Unilateral Climate Policy: Can OPEC Resolve the Leakage Problem?

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ABSTRACT

In the absence of a global agreement to reduce greenhouse gas emissions, individual countries have introduced national climate policies. Unilateral action involves the risk of relocating emissions to regions without climate regulations, i.e., emission leakage. A major channel for leakage are price changes in the international oil market. Previous studies on leakage have assumed competitive behavior in this market. Here, we consider alternative assumptions about OPEC's behavior in order to assess how these affect leakage and costs of unilateral climate policies. Our results based on simulations with a large-scale computable general equilibrium model of the global economy suggest that assumptions on OPEC's behavior are crucial to the impact assessment of unilateral climate policy measures. We find that leakage through the oil market may become negative when OPEC is perceived as a dominant producer, thereby reducing overall leakage drastically compared to a setting where the oil market is perceived competitive.

Keywords: Carbon Leakage, Oil Market, OPEC Behavior

1. INTRODUCTION

In the absence of an effective global agreement to mitigate climate change, individual countries lead the way with unilateral greenhouse gas (GHG) emission reductions. The most prominent example is the European Union (EU), which adopted legally binding emission reduction targets until 2020 to be achieved through an EU-wide emissions trading system.

One major problem with unilateral action, however, is the risk of emission leakage, i.e., the relocation of emissions to regions without climate regulations. Leakage mainly occurs through two intertwined channels. The first channel is the so-called fossil-fuel-price channel: Reduced fuel demand of emission-constrained regions depresses international fuel prices, which in turn stimulates fuel consumption and thus emissions in regions without emission constraints. The second channel is the so-called competitiveness channel for emission-intensive and trade-exposed (EITE) goods, such as steel, cement, or chemical products: Emission constraints raise production costs for these industries, reducing their competitiveness in the world market which triggers more production and emissions in unregulated regions.

The policy debate focuses on leakage through the competitiveness channel, mirroring concerns of regulated EITE industries on adverse production impacts. Several anti-leakage measures

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for EITE sectors are implemented or discussed. For instance, the EU has decided to allocate free allowances to EITE industries under the provisions of its emissions trading system. Another possible supplemental instrument are tariffs on the carbon embodied in imported goods from unregulated regions.

In the applied economic literature, leakage induced by unilateral emission constraints and the impacts of domestic policy measures to reduce carbon leakage have been analyzed in various papers including Bernard et al (2007), Mattoo et al. (2009), Böhringer et al. (2010, 2011, 2012a), and Fischer and Fox (2012). A common finding is that leakage takes place to a larger extent through the fossil-fuel-price channel. However, these studies are based on the assumption of competitive international oil markets, disregarding empirical evidence on non-competitive behavior of OPEC (see e.g. Griffin, 1985; Alhajji and Huettner, 2000a,b; Smith, 2005; Hansen and Lindholt, 2008).

The purpose of this study is to investigate how different prescriptions of OPEC's behavior affect the extent of carbon leakage triggered by emission regulation of the EU or other industrialized countries. That is, are the leakage rates much changed when we replace the paradigm of competitive behavior with alternative assumptions about OPEC's behavior? Furthermore, how will the (cost-)effectiveness of anti-leakage measures for EITE industries such as carbon tariffs change when we alter our behavioral assumption about OPEC?

Our analysis suggests that OPEC's behavior may have substantial impacts on overall leakage rates. This is especially the case if OPEC acts as a dominant producer maximizing profits subject to price responsiveness of the residual demand, i.e., global demand minus Non-OPEC supply. When the EU imposes carbon pricing, OPEC may in fact find it profitable to cut back supply to such an extent that the oil price *increases*. This is quite the opposite of what would happen in a competitive oil market setting. A higher oil price implies that oil consumption outside the EU declines, i.e., there is a *negative* leakage effect in the oil market. Overall leakage is still positive though, but the leakage rate declines from almost 20% in the reference analysis with competitive oil supply to less than 10% when OPEC acts as a dominant producer. If the EU also introduces carbon tariffs on EITE imports, overall leakage drops to 4% (vis-à-vis 14% in the reference setting with competitive OPEC behavior). Our findings are based on simulations with a large-scale computable general equilibrium (CGE) model of global production, trade and energy usage. The model due to Böhringer and Rutherford (2010) is extended to consider alternative assumptions on OPEC's behavior.

Our paper contributes to an extensive literature on strategic behavior related to climate policies, especially with respect to the battle on carbon rents and oil resource rents between OPEC and countries that adopt emission constraints. This literature has not focused on carbon leakage though. Some of the early studies include Wirl (1994, 1995), Tahvonen (1995, 1996), Bråten and Golombek (1998) and Rubio and Escriche (2001). Building on this literature, Liski and Tahvonen (2004) set up a differential game between a fossil fuel exporting cartel and a coalition of consumers who face a pollution externality. They show that the optimal emission tax consists of a Pigouvian part and a tariff element, which can be either positive or negative. If the cost related to pollution is not too high, consumers shift over resource rents through the tariff and can even be better off than without pollution at all. Dullieux et al. (2011) introduce a ceiling constraint for the carbon concentration in the atmosphere. They find that consumers are always able to save carbon rents and resource rents, while the exporting cartel is only able to shift carbon rents if the marginal damage under the ceiling is sufficiently small.

In a similar vein, Wirl (2012) sets out a differential game between a fossil fuel exporting cartel and a coalition of consumers who face external costs from global warming. In comparing

price to quantity instruments for both the cartel and the consumers' coalition, he finds that each player can save more resource rents as well as carbon rents when implementing a price instead of a fixed quantity. Strand (2013) employs a static theoretical framework, where a "policy bloc" imports fuel from a welfare optimizing fuel exporter, and introduces either a tax or a cap-and-trade scheme to reduce emissions from fuel consumption. In each case, there is a fringe of competitive importers, as well as an efficient CDM-like offset market. He shows that the "policy bloc" prefers the tax over the cap-and-trade scheme, as the fuel export price is lower due to less strategic scope for the fuel exporter. Wie et al. (2011) conclude that climate policies in fuel consuming countries make it optimal for OPEC to increase subsidies to domestic oil consumers. Haurie and Vielle (2010) show with a CGE model that under different (global) carbon taxes it is optimal for OPEC, when behaving as a dominant producer, to cut back on supply substantially and lose market share in order to not letting the oil price drop too much. This is in line with our conclusions.

The remainder of this paper is organized as follows. In Section 2, we put forward various formulations of OPEC behavior, which have been discussed and to some extent empirically tested in the literature. In Section 3, we present the CGE model underlying our quantitative analysis and the policy scenarios we are investigating. In Section 4, we present and discuss simulation results. In Section 5, we conclude.

2. ALTERNATIVE FORMULATIONS OF OPEC BEHAVIOR

The characterization of oil markets, which is commonly used in CGE models, assumes price-taking (competitive) behavior. In this section we describe alternative non-competitive formulations of OPEC behavior in the oil market, which we later implement in the CGE model.

2.1 Fixed Production or Fixed Price

OPEC's total production of crude oil is regulated through country-specific production quotas, which are updated about twice a year (depending e.g. on the market situation). However, there is no secret that production quotas are every so often exceeded. The additional volume though is relatively small. Thus, at least in the short run, one alternative formulation of OPEC's behavior is to keep output fixed.

From 2000 to 2005, OPEC had a price target of $22–28 per barrel of oil, meaning that OPEC intended to adjust its supply in order to keep oil prices within this price band. Yet, the strong growth in oil demand put more and more pressure on the oil price, making it very difficult for OPEC to keep prices below the upper bound of the price band. As a consequence the price band was abandoned in early 2005, when prices on OPEC oil were around $40 per barrel. Since then, representatives of OPEC countries have regularly suggested new price targets, but no official targets have been expressed. Nevertheless, it seems reasonable to argue that OPEC might regulate supply in order to attain an oil price level which the producer group thinks is profitable in the medium to long run.

