leakage will be a fair approximation of leakage via the competitiveness channel.²²

To be more specific, in the first variant mimicking Alternative II (the competitiveness channel), we fix bilateral trade in fossil fuels (including refined oil – OIL) by implementing endogenously determined import taxes on these fuels. It is important to be aware though that leakage in this variant occurs not only via the EITE sectors but also via the other non-fuel sectors (see Table 2). In the second variant mimicking Alternative III, we instead fix bilateral trade in all goods except fossil fuels, Transport (TRN) and Services (SER) between the policy region and other regions. Then we are left with leakage via the fossil fuel markets and via trade in transport and services. We refer to this as the fossil fuel channel, although it also includes some leakage via trade through transport activities and services.²³ Hence, when summing leakage via these two channels, we will probably double count some leakage.

As mentioned in the beginning of Section 2, the Energy Modeling Forum 29 (Böhringer et al., 2012; Weitzel et al., 2012) suppressed the fossil fuel channel by keeping international fuel *prices* fixed (instead of keeping fuel *trade* fixed). As also explained in Section 2, we believe that shutting down either of the two trade channels gives a better representation of the other leakage channel than fixing the price. Still, we report the effects of the EMF29 approach in our sensitivity analysis, where we also discuss the two approaches further.

We start by constructing figures similar to Figure 1, where we track how the leakage rate varies with the energy supply (Figure 3) and demand (Figure 4) elasticities for the REF scenario. As shown in Figure 1, we show both total leakage and leakage via the two channels. Overall, we notice that the numerical CGE results are qualitatively the same, and consistent with the theoretical Propositions 1 and 2.

In quantitative terms, the figures show that both supply and demand responsiveness matter significantly for the extent of leakage. For instance, reducing the fuel supply elasticity from 1 to 0.5 increases the leakage rate by more than one third, whereas increasing the demand (substitution) elasticities from 0.5 to 1 increases the rate by almost one quarter. Furthermore, we see that (not surprisingly) leakage via the fossil fuel channel is much more sensitive to the supply and demand elasticities than leakage via the competitiveness channel - with one exception, however: A change in the demand elasticity has a large impact on leakage via the competitiveness channel if the elasticity is low – when demand responsiveness increases, domestic producers will to a larger extent reduce emissions intensity instead of output. This is

²² An alternative approach, which would also work for more substantial emissions reductions in the EU, could be to fix fuel trade in and out of the non-policy region, but not necessarily in and out of the policy region. This would implicitly allow global net trade in fossil fuels to deviate from zero, which obviously goes against the standard equilibrium assumption in a CGE model, but it would shut down the fossil fuel leakage channel in a similar manner as in the current approach and thus give an indication of leakage via the competitiveness channel.

²³ In the GTAP data, domestic transport sectors do not only satisfy domestic transport demands but also contribute to international transport margins to accommodate trade in other goods. The reason for not fixing trade in Services is the balance-of-payment constraint which requires the value of net trade to align with the initial base-year trade deficit or surplus. If there is only trade in fossil fuels (and transport) and the policy region imposes a CO₂ price on fossil fuels, the fossil fuel channel will be hampered by the balance-of-payment constraint – note that Services is a very large sector in monetary terms, but not in terms of emissions.

also why the total leakage shows a U-shape, as we showed analytically (see Proposition 1c), and has been found numerically also in Burniaux and Oliveira Martins (2012).²⁴

Figure 3. Impacts of the fossil fuel supply elasticities on the leakage rates

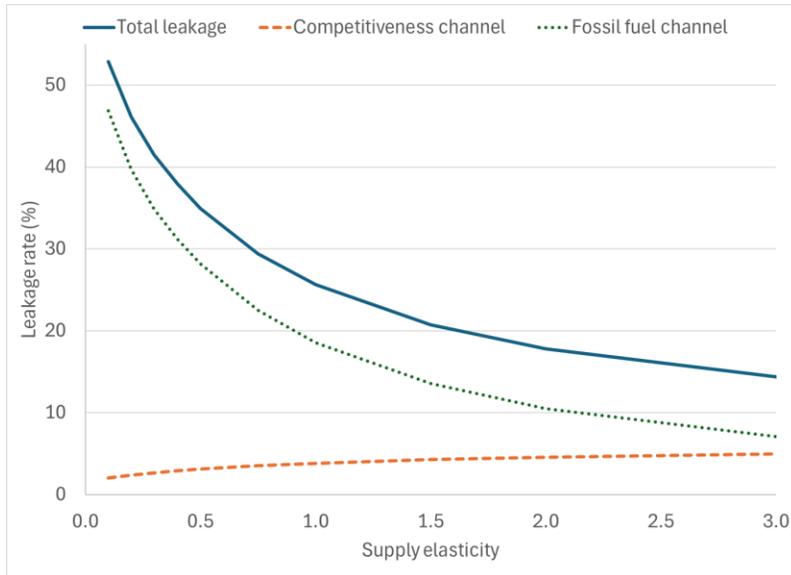
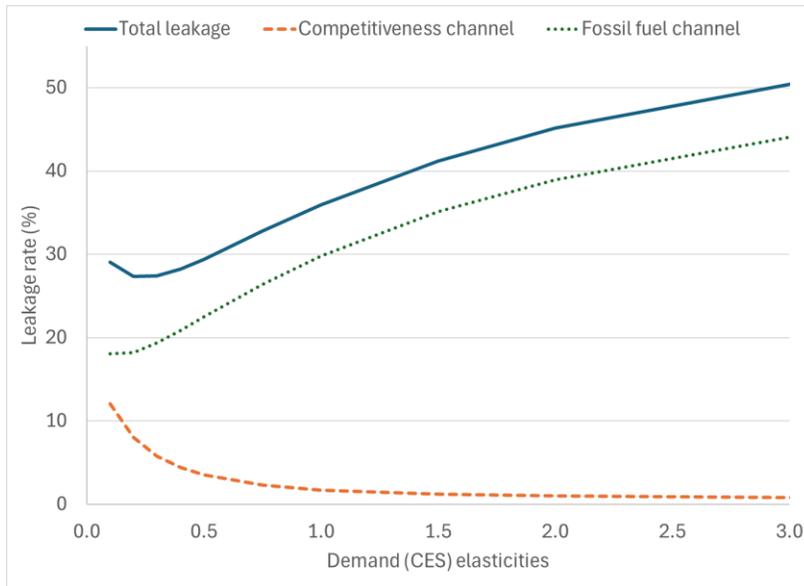


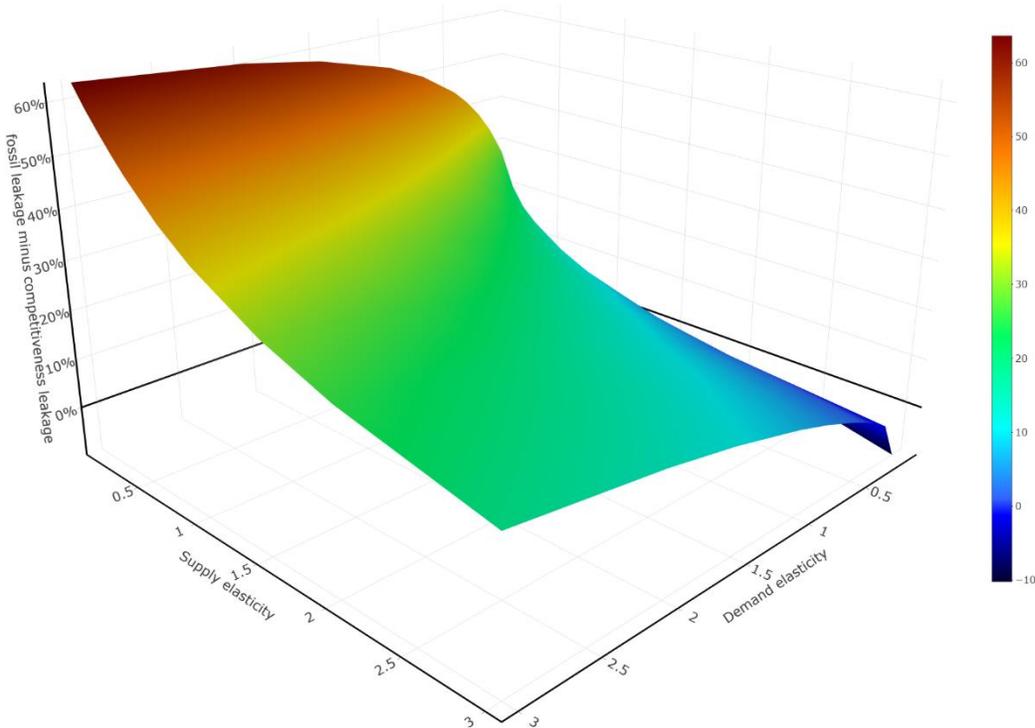
Figure 4. Impacts of the energy demand (CES) elasticities on the leakage rates



²⁴ Whereas total leakage is decreasing for demand elasticities below 1 in Figure 1, we see that it increases for demand elasticities above 0.2 in the CGE simulations in Figure 4. Note, however, that the demand elasticity in Figure 4 refers to *substitution* elasticities in the CES functions (see Section 3). Furthermore, as shown in Proposition 1c, the lower is the share of fuel used in the trade-exposed sector (here: EITE-sectors), the more likely it is that leakage is increasing with the demand elasticity. In the empirical data entering the numerical CGE results simulations, this share is much lower than 50%, which was used in the PE model of Section 2 to construct Figure 1.

Furthermore, Figures 3 and 4 indicate that leakage via the fossil fuel channel is in most cases dominant, except if the supply elasticity is high and the demand elasticity is low. Figure 5 illustrates this more clearly for different combinations of supply and demand elasticities. However, if the supply elasticity is substantially higher than the demand (substitution) elasticities, leakage via the two channels are about the same size.

Figure 5. Relative importance of the two leakage channels for different supply and demand elasticities.



Note: The vertical axis shows the leakage rate via the fossil fuel channel minus the leakage rate via the competitiveness channel (in percentage terms). The numbers behind the figure are shown in Appendix C.

Figures 3 and 4 also indicate that in most cases total leakage is notably higher than the sum of leakage via the two channels, which is consistent with Proposition 2. In other words, leakage via the fossil fuel channel and the competitiveness channel seem to reinforce each other – especially when elasticities are high. As explained in Section 2, the reason is the following: When EITE production in non-EU regions increases due to EU climate policies, fuel demand in those regions increases. With trade restrictions for fossil fuels, this will lead to higher fuel prices and hence dampen the expansion of EITE production. Allowing for free trade in fossil fuels, however, will bring more fuel to non-EU regions, implying further expansion of EITE production there. In other words, the fossil fuel channel lets non-EU regions exploit their improved competitiveness in the EITE sectors (vis-à-vis the EU) to a larger extent. The quantitative

results should be interpreted with some caution, though, as the decomposition of the two leakage channels is not straightforward in the CGE framework.²⁵

Next, we turn to the effects of anti-leakage policies, which target leakage via the competitiveness channel. In practice (and likewise in our simulations), these policies only apply to the EITE sectors, which in our dataset consist of Chemical Products, Non-Metallic Minerals, Iron and Steel, and Non-Ferrous Metals.²⁶ The anti-leakage policies we consider are either implicit subsidies to domestic production of the EITE goods (OBR), taxes on imports of such goods (TRF), or a combination of the latter and implicit subsidies to export of such goods (BCA). Whereas the EU (and many other regions) up to now has applied OBR to counteract leakage, there will be a gradual shift towards TRF over the next decade as outlined in the EU's CBAM.²⁷ Full BCA has been discussed in the EU, but so far not implemented, mainly due to WTO concerns (Böhringer et al. (2022)).

Figures 6 and 7 show how much the leakage rate declines (in percentage points) for the three anti-leakage policies compared to the REF scenario as a function of the fossil fuel supply elasticities and (CES) energy demand elasticities. We notice that OBR is least effective, and BCA most effective, in reducing leakage. Furthermore, the figures show that the anti-leakage policies are most effective when the supply elasticity is high and when the demand elasticity is low. This is consistent with our analytical finding in Proposition 3. It is also in line with Figures 3 and 4 (and Proposition 1), which showed that leakage via the competitiveness channel increases with the supply elasticity and decreases with the demand elasticity – hence, it is reasonable that the anti-leakage measures (targeting this channel) have the biggest effects when the supply elasticity is large and the demand elasticity is small. The same pattern appears when we consider different combinations of supply and demand elasticities.

²⁵ If the supply elasticity is around ten times higher than the (CES) demand elasticities, the result is reversed. Recall, however, that we probably double count some leakage in the way we derive leakage rates for the two channels, and thus slightly overestimate leakage via the two channels separately.

²⁶ Refined Oil could be also counted as an EITE sectors, but since emissions are a by-product of mainly *using* refined oil, we treat this energy carrier together with other fossil fuels.

²⁷ One important difference between EU's CBAM (Carbon Border Adjustment Mechanism) and our policy instrument TRF is that the former considers *actual* emissions intensities at the firm level of producing the product imported, whereas the latter considers the *average* emissions intensities of producing the product *within the EU*.

Figure 6. Impacts of the supply elasticity on the leakage rates under different anti-leakage policies.

