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Abstract:
The starting point of this paper is a climate coalition which seeks to reduce global emissions. It is well known from the literature on (spatial) carbon leakage that the climate effect of unilateral measures may be partly offset by the actions of the free-riders. Furthermore, from the literature on the green paradox, we know that stringent demand-side policies in the future may increase present emissions. The novelty of this paper is that we also explore how the coalition's future policies regarding own fossil fuel production (supply-side policies) affect the present emissions from the free-riders. In particular, we find that a credible announcement of future unilateral supply-side policies reduces early foreign emissions. We derive the optimal combination of consumer taxes and producer taxes when both spatial and intertemporal leakages from the free-riders are taken into account. We show that the tax shares generally differ over time, and that a declining present value of the social cost of carbon over time supports a time path where the consumer tax's share of the total carbon tax also declines over time. We illustrate our findings with a numerical model for the global fossil fuel markets, considering European unilateral carbon policies.

Keywords: climate coalition; carbon leakage; green paradox; supply-side climate policy; demand-side climate policy

JEL classification: H23; Q41; Q54

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Sammendrag

Utgangspunktet for denne studien er en klimakoalisjon som samarbeider om å redusere de globale utslippene. Det er vel kjent fra litteraturen om (geografisk) karbonlekkasje at klimaeffekten av ensidige tiltak kan bli delvis motvirket av responsen fra land som står utenfor koalisjonen («gratispassasjerene»). Vi vet også fra litteraturen om «det grønne paradokset» at stigende karbonavgifter over tid kan øke dagens produksjon av fossil energi, og derigjennom utslipp. Vårt bidrag til litteraturen er at vi undersøker hvordan koalisjonens fremtidige klimapolitikk rettet mot deres egen *produksjon av fossil energi* påvirker dagens utslipp fra gratispassasjerene. Spesielt finner vi at en troverdig plan for framtidig tilbudssidepolitikk reduserer dagens utslipp fra gratispassasjerene. Vi finner den optimale kombinasjonen av avgifter på konsum og produksjon når det tas hensyn til både geografisk og intertemporal lekkasje fra gratispassasjerene. Vi viser at, på ethvert tidspunkt, skal summen av konsumentavgift og produsentavgift være lik den marginale skaden av utslipp. Andelen konsumentavgift/produsentavgift av den totale avgiften vil imidlertid variere over tid. Den vil avhenge av miljøskaden, geografisk lekkasje, intertemporal lekkasje, og netto importkostander fra fossil energi. For eksempel vil en nedgang i nåverdien av den marginale miljøskaden over tid støtte en avgiftsbane der også konsumentavgiftens andel av den totale avgiften faller over tid. Vi illustrerer våre analytiske resultater med en numerisk modell av de globale fossile energimarkedene, der vi vurderer virkningene av en ensidig europeisk klimapolitikk.

1 Introduction

The Paris climate conference (COP21) in December 2015 led to an ambitious global agreement on the goal for global warming; it should stay well below 2°C. However, the emission pledges made by the signatories are far from sufficient to reach the 2 degree target. Furthermore, the commitments are not legally binding.[1] It is therefore reasonable to suspect that the nonbinding promises for emission reductions will not be implemented by all countries.

Hence, there is a need for knowledge about how to construct more ambitious agreements in a world where the willingness to contribute is very unevenly distributed across countries. The starting point of this paper is that a group of countries establish a climate coalition which seeks to reduce *global* emissions, whereas the rest of the world pursues their self-interest.

Both reduced consumption of fossil fuels (demand-side policies) and reduced supply of fossil fuels (supply-side polices) within the climate coalition affect the world market prices, and thereby emissions from the free-riders. Therefore, in order to design efficient climate policies, the climate coalition must take into account the responses from the free-riders.

As fossil fuels are non-renewable resources, a climate coalition's (credible) commitment to future climate policies will typically change the free-riders optimal extraction path for their non-renewable resources. This again will influence fossil fuel prices and the free-riders' emissions from consumption of fossil fuels, both in the present and in the future.

Thus, the coalition's climate policy measures in one period affect the emissions from the free-riders both in the same period (spatial leakage) and in the other periods (intertemporal leakage). In the next section we provide a literature overview of supply versus demand-side policies, and spatial and intertemporal leakage. Our theoretical contribution to the literature is that we investigate how supply-side measures, i.e., policies that reduce domestic fossil fuel extraction, affect intertemporal leakage from the free-riders. Furthermore, we derive the climate coalition's optimal combination of demand-side and supply-side policies when both spatial and intertemporal leakages from the free-riders are taken into account. The present paper is, to the authors' best knowledge, the first paper to address supply versus demand-side policies in a dynamic model with free riders.

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[1] The agreement refers to the Intended Nationally Determined Contributions (INDC) submitted by the parties before the meeting. However, the targets specified in the INDCs are not legally binding, and there is no enforcement mechanism to ensure that the pledges are met. Moreover, it is not clear to what extent the targets specified in the INDCs always represent emission reductions comparted to a BAU scenario.