2.2 Target Revenue

An alternative to targeting production or price is to target revenue (e.g., Alhajji and Huettner, 2000b). The assumption is that OPEC countries target a certain revenue to balance their budget, i.e., they choose a level of output that generates the targeted revenue. Let the exogenous revenue target be given by R, which we interpret as gross revenues. Moreover, let x_{OPEC} denote OPEC

supply, p the worldwide oil price, and $p = p_R(x_{OPEC})$ the residual inverse demand function for OPEC, which accounts for price responses in both demand and Non-OPEC supply. Then we have:

$$p_R(x_{OPEC})x_{OPEC} = R \tag{1}$$

If maximizing gross revenues has an internal solution, say at $x_{OPEC} = x^*$ with $R = R^*$, it follows that any x_{OPEC} below or above x^* must give a lower R. Thus, if we let $x(R)$ denote the output level that gives revenue R, it follows that $x(R)$ cannot have any solution for $R > R^*$, $x(R^*) = x^*$, and $x(R)$ have at least two solutions for $R < R^*$ (for R sufficiently close to R^*). This is referred to as a backward bending supply curve. It seems most realistic to assume $x < x^*$ whenever there are solutions both below and above x^*, because a lower x implies lower capacity and extraction costs.

2.3 Dominant Producer

The alternatives to competitive behavior discussed so far postulate that OPEC targets either its production or gross revenue, or the oil price. From an economic perspective, it is more appealing to assume profit-maximizing behavior. The latter is reflected by the dominant producer hypothesis, where the dominant producer—in our case OPEC –maximizes profits, taking into account price responses both on the demand side and among other producers (Smith, 2005; Hansen and Lindholt, 2008).

Let x_j denote production of producer (group) j, where $j = OPEC$, $NOPEC$ ($NOPEC$ denotes Non-OPEC countries). Further, let $x_{NOPEC}(p)$ denote Non-OPEC's supply function, and $x_D(p)$ the global oil demand function, where $x_D = x_{OPEC} + x_{NOPEC}$. Thus, OPEC's residual demand function ("call for OPEC") is $x_{OPEC}(p) = x_D(p) - x_{NOPEC}(p)$. OPEC's maximization problem can then be written:

$$\underset{p}{\text{Max}} \, \{(x_D(p) - x_{NOPEC}(p))p - c(x_D(p) - x_{NOPEC}(p))\} \tag{2}$$

This gives the following first-order condition (with respect to p):

$$(x_D{}'(p) - x_{NOPEC}{}'(p))p + (x_D(p) - x_{NOPEC}(p)) - c'(x_D(p) - x_{NOPEC}(p))(x_D{}'(p) - x_{NOPEC}{}'(p)) = 0 \tag{3}$$

or (simplifying):

$$p + \frac{x_{OPEC}}{(x_D{}'(p) - x_{NOPEC}{}'(p))} = c'(x_{OPEC}) \tag{4}$$

The second term is negative, and is bigger in absolute value the lower is the price responsiveness of global oil demand and Non-OPEC oil supply. If either of these is very price elastic, it is optimal for the dominant producer to choose a price just above marginal costs. Otherwise, it is optimal to choose a more substantial markup.

What happens if a region such as the EU decides to cap their emissions of CO_2? To simplify, we disregard emissions from other sources than oil, meaning that there is de facto a cap on oil consumption in the EU.[1] It is straightforward to show that the first-order condition for OPEC then changes to:

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1. In the CGE analysis below, we relax this assumption and consider CO_2 emissions from all fossil fuels.

$$p + \frac{x_{OPEC}}{(x_{D,NONEU}{}'(p) - x_{NOPEC}{}'(p))} = c{}'(x_{OPEC}) \tag{5}$$

where $x_{D,NONEU}$ denotes oil demand outside the EU. We see that the only difference between (4) and (5) is that $x_D{}'(p)$ is replaced by $x_{D,NONEU}{}'(p)$, which means that the denominator has declined. Consider the case where the EU cap is only marginally below the business-as-usual (BaU) level. What happens to OPEC's optimal oil price level p? Assume first that the oil price is unchanged from the BaU level. Then x_{OPEC} is practically unchanged. However, this means that the second term on the left-hand side of equation (5) has increased in absolute value, implying instead that it is optimal for OPEC to increase the oil price vis-à-vis the BaU level. That is, policies to cap oil consumption in one region leads to a *higher* oil price, given that the cap is not too strict. If the cap is stricter, the nominator in (5) decreases if p is unchanged, which implies that the optimal oil price may be either higher or lower than the BaU price level.

The explanation for a higher oil price is that OPEC by assumption knows that the region's CO_2 price will adjust endogenously depending on the global oil price. Thus, it is optimal for the producer group to try to reap a larger share of the oil rent. This would be different if the region instead introduced a fixed CO_2 tax. One important implication of a higher oil price is that carbon leakage becomes *negative* (again, disregarding other fossil fuels). In the numerical simulations below we shall see that this finding is indeed relevant also in a more sophisticated model based on real world data.

3. NUMERICAL MODEL AND POLICY SCENARIOS

3.1 Model Description

Our numerical analysis employs a standard multi-region, multi-sector computable general equilibrium model of global trade and energy (Böhringer and Rutherford, 2010)[2] which we extend to reflect alternative assumptions on OPEC's behavior. Parameterization of the model is based on the latest version of the *Global Trade Analysis Project* (GTAP) dataset which includes detailed national accounts on production and consumption (input-output tables) together with bilateral trade flows and CO_2 emissions for up to 129 regions and 57 sectors for the year 2007 (version 8 of GTAP—see Narayanan et al., 2012). We aggregate the GTAP accounts towards a composite dataset that reflects the specific requirements of the policy issue under investigation. At the sectoral level, our composite dataset includes all major primary and secondary energy carriers: coal, crude oil, natural gas, refined oil products, and electricity. In addition, we separate the main emission-intensive and trade-exposed (EITE) sectors:[3] chemical products, non-metallic minerals, iron and steel products, and non-ferrous metals; these sectors are most affected from shifts in comparative advantage triggered by unilateral emission regulation and thus qualify as the prime candidates for carbon tariffs. At the regional level, the composite dataset accounts for nine geopolitically important regions, including the EU as our reference region for unilateral climate policy and a composite OPEC region. Table 1 summarizes the sectors (commodities) and regions present in our analysis.

CGE models build upon general equilibrium theory that combines behavioral assumptions on rational economic agents with the analysis of equilibrium conditions. Our model features a

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2. Appendix A provides an algebraic summary of the core model structure.
3. Note that the group of EITE sectors also includes refined oil products (see Table 1).

Table 1: Model Sectors and Regions

Sectors and commodities	Countries and regions
Energy	Europe—EU-27 plus EFTA
Coal	United States of America
Crude oil	Russia
Natural gas	Remaining Annex 1
Refined oil products*	China
Electricity	India
*Emission-intensive & trade-exposed sectors**	Other middle income countries
Chemical products	Other low income countries
Non-metallic minerals	OPEC
Iron and steel industry	
Non-ferrous metals	
Transport sectors	
Air transport	
Water transport	
Other transport	
Other industries and services	
All other manufactures and services	

* Included in the group of *energy-intensive and trade-exposed industries* (EITE).

representative agent in each region that receives income from three primary factors: labour, capital, and fossil fuel resources. Labour and capital are intersectorally mobile within a region but immobile between regions. Fossil fuel resources are specific to fossil fuel production sectors in each region. Fossil fuel production is represented by a constant elasticity of substitution (CES) cost function, where at the top level the demand for the specific resource trades off with a Leontief composite of capital, labour, intermediate material, gas, oil, coal and electricity demands. The elasticities of substitution in fossil fuel sectors are calibrated to match exogenous estimates of fossil-fuel supply elasticities (Graham et al., 1999; Krichene, 2002; Ringlund et al., 2008). All other commodities are produced according to a nested CES cost function with five levels. At the top level, a CES composite of intermediate material demands trades off with a CES composite of energy, capital, and labour. At the second level, a CES function describes the substitution possibilities between intermediate demand for the energy aggregate (combining electricity, coal, gas, and oil) and a value-added composite of labour and capital. At the third level, capital and labour trade off according to a CES function; likewise, within the energy aggregate, electricity trades off with the composite of fossil fuels (coal, gas, oil). At the fourth level, a CES function describes the substitution possibilities between coal and the composite of oil and gas. At the fifth level, oil and gas trade off according to a CES function.