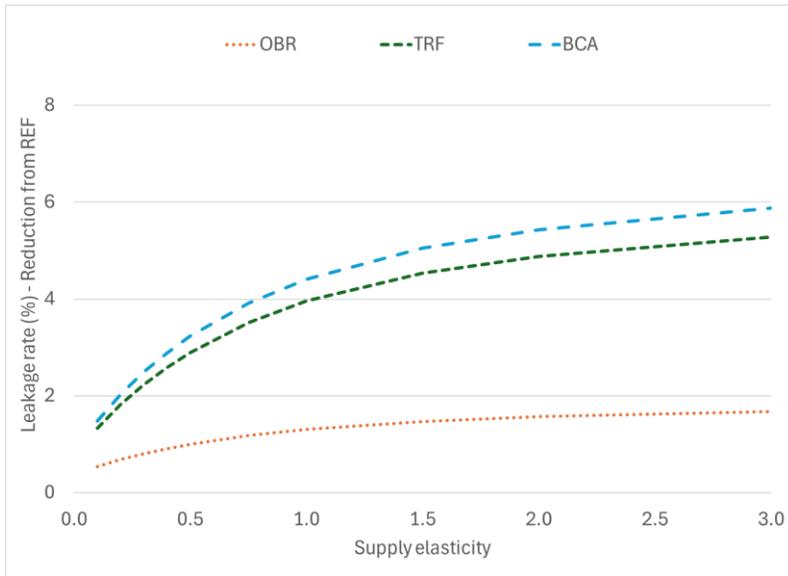
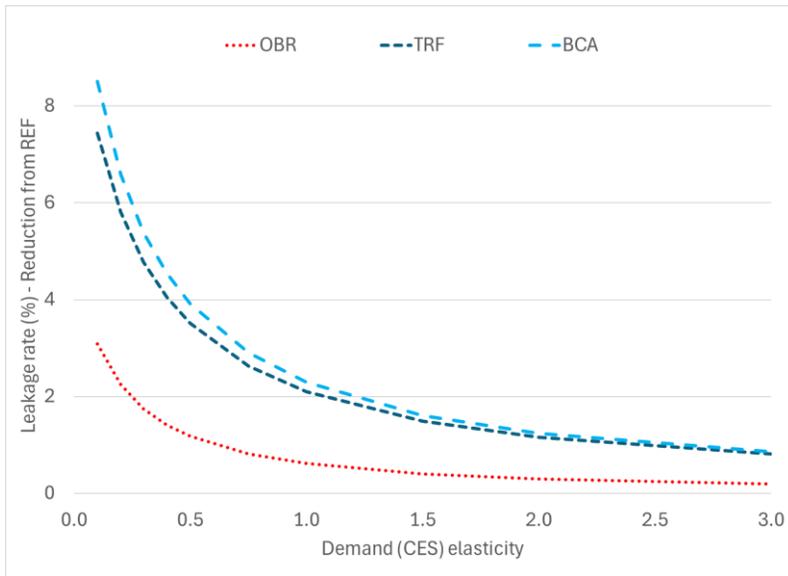
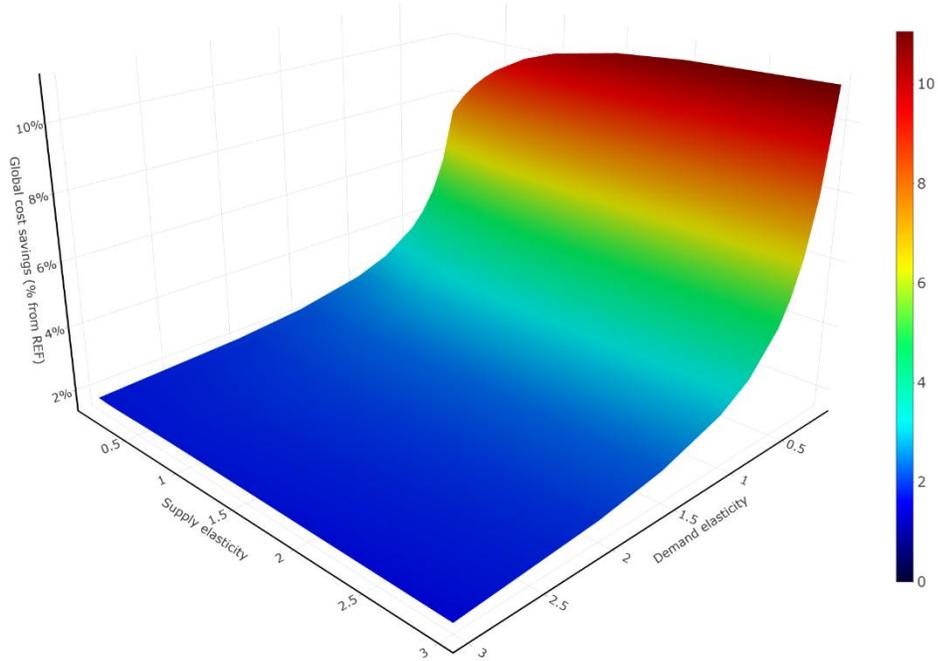


Figure 7. Impacts of the demand (CES) elasticity on the leakage rates under different anti-leakage policies.



Figures 8-10 show the global cost savings of implementing anti-leakage measures OBR, TRF and BCA for different combinations of supply and demand elasticities. Echoing the effects on leakage, we see that cost savings are highest when the supply elasticity is high and the (CES) demand elasticities are low. The demand elasticity is particularly important, while the supply elasticity plays a slightly smaller role. This is especially the case for OBR, where the effects of an increase in the supply elasticity are reversed when the demand elasticity is high.

Figure 8. Global cost savings (in % from REF) when implementing OBR for different combinations of supply and (CES) demand elasticities.



Note: The numbers behind Figs. 8-10 are shown in Appendix C.

Figure 9. Global cost savings (in % from REF) when implementing TRF for different combinations of supply and (CES) demand elasticities.

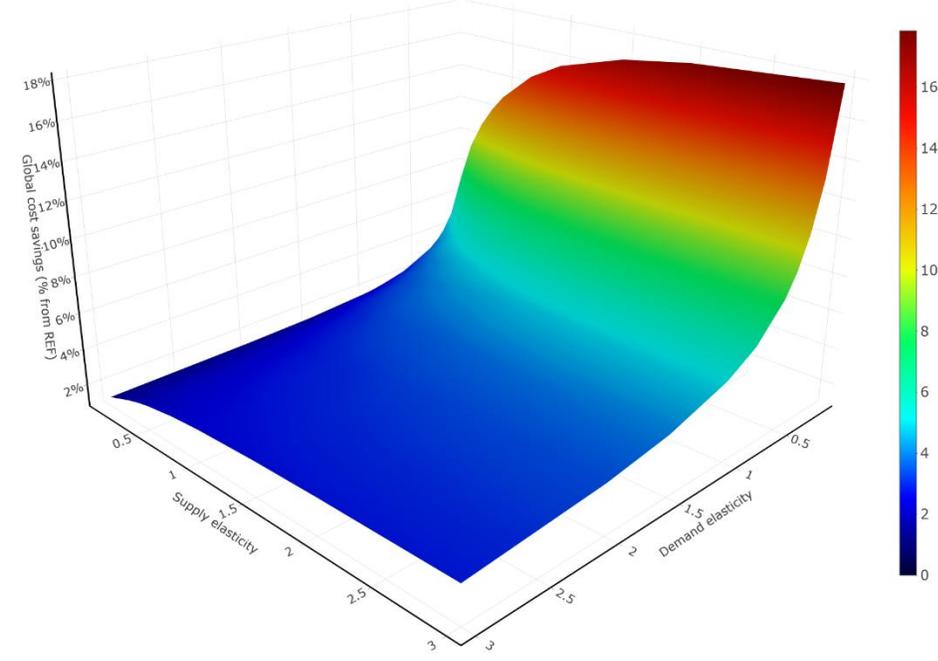
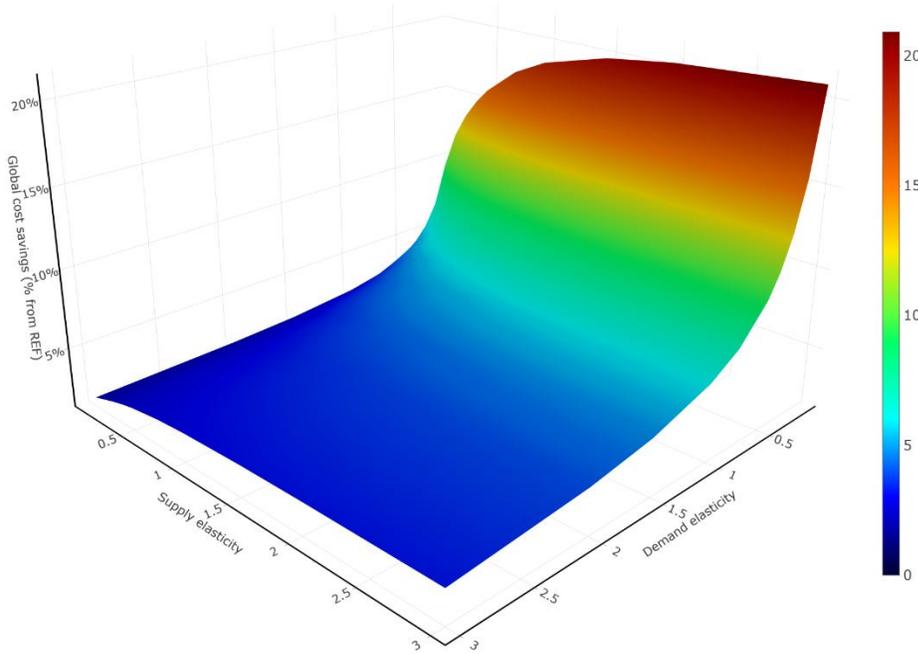


Figure 10. Global cost savings (in % from REF) when implementing BCA for different combinations of supply and (CES) demand elasticities.



BCA consistently delivers the largest cost savings because it addresses leakage through the competitiveness channel more directly and comprehensively. The cost savings of BCA are in most cases 20-40% higher than those of TRF. BCA outperforms OBR in particular when the supply elasticity is high whereas there are hardly differences in cost savings when the supply elasticity is low while demand elasticities are high. TRF also outperforms OBR when the supply elasticity is high or moderate, but the ranking is reversed when fuel supply is very inelastic. Thus, when assessing anti-leakage measures targeting EITE sectors, not only characteristics of the EITE market are important to consider but also characteristics of the fossil fuel market.

The importance of the supply elasticity for the global cost-effectiveness ranking reflects that OBR has one intended and one unintended effect. The intended effect is obviously to mitigate leakage, while the unintended effect is that the implicit output subsidy of OBR stimulates too much use of EITE products (see Böhringer et al. (2017a, 2025)). BCA and TRF do not share this unintended effect as they depress foreign supply rather than stimulating domestic supply. This unintended effect of OBR is, however, moderated when the fuel supply is inelastic as this dampens the potential for increased global supply of (fossil fuel intensive) EITE production.

3.3 Sensitivity analysis

To verify the robustness of our findings, we conduct sensitivity analysis along various dimensions.

First, we examine the implications of price-responsiveness in EITE trade, which is governed by the choice of Armington elasticities for EITE goods. The higher these elasticities are, the stronger the leakage through the competitiveness channel, as EITE products from the CO₂ pricing region can be more easily substituted on domestic and foreign markets. This is confirmed by the comparison of Figures 3-4 and

Figures B1-B2 in Appendix B. Correspondingly, the (cost-) effectiveness of anti-leakage measures increases towards higher Armington elasticities, as is the case for the cost savings achieved by implementing such measures. The qualitative pattern is very similar to the central case simulations, and all of our analytical results are confirmed.

Second, we investigate how the stringency of unilateral climate policy affects our key findings. For this, we consider different emissions reduction targets, i.e., 10% or 30% reduction instead of 20%. As shown in Figures B3-B4, the pattern is quite similar to our central case simulations. The impacts of anti-leakage measures on leakage rates are in line with the analytical results, i.e., leakage reduction increases with the fossil fuel supply elasticity and decreases with the energy demand elasticity. Global cost savings of all three anti-leakage measures are decreasing with the demand elasticity, irrespective of simulated emissions reduction target; the results are slightly more mixed for the supply elasticity, but in most cases the global cost savings are increasing with this elasticity. Furthermore, the two leakage channels are reinforcing each other in the case with 10% emissions reduction.²⁸

Third, we examine how structural differences in trade and emissions intensity for the unilaterally acting region play out when we consider the US instead of the EU as the policy region implementing a 20% emissions reduction. The results are again consistent with the analytical propositions (see Figure B5). That is, the two leakage channels are reinforcing each other, and the effects of anti-leakage measures on the leakage rate are stronger with higher fossil fuel supply elasticities and with lower energy demand elasticities. Global cost savings are significantly decreasing with the demand elasticity, while the results are mixed for the supply elasticity. With OBR, the cost savings are slightly decreasing with the supply elasticity, even though the reduction in leakage becomes stronger. We observed a similar effect in the main simulations for the EU in the case when the demand elasticity was high (see Figure 8). For the two other anti-leakage measures, the global cost savings increase with the supply elasticity when the elasticity is initially low, but then becomes more or less insensitive to this elasticity. Another interesting observation is that the global cost savings from OBR and BCA are quite similar when the US is the policy region, and OBR provides larger welfare gains than TRF. These results are very different from the central case simulations (with the EU as the policy region) reflecting structural differences in the base-year data between the EU and US economies. On the one hand, the EU has more trade with other regions and lower emissions intensities in EITE production. Together this implies higher leakage rates via the competitiveness channel for the EU than for the US (see Figures 3-4 and C5). As a consequence, anti-leakage measures are more effective in reducing leakage in the EU than in the US (see Figures 6-7 and C5). On the other hand, whereas the EU is a large net importer of fossil fuels (especially oil and gas), the US is a large fossil fuel producer. This implies higher leakage rates via the fossil fuel channel for the EU than for the US.

Finally, we also include a simulation where leakage via the competitiveness channel is modeled in a different way – in line with the EMF29 studies (as explained in the beginning of Section 2). Instead of fixing the trade volumes between the EU and the rest of the world, we fix the market prices of fossil

²⁸ This is not simulated for 30% emissions reduction. As explained in Section 3, fixing fossil fuel trade is difficult since the EU doesn't have much own production of fossil fuels and thus imports most of its fuel use. As 30% emissions reduction will imply more or less 30% reduction in fuel use, keeping fossil fuel import levels fixed becomes close to infeasible and thus difficult to simulate. Although alternative approaches could be considered (see footnote 22), we have not performed such a simulation.

fuels supplied by non-EU regions at the base-year level.²⁹ In this way climate policy in the EU does not stimulate fuel demand in other regions via lower fossil fuel prices. Note, however, that this also implies that increased fuel demand from EITE producers in non-EU regions (due to leakage via the competitiveness channel) by construction does *not* drive up fuel prices in those regions, which is rather unrealistic. As shown in Figure B6, leakage via the competitiveness channel is then more or less insensitive to the supply elasticity, which is not surprising since the elasticity no longer has an influence on the fuel price abroad (whereas in our central case settings, the fuel price is affected via increased demand in the EITE sectors). Leakage via the competitiveness channel is still decreasing with the energy demand elasticity, however, as in our central case simulations: When energy demand is more elastic, it is easier to reduce emissions without having to reduce EITE output.³⁰

5. Conclusions

A major problem with the unilateral implementation of strict climate protection measures is the risk of carbon leakage. As a climate front-runner the EU has addressed this problem in the design of the EU Emissions Trading System (EU ETS) by generously allocating free allowances to sectors at risk of carbon leakage. Now, free allocation is gradually being replaced by EU's CBAM, an alternative anti-leakage measure. In the economic literature, there appears to be a strong discrepancy between the results of empirical ex-post and numerical ex-ante studies of carbon leakage, suggesting that knowledge about the extent and drivers of leakage, and thus the effects of anti-leakage measures, is still limited.