Final consumption demand in each region is determined by the representative agent who maximizes welfare subject to a budget constraint with fixed investment and exogenous government provision of public goods and services. Consumption demand of the representative agent is given as a CES composite that combines consumption of composite energy and an aggregate of other consumption goods.

Crude oil is treated as a homogeneous commodity, i.e., all crude oil flows through a global market with one world-market price. For all other commodities, bilateral trade is specified following Armington's differentiated goods approach, where domestic and foreign goods are distinguished by origin (Armington, 1969). A balance of payment constraint incorporates the base-year trade deficit or surplus for each region. CO_2 emissions are linked in fixed proportions to the use of coal,

Table 2: Alternative Formulations of OPEC Behavior in the CGE Model

COM	OPEC behaves as a competitive producer (no strategic OPEC response).
FFP	OPEC rations crude oil supply to hold the world market crude oil price at the business-as-usual level.
FFQ	OPEC holds its crude oil supply constant at the business-as-usual level.
FFR	OPEC rations crude oil supply in order to hold their crude oil revenues constant at the business-as-usual level.
DOM	OPEC exploits market power to maximize its profit in the oil market, i.e., OPEC behaves as a dominant producer.

Table 3: Climate Policy Scenarios in the EU

TAX	The EU implements a uniform CO_2 price.
BTA	The EU implements a uniform CO_2 price joint with carbon tariffs on EITE imports.

oil and gas, with CO_2 coefficients differentiated by fuels. Having set up the nesting structure of the CES functions in production and consumption, the free parameters are determined through exogenous elasticites and the benchmark data as provided by the GTAP database.[4]

Table 2 summarizes the five alternative assumptions on OPEC behavior that we simulate in the CGE model. These are based on the formulations discussed in Section 2. *COM* is the reference behavior, where OPEC behaves competitively. We will refer to the other alternatives as strategic behavior. For the strategic responses *FFP*, *FFQ* and *FFR*, OPEC rations its crude oil supply in order to meet the respective strategic objectives, i.e., quantity, price or revenue targets. These targets are set to the pre-policy level, i.e., the business-as-usual (BaU) situation without climate policy regulations. Implementation of the dominant producer (*DOM*) behavior in the BaU involves a cost-markup calibration for OPEC's crude oil production which is consistent with profit maximization given the benchmark data.

3.2 Policy Scenarios

We consider two alternative climate policy scenarios in the EU (strictly speaking, EU + EFTA, cf. Table 1), see Table 3. In the first scenario—labelled TAX—the EU imposes an economy-wide CO_2 price, either through a uniform CO_2 tax or a comprehensive emissions trading system. In the second scenario—labelled BTA—the EU in addition implements carbon tariffs for EITE sectors, that is, tariffs on the carbon embodied in imported EITE goods.[5]

The two climate policy scenarios are simulated for all five alternative OPEC formulations listed in Table 2. Unless otherwise stated, impacts are reported as percentage changes in key indicators from the business-as-usual (BaU) situation without emission regulation.

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4. The GTAP database contains Armington trade elasticities and value-added elasticities.

5. The tariff is applied to the specific embodied carbon of imported goods from trading partners. Embodied carbon in our simulations includes both the direct CO_2 content from combustion of fossil fuels and the indirect CO_2 content originating from the use of electricity as an intermediate input.

Given the global public good nature of emission reduction, the EU applies the same global CO_2 emissions constraint across all central case simulations. Thus, the global environmental effectiveness remains identical, and we can compare adjustment costs without taking into account the damages of climate change, which are difficult to quantify. The global emission target is determined by the world-wide CO_2 emissions that emerge from the *TAX* scenario where the EU reduces domestic CO_2 emissions by 20% compared to the BaU emission level and OPEC behaves in a competitive manner (variant *COM*).[6] Keeping with the global emission constraint requires that the domestic emission reduction target of the unilaterally abating region—here the EU—is scaled endogenously to compensate for policy-induced changes in emission leakage. This implies that whenever the leakage rate differs from the rate in scenario TAX and competitive OPEC behavior (*COM*), the domestic emission reduction within the EU will also be different. As seen below, this will be the case if we adopt alternative OPEC behavior or apply additional carbon tarrifs. Leakage reduction through carbon tariffs, for example, implies that the EU can reduce its CO_2 price compared to the respective TAX scenario in order to meet the global emission constraint.

Despite the public good nature of emission reductions, it can be questioned whether the EU would really adjust its climate policy in order to reach a global emission target. We return to this issue below, where we also report the results of instead assuming a fixed domestic emission reduction target, or a fixed price on emissions. It is then more difficult to interpret the differences in adjustment costs, as the environmental impacts typically vary across scenarios.

4. NUMERICAL RESULTS

We first consider how climate policies in the EU affect the international crude oil market, given the different OPEC assumptions described above. Figure 1 shows the effects on the oil price, OPEC and Non-OPEC supply, and EU and Non-EU consumption of crude oil.[7] When we compare the fixed price and fixed supply alternatives, we notice that the latter alternative is closer to the reference assumption of competitive behavior by OPEC, in which case the oil price is reduced relatively more than OPEC supply. With a fixed price, Non-OPEC supply increases slightly while crude oil consumption outside the EU increases much less compared to the reference case with competitive OPEC behavior.

If we rather assume that OPEC aims to maintain a fixed amount of gross revenue from crude oil sales, OPEC has to increase supply by more than 2.0%, in which case the crude oil price drops by the same rate. The intuition here is the following: A change in OPEC supply by x% changes the oil price by less than x%, implying that OPEC's gross revenues are increasing in OPEC supply. Thus, since climate policies in the EU have a dampening effect on OPEC revenues (through lower price and/or lower supply), OPEC must raise production to maintain its initial revenue. Crude oil consumption outside the EU then increases more than under the reference (competitive) assumption.

In the dominant producer case (*DOM*) we find that it is optimal for OPEC to cut back on supply even more than in the case with a fixed price target.[8] CO_2 emissions pricing in the EU then

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6. In our results section we also discuss how impacts change for the case that we introduce a target for EU emissions only as well as for the case of a fixed CO_2 tax.

7. In Table B1 and B2 in the Appendix we show regional shares of crude oil supply and (refined) oil consumption in the different scenarios.

8. OPEC's share in world crude oil supply changes only moderately across the scenarios in accordance with its supply decision. In BaU it amounts to 47.2% in BaU, is largest in FFR under BTA (48.6%) and smallest in DOM under BTA (45.6%).

Figure 1: Effects on the Crude Oil Price, Crude Oil Supply in OPEC and Non-OPEC, and Crude Oil Demand in EU and Non-EU in the TAX Scenario (% from BaU) for the Five Alternative Assumptions on OPEC Behavior
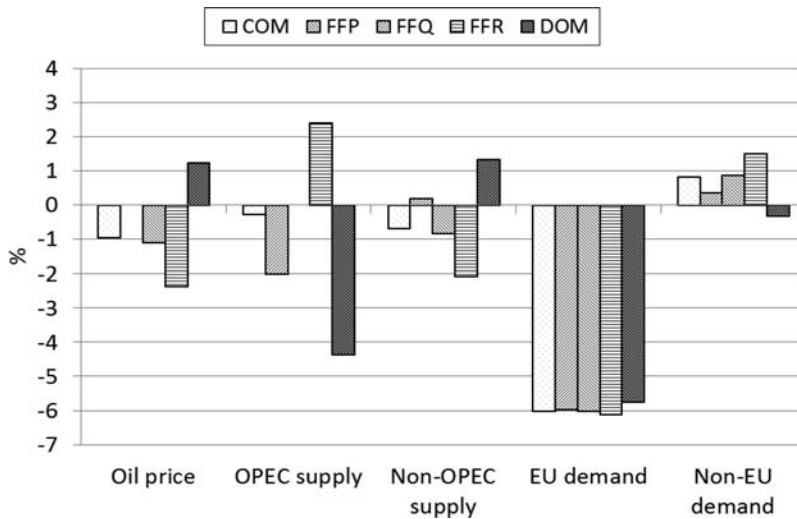
implies that the global price of crude oil *increases* rather than *decreases* (see our analytical finding at the end of Section 2). With higher crude oil prices, oil producers outside OPEC step up their production while crude oil consumption outside the EU declines. As a consequence, leakage through the oil market becomes negative instead of positive.

Under strategic profit maximization, we notice that OPEC decides to capture a larger part of the total oil rent (i.e., the difference between the end-user price and unit production costs—see the theoretical literature on the strategic interaction between OPEC and oil consuming countries referred to in the introduction). The main explanation is that OPEC knows (by assumption) that a higher oil price will reduce the CO_2 price in the EU that is necessary to achieve the emission reduction target (see Figure 3 below). A further explanation for OPEC supply rationing in the *DOM* variant is that emissions pricing reduces the oil intensity of the EU economy, e.g., through more energy-efficient means of transport and capital equipments. Hence, the price responsiveness of oil demand in the EU declines,[9] and this makes it more profitable for OPEC to restrict supply in order to achieve a higher price (Kverndokk and Rosendahl, 2013).

Figure 2 shows the impacts in the oil market when the EU complements domestic emissions pricing with carbon tariffs on imports of EITE goods (scenario BTA). We see that the effects are quite similar to those in Figure 1 for the TAX scenario. If we focus on the case where OPEC acts as a dominant producer, the price and quantity effects are slightly stronger than in the scenario with domestic emissions pricing only. That is, BTA makes it even more profitable for OPEC to cut back on supply in order to achieve higher oil prices. Again, the explanation is related to the effects on the CO_2 price, which is lower for the dominant producer variant (*DOM*) as compared to the competitive producer variant (*COM*), see Figure 3. Furthermore, a lower CO_2 price means a lower

9. The price elasticity of EU oil demand (which is endogenous in our CGE model) declines by 10–15% when going from the BaU scenario to the TAX scenario. Price responsiveness outside the EU also declines slightly, so that the price elasticity of global oil demand declines by around 5%.

Figure 2: Effects on the Crude Oil Price, Crude Oil Supply in OPEC and Non-OPEC, and Crude Oil Demand in EU and Non-EU in the BTA Scenario (% from BaU) for the Five Alternative Assumptions on OPEC Behavior
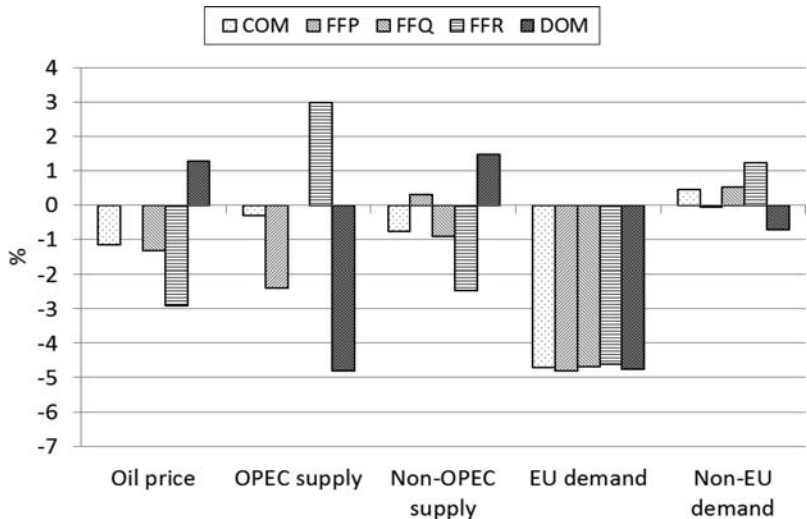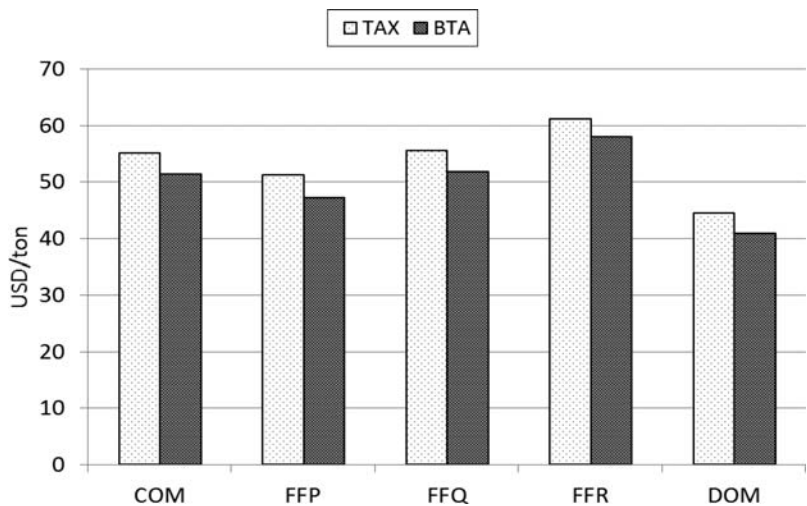

Figure 3: CO_2 Price in the EU under TAX and BTA for the Five Alternative Assumptions on OPEC Behavior (USD/ton)

carbon tariff on goods imported from other regions, which stimulates oil demand from these regions, too (again, compared to the *COM* variant where OPEC acts competitively).

Concerning crude oil consumption in the EU, there are two opposing effects of a higher oil price. On the one hand, a higher oil price incentivizes oil consumers in the EU to switch from oil to other fossil fuels. On the other hand, the higher oil price means that the EU to a lesser extent has to compensate for carbon leakage in order to meet the global emissions target. Hence, the EU's domestic emissions do not have to decrease as much as with a lower oil price (cf. the CO_2 prices),

Figure 4: Fuel-specific Leakage Rates under TAX and BTA for the Five Alternative OPEC Behaviors (%)
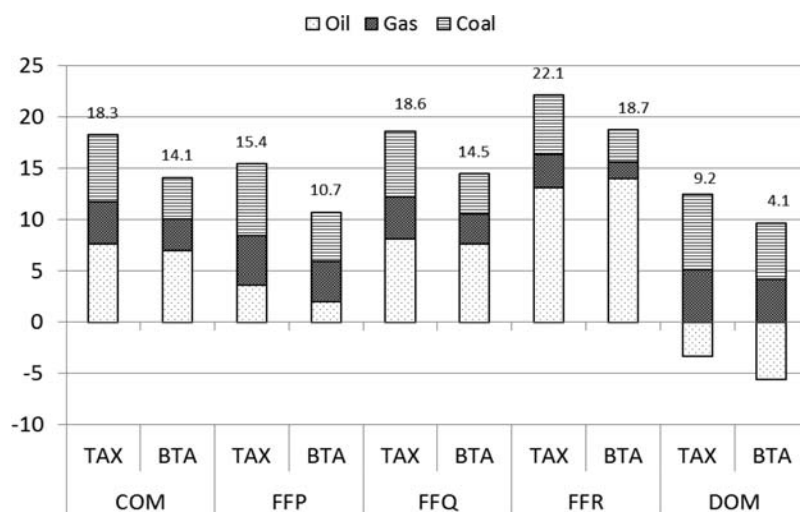
Note: The numbers indicate total leakage rates.

and thus consumption of all fossil fuels increases relative to scenarios with a lower oil price. In the TAX scenario, the latter effect dominates, as the EU consumes more crude oil under *DOM* than under *COM*, while in the BTA scenario the two effects more or less cancel out. We see a similar pattern when comparing the results of the *FFP* and *FFR* variants.

What are the implications for carbon leakage induced by unilateral EU climate policies? Figure 4 shows the overall and fuel-specific leakage rates under TAX and BTA for the five alternative assumptions about OPEC behavior.[10] For the reference assumption of competitive behavior (*COM*), the leakage rate amounts to 18.3% in the TAX scenario, and drops to 14.1% in the BTA scenario. Thus, roughly one quarter of leakage is avoided by introducing carbon tariffs. These figures are in line with previous estimates in the literature (e.g., Böhringer et al., 2012b). A little more than one third of the leakage is due to increased emissions in other industrialized countries. This is the case both under TAX and BTA.