Therefore, the aim of this paper has been to expand knowledge about drivers of leakage and the effects of anti-leakage measures. As far as we know, our paper is the first study to i) give a systematic analysis of the interactions between the fossil fuel channel and the competitiveness channel for leakage, ii) provide a thorough investigation of how fossil fuel supply and demand elasticities affect leakage (not only via the fossil fuel channel but also via the competitiveness channel), and iii) examine how these elasticities affect leakage and cost-effectiveness of different anti-leakage measures. All these points have been assessed both analytically and numerically in our paper.

The first main result of our analysis is that the two leakage channels are highly intertwined. When considering the competitiveness channel, it is common to exclusively focus on trade exposure and trade responsiveness of steel, cement and other emissions-intensive goods. However, the production of these goods usually requires substantial inputs of fossil fuels, and hence characteristics of international fuel markets also affect how foreign production of emissions-intensive and trade-exposed goods may respond to reduced domestic production. Thus, it is reasonable that the two channels for leakage may affect each other, but less obvious in what way. One of our main results is that the two leakage channels *reinforce* each other.

As the leakage channels are intertwined, the fossil fuel supply and demand elasticities will not only affect leakage via the fossil fuel channel, but also via the competitiveness channel. The second main result of

²⁹ Fuel supply by fuel producing regions is then endogenously adjusted to keep fuel prices in real terms at their base-year levels.

³⁰ Leakage via the fossil fuel channel could in this case be computed as the difference between total leakage and leakage via the competitiveness channel. However, that would implicitly assume that there is no interaction between leakage via the two channels. Besides going against our analytical findings, such an assumption also goes against the fact that fuel and EITE sectors are significantly intertwined, especially within a GE framework.

our analysis is that both these elasticities have opposite effects on leakage via the two channels. When it comes to total leakage, the effects of the fossil fuel supply and demand elasticities mostly follow the pattern of the fossil fuel channel: The leakage rate monotonically decreases with the supply elasticity, while it increases with the demand elasticity as long as this elasticity is not too small.

The third main result of our analysis – relating to the previous insights –, is that the *effectiveness* (in terms of leakage reduction) of anti-leakage measures such as output-based rebating (or allocation) and border carbon adjustments improves with the fossil fuel supply elasticity and decreases with the fossil fuel demand elasticity. Our quantitative analysis suggests that a similar pattern holds when it comes to the *cost-effectiveness* of the anti-leakage measures. Thus, when considering whether to implement anti-leakage measures, not only leakage exposure but also characteristics of international fuel markets should be assessed. When it comes to the ranking (in terms of cost-effectiveness) of the different measures, full border carbon adjustments (import tariff combined with export rebate) almost always rank highest, whereas the ranking between import tariff alone and output-based rebate varies depending on the fossil fuel elasticities – tariff ranks higher if the supply elasticity is moderate or high while rebate ranks higher if the elasticity is low.

The quantitative results from our numerical simulation mimicking EU's climate policy confirm that leakage via the fossil fuel channel dominates leakage via the competitiveness channel – unless the supply elasticity is very large *and* the demand elasticity very small. Hence, the dominant (exclusive) focus in the EU climate policy debate on leakage through the competitiveness channel might be somewhat misplaced given its relatively modest importance and thus limited overall effectiveness of supplemental policy measures such as output-based rebates and border carbon adjustments targeted to reduce leakage through the competitiveness channel.

Our analysis highlights two important strands for future research. First, there is a need for solid empirical evidence on the price-responsiveness of fossil fuel supply and demand, as these elasticities are crucial for the extent of leakage as well as the effects of anti-leakage measures. Although there are a large number of empirical studies on the elasticity of fossil fuels, particularly oil demand, there is no clear consensus on the size of these elasticities.³¹ Second, there is a need to reinforce applied research on the role of supply-side climate policies, that is, unilateral cutbacks in the supply of fossil fuels (Asheim et al. (2019)). Whereas demand-side climate policies such as CO₂ pricing may lead to carbon leakage via increased fuel demand abroad, supply-side climate policies may lead to supply leakage, i.e., increased fuel supply abroad. The size of fossil fuel supply and demand elasticities is crucial for both kinds of leakage, but the effects go in opposite directions. Higher leakage via the fossil fuel channel means lower supply leakage, and vice versa.

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³¹ Prest et al. (2024) review crude oil supply and demand elasticities. They come up with supply elasticities varying between 0.25 and 0.55 and demand elasticities varying between -0.15 and -0.53. For coal and natural gas, there is even less consensus. A complicating factor is that coal and especially natural gas markets are less integrated than the oil market due to higher transport costs.

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Appendix A. Analytical proofs

Here we derive reduced form expressions for the effects of increasing the CO₂ price in region 1 (from zero) on prices, quantities and leakage rates under the three different alternatives listed in the main text. At the end of this appendix, we consider effects of output-based rebate (OBR).

First, note that before the CO₂ price is increased, supply and demand of fossil fuels as well as production of the tradable good are equal across the two regions: $S_1 = S_2 = S$, $D_1^n = D_2^n = D^n$, $D_1^t = D_2^t = D^t$ and $y_1 = y_2 = y$. We also have initially that $S = D^n + D^t$, where $D^t = e_0 y_0$ is initial fuel use in the tradable sector in both regions.

As noted in the main text, prices and quantities are normalized so that $S_i = 1$, $p_i = 1$ and $p^y = 1$, but initially we choose to write S_i , p_i and p^y explicitly. $S_i = 1$ and $p_i = 1$ implies $s = 1$, and hence we drop s below.

Alternative I.

We start with alternative I, where there is trade in both the fossil fuel and the tradable good.

We differentiate Eqs. (1)-(4) in the main text, plus the market equilibrium conditions in the two markets:

$$(1-1) \quad dS_i = \gamma(p)^{\gamma-1} dp$$

$$(2-1) \quad cdy_i = dp^y - (dp + d\tau_i)e_i - (p + \tau_i)de_i + \hat{\varepsilon}e_i^{-\hat{\varepsilon}-1}de_i = dp^y - e_i(dp + d\tau_i)$$

$$(3-1) \quad de_i = -\varepsilon\hat{\varepsilon}^\varepsilon (p + \tau_i)^{-\varepsilon-1} (dp + d\tau_i) = -\frac{\varepsilon e_i}{p} (dp + d\tau_i)$$

$$(4-1) \quad \begin{aligned} cdD_i &= -c\delta d^n (p + \tau_i)^{-\delta-1} (dp + d\tau_i) \\ &+ \hat{\varepsilon}^\varepsilon (p_i + \tau_i)^{-\varepsilon} \left[dp^y - (dp + d\tau_i)e_i - (p_i + \tau_i)de_i + \hat{\varepsilon}e_i^{-\hat{\varepsilon}-1}de_i \right] \\ &- \varepsilon\hat{\varepsilon}^\varepsilon (p + \tau_i)^{-\varepsilon-1} (dp + d\tau_i) \left(p_y - (p_i + \tau_i)e_i - (e_i^{-\hat{\varepsilon}} - \bar{e}) \right) \\ &= -c\delta d^n p^{-\delta-1} (dp + d\tau_i) + e_i \left[dp^y - e_i(dp + d\tau_i) \right] - \varepsilon e_i p^{-1} c y_i (dp + d\tau_i) \end{aligned}$$

$$(5-1) \quad \sum_i dS_i = \sum_i dD_i$$

$$(6-1) \quad \sum_i dy_i = 0$$

where we used $p + \tau_i = \hat{\varepsilon}e_i^{-\hat{\varepsilon}-1}$, $e_i = \hat{\varepsilon}^\varepsilon (p_i + \tau_i)^{-\varepsilon}$, $c y_i = p_y - (p + \tau_i)e_i - (e_i^{-\hat{\varepsilon}} - \bar{e})$ and $\tau_i = 0$ (initially).

We see from (1-1) that $dS_1 = dS_2$, and from (6-1) we have $dy_1 = -dy_2$.

Applying the latter condition in (2-1), we get:

$$dp^y - e_1(dp + d\tau_1) = -dp^y + e_2 dp$$

which gives (replacing $e_i = e_0$):

$$dp^y = e_0 \left(dp + \frac{d\tau_1}{2} \right)$$

From (1-l) and (5-l) we have:

$$dD_1 + dD_2 = 2\gamma(p)^{\gamma-1} dp$$

Inserting from (4-l) we get:

$$\begin{aligned} & -c\delta d^n p^{-\delta-1} (dp + d\tau_1) + e_1 \left[dp^y - (dp + d\tau_1)e_1 \right] - \varepsilon e_1 p^{-1} c y_1 (dp + d\tau_1) \\ & -c\delta d^n p^{-\delta-1} dp + e_2 \left[dp^y - e_2 dp \right] - \varepsilon e_2 p^{-1} c y_2 dp = 2c\gamma p^{\gamma-1} dp \end{aligned}$$

Reorganizing and replacing e_j and y_j with the common initial values e_0 and y_0 we get:

$$\begin{aligned} & \left[2c\gamma p^{\gamma-1} + 2c\delta d^n p^{-\delta-1} + 2e_0^2 + 2\varepsilon e_0 c y_0 p^{-1} \right] dp + \left[-2e_0 \right] dp^y \\ & + \left[c\delta d^n p^{-\delta-1} + e_0^2 + \varepsilon e_0 c y_0 p^{-1} \right] d\tau_1 = 0 \end{aligned}$$

Inserting from the expression for dp^y above, we get:

$$\left[2c\gamma p^{\gamma-1} + 2c\delta d^n p^{-\delta-1} + 2\varepsilon e_0 c y_0 p^{-1} \right] dp + \left[c\delta d^n p^{-\delta-1} + \varepsilon e_0 c y_0 p^{-1} \right] d\tau_1 = 0$$

or:

$$\frac{dp}{d\tau_1} = - \frac{\delta d^n p^{-\delta} + \varepsilon e_0 y_0}{2[\gamma p^\gamma + \delta d^n p^{-\delta} + \varepsilon e_0 y_0]} = - \frac{\lambda}{2[\gamma + \lambda]} < 0$$

where $\lambda = \delta D^n + \varepsilon D^s$ is the weighted price elasticity of demand and we have applied the normalization stated above. Thus, the fossil fuel price increase, relative to the carbon price increase, depends on the relative size of the demand elasticities versus the supply elasticity. The higher the demand elasticities (compared to the supply elasticity), the bigger the price reduction in the market price of fossil fuels.

From the expression for dp^y above, we can then find:

$$\frac{dp^y}{d\tau_1} = \frac{e_0}{2} \left(1 - \frac{\lambda}{\gamma + \lambda} \right) > 0$$

Turning to quantities, from a) we can derive the effects on fuel supply in the two regions:

$$\frac{dS_i}{d\tau_1} = - \frac{\gamma \lambda}{2[\gamma + \lambda]}$$

Considering next the effects on demand

$$\begin{aligned}
dD_1 &= -\delta d^n p^{-\delta-1} (dp + d\tau_1) + e_1 c^{-1} (dp^y - e_1 (dp + d\tau_1)) - \varepsilon e_1 p^{-1} c^{-1} c y_1 (dp + d\tau_1) \\
&= [-\delta d^n p^{-\delta-1} - e_1^2 c^{-1} - \varepsilon e_1 y_1 p^{-1}] dp + e_1 c^{-1} dp^y + [-\delta d^n p^{-\delta-1} - e_1^2 c^{-1} - \varepsilon e_1 y_1 p^{-1}] d\tau_1
\end{aligned}$$

Reorganizing and again inserting $e_1 = e_0$ and $y_1 = y_0$:

$$\begin{aligned}
\frac{dD_1}{d\tau_1} &= [-\delta d^n p^{-\delta-1} - e_0^2 c^{-1} - \varepsilon e_0 y_0 p^{-1}] \frac{dp}{d\tau_1} + e_0 c^{-1} \frac{dp^y}{d\tau_1} + [-\delta d^n p^{-\delta-1} - e_0^2 c^{-1} - \varepsilon e_0 y_0 p^{-1}] \\
&= [-\delta d^n p^{-\delta-1} - e_0^2 c^{-1} - \varepsilon e_0 y_0 p^{-1}] \frac{-\lambda}{2[\gamma + \lambda]} + e_0 c^{-1} \frac{e_0}{2} \left(1 - \frac{\lambda}{[\gamma + \lambda]} \right) + [-\delta d^n p^{-\delta-1} - e_0^2 c^{-1} - \varepsilon e_0 y_0 p^{-1}] \\
&= -\frac{\lambda}{2[\gamma + \lambda]} [-\delta D^n p^{-1} - e_0^2 c^{-1} + e_0^2 c^{-1} - \varepsilon e_0 y_0 p^{-1}] - \frac{e_0^2 c^{-1}}{2} - \delta D^n p^{-1} - \varepsilon D' p^{-1} \\
&= \lambda \left[\frac{\lambda}{2[\gamma + \lambda]} - 1 \right] - \frac{e_0^2}{2c} < 0
\end{aligned}$$

where we again applied the normalization. Demand for fossil fuels in region 1 declines partly via reduced demand in the non-tradable sector and reduced fuel intensity in the tradable sector (first part), and partly via reduced output in the tradable sector (second part) – see below.

$$\begin{aligned}
dD_2 &= -\delta d^n p^{-\delta-1} dp + e_2 c^{-1} (dp^y - e_2 dp) - \varepsilon e_2 p^{-1} c^{-1} c y_2 dp \\
&= [-\delta d^n p^{-\delta-1} - e_2^2 c^{-1} - \varepsilon e_2 y_2 p^{-1}] dp + e_2 c^{-1} dp^y
\end{aligned}$$

$$\begin{aligned}
\frac{dD_2}{d\tau_1} &= [-\delta d^n p^{-\delta-1} - e_0^2 c^{-1} - \varepsilon e_0 y_0 p^{-1}] \frac{dp}{d\tau_1} + e_0 c^{-1} \frac{dp^y}{d\tau_1} \\
&= [-\delta d^n p^{-\delta-1} - e_0^2 c^{-1} - \varepsilon e_0 y_0 p^{-1}] \frac{-\lambda}{2[\gamma + \lambda]} + e_0 c^{-1} \frac{e_0}{2} \left(1 - \frac{\lambda}{[\gamma + \lambda]} \right) \\
&= -\frac{\lambda}{2[\gamma + \lambda]} [-\delta D^n p^{-1} - \varepsilon e_0 y_0 p^{-1}] + \frac{e_0^2 c^{-1}}{2} = \frac{\lambda^2}{2[\gamma + \lambda]} + \frac{e_0^2}{2c} > 0
\end{aligned}$$

Demand for fossil fuels in region 2 increases, partly via reduced global fuel price (first term) and partly via increased output caused by higher output price in the tradable sector (second term).