Oil-specific leakage mirrors our findings for changes in crude oil demand outside the EU (see Figures 1 and 2). For instance, when the oil price is fixed (*FFP*), oil-specific leakage is small,[11] which in turn stimulates substitution of crude oil for gas and coal in production. Thus, less leakage through the oil market entails more leakage through the gas and coal markets and vice versa.[12]

10. The leakage rate is defined as the change in emissions of regions without emission regulation over the domestic emission reduction of the regulated regions. A leakage rate of 50%, for instance, means that half of the domestic emission reduction is offset by increases in emissions abroad. The fuel-specific leakage rates give the change in oil-, gas- and coal-related emissions, respectively, over the domestic emission reduction of the regulated regions. Consequently, the leakage rate is the sum of the fuel-specific leakage rates.

11. Oil consumption outside the EU increases slightly even if the oil price is held fixed and coal and gas prices decline (see Figure 1). The reason is that energy-intensive production outside the EU increases due to the CO_2-price imposed on EU industries, which leads to higher demand for all energy goods.

12. This is of course true if we compare leakage rates for the different assumptions about OPEC under one policy (either TAX or BTA), but not if we cross-compare between TAX and BTA.

Figure 5: Global Adjustment Costs under TAX and BTA for the Five Alternative Assumptions on OPEC Behavior (% from BaU)
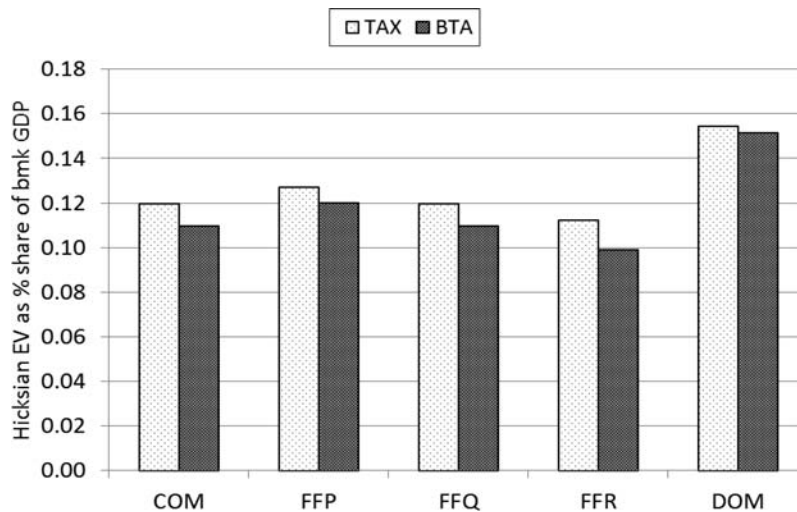

Hence, as the figure indicates, keeping OPEC's supply, OPEC's revenue or the international crude oil price fixed leads to only moderate changes in the leakage rates.

Much more remarkable are the implications for leakage when we assume that OPEC acts as a dominant producer, see Figure 4. With CO_2 pricing only, the leakage rate is halved to 9.2%, and drops to 4.1% as the EU implements additional border tax adjustments (cf. Figure 4)—in this case, leakage through the competitiveness channel, i.e., relocation of EITE production to regions without emission regulation, is more or less absent. Although increased emissions due to higher consumption of coal and natural gas more than compensate for the negative oil-specific leakage, the crude oil market setting under *DOM* has a strong impact on overall carbon leakage, which is significantly lower than for the reference assumption of competitive OPEC behavior.

Although OPEC's behavior under the dominant producer assumption leads to negative leakage through the oil market and thereby depresses the CO_2 price in the EU, the global adjustment costs—evaluated as Hicksian equivalent variation as share of business-as-usual GDP—are up to 50% higher in this case than if OPEC behaves competitively or keeps price, supply or revenue fixed (see Figure 5). The reasoning behind is that in the *DOM* variant too much mitigation takes place through reduced oil consumption in order to achieve the given target level of global emissions. Some of this mitigation occurs outside the EU, i.e., in regions without climate policy, due to OPEC's decision to cut back on supply as a response to the EU's climate policy. For the global economy, it would have been less costly if some of the reduction in oil consumption was replaced by bigger reductions in coal and gas consumption. We also notice that carbon tariffs reduce global adjustment costs in all scenarios, but in the dominant producer model the global cost savings are rather small.

Figure 6 shows that the EU's costs do not increase if OPEC acts as a dominant producer. On the one hand, higher oil prices imply that mitigation takes place to a larger extent via reduced oil consumption, and to a lesser extent via reduced coal and gas consumption (compared to our reference assumption with competitive OPEC behavior). On the other hand, the lower leakage rates and corresponding reduction in the CO_2 price imply less overall mitigation within the EU (and less emissions outside the EU), which reduces compliance costs for the EU.

Figure 6: Adjustment Costs for EU, OPEC and Rest-of-world under TAX and BTA for the Five Alternative Assumptions on OPEC Behavior
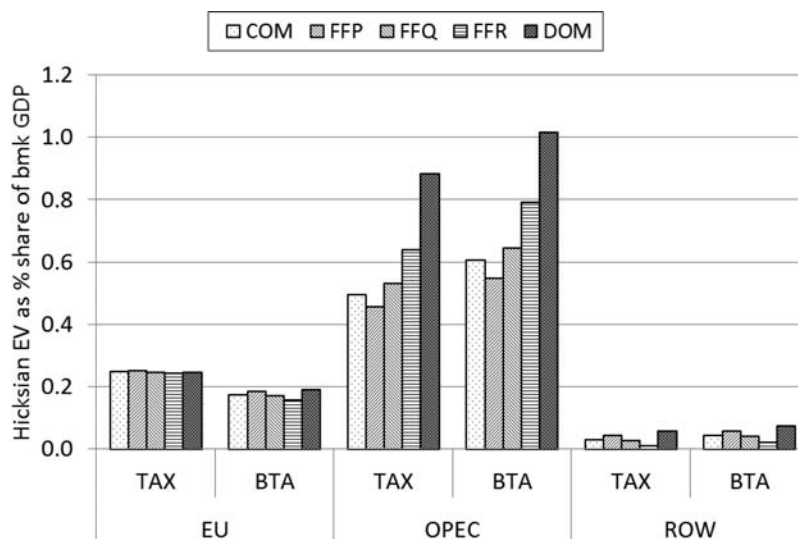
As expected, aggregate costs in non-EU and non-OPEC countries are highest when OPEC acts as a dominant producer and the oil price increases. OPEC countries are hit relatively hard by stringent climate policies in the EU, as demand for their oil exports declines.[13] In Appendix B we show adjustment costs for all regions in the model in the different scenarios. There we notice that Russia, also a major fossil fuel exporter, is hit as hard as OPEC in the *COM* scenarios. China also faces adjustment costs comparable with the EU costs (in relative terms), while other regions either experience more modest costs or negative costs (the latter applies to USA and India). The results are substantially changed, however, when OPEC behaves as a dominant producer. Then oil importers are hit harder than in the *COM* scenarios (e.g., China, India and USA), while Russia's adjustment costs become very low.[14]

In terms of adjustment costs, the EU is able to improve through the introduction of border tariffs compared to the TAX scenarios for each of the five assumptions about OPEC. There are two effects driving this result. Firstly, EU's terms-of-trade improve through the tariffs on EITE imports, and secondly, the EU is rewarded for leakage reduction by endogenous downscaling of the domestic emission reduction target, pushing the domestic CO_2 price downward.

In our central case simulations we have assumed that the EU is concerned about global CO_2 emissions, and thus adjusts its CO_2 price in order to compensate for carbon leakage.[15] Alter-

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13. Interestingly, OPEC losses are particularly pronounced for the dominant producer assumption. The reason is that in the *DOM* variant we have assumed lower crude oil production costs for OPEC, and a positive markup, in order to make this alternative consistent with the benchmark data. Hence, OPEC earns more from its crude production, and thus loses more when oil demand declines. Note that regional welfare levels are the same across the various OPEC assumptions in the BaU scenario, as these are given by the benchmark GTAP data.

14. Note that in the short-run, adjustment costs could be higher than the simulated costs in our general equilibrium model, as unemployment could increase temporarily and capital stock in emission-intensive sectors may become obsolete.

15. As a matter of fact, the allocation of free allowances in the EU ETS to EITE industries is much driven by concerns on carbon leakage.

natively, we may assume that the EU, although concerned about global emissions, sets its target for domestic emissions only. For instance, the EU has a specific goal of 20% reductions in GHG emissions in 2020 vis-à-vis 1990 levels, which could be raised to 30% if a sufficiently ambitious international climate agreement is reached.[16] Moreover, the main climate policy instrument in the EU is the EU Emission Trading System (EU ETS), which has a quantitative cap on total emissions within mainly electricity and industry sectors. With a target for EU emissions instead of global emissions, the incentives for OPEC to cut back on supply weaken in the *DOM* variant, as the EU is no longer concerned about the effects on emissions outside the EU. OPEC's supply reduction is still larger than in the competitive case, but the oil price now decreases. The leakage rate is 16.5% with OPEC being a dominant producer, compared to 18.3% with OPEC behaving competitively (in the TAX scenarios). Hence, whether OPEC thinks that the EU in the long run will adjust its emissions target in response to changes in fossil fuels markets, has substantial impacts on the leakage rates.

Although the EU ETS has a quantitative cap on total emissions, the cap has been up for discussion due to particularly low CO_2 prices in the aftermath of the economic downturn in Europe. Hence, one could argue that the cap is not totally fixed, and that the EU does not want too low (or too high) CO_2 prices. The extreme opposite of a fixed cap is a fixed price on CO_2 emissions, which has been favoured by many economists. As mentioned in the introduction, Wirl (2012) and Strand (2013) have shown that a fixed price is is the preferred strategic climate policy instrument for a large fuel importer (e.g., the EU) facing a strategic fuel exporter (e.g., OPEC). Although not on the table now, it could become an option in the future, both in the EU as well as in other countries (e.g., the U.S.). If the EU implements a fixed CO_2 price rather than a fixed cap, the strategic influence of OPEC through affecting the CO_2 price in the EU vanishes completely. OPEC then is to a lesser extent able to shift carbon rents and resource rents through higher oil prices. In this setting, the outcome is relative similar whether OPEC behaves as a competitive (*COM*) or a dominant producer (*DOM*). The leakage rates now become 18.3% and 17.6% in the two cases, respectively.

Thus, when the EU or other large countries consider whether to implement a fixed price, a fixed domestic quantity, or a quantity that adjusts according to changes in global emissions, they should be aware that the policy choice can have significant effects on carbon leakage rates. When it comes to welfare, a fixed domestic emission reduction target or a fixed emission price incur less costs on other regions than a fixed global target. This is due to the lower markup in the oil market in the former scenarios. For the EU, however, a fixed global target may be preferred. If we compare adjustment costs for the EU per ton global emissions reductions, the costs are slightly lower with a fixed global target than with a fixed domestic target or a fixed CO_2 price. The explanation is that more of the emissions reductions are shifted to non-EU countries in the case with a global target.

To test the robustness of our results, we have performed a series of sensitivity analysis varying the unilateral emission reduction target, the Armington elasticities for EITE goods, and the fossil fuel supply elasticities. Table 4 reports leakage rates and global adjustment costs for the TAX and BTA scenarios, focusing on the two variants where OPEC behaves competitively (*COM*) and as a dominant producer (*DOM*) respectively.[17]

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16. These goals are also put forward as pledges for 2020 in the Doha amendment to the Kyoto Protocol (see https://unfccc.int/files/kyoto_protocol/application/pdf/kp_doha_amendment_english.pdf).

17. As in our core simulations, we assume that the EU adjusts its emissions price to keep global emissions at the outcome of the TAX scenario.

Table 4: Sensitivity Analysis

| | Leakage rates (%) | | | | Global adjustment costs (EV as % share of BaU GDP) | | | |
| | COM | | DOM | | COM | | DOM | |
	TAX	BTA	TAX	BTA	TAX	BTA	TAX	BTA
ref	18.3	14.1	9.2	4.1	0.12	0.11	0.15	0.15
				Emission reduction target				
0.5·*ref*	15.4	12.5	6.3	1.5	0.04	0.03	0.06	0.06
1.5·*ref*	21.5	15.9	11.7	5.5	0.28	0.25	0.29	0.27
				Armington elasticities for EITE goods				
0.5·*ref*	16.6	14.3	7.4	4.4	0.12	0.11	0.15	0.15
2·*ref*	20.8	14.1	12.5	3.9	0.13	0.11	0.16	0.15
				Fossil fuel supply elasticities				
0.5·*ref*	25.4	21.8	9.2	5.7	0.12	0.11	0.16	0.16
2·*ref*	13.8	9.3	12.1	7.3	0.12	0.11	0.13	0.12

Firstly, we vary the reference emission reduction target of 20% to either 10% (0.5·*ref*) or 30% (1.5·*ref*). As expected, leakage increases in the stringency of the unilateral emission reduction target. The differences in leakage rates between the *COM* and the *DOM* alternatives remain robust. When OPEC acts as a dominant producer and the EU levies carbon tariffs on imported EITE goods, leakage vanishes almost completely for the 10% emission reduction target. Global adjustment costs increase overproportionally towards higher emission reduction targets, both under *COM* and *DOM*. Emission reduction is getting increasingly expensive as low-cost abatement options are exhausted. As in our reference case setting, global costs are highest when OPEC acts as a dominant producer; likewise carbon tariffs hardly reduce these costs in this case (*DOM*_BTA).

Regarding the choice of key elasticities we consider the cases where we either halve (0.5·*ref*) or double (2·*ref*) the Armington elasticities in EITE sectors or the fossil fuel supply elasticities respectively. For domestic emissions pricing in the EU without supplemental carbon tariffs (TAX), higher Armington elasticities imply higher leakage rates. Leakage through the competitiveness channel increases, as EITE goods become closer substitutes on international markets. Carbon tariffs counteract leakage through this channel, keeping leakage rates relatively stable across alternative choices for Armington elasticities.

For competitive OPEC behavior higher fossil fuel supply elasticities work in the opposite direction than higher Armington elasticities, since fossil fuel suppliers react stronger to negative demand shocks induced by climate policies. However, when OPEC acts as a dominant producer, higher price responsiveness by Non-OPEC producers also implies that the producer group is less able to exploit market power, i.e., higher crude oil prices trigger more Non-OPEC supply than in the case of lower fossil fuel supply elasticities. With higher fuel supply elasticities the market moves more in the direction of the competitive setting, and leakage increases rather than decreases. When supply elasticities are lower, OPEC's market power increases such that leakage through the oil market decreases. Yet, as leakage through the competitive coal and gas markets increases, the net effect on leakage is close to zero in our simulations (compare the outcome for lower fuel supply elasticities with the outcome of our reference scenario for the combination *DOM*_TAX).

Global adjustment costs are not much changed when we vary the Armington or fossil fuel elasticities (except for the case of higher fossil fuel elasticities when the oil market gets closer to a competitive market).

To sum up: Our main conclusions—lower leakage rates and higher global adjustment costs for the case that OPEC behaves as a dominant producer—are robust across alternative choices for emission reduction targets and key elasticities.[18]

5. CONCLUSIONS

In this paper we have shown that the extent of carbon leakage for unilateral climate policies depends crucially on how OPEC behaves in the oil market. For our central case parameterization, we have seen that leakage induced by unilateral CO_2 pricing in the EU may vary between 9% and 22%, depending on OPEC's behavior. If CO_2 pricing is supplemented with carbon tariffs, so that leakage through the EITE markets (the competitiveness channel) is more or less mitigated, overall leakage rates vary between 4% and 19%. Thus, leakage through international energy markets (the fossil-fuel-price channel) depends very much on how OPEC responds to unilateral climate policies.