Finally, we have production in the tradable sector:

$$\begin{aligned}
dy_1 &= c^{-1} dp^y - e_1 c^{-1} (dp + d\tau_1) \\
\frac{dy_1}{d\tau_1} &= \frac{e_0}{2c} \left(1 - \frac{\lambda}{\gamma + \lambda} \right) - \frac{e_0}{c} \left(-\frac{\lambda}{2(\gamma + \lambda)} + 1 \right) = -\frac{e_0}{2c} < 0
\end{aligned}$$

We see that production changes because of the direct cost increase from higher costs per unit of fuel.

$$\frac{dy_2}{d\tau_1} = -\frac{dy_1}{d\tau_1} = \frac{e_0}{2c} > 0$$

Finally, we are interested in the leakage rate:

$$\begin{aligned} L^I &= -\frac{dD_2}{dD_1} = -\frac{\frac{\lambda^2}{2[\gamma+\lambda]} + \frac{e_0^2}{2c}}{\lambda \left[\frac{\lambda}{2[\gamma+\lambda]} - 1 \right] - \frac{e_0^2}{2c}} = \frac{c\lambda^2 + e_0^2[\gamma+\lambda]}{2c\lambda[\gamma+\lambda] - c\lambda^2 + e_0^2[\gamma+\lambda]} \\ &= \frac{c\lambda^2 + e_0^2[\gamma+\lambda]}{c\lambda^2 + e_0^2[\gamma+\lambda] + 2c\gamma\lambda} = \frac{c\lambda^2 + e_0^2(\lambda+\gamma)}{c\lambda(\lambda+2\gamma) + e_0^2(\lambda+\gamma)} \end{aligned}$$

We see that the leakage rate is strictly between zero and one.

Next, we are interested in how the leakage rate depends on the elasticities, where we hold initial levels of prices and quantities unchanged.³²

We then find (where N is the denominator in the expression for L):

$$\begin{aligned} \frac{dL^I}{d\gamma} &= \frac{1}{N^2} \left\{ e_0^2 [c\lambda(\lambda+2\gamma) + e_0^2(\gamma+\lambda)] - [c\lambda^2 + e_0^2(\gamma+\lambda)](2c\lambda + e_0^2) \right\} \\ &= \frac{1}{N^2} \left\{ e_0^2 2c\gamma\lambda - [c\lambda^2 + e_0^2(\gamma+\lambda)] 2c\lambda \right\} = -\frac{1}{N^2} \left\{ [c\lambda^2 + e_0^2\lambda] 2c\lambda \right\} < 0 \end{aligned}$$

Thus, the leakage rate decreases unambiguously with the supply elasticity.

For the demand elasticities we differentiate with respect to λ :

$$\begin{aligned} \frac{dL^I}{d\lambda} &= \frac{1}{N^2} \left\{ (2c\lambda + e_0^2) [c\lambda(\lambda+2\gamma) + e_0^2(\gamma+\lambda)] - [c\lambda^2 + e_0^2(\gamma+\lambda)] (2c\lambda + 2c\gamma + e_0^2) \right\} \\ &= \frac{1}{N^2} \left\{ (2c\lambda + e_0^2) (c\lambda(\lambda+2\gamma) + e_0^2(\gamma+\lambda) - c\lambda^2 - e_0^2(\gamma+\lambda)) - 2c\gamma (c\lambda^2 + e_0^2(\gamma+\lambda)) \right\} \\ &= \frac{1}{N^2} \left\{ 2c^2\lambda^2\gamma - 2e_0^2c\gamma^2 \right\} = \frac{2c\gamma}{N^2} \left\{ c\lambda^2 - e_0^2\gamma \right\} \end{aligned}$$

We see that $\frac{dL}{d\lambda} > 0$ iff $c\lambda^2 > e_0^2\gamma$.

Alternatively:

³² Since prices are normalized to zero, we then do not need to change any of the other parameters when changing an elasticity.

$$\frac{dL}{d\lambda} > 0 \text{ iff } \frac{\lambda^2}{\gamma} > \frac{e_0^2}{c}.$$

We see that the more important fuel use is in the tradable sector, and the more output abroad responds to the domestic carbon price, the more likely it is that the leakage rate *decreases* with the demand elasticity. However, the sign also depends on the two elasticities – we see that for λ sufficiently small, $\frac{dL}{d\lambda} < 0$, whereas for λ sufficiently large, $\frac{dL}{d\lambda} > 0$. Hence, the leakage rate will have a U-shape as we increase (either of) the demand elasticities.

This completes the proofs of Proposition 1c.

Alternative II.

Next, we consider Alternative II, where there is no fossil fuel trade, but trade in the tradable good. Again, we start by differentiating the same equations as in Alternative I:

$$(1-II) \quad dS_i = \gamma(p_i)^{\gamma-1} dp_i$$

$$(2-II) \quad cdy_i = dp^y - (dp_i + d\tau_i)e_i - (p_i + \tau_i)de_i + \hat{\varepsilon}e_i^{-\hat{\varepsilon}-1}de_i = dp^y - (dp_i + d\tau_i)e_i$$

$$(3-II) \quad de_i = -\varepsilon\hat{\varepsilon}^{\varepsilon}(p_i + \tau_i)^{-\varepsilon-1}(dp_i + d\tau_i) = -\varepsilon e_i p_i^{-1}(dp_i + d\tau_i)$$

$$(4-II) \quad cdD_i = -c\delta d^n p_i^{-\delta-1}(dp_i + d\tau_i) + e_i [dp^y - (dp_i + d\tau_i)e_i] - \varepsilon e_i p_i^{-1}(dp_i + d\tau_i)cy_i$$

$$(5-II) \quad dS_i = dD_i$$

$$(6-II) \quad \sum_i dy_i = 0$$

From (6-II) we have $dy_1 = -dy_2$.

Applying the latter condition in (2-II), and using $e_i = e_0$, we get:

$$dp^y - e_0(dp_1 + d\tau_1) = -(dp^y - e_0 dp_2), \text{ which gives:}$$

$$dp^y = \frac{e_0}{2}(dp_1 + d\tau_1 + dp_2)$$

From (1-II), (4-II) and (5-II) we have:

$$-c\delta d^n p_i^{-\delta-1}(dp_i + d\tau_i) + e_i [dp^y - (dp_i + d\tau_i)e_i] - \varepsilon e_i p_i^{-1}(dp_i + d\tau_i)cy_i = c\gamma(p_i)^{\gamma-1} dp_i$$

Reorganizing we get:

$$dp_i [c\delta d^n p_i^{-\delta-1} + e_0^2 + \varepsilon e_0 cy_i p_i^{-1} + c\gamma(p_i)^{\gamma-1}] - e_0 dp^y + d\tau_i [c\delta d^n p_i^{-\delta-1} + e_0^2 + \varepsilon e_0 cy_i p_i^{-1}] = 0$$

Inserting from the expression for dp^y above, we get:

$$\left[c\delta d^n p_1^{-\delta-1} + \frac{e_0^2}{2} + \varepsilon e_0 c y_1 p_1^{-1} + c\gamma (p_1)^{\gamma-1} \right] dp_1 - \frac{e_0^2}{2} dp_2 + \left[c\delta d^n p_1^{-\delta-1} + \frac{e_0^2}{2} + \varepsilon e_0 c y_1 p_1^{-1} \right] d\tau_1 = 0$$

$$\left[c\delta d^n p_2^{-\delta-1} + \frac{e_0^2}{2} + \varepsilon e_0 c y_2 p_2^{-1} + c\gamma (p_2)^{\gamma-1} \right] dp_2 - \frac{e_0^2}{2} dp_1 - \frac{e_0^2}{2} d\tau_1 = 0$$

Using the normalization of initial values ($p_i = 1$ and $y_i = y_0$) it becomes:

$$\left[c\delta d^n + \frac{e_0^2}{2} + \varepsilon e_0 y_0 c + c\gamma \right] dp_1 - \frac{e_0^2}{2} dp_2 + \left[c\delta d^n + \frac{e_0^2}{2} + \varepsilon e_0 y_0 c \right] d\tau_1 = 0$$

$$\left[c\delta d^n + \frac{e_0^2}{2} + \varepsilon e_0 y_0 c + c\gamma \right] dp_2 - \frac{e_0^2}{2} dp_1 - \frac{e_0^2}{2} d\tau_1 = 0$$

$$\text{Let } \Lambda = \left[c\delta d^n + \frac{e_0^2}{2} + \varepsilon e_0 y_0 c + c\gamma \right]$$

We then have for region 2:

$$dp_2 = \frac{e_0^2}{2\Lambda} (dp_1 + d\tau_1)$$

Inserting into the equation for region 1 we get:

$$\Lambda dp_1 - \frac{e_0^2}{2} \frac{e_0^2}{2\Lambda} (dp_1 + d\tau_1) + \left[c\delta d^n + \frac{e_0^2}{2} + \varepsilon e_0 y_0 c \right] d\tau_1 = 0$$

Reorganizing:

$$dp_1 \left[\Lambda - \frac{e_0^4}{4\Lambda} \right] + d\tau_1 \left[c\delta d^n + \frac{e_0^2}{2} + \varepsilon e_0 y_0 c - \frac{e_0^4}{4\Lambda} \right] = 0$$

$$\frac{dp_1}{d\tau_1} = - \frac{\left[c\delta d^n + \frac{e_0^2}{2} + \varepsilon e_0 y_0 c - \frac{e_0^4}{4\Lambda} \right]}{\left[\Lambda - \frac{e_0^4}{4\Lambda} \right]} = - \frac{\left[c\delta d^n \Lambda + \frac{e_0^2}{2} \Lambda + \varepsilon e_0 y_0 c \Lambda - \frac{e_0^4}{4} \right]}{\left[\Lambda^2 - \frac{e_0^4}{4} \right]}$$

$$\frac{dp_2}{d\tau_1} = \frac{e_0^2}{2\Lambda} \left(1 - \frac{\left[c\delta d^n \Lambda + \frac{e_0^2}{2} \Lambda + \varepsilon e_0 y_0 c \Lambda - \frac{e_0^4}{4} \right]}{\left[\Lambda^2 - \frac{e_0^4}{4} \right]} \right)$$

$$\frac{dp^y}{d\tau_1} = \frac{e_0}{2} \left(\frac{dp_1}{d\tau_1} + 1 + \frac{dp_2}{d\tau_1} \right) = \frac{e_0}{2} \left(1 - \frac{\left[c\delta d^n \Lambda + \frac{e_0^2}{2} \Lambda + \varepsilon e_0 y_0 c \Lambda - \frac{e_0^4}{4} \right]}{\left[\Lambda^2 - \frac{e_0^4}{4} \right]} \right) \left(1 + \frac{e_0^2}{2\Lambda} \right)$$

From (1-II) and (5-II) we then get:

$$\frac{dD_1}{d\tau_1} = \frac{dS_1}{d\tau_1} = - \frac{\gamma \left[c\delta d^n \Lambda + \frac{e_0^2}{2} \Lambda + \varepsilon e_0 y_0 c \Lambda - \frac{e_0^4}{4} \right]}{\left[\Lambda^2 - \frac{e_0^4}{4} \right]}$$

$$\frac{dD_2}{d\tau_1} = \frac{dS_2}{d\tau_1} = \frac{\gamma e_0^2}{2\Lambda} \left(1 - \frac{\left[c\delta d^n \Lambda + \frac{e_0^2}{2} \Lambda + \varepsilon e_0 y_0 c \Lambda - \frac{e_0^4}{4} \right]}{\left[\Lambda^2 - \frac{e_0^4}{4} \right]} \right)$$

The leakage rate becomes:

$$\begin{aligned} L^H &= - \frac{dD_2}{dD_1} = - \frac{\frac{\gamma e_0^2}{2\Lambda} \left(1 - \frac{\left[c\delta d^n \Lambda + \frac{e_0^2}{2} \Lambda + \varepsilon e_0 y_0 c \Lambda - \frac{e_0^4}{4} \right]}{\left[\Lambda^2 - \frac{e_0^4}{4} \right]} \right)}{- \frac{\gamma \left[c\delta d^n \Lambda + \frac{e_0^2}{2} \Lambda + \varepsilon e_0 y_0 c \Lambda - \frac{e_0^4}{4} \right]}{\left[\Lambda^2 - \frac{e_0^4}{4} \right]}} \\ &= \frac{\frac{e_0^2}{2\Lambda} \left(\left[\Lambda^2 - \frac{e_0^4}{4} \right] - \left[c\delta d^n \Lambda + \frac{e_0^2}{2} \Lambda + \varepsilon e_0 y_0 c \Lambda - \frac{e_0^4}{4} \right] \right)}{\left[c\delta d^n \Lambda + \frac{e_0^2}{2} \Lambda + \varepsilon e_0 y_0 c \Lambda - \frac{e_0^4}{4} \right]} = \frac{e_0^2 \left(\Lambda - c\delta d^n - \frac{e_0^2}{2} - \varepsilon e_0 y_0 c \right)}{\left[2c\delta d^n \Lambda + e_0^2 \Lambda + 2\varepsilon e_0 y_0 c \Lambda - \frac{e_0^4}{2} \right]} \end{aligned}$$

After reinserting for $\Lambda = \left[c\delta d^n + \frac{e_0^2}{2} + \varepsilon e_0 y_0 c + c\gamma \right]$ and rearranging, we get:

$$L'' = \frac{\gamma e_0^2}{2c\lambda(\lambda + \gamma) + e_0^2(2\lambda + \gamma)}$$

We can then find the effects on leakage of changing the elasticities (where N is the denominator of L''):

$$\frac{dL''}{d\gamma} = \frac{1}{N^2} \left\{ e_0^2 \left[2c\lambda(\lambda + \gamma) + e_0^2(2\lambda + \gamma) \right] - \gamma e_0^2 (2c\lambda + e_0^2) \right\} = \frac{2e_0^2\lambda}{N^2} [c\lambda + e_0^2] > 0$$

For the demand elasticities, it follows straightforwardly from the expression for L that $\frac{dL''}{d\lambda} < 0$.