Leakage rates at the lower end of our estimated range are obtained if we assume that OPEC acts as a dominant producer, i.e., maximizes net revenues from its crude oil production. In this case, OPEC finds it profitable to cut back its supply of oil to an extent that the world market price of oil increases instead of decreases, which would emerge for competitive OPEC behavior. This is because OPEC anticipates that the EU will adjust domestic emissions to reach a given global emission level. Hence, a higher oil price leads to a lower CO_2 price shifting carbon rents and oil resource rents in favour of OPEC.

If the EU sets its climate policy target only with respect to its own emissions, implemented through an emissions trading system with a fixed cap on domestic emissions, OPEC is less able to affect the CO_2 price and thereby shift oil rents by increasing the oil price. Hence, leakage is less reduced compared to the reference (competitive) case. This is even more so if the EU implements a fixed CO_2 price, i.e., a tax on CO_2 emissions.

It should be noted that the EU may affect OPEC's strategic influence and behavior through its choice between a fixed target for global or own emissions, or a fixed price on emissions. Implementing a fixed target on global emissions will lead to lower leakage rates, but higher global adjustment costs when OPEC behaves as a dominant producer. Adjustment costs in the EU are not much affected though, since more of the emissions reductions are shifted to non-EU countries when OPEC imposes large cutbacks in its oil supply. In fact, if we compare adjustment costs for the EU per ton global emissions reductions, the costs are slightly lower with a fixed global target than with a fixed domestic target or a fixed CO_2 price. Hence, if the EU is able to introduce a credible target for global emissions, the EU is able to shift some of the burden of global emissions reductions to non-EU countries, thereby playing on the strategic behavior of OPEC.

Finally, we notice that our analysis adopts a static perspective, in line with the bulk part of the applied literature on leakage. An interesting extension, given that oil is a non-renewable resource, could be to formulate a dynamic or intertemporal model in the tradition of Hotelling (1931). We leave this to future research.

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18. Unless supply elasticities are quite high, so that OPEC is hardly able to exploit market power.

ACKNOWLEDGEMENTS

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APPENDIX A: ALGEBRAIC MODEL SUMMARY

Two classes of conditions characterize the competitive equilibrium for our model: zero profit conditions and market clearance conditions. The former class determines activity levels and the latter determines price levels. In our algebraic exposition, the notation $\prod_{ir}^u$ is used to denote the profit function of sector i in region r where u is the name assigned to the associated production activity. Differentiating the profit function with respect to input and output prices provides compensated demand and supply coefficients (Hotelling's lemma), which appear subsequently in the market clearance conditions. We use i and j as indexes for commodities (including a composite public good G and a composite investment good I) and r and s as indexes for regions. The label EG represents the set of energy goods and the label FF denotes the subset of fossil fuels. Tables A.1–A.6 explain the notations for variables and parameters employed within our algebraic exposition.

A.1 Zero Profit Conditions

1. Production of goods except fossil fuels ($i \notin FF$):

$$\prod_{ir}^Y = p_{ir} - \sum_{j \notin EG} \theta_{jir} p_{jr}^A - \theta_{ir}^{KLE} \left[\theta_{ir}^E p_{ir}^{E^{1-\sigma_{ir}^{KLE}}} \right.$$

$$\left. + (1 - \theta_{ir}^E) \left(\theta_{ir}^L w_r^{1-\sigma_{ir}^{KL}} + (1 - \theta_{ir}^L) v_r^{1-\sigma_{ir}^{KL}} \right)^{\frac{1-\sigma_{ir}^{KLE}}{1-\sigma_{ir}^{KL}}} \right]^{\frac{1}{1-\sigma_{ir}^{KLE}}} \leq 0$$

2. Production of fossil fuels ($i \in FF$):

$$\Pi_{ir}^Y = p_{ir} - \left[\theta_{ir}^Q q_{ir}^{1-\sigma_{ir}^Q} + (1-\theta_{ir}^Q)\left(\theta_{Lir}^{FF}w_r + \theta_{Kir}^{FF}v_r + \sum_j \theta_{jir}^{FF}(p_{jr}^A + p_r^{CO_2}a_j^{CO_2})\right)^{1-\sigma_{ir}^Q}\right]^{\frac{1}{1-\sigma_{ir}^Q}} \leq 0$$

3. Sector-specific energy aggregate

$$\Pi_{ir}^E = p_{ir}^E - \left\{ \theta_{ir}^{ELE}p_{ELE,r}^{A\,1-\sigma_{ir}^{ELE}} + (1-\theta_{ir}^{ELE})\left[\theta_{ir}^{COA}(p_{COA,r}^A + t_{ir}^{CO_2}a_{COA}^{CO_2})^{1-\sigma_{ir}^{COA}}\right.\right.$$

$$\left.\left. + (1-\theta_{ir}^{COA})\left(\sum_{j \in LQ}\theta_{jir}^{LQ}(p_{jr}^A + p_r^{CO_2}a_j^{CO_2})^{1-\sigma_{ir}^{LQ}}\right)^{\frac{1-\sigma_{ir}^{COA}}{1-\sigma_{ir}^{LQ}}}\right]^{\frac{1-\sigma_{ir}^{ELE}}{1-\sigma_{ir}^{COA}}}\right\}^{\frac{1}{1-\sigma_{ir}^{ELE}}}$$

4. Armington aggregate:

$$\Pi_{ir}^A = p_{ir}^A - \left(\theta_{ir}^A(p_{ir})^{1-\sigma_{ir}^A} + (1-\theta_{ir}^A)(p_{ir}^M)^{1-\sigma_{ir}^A}\right)^{\frac{1}{1-\sigma_{ir}^A}} \leq 0$$

5. Aggregate imports across import regions:

$$\Pi_{ir}^M = p_{ir}^M - \left(\sum_s \theta_{isr}^M p_{is}^{1-\sigma_{ir}^M}\right)^{\frac{1}{1-\sigma_{ir}^M}} \leq 0$$

6. Household consumption demand:

$$\Pi_r^C = p_r^C - \left(\theta_{Cr}^E p_{Cr}^{E\,1-\sigma_{Cr}^E} + (1-\theta_{Cr}^E)\left[\prod_{i \notin EG}(p_{ir}^A)^{\gamma_{ir}}\right]^{1-\sigma_{Cr}^E}\right)^{\frac{1}{1-\sigma_{Cr}^E}} \leq 0$$

A.2 Market Clearance Conditions

7. Labor:

$$\overline{L}_r \geq \sum_j Y_{jr}\frac{\partial \Pi_{jr}^Y}{\partial w_r}$$

8. Capital:

$$\overline{K}_r \geq \sum_i Y_{ir}\frac{\partial \Pi_{ir}^Y}{\partial v_r}$$

9. Natural resources ($i \in FF$):

$$\overline{Q}_{ir} \geq Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial q_{ir}}$$

10. Output:

$$Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial p_{ir}} \geq \sum_j A_{jr} \frac{\partial \Pi_{jr}^A}{\partial p_{ir}} + \sum_s M_{is} \frac{\partial \Pi_{is}^M}{\partial p_{ir}}$$

11. Armington aggregate:

$$A_{ir} \geq \sum_j Y_{jr} \frac{\partial \Pi_{jr}^Y}{\partial p_{ir}^A} + C_r \frac{\partial \Pi_r^C}{\partial p_{ir}^A}$$

12. Import aggregate:

$$M_{ir} \geq A_{ir} \frac{\partial \Pi_{ir}^A}{\partial p_{ir}^M}$$

13. Sector-specific energy aggregate:

$$E_{ir} \geq Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial p_{ir}^E}$$

14. Public consumption:

$$Y_{Gr} \geq \overline{G}_r$$

15. Investment:

$$Y_{Ir} \geq \overline{I}_r$$

16. Carbon emissions:

$$\overline{CO2}_r \geq \sum_i A_{ir} a_i^{CO_2}$$

17. Household consumption (income-expenditure balance):

$$C_r p_r^C = w_r \overline{L}_r + v_r \overline{K}_r + \sum_{j \in FF} q_{jr} \overline{Q}_{jr} + p_{Ir} \overline{Y}_{Ir} + p_{Gr} \overline{Y}_{Gr} + \overline{B}_r + p_r^{CO_2} \overline{CO2}_r$$