This completes the proofs of Proposition 1b.

We see that the supply elasticity has the opposite effect on leakage in Alternative II than in Alternative I. The demand elasticities now have an unambiguous effect, having the same effect as in Alternative I iff

$$\frac{\lambda^2}{\gamma} < \frac{e_0^2}{c}.$$

We notice that if $e_0 = 0$, i.e., the tradable good does not use any fossil fuel, the emissions tax in region 1 no longer has any impacts on region 2: $\frac{dp_2}{d\tau_1} = \frac{dS_2}{d\tau_1} = 0$.

Alternative III.

Finally, we consider Alternative III, where there is fossil fuel trade, but no trade in the tradable good. As before, we start by differentiating the equations:

$$(1-III) \quad dS_i = \gamma(p)^{\gamma-1} dp$$

$$(2-III) \quad cdy_i = dp_i^y - (dp + d\tau_i)e_i - pde_i + \hat{\varepsilon}e_i^{-\hat{\varepsilon}-1}de_i = dp_i^y - (dp + d\tau_i)e_i$$

$$(3-III) \quad de_i = -\varepsilon\hat{\varepsilon}^\varepsilon (p + \tau_i)^{-\varepsilon-1} (dp + d\tau_i) = -\varepsilon e_i p^{-1} (dp + d\tau_i)$$

$$(4-III) \quad cdD_i = -c\delta d^n p^{-\delta-1} (dp + d\tau_i) + e_i \left[dp_i^y - (dp + d\tau_i)e_i \right] - \varepsilon e_i p^{-1} (dp + d\tau_i) cy_i$$

$$(5-III) \quad \sum_i dS_i = \sum_i dD_i$$

$$(6-III) \quad dy_i = 0$$

From (6-III) and (2-III) we have:

$$dp_i^y = (dp + d\tau_i)e_0$$

From (1-III) and (5-III) we have:

$$dD_1 + dD_2 = 2\gamma(p)^{\gamma-1} dp$$

Inserting from (4-III) and using $dp_i^y = (dp + d\tau_i)e_0$ we get:

$$-c\delta d^n p^{-\delta-1} (dp + d\tau_1) - \varepsilon e_0 p^{-1} (dp + d\tau_1) c\gamma_1 - c\delta d^n p^{-\delta-1} dp - \varepsilon e_0 p^{-1} c\gamma_2 dp = 2c\gamma(p)^{\gamma-1} dp$$

Reorganizing we get:

$$\left[2c\delta d^n p^{-\delta-1} + \varepsilon e_0 p^{-1} c\gamma_0 + 2c\gamma(p)^{\gamma-1} \right] dp = \left[-c\delta d^n p^{-\delta-1} - \varepsilon e_0 p^{-1} c\gamma_0 \right] d\tau_1$$

or:

$$\frac{dp}{d\tau_1} = -\frac{\delta d^n p^{-\delta} + \varepsilon e_0 \gamma_0}{2(\delta d^n p^{-\delta} + \varepsilon e_0 \gamma_0 + \gamma p^\gamma)} = -\frac{\lambda}{2(\lambda + \gamma)} < 0$$

Inserting into dp_i^y we get:

$$\frac{dp_1^y}{d\tau_1} = \frac{e_0 (\delta d^n p^{-\delta} + \varepsilon e_0 \gamma_0 + 2\gamma p^\gamma)}{2(\delta d^n p^{-\delta} + \varepsilon e_0 \gamma_0 + \gamma p^\gamma)} = \frac{e_0 (\lambda + 2\gamma)}{2(\lambda + \gamma)} > 0$$

$$\frac{dp_2^y}{d\tau_1} = -\frac{e_0 (\delta d^n p^{-\delta} + \varepsilon e_0 \gamma_0)}{2(\delta d^n p^{-\delta} + \varepsilon e_0 \gamma_0 + \gamma p^\gamma)} = -\frac{e_0 \lambda}{2(\lambda + \gamma)} < 0$$

For fuel supply we get:

$$\frac{dS_i}{d\tau_1} = -\frac{\gamma\lambda}{2(\lambda + \gamma)} < 0$$

For fuel demand we get (where we use that $dp_i^y = (dp + d\tau_i)e_0$):

$$dD_i = -\delta D^n (dp + d\tau_i) - \varepsilon D^t (dp + d\tau_i)$$

$$\begin{aligned} \frac{dD_1}{d\tau_1} &= (-\delta D^n - \varepsilon D^t) \frac{dp}{d\tau_1} - \delta D^n - \varepsilon D^t = -(\delta D^n + \varepsilon D^t) \left(-\frac{\lambda}{2(\lambda + \gamma)} \right) - \delta D^n - \varepsilon D^t \\ &= \frac{\lambda^2 - 2(\lambda + \gamma)\lambda}{2(\lambda + \gamma)} = -\frac{\lambda(\lambda + 2\gamma)}{2(\lambda + \gamma)} < 0 \end{aligned}$$

$$\frac{dD_2}{d\tau_1} = [-\delta D^n - \varepsilon D^t] \frac{dp}{d\tau_1} = [-\delta D^n - \varepsilon D^t] \left(-\frac{\lambda}{2(\lambda + \gamma)} \right) = \frac{\lambda^2}{2(\lambda + \gamma)} > 0$$

Finally, the leakage rate becomes:

$$L^{III} = -\frac{dD_2}{dD_1} = -\frac{\frac{\lambda^2}{2(\lambda+\gamma)}}{\frac{\lambda(\lambda+2\gamma)}{2(\lambda+\gamma)}} = \frac{\lambda}{\lambda+2\gamma},$$

Which again is between 0 and 1.

We see immediately that $\frac{dL}{d\gamma} < 0$ and $\frac{dL}{d\lambda} > 0$.

This completes the proofs of Proposition 1a.

Comparing leakage rates in the three alternatives

Here we show that the sum of leakage rates in Alternatives II and III is always smaller than the leakage rate in Alternative I. We first repeat the leakage rates in the three alternatives:

$$L^I = \frac{c\lambda^2 + e_0^2(\lambda + \gamma)}{c\lambda(\lambda + 2\gamma) + e_0^2(\lambda + \gamma)}$$

$$L^{II} = \frac{e_0^2\gamma}{2c\lambda(\lambda + \gamma) + e_0^2(2\lambda + \gamma)}$$

$$L^{III} = \frac{\lambda}{\lambda + 2\gamma}$$

We are interested in the difference $L^I - (L^{II} + L^{III})$, i.e.:

$$L^I - (L^{II} + L^{III}) = \frac{c\lambda^2 + e_0^2(\lambda + \gamma)}{c\lambda(\lambda + 2\gamma) + e_0^2(\lambda + \gamma)} - \frac{e_0^2\gamma}{2c\lambda(\lambda + \gamma) + e_0^2(2\lambda + \gamma)} - \frac{\lambda}{\lambda + 2\gamma}$$

We can show (after some tedious derivations) that $L^I - (L^{II} + L^{III}) > 0$ irrespective of the parameters of the model, hence confirming Proposition 2. That is, total leakage when there is trade in both markets is higher than the sum of leakage in the respective markets (when there is no trade in the other market). Hence, leakage in the two markets reinforces each other.

Effects of OBR

We next examine the effects of implementing output-based rebate (OBR), focusing on Alternative I with full trade. OBR is modeled as an (implicit) production subsidy σ_1 in region 1 that goes along with the CO₂ price, and we assume a 100% rebate. This means that the CO₂ price value of the OBR subsidy payments

equals the total value of the CO₂ price payments: $\sigma_1 \sigma_1 y_1 = \tau_1 e_1 y_1$. The marginal effect of increasing the CO₂ price from zero is then $d\sigma_1 = e_0 d\tau_1$.

We first differentiate the same equations as above. Eqs. (1-I), (3-I), (5-I) and (6-I) are unchanged, but for the two other equations we get:

$$\begin{aligned}
 (2-IV) \quad cdy_i &= dp^y + d\sigma_i - (dp + d\tau_i)e_i - (p + \tau_i)de_i + \hat{\varepsilon}e_i^{-\hat{\varepsilon}-1}de_i = dp^y - e_i dp \\
 cdD_i &= -c\delta d^n (p + \tau_i)^{-\delta-1} (dp + d\tau_i) \\
 &+ \hat{\varepsilon}^\varepsilon (p_i + \tau_i)^{-\varepsilon} \left[dp^y + d\sigma_i - (dp + d\tau_i)e_i - (p_i + \tau_i)de_i + \hat{\varepsilon}e_i^{-\hat{\varepsilon}-1}de_i \right] \\
 (4-IV) \quad &- \varepsilon \hat{\varepsilon}^\varepsilon (p + \tau_i)^{-\varepsilon-1} (dp + d\tau_i) \left(p_y - (p_i + \tau_i)e_i - (e_i^{-\hat{\varepsilon}} - \bar{e}) \right) \\
 &= -c\delta d^n p^{-\delta-1} (dp + d\tau_i) + e_i \left[dp^y - e_i dp \right] - \varepsilon e_i p^{-1} c y_i (dp + d\tau_i)
 \end{aligned}$$

We repeat the exercise from Alternative I with the slightly revised equations.

As before, we have $dS_1 = dS_2$ and $dy_1 = -dy_2$. From (2) it then follows that $dy_i = 0$, i.e., production of the trade-exposed good is now unchanged in the two regions (because of OBR).

Applying $dy_i = 0$ in (2-IV), we then get:

$$dp^y = e_0 dp$$

From (1) and (5) we have (as before):

$$dD_1 + dD_2 = 2\gamma (p)^{\gamma-1} dp$$

Inserting from (4-IV) we get:

$$\begin{aligned}
 &-c\delta d^n p^{-\delta-1} (dp + d\tau_1) + e_1 \left[dp^y - e_1 dp \right] - \varepsilon e_1 p^{-1} c y_1 (dp + d\tau_1) \\
 &-c\delta d^n p^{-\delta-1} dp + e_2 \left[dp^y - e_2 dp \right] - \varepsilon e_2 p^{-1} c y_2 dp = 2c\gamma p^{\gamma-1} dp
 \end{aligned}$$

Reorganizing and replacing e_j and y_j with the common initial values e_0 and y_0 we get:

$$\begin{aligned}
 &\left[2c\gamma p^{\gamma-1} + 2c\delta d^n p^{-\delta-1} + 2e_0^2 + 2\varepsilon e_0 c y_0 p^{-1} \right] dp + \left[-2e_0 \right] dp^y \\
 &+ \left[c\delta d^n p^{-\delta-1} + \varepsilon e_0 c y_0 p^{-1} \right] d\tau_1 + \left[e_0 p - \hat{\varepsilon} e_0^{-\hat{\varepsilon}} \right] (de_1 + de_2) = 0
 \end{aligned}$$

Inserting from the expression for dp^y above, we get:

$$\left[2c\gamma p^{\gamma-1} + 2c\delta d^n p^{-\delta-1} + 2\varepsilon e_0 c y_0 p^{-1} \right] dp + \left[c\delta d^n p^{-\delta-1} + \varepsilon e_0 c y_0 p^{-1} \right] d\tau_1 = 0$$

or (after normalization):

$$\frac{dp}{d\tau_1} = -\frac{\delta d^n p^{-\delta} + \varepsilon e_0 y_0}{2[\gamma p^\gamma + \delta d^n p^{-\varepsilon} + \varepsilon e_0 y_0]} = -\frac{\lambda}{2[\lambda + \gamma]} < 0$$

From the expression for dp^y above, we can then find:

$$\frac{dp^y}{d\tau_1} = -\frac{e_0 \lambda}{2[\lambda + \gamma]} < 0$$

Turning to quantities, from (1-l) we can derive the effects on fuel supply in the two regions:

$$\frac{dS_i}{d\tau_1} = -\frac{\gamma \lambda}{2[\lambda + \gamma]}$$

Considering next the effects on demand

$$\begin{aligned} dD_1 &= -\delta d^n p^{-\delta-1} (dp + d\tau_1) + e_1 c^{-1} (dp^y - dp e_1) - \varepsilon e_1 p^{-1} c^{-1} (dp + d\tau_1) c y_1 \\ &= [-\delta d^n p^{-\delta-1} - e_1^2 c^{-1} - \varepsilon e_1 y_1 p^{-1}] dp + e_1 c^{-1} dp^y + [-\delta d^n p^{-\delta-1} - \varepsilon e_1 y_1 p^{-1}] d\tau_1 \end{aligned}$$

Reorganizing and again inserting $e_1 = e_0$ and $y_1 = y_0$ and normalizing:

$$\begin{aligned} \frac{dD_1}{d\tau_1} &= [-\delta d^n p^{-\delta-1} - e_0^2 c^{-1} - \varepsilon e_0 y_0 p^{-1}] \frac{dp}{d\tau_1} + e_0 c^{-1} \frac{dp^y}{d\tau_1} + [-\delta d^n p^{-\delta-1} - \varepsilon e_0 y_0 p^{-1}] \\ &= [-\delta d^n - e_0^2 c^{-1} - \varepsilon e_0 y_0] \frac{-\lambda}{2[\lambda + \gamma]} - e_0 c^{-1} \frac{e_0 \lambda}{2[\lambda + \gamma]} + [-\delta d^n - \varepsilon e_0 y_0] \\ &= -\frac{\lambda}{2[\lambda + \gamma]} [-\delta D^n - e_0^2 c^{-1} - \varepsilon e_0 y_0 + e_0^2 c^{-1}] - \delta D^n - \varepsilon D^t = \lambda \left[\frac{\lambda}{2[\lambda + \gamma]} - 1 \right] < 0 \end{aligned}$$

$$\begin{aligned} dD_2 &= -\delta d^n p^{-\delta-1} dp + e_2 c^{-1} (dp^y - e_2 dp) - \varepsilon e_2 p^{-1} c^{-1} c y_2 dp \\ &= [-\delta d^n p^{-\delta-1} - e_2^2 c^{-1} - \varepsilon e_2 y_2 p^{-1}] dp + e_2 c^{-1} dp^y \end{aligned}$$

$$\begin{aligned} \frac{dD_2}{d\tau_1} &= [-\delta d^n p^{-\delta-1} - e_0^2 c^{-1} - \varepsilon e_0 y_0 p^{-1}] \frac{dp}{d\tau_1} + e_0 c^{-1} \frac{dp^y}{d\tau_1} \\ &= \left[-\delta d^n p^{-\delta-1} - \frac{e_0^2}{c} - \frac{\varepsilon e_0 y_0}{p} \right] \frac{-\lambda}{2[\lambda + \gamma]} - e_0 c^{-1} \frac{e_0 \lambda}{2[\lambda + \gamma]} = -\frac{\lambda}{2[\lambda + \gamma]} [-\delta D^n - \varepsilon e_0 y_0] = \frac{\lambda^2}{2[\lambda + \gamma]} > 0 \end{aligned}$$

Finally, we are interested in the leakage rate:

$$L^{OBR} = -\frac{dD_2}{dD_1} = -\frac{\frac{\lambda^2}{2[\lambda+\gamma]}}{\lambda\left[\frac{\lambda}{2[\lambda+\gamma]}-1\right]} = -\frac{\lambda}{\lambda-2[\lambda+\gamma]} = \frac{\lambda}{\lambda+2\gamma}$$

We see that the leakage rate is strictly between zero and one, and is in fact identical to L''' , that is, leakage via the fossil fuel channel. This is not surprising, as the OBR-subsidy is used to exactly shut down the trade-exposed channel.

Next, we are interested in to what extent OBR reduces leakage, i.e., $L^I - L^{OBR}$:

$$\begin{aligned} L^I - L^{OBR} &= \frac{c\lambda^2 + e_0^2(\lambda+\gamma)}{c\lambda(\lambda+2\gamma) + e_0^2(\lambda+\gamma)} - \frac{\lambda}{\lambda+2\gamma} \\ &= \frac{1}{\Psi} \left\{ (c\lambda^2 + e_0^2(\lambda+\gamma))(\lambda+2\gamma) - \lambda(c\lambda(\lambda+2\gamma) + e_0^2(\lambda+\gamma)) \right\} = \frac{1}{\Psi} [2e_0^2\gamma(\lambda+\gamma)] \end{aligned}$$

where

$$\Psi = (c\lambda(\lambda+2\gamma) + e_0^2(\lambda+\gamma))(\lambda+2\gamma)$$

Differentiating this with respect to γ and λ we find (after some tedious derivations):

$$\frac{d(L^I - L^{OBR})}{d\gamma} > 0$$

$$\frac{d(L^I - L^{OBR})}{d\lambda} < 0$$

which confirms Proposition 3

Effects of BCA

We next examine the effects of implementing border carbon adjustment (BCA), again focusing on Alternative I with full trade. BCA is modeled as a tariff t_1 on imports of y_2 into region 1, combined with an export rebate r_1 to exports of y_1 from region 1 to region 2. Both the tariff and the rebate are set equal to the emissions intensity in region 1 multiplied by the emissions price in region 1, i.e. $t_1 = r_1 = e_1\tau_1$.³³ It follows that producers in the two regions are indifferent between selling in region 1 or 2 if and only if $p_1^y - p_2^y = e_1\tau_1$. If this condition is not fulfilled, both producers would only sell in one and the same region, which would not hold in equilibrium. Hence, the condition must hold.

³³ In the economics literature, different tariff designs have been considered, including the one used here (see e.g. Böhringer et al., 20xx). Note also that since $e_1 = e_2$ initially, we would get the same result if the tariff was based on the emissions intensity abroad. Finally, note that EU's CBAM is somewhat different as it depends on the emissions intensity of the importing firm.

We first differentiate the same equations as above. Eqs. (1-I), (3-I), (5-I) and (6-I) are again unchanged, but for the two other equations we get:

$$(2-V) \quad cdy_i = dp_i^y - (dp + d\tau_i)e_i - (p + \tau_i)de_i + \hat{\varepsilon}e_i^{-\hat{\varepsilon}-1}de_i = dp_i^y - e_i(dp + d\tau_i)$$

$$(4-V) \quad \begin{aligned} cdD_i &= -c\delta d^n (p + \tau_i)^{-\delta-1} (dp + d\tau_i) \\ &+ \hat{\varepsilon}^\varepsilon (p_i + \tau_i)^{-\varepsilon} \left[dp_i^y - (dp + d\tau_i)e_i - (p_i + \tau_i)de_i + \hat{\varepsilon}e_i^{-\hat{\varepsilon}-1}de_i \right] \\ &- \varepsilon \hat{\varepsilon}^\varepsilon (p + \tau_i)^{-\varepsilon-1} (dp + d\tau_i) \left(p_i^y - (p_i + \tau_i)e_i - (e_i^{-\hat{\varepsilon}} - \bar{e}) \right) \\ &= -c\delta d^n p^{-\delta-1} (dp + d\tau_i) + e_i \left[dp_i^y - e_i(dp + d\tau_i) \right] - \varepsilon e_i p^{-1} c y_i (dp + d\tau_i) \end{aligned}$$

As before, we have $dS_1 = dS_2$ and $dy_1 = -dy_2$.

From (2-V) we have:

$$\begin{aligned} cdy_1 &= dp_1^y - e_1(dp + d\tau_1) \\ cdy_2 &= dp_2^y - e_2 dp = dp_1^y - e_1 d\tau_1 - \tau_1 de_1 - e_2 dp \end{aligned}$$

where we used $dp_1^y - dp_2^y = e_1 d\tau_1 + \tau_1 de_1$.

Initially, we have $\tau_1 = 0$ and $e_1 = e_2 = e_0$, and thus $dy_i = 0$. Hence, production of the trade-exposed good is unchanged in the two regions, just as in the case with OBR.

Applying $dy_i = 0$ in (2-V), we then get:

$$\begin{aligned} dp_1^y &= e_0(dp + d\tau_1) \\ dp_2^y &= e_0 dp \end{aligned}$$

From (1) and (5) we have (as before):

$$dD_1 + dD_2 = 2\gamma(p)^{\gamma-1} dp$$

Inserting from (4-V) we get:

$$\begin{aligned} &-c\delta d^n p^{-\delta-1} (dp + d\tau_1) + e_1 \left[dp_1^y - e_1(dp + d\tau_1) \right] - \varepsilon e_1 p^{-1} c y_1 (dp + d\tau_1) \\ &-c\delta d^n p^{-\delta-1} dp + e_2 \left[dp_2^y - e_2 dp \right] - \varepsilon e_2 p^{-1} c y_2 dp = 2c\gamma p^{\gamma-1} dp \end{aligned}$$

Reorganizing and replacing e_j and y_j with the common initial values e_0 and y_0 , and using

$dp_1^y - dp_2^y = e_1 d\tau_1$, we get:

$$\begin{aligned} &\left[2c\gamma p^{\gamma-1} + 2c\delta d^n p^{-\delta-1} + 2e_0^2 + 2\varepsilon e_0 c y_0 p^{-1} \right] dp + \left[-2e_0 \right] dp_1^y \\ &+ \left[c\delta d^n p^{-\delta-1} + 2e_0^2 + \varepsilon e_0 c y_0 p^{-1} \right] d\tau_1 + \left[e_0 p - \hat{\varepsilon} e_0^{-\hat{\varepsilon}} \right] (de_1 + de_2) = 0 \end{aligned}$$

Inserting from the expression for dp_1^y above, we get (the last term above is zero):

$$\left[2c\gamma p^{\gamma-1} + 2c\delta d^n p^{-\delta-1} + 2\varepsilon e_0 c y_0 p^{-1}\right] dp + \left[c\delta d^n p^{-\delta-1} + \varepsilon e_0 c y_0 p^{-1}\right] d\tau_1 = 0$$

or (after normalization):

$$\frac{dp}{d\tau_1} = -\frac{\delta d^n p^{-\delta} + \varepsilon e_0 y_0}{2[\gamma p^\gamma + \delta d^n p^{-\varepsilon} + \varepsilon e_0 y_0]} = -\frac{\lambda}{2[\lambda + \gamma]} < 0$$

From the expressions for dp_i^y above, we can then find:

$$\frac{dp_1^y}{d\tau_1} = e_0 \left(1 - \frac{\lambda}{2[\lambda + \gamma]}\right) > 0$$

$$\frac{dp_2^y}{d\tau_1} = -\frac{e_0 \lambda}{2[\lambda + \gamma]} < 0$$

Turning to quantities, from (1-I) we can derive the effects on fuel supply in the two regions:

$$\frac{dS_i}{d\tau_1} = -\frac{\gamma \lambda}{2[\lambda + \gamma]}$$

Considering next the effects on demand from (4-V):

$$\begin{aligned} dD_1 &= -\delta d^n p^{-\delta-1} (dp + d\tau_1) + e_1 c^{-1} (dp_1^y - e_1 (dp + d\tau_1)) - \varepsilon e_1 p^{-1} y_1 (dp + d\tau_1) \\ &= \left[-\delta d^n p^{-\delta-1} - e_1^2 c^{-1} - \varepsilon e_1 y_1 p^{-1}\right] dp + e_1 c^{-1} dp_1^y + \left[-\delta d^n p^{-\delta-1} - e_1^2 c^{-1} - \varepsilon e_1 y_1 p^{-1}\right] d\tau_1 \end{aligned}$$

Reorganizing and again inserting $e_1 = e_0$ and $y_1 = y_0$ and normalizing:

$$\begin{aligned} \frac{dD_1}{d\tau_1} &= \left[-\delta d^n p^{-\delta-1} - e_0^2 c^{-1} - \varepsilon e_0 y_0 p^{-1}\right] \frac{dp}{d\tau_1} + e_0 c^{-1} \frac{dp_1^y}{d\tau_1} + \left[-\delta d^n p^{-\delta-1} - e_0^2 c^{-1} - \varepsilon e_0 y_0 p^{-1}\right] \\ &= \left[-\delta d^n - e_0^2 c^{-1} - \varepsilon e_0 y_0\right] \frac{-\lambda}{2[\lambda + \gamma]} + e_0 c^{-1} e_0 \left(1 - \frac{\lambda}{2[\lambda + \gamma]}\right) + \left[-\delta d^n - e_0^2 c^{-1} - \varepsilon e_0 y_0\right] \\ &= -\frac{\lambda}{2[\lambda + \gamma]} \left[-\delta D^n - e_0^2 c^{-1} - \varepsilon e_0 y_0 + e_0^2 c^{-1}\right] - \delta D^n - \varepsilon D^t = \lambda \left[\frac{\lambda}{2[\lambda + \gamma]} - 1\right] < 0 \end{aligned}$$

$$\begin{aligned} dD_2 &= -\delta d^n p^{-\delta-1} dp + e_2 c^{-1} (dp_2^y - e_2 dp) - \varepsilon e_2 p^{-1} c^{-1} c y_2 dp \\ &= \left[-\delta d^n p^{-\delta-1} - e_2^2 c^{-1} - \varepsilon e_2 y_2 p^{-1}\right] dp + e_2 c^{-1} dp_2^y \end{aligned}$$

$$\begin{aligned}\frac{dD_2}{d\tau_1} &= \left[-\delta d^n p^{-\delta-1} - e_0^2 c^{-1} - \varepsilon e_0 y_0 p^{-1} \right] \frac{dp}{d\tau_1} + e_0 c^{-1} \frac{dp_2^y}{d\tau_1} \\ &= \left[-\delta d^n p^{-\delta-1} - \frac{e_0^2}{c} - \frac{\varepsilon e_0 y_0}{p} \right] \frac{-\lambda}{2[\lambda + \gamma]} - e_0 c^{-1} \frac{e_0 \lambda}{2[\lambda + \gamma]} = -\frac{\lambda}{2[\lambda + \gamma]} \left[-\delta D^n - \varepsilon e_0 y_0 \right] = \frac{\lambda^2}{2[\lambda + \gamma]} > 0\end{aligned}$$

Finally, we are interested in the leakage rate:

$$L^{BCA} = -\frac{dD_2}{dD_1} = -\frac{\frac{\lambda^2}{2[\lambda + \gamma]}}{\lambda \left[\frac{\lambda}{2[\lambda + \gamma]} - 1 \right]} = -\frac{\lambda}{\lambda - 2[\lambda + \gamma]} = \frac{\lambda}{\lambda + 2\gamma}$$