Table A.1: Sets and Indexes

i,j	Indexes for commodities (including a composite public good *G* and a composite investment good *I*)
r,s	Indexes for regions
EG	All energy goods: Coal, crude oil, refined oil, gas and electricity
FF	Primary fossil fuels: Coal, crude oil and gas
LQ	Liquid fuels: Crude oil and gas

Table A.2: Activity Variables

Y_{ir}	Production in sector i and region r
E_{ir}	Aggregate energy input in sector i and region r
M_{ir}	Aggregate imports of good i and region r
A_{ir}	Armington aggregate for good i in region r
C_r	Aggregate household consumption in region r

Table A.3: Price Variables

p_{ir}	Output price of good i produced in region r
p_{ir}^E	Price of aggregate energy in sector i and region r
p_{ir}^M	Import price aggregate for good i imported to region r
p_{ir}^A	Price of Armington good i in region r
p_r^C	Price of aggregate household consumption in region r
w_r	Wage rate in region r
v_r	Price of capital services in region r
q_{ir}	Rent to natural resources in region r ($i \in FF$)
$p_r^{CO_2}$	CO_2 emission price in region r

Table A.4: Cost Shares

θ_{jir}	Cost share of intermediate good j in sector i and region r ($i \notin FF$)
θ_{ir}^{KLE}	Cost share of KLE aggregate in sector i and region r ($i \notin FF$)
θ_{ir}^E	Cost share of energy composite in the KLE aggregate in sector i and region r ($i \notin FF$)
θ_{ir}^L	Cost share of labor in value-added composite of sector i and region r ($i \notin FF$)
θ_{ir}^Q	Cost share of natural resources in sector i and region r ($i \in FF$)
θ_{Tir}^{FF}	Cost share of good i ($T = i$) or labor ($T = L$) or capital ($T = K$) in sector i and region r ($i \in FF$)
θ_{ir}^{ELE}	Cost share of electricity in energy composite in sector i in region r ($i \notin FF$)
θ_{ir}^{COA}	Cost share of coal in fossil fuel composite in sector i in region r ($i \notin FF$)
θ_{jir}^{LQ}	Cost share of liquid fossil fuel j in liquid energy aggregate in sector i in region r ($i \notin FF, j \in LQ$)
θ_{isr}^M	Cost share of imports of good i from region s to region r
θ_{ir}^A	Cost share of domestic variety in Armington good i of region r
θ_{Cr}^E	Cost share of composite energy demand in household consumption in region r
γ_{ir}	Cost share of non-energy good i in non-energy household consumption demand in region r

Table A.5: Elasticities

σ_{ir}^{KL}	Substitution between labor and capital in value-added composite	Narayanan et al. (2012)
σ_{ir}^{KLE}	Substitution between energy and value-added in production	0.5
σ_{ir}^Q	Substitution between natural resources and other inputs in fossil fuel production calibrated to exogenous supply elasticities μ_{FF}	$\mu_{COA} = 4.0, \mu_{CRU} = 1.0\ \mu_{GAS} = 1.0$
σ_{ir}^{ELE}	Substitution between electricity and the fossil fuel aggregate	0.5
σ_{ir}^{COA}	Substitution between coal and the liquid fossil fuel composite	0.25 (1 for $i = ELE$)
σ_{ir}^{LQ}	Substitution between gas and oil in the liquid fossil fuel composite	0.75 (1 for $i = ELE$)
σ_{ir}^A	Substitution between the import aggregate and the domestic input	Narayanan et al. (2012)
σ_{ir}^M	Substitution between imports from different regions	Narayanan et al. (2012)
σ_{Cr}^E	Substitution between energy and non-energy inputs in consumption	0.5

Table A.6: Endowments and Emissions Coefficients

$\overline{L}_r$	Aggregate labor endowment in region r
$\overline{K}_r$	Aggregate capital endowment in region r
$\overline{Q}_{ir}$	Endowment of natural resource i in region r ($i \in FF$)
$\overline{G}_r$	Public good provision in region r
$\overline{I}_r$	Investment demand in region r
$\overline{B}_r$	Balance of payment deficit or surplus in region r
$\overline{CO2}_r$	CO_2 emission constraint for region r
$a_i^{CO_2}$	CO_2 emissions coefficient for fossil fuel i ($i \in FF$)

APPENDIX B: SUPPLEMENTARY RESULTS

Table B.1: Regional Shares of Crude Oil Supply in Different Scenarios (%)

	BAU	COM TAX	COM BTA	FFP TAX	FFP BTA	FFQ TAX	FFQ BTA	FFR TAX	FFR BTA	DOM TAX	DOM BTA
Europe	6.9	6.8	6.8	6.9	6.9	6.8	6.8	6.7	6.6	7.0	7.0
USA	7.4	7.4	7.4	7.5	7.5	7.4	7.4	7.3	7.2	7.6	7.7
Russia	13.5	13.5	13.6	13.7	13.7	13.5	13.6	13.3	13.3	13.9	13.9
Remaining Annex 1	4.1	4.1	4.1	4.1	4.1	4.1	4.0	4.0	4.0	4.2	4.2
China	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.5	4.5	4.7	4.7
India	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.9	0.9
Other middle income countries	12.2	12.1	12.1	12.3	12.3	12.1	12.1	11.9	11.8	12.5	12.5
Other low income countries	3.3	3.3	3.2	3.3	3.3	3.2	3.2	3.2	3.2	3.3	3.4
OPEC	47.2	47.3	47.3	46.7	46.5	47.4	47.5	48.4	48.6	45.8	45.6

Table B.2: Regional Shares of Refined Oil Consumption in Different Scenarios (%)

	BAU	COM TAX	COM BTA	FFP TAX	FFP BTA	FFQ TAX	FFQ BTA	FFR TAX	FFR BTA	DOM TAX	DOM BTA
Europe	32.3	30.9	31.0	31.0	31.1	30.9	31.0	30.7	30.9	31.2	31.3
USA	17.0	17.4	17.4	17.4	17.3	17.4	17.4	17.4	17.4	17.3	17.3
Russia	2.8	2.9	2.8	2.9	2.8	2.9	2.8	2.9	2.8	2.9	2.8
Remaining Annex 1	14.0	14.2	14.2	14.2	14.2	14.3	14.2	14.3	14.3	14.2	14.2
China	7.9	8.1	8.0	8.0	8.0	8.1	8.0	8.1	8.0	8.0	8.0
India	3.9	4.0	3.9	3.9	3.9	4.0	3.9	4.0	4.0	3.9	3.9
Other middle income countries	14.8	15.1	15.1	15.1	15.1	15.1	15.1	15.2	15.2	15.1	15.0
Other low income countries	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
OPEC	5.5	5.7	5.6	5.7	5.6	5.7	5.6	5.6	5.6	5.6	5.6

Table B.3: Regional Adjustment Costs in the Different Scenarios (Hicksian equivalent variation as % share of BaU GDP)

	COM TAX	COM BTA	FFP TAX	FFP BTA	FFQ TAX	FFQ BTA	FFR TAX	FFR BTA	DOM TAX	DOM BTA
Europe	0.25	0.17	0.25	0.18	0.25	0.17	0.24	0.16	0.25	0.19
USA	−0.04	−0.05	−0.02	−0.02	−0.04	−0.05	−0.07	−0.09	0.01	0.01
Russia	0.48	0.68	0.28	0.43	0.51	0.72	0.77	1.07	0.01	0.13
Remaining Annex 1	0.00	0.00	0.03	0.04	0.00	0.00	−0.04	−0.05	0.07	0.08
China	0.12	0.16	0.14	0.19	0.11	0.16	0.08	0.13	0.16	0.21
India	−0.06	−0.03	0.00	0.04	−0.07	−0.04	−0.15	−0.14	0.08	0.12
Other middle income countries	0.08	0.10	0.09	0.11	0.08	0.09	0.06	0.08	0.10	0.12
Other low income countries	0.09	0.14	0.05	0.08	0.10	0.14	0.15	0.21	0.00	0.03
OPEC	0.50	0.61	0.46	0.55	0.53	0.65	0.64	0.79	0.88	1.02