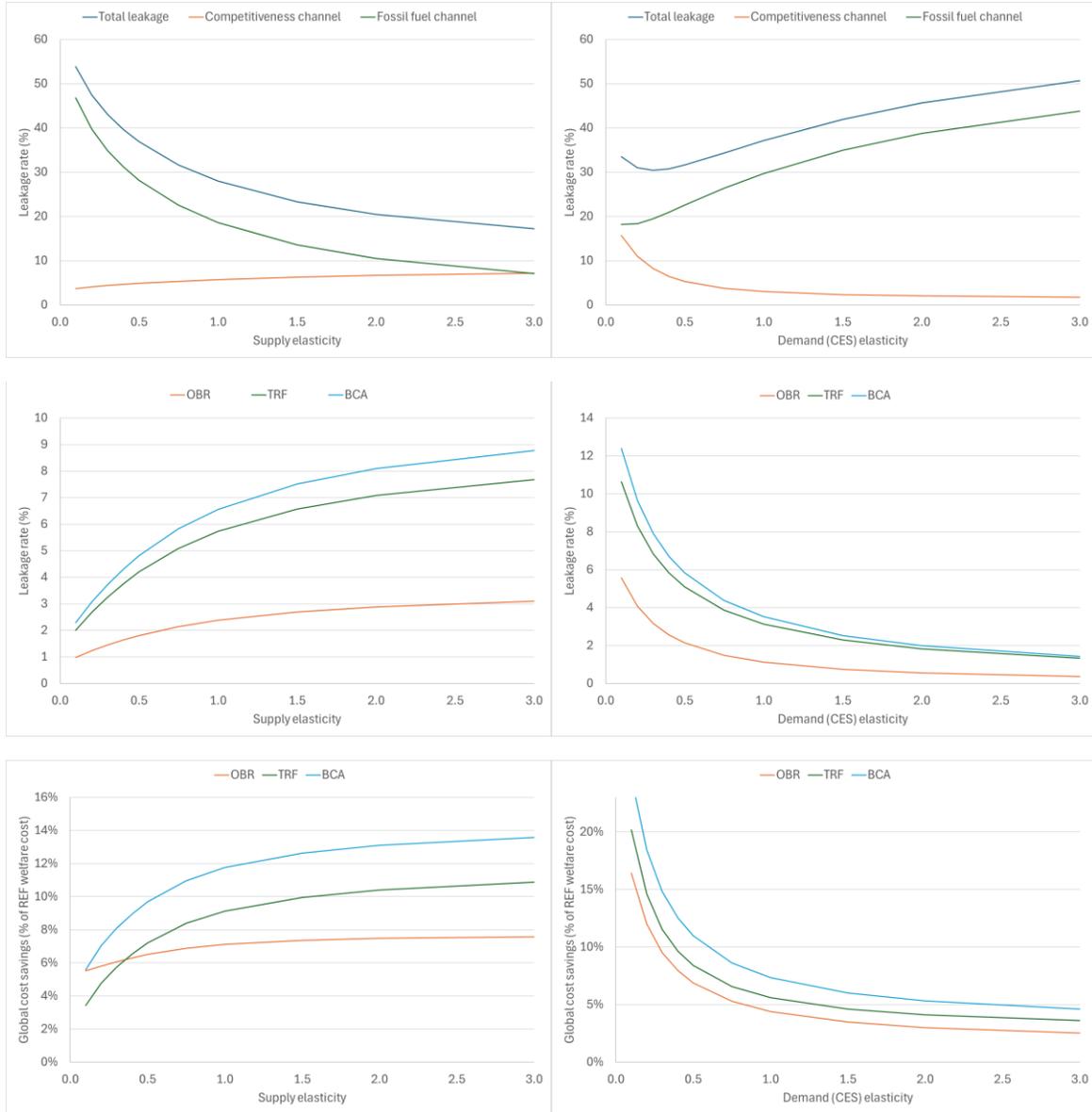
We see that the expression is the same as for OBR. We also see that all quantity effects are the same as with OBR – the only difference is the effect on dp_1^y (which increases with BCA, while decreasing with OBR). Note, however, that these identical quantity effects come because we have assumed fixed demand for the trade-exposed good.

Finally, since the leakage rate is the same with BCA as with OBR, it also follows that the leakage reduction is the same, and that the derivatives of the leakage reduction with respect to the elasticities are the same.

Appendix B. Figures based on sensitivity analysis

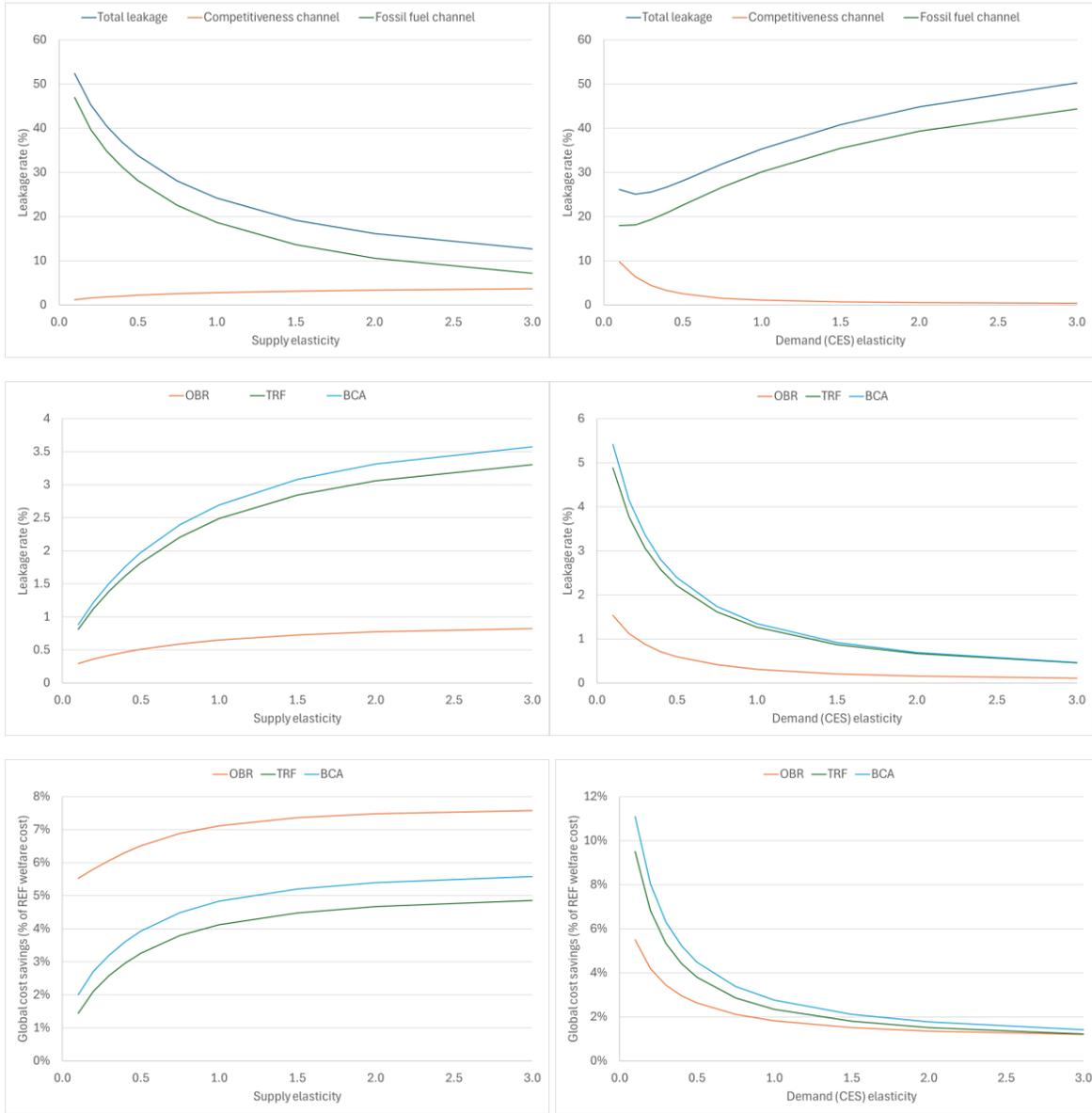
Here we present figures from the sensitivity analysis, which are discussed in the main text.

Figure B1. Effects on leakage rate with high Armington elasticity (20% emissions reduction in the EU)



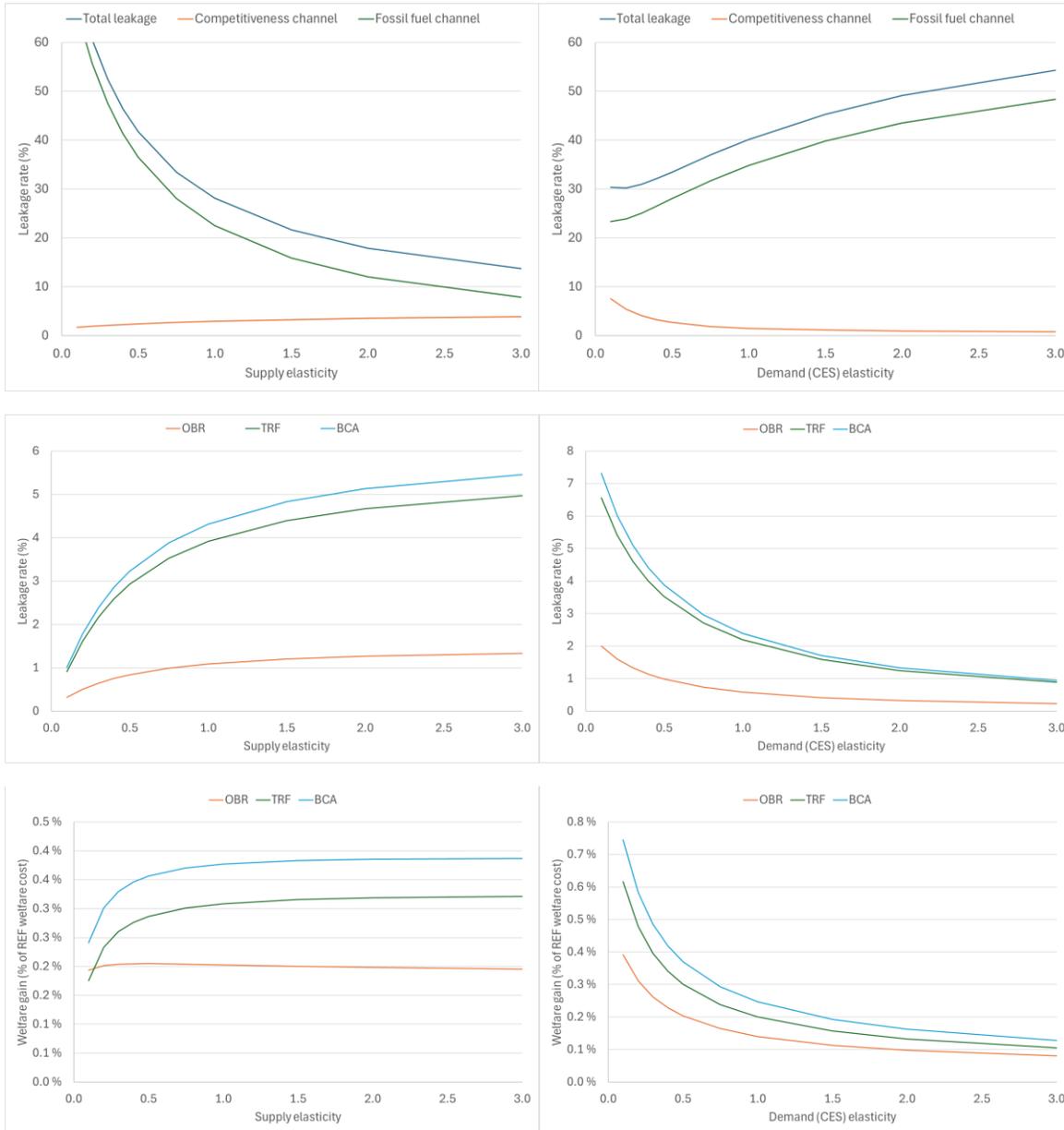
Note: Leakage reductions are the differences in leakage rate (in percent) between REF and the anti-leakage policy. Global cost savings are the increase in global welfare in proportion to the welfare cost of REF (vis-à-vis BaU) (in percent). When varying the supply elasticity, the CES demand elasticities are set to 0.5. When varying the demand elasticity, the supply elasticity is set to 0.75.

Figure B2. Effects on leakage rate with low Armington elasticity (20% emissions reduction in the EU)



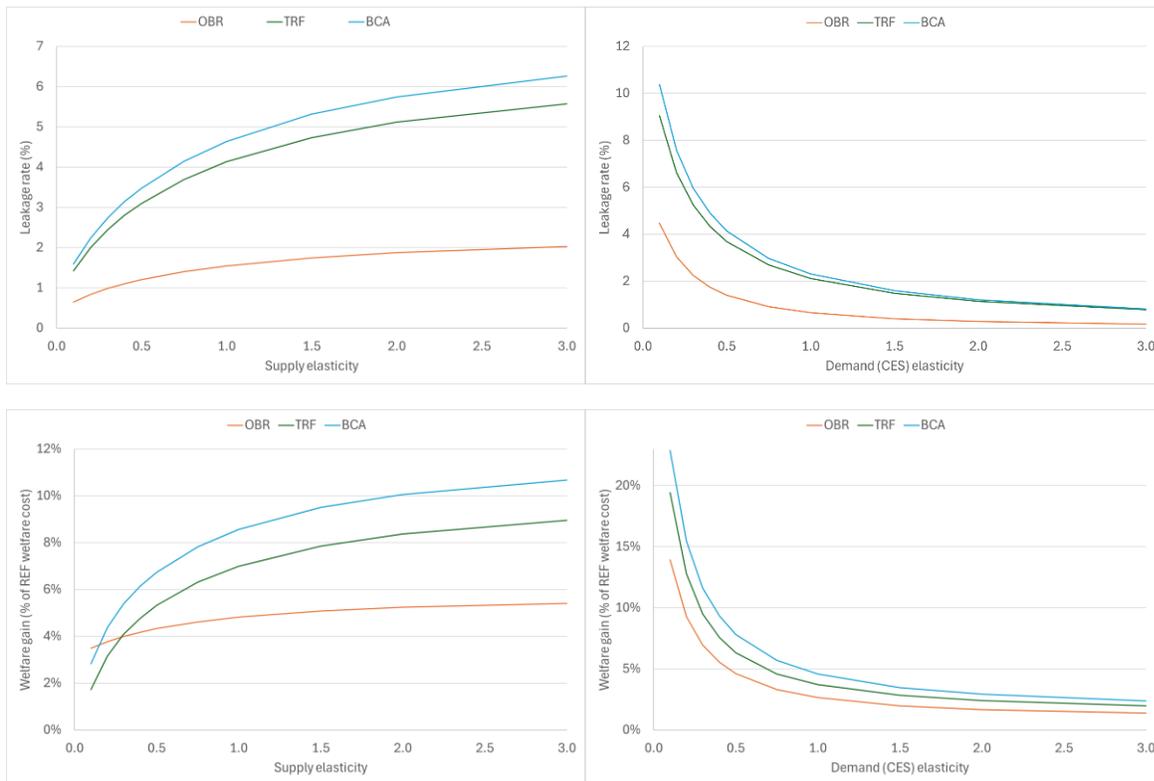
Note: Leakage reductions are the differences in leakage rate (in percent) between REF and the anti-leakage policy. Global cost savings are the increase in global welfare in proportion to the welfare cost of REF (vis-à-vis BaU) (in percent). When varying the supply elasticity, the CES demand elasticities are set to 0.5. When varying the demand elasticity, the supply elasticity is set to 0.75.

Figure B3. Effects on leakage, leakage reductions and global cost savings with 10% emissions reduction in the EU.



Note: Leakage reductions are the differences in leakage rate (in percent) between REF and the anti-leakage policy. Global cost savings are the increase in global welfare in proportion to the welfare cost of REF (vis-à-vis BaU) (in percent). When varying the supply elasticity, the CES demand elasticities are set to 0.5. When varying the demand elasticity, the supply elasticity is set to 0.75.

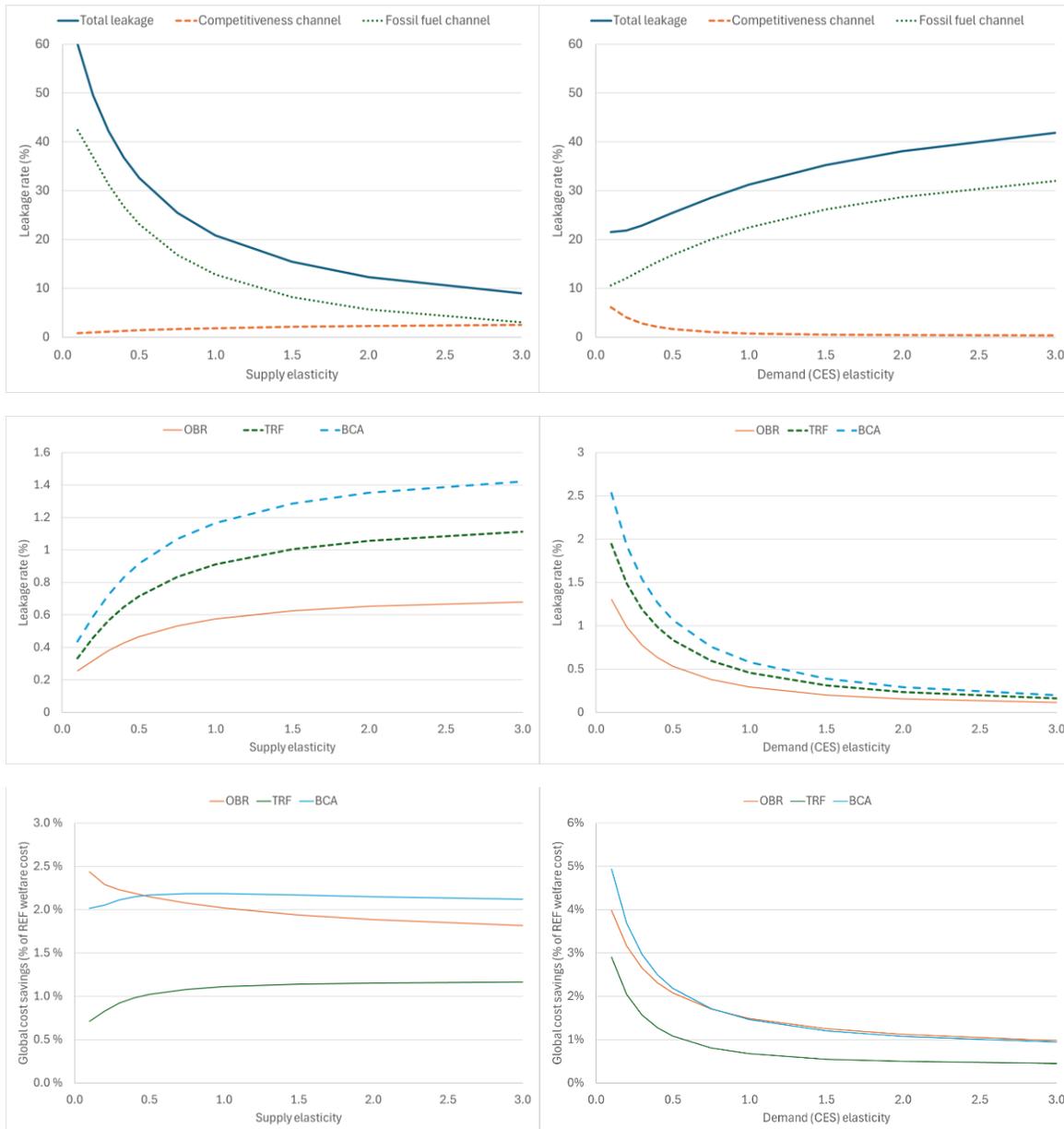
Figure B4. Effects on leakage reduction and global cost savings with 30% emissions reduction in the EU³⁴



Note: Leakage reductions are the differences in leakage rate (in percent) between REF and the anti-leakage policy. Global cost savings are the increase in global welfare in proportion to the welfare cost of REF (vis-à-vis BaU) (in percent). When varying the supply elasticity, the CES demand elasticities are set to 0.5. When varying the demand elasticity, the supply elasticity is set to 0.75.

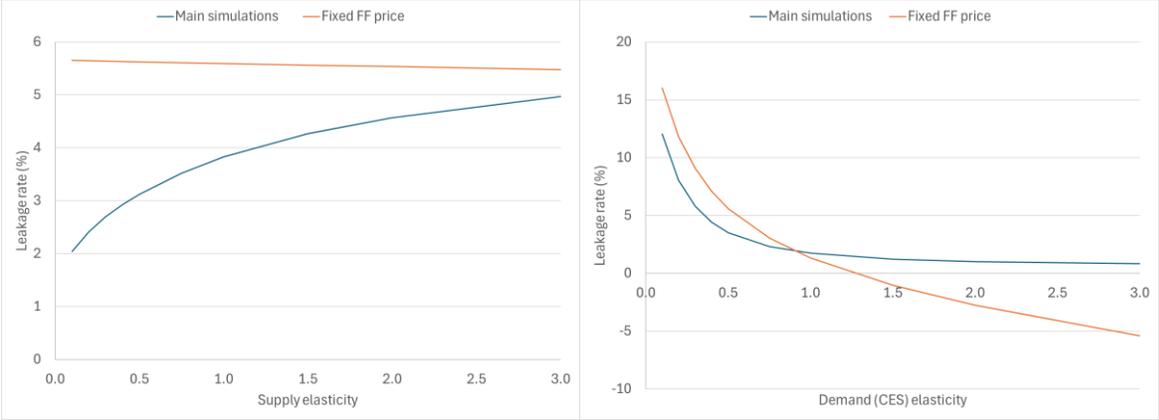
³⁴ As explained in the main text, we have not simulated the two leakage channels individually in this case.

Figure B5. Effects on leakage, leakage reduction and global cost savings with USA being the policy region (20% emissions reduction)



Note: Leakage reductions are the differences in leakage rate (in percent) between REF and the anti-leakage policy. Global cost savings are the increase in global welfare in proportion to the welfare cost of REF (vis-à-vis BaU) (in percent). When varying the supply elasticity, the CES demand elasticities are set to 0.5. When varying the demand elasticity, the supply elasticity is set to 0.75.

Figure B6. Leakage rate via the competitiveness channel derived in two different ways; i) as in main simulations, ii) with fixed fossil fuel prices



Note: When varying the supply elasticity, the CES demand elasticities are set to 0.5. When varying the demand elasticity, the supply elasticity is set to 0.75.

Appendix C. Tables with numbers behind figures in Section 3.2

Table C1. Numbers behind Figure 5

		Supply elasticity									
		0.1	0.2	0.3	0.4	0.5	0.75	1	1.5	2	3
Demand elasticity	0.1	28.0	20.5	15.9	12.7	10.3	6.1	3.2	-0.4	-2.7	-10.2
	0.2	33.9	26.2	21.3	17.7	15.0	10.2	6.9	2.7	0.2	-2.7
	0.3	38.4	30.6	25.6	21.9	18.9	13.6	9.9	5.2	2.4	-0.8
	0.4	42.0	34.3	29.1	25.3	22.2	16.5	12.5	7.4	4.3	0.8
	0.5	44.8	37.3	32.2	28.2	25.0	19.0	14.8	9.3	6.0	2.1
	0.75	50.0	43.0	38.0	34.0	30.6	24.1	19.5	13.3	9.5	5.0
	1	53.5	47.1	42.2	38.3	34.8	28.1	23.2	16.6	12.3	7.3
	1.5	58.0	52.4	48.0	44.2	40.8	33.9	28.7	21.6	16.9	11.2
	2	60.7	55.8	51.7	48.0	44.8	37.9	32.7	25.4	20.4	14.2
	3	63.6	59.6	56.1	52.8	49.7	43.2	38.1	30.6	25.4	18.7

Note: The numbers shows the leakage rate via the fossil fuel channel minus the leakage rate via the competitiveness channel (in percentage terms).

Table C2. Numbers behind Figure 8

		Supply elasticity									
		0.1	0.2	0.3	0.4	0.5	0.75	1	1.5	2	3
Demand elasticity	0.1	7.4 %	8.0 %	8.5 %	8.9 %	9.2 %	9.8 %	10.2 %	10.6 %	10.9 %	11.1 %
	0.2	5.8 %	6.1 %	6.4 %	6.6 %	6.9 %	7.3 %	7.5 %	7.8 %	7.9 %	8.1 %
	0.3	4.8 %	5.0 %	5.2 %	5.4 %	5.5 %	5.8 %	6.0 %	6.2 %	6.3 %	6.4 %
	0.4	4.1 %	4.3 %	4.4 %	4.6 %	4.7 %	4.9 %	5.1 %	5.2 %	5.3 %	5.3 %
	0.5	3.7 %	3.8 %	3.9 %	4.0 %	4.1 %	4.3 %	4.4 %	4.5 %	4.6 %	4.6 %
	0.75	3.0 %	3.0 %	3.1 %	3.2 %	3.2 %	3.4 %	3.4 %	3.5 %	3.5 %	3.5 %
	1	2.6 %	2.6 %	2.7 %	2.7 %	2.8 %	2.8 %	2.9 %	2.9 %	2.9 %	2.9 %
	1.5	2.2 %	2.2 %	2.2 %	2.2 %	2.2 %	2.3 %	2.3 %	2.3 %	2.3 %	2.3 %
	2	2.0 %	1.9 %	2.0 %	2.0 %	2.0 %	2.0 %	2.0 %	2.0 %	2.0 %	1.9 %
	3	1.8 %	1.7 %	1.7 %	1.7 %	1.7 %	1.7 %	1.7 %	1.7 %	1.7 %	1.6 %

Note: Global cost savings (in % from REF) when implementing OBR for different combinations of supply and (CES) demand elasticities.

Table C3. Numbers behind Figure 9

		Supply elasticity									
		0.1	0.2	0.3	0.4	0.5	0.75	1	1.5	2	3
Demand elasticity	0.1	7.1 %	9.4 %	10.9 %	12.0 %	12.9 %	14.6 %	15.6 %	16.7 %	17.3 %	17.8 %
	0.2	4.9 %	6.6 %	7.7 %	8.6 %	9.3 %	10.6 %	11.4 %	12.3 %	12.8 %	13.3 %
	0.3	3.7 %	5.1 %	6.0 %	6.8 %	7.4 %	8.5 %	9.1 %	9.9 %	10.3 %	10.7 %
	0.4	3.0 %	4.2 %	5.0 %	5.6 %	6.2 %	7.1 %	7.7 %	8.3 %	8.7 %	9.0 %
	0.5	2.6 %	3.6 %	4.3 %	4.9 %	5.3 %	6.2 %	6.7 %	7.2 %	7.5 %	7.9 %
	0.75	2.0 %	2.7 %	3.3 %	3.8 %	4.1 %	4.8 %	5.2 %	5.6 %	5.9 %	6.1 %
	1	1.7 %	2.3 %	2.8 %	3.2 %	3.5 %	4.0 %	4.4 %	4.7 %	4.9 %	5.1 %
	1.5	1.5 %	1.9 %	2.2 %	2.6 %	2.8 %	3.2 %	3.5 %	3.8 %	3.9 %	4.0 %
	2	1.4 %	1.7 %	2.0 %	2.3 %	2.5 %	2.8 %	3.0 %	3.2 %	3.3 %	3.4 %
	3	1.3 %	1.5 %	1.8 %	2.0 %	2.1 %	2.4 %	2.5 %	2.7 %	2.7 %	2.8 %

Note: Global cost savings (in % from REF) when implementing TRF for different combinations of supply and (CES) demand elasticities.

Table C4. Numbers behind Figure 10

		Supply elasticity									
		0.1	0.2	0.3	0.4	0.5	0.75	1	1.5	2	3
Demand elasticity	0.1	9.5 %	12.0 %	13.6 %	14.8 %	15.8 %	17.5 %	18.6 %	19.8 %	20.4 %	20.9 %
	0.2	6.8 %	8.6 %	9.9 %	10.8 %	11.6 %	13.0 %	13.8 %	14.8 %	15.3 %	15.7 %
	0.3	5.3 %	6.8 %	7.8 %	8.6 %	9.2 %	10.4 %	11.1 %	11.9 %	12.3 %	12.7 %
	0.4	4.4 %	5.6 %	6.5 %	7.2 %	7.8 %	8.8 %	9.4 %	10.0 %	10.4 %	10.7 %
	0.5	3.8 %	4.9 %	5.6 %	6.2 %	6.7 %	7.6 %	8.2 %	8.8 %	9.1 %	9.4 %
	0.75	3.0 %	3.7 %	4.3 %	4.8 %	5.2 %	5.9 %	6.4 %	6.8 %	7.0 %	7.3 %
	1	2.5 %	3.2 %	3.6 %	4.1 %	4.4 %	5.0 %	5.3 %	5.7 %	5.9 %	6.1 %
	1.5	2.1 %	2.6 %	2.9 %	3.3 %	3.5 %	4.0 %	4.2 %	4.5 %	4.6 %	4.8 %
	2	2.0 %	2.3 %	2.6 %	2.9 %	3.1 %	3.4 %	3.6 %	3.9 %	4.0 %	4.0 %
	3	1.8 %	2.0 %	2.3 %	2.5 %	2.6 %	2.9 %	3.0 %	3.2 %	3.2 %	3.3 %

Note: Global cost savings (in % from REF) when implementing BCA for different combinations of supply and (CES) demand elasticities.