1.1 Review of the literature

In the review of relevant literature we distinguish between two dimensions of emission leakage: spatial and intertemporal, and between two sources for the leakage: demand-side policy and supply-side policy in the regulating country.

Most studies of spatial carbon leakages have so far been done in a static framework, in which there is obviously no intertemporal leakage. Furthermore, the studies typically target consumption of fossil fuels, i.e., demand-side policies. Policy measures that reduce fossil fuel demand lead to lower international energy prices, and may also reduce the competitiveness of domestic firms in the world markets for energy-intensive goods. Both effects cause increased consumption of and emissions from fossil fuels among free-riders (positive spatial leakage). In the literature, this is commonly referred to as “carbon leakage”, and often measured in percentages of the domestic emission reduction in the regulating country (leakage rate). There is a vast literature on spatial carbon leakage (see, e.g., Rauscher, 1997 and Böhringer et al., 2010). Most studies suggest a leakage rate in the range of 5-30 percent. That is, a reduction of 100 units of CO_2 in the regulating country leads to an increase of 5-30 units of CO_2 in non-regulating countries (see, e.g., Zhang, 2012; Böhringer et al., 2012). There are, however, a few studies with negative leakage (Elliott and Fullerton, 2014) or leakage rates above 100 percent (Babiker, 2005).

To counteract the carbon leakage following from demand-side measures, supply-side policies have been suggested (see, e.g., Bohm 1993). Lower supply of fossil fuels cause the prices to rise and leads to lower consumption among the free-riders (negative spatial leakage).[2] In a static model, Hoel (1994) derived theoretically the (second-best) optimal combination of producer and consumer taxes in a climate coalition, given a target for global emission reductions. Golombek et al. (1995) and Fæhn et al. (2016) provide numerical illustrations of the optimal combination of demand-side versus supply-side policies in a static setting. Harstad (2012) shows that leakage can be completely avoided by buying marginal foreign fuel deposits for conservation. Although this is a promising result, buying foreign deposits for internal conservation may face several practical and political problems. Furthermore, neither of the above papers on supply-side policies explicitly addresses the problem of intertemporal leakage.

Intertemporal emission leakage follows from the fact that fossil fuels are non-renewable resources. This was early recognized by Sinclair (1992), who pointed out that attempts to curb fossil fuel usage

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[2] Asheim (2013) gives a distributional argument for supply-side policies.

trigger a response from the fossil fuel producers. In particular, present value carbon taxes should decline over time as increasing carbon taxes accelerates emissions. The reason is that the future value of the fossil fuel resource is deteriorated by increasing taxes, making it profitable to move extraction forward in time. By similar reasoning, Sinn (2008) argues that climate policies might actually increase emissions, at least in the short run, and termed this effect the “green paradox”. There is a large literature following up on this phenomenon (see, e.g., Gerlagh, 2010; Hoel 2010, 2011; van der Ploeg and Withagen, 2012a, 2012b; Eichner and Pethig, 2015; Ritter and Schopf, 2014; Jensen et al., 2015).

None of the above mentioned studies on intertemporal leakage examines supply-side policies. Hoel (2013) investigates whether there also might be some kind of green paradox related to supply-side policies. However, he considers a single region and thereby ignores spatial and intertemporal leakage caused by the free-riders’ response to supply-side policies within a coalition.

The novelty of this paper is that we address both dimensions of emission leakage (spatial and intertemporal) and considers both sources for the leakage (demand-side policy and supply side policy). This enables us to find the optimal combination of demand-side policy and supply-side policy over time.

1.2 Main results

In the present paper, we use a two-period, two-region analytical model to analyse the welfare impacts of domestic climate policy measures in a climate coalition. Emissions arise from consumption of a carbon intensive good controlled by resource owners who choose the extraction profile that maximizes the present value of their reserves. Extraction costs are increasing in cumulative extraction, leading to less than full extraction of known carbon reserves. The climate coalition takes account of both spatial and intertemporal leakages when designing the optimal combination of domestic demand and supply-side measures.

We find that demand-side policies lead to positive intertemporal and spatial leakages, whereas supply-side policies lead to leakages of the same magnitudes, but with negative signs. For example, if the coalition decides today to reduce future domestic demand for fossil fuels and this is announced and considered credible, foreign consumption of fossils fuels increases both today and in the future. However, if the coalition instead credibly announces reductions in future domestic supply of fossil fuels, foreign consumption decreases both today and in the future. Note that the latter case is the opposite of the green paradox: credible commitment to stringent future carbon mitigation measures reduces current fossil fuel consumption. Further, optimal climate policy implies a combination of demand and supply-side policies such that the total carbon tax equals the marginal environmental damage caused by current period emissions. Thus, we show that an important result from the static model in Hoel (1994) also holds in an intertemporal setting. We also derive results about the development of the optimal demand and supply-side tax trajectories. In particular, we investigate how the development of the social cost of carbon over time affects the distribution of the carbon tax across consumers and producers. We find that a declining social cost of carbon over time typically supports a decline in the consumer tax's share of the total carbon tax over time.

We illustrate our results with a numerical model for the global fossil fuels markets, assuming that the coalition is the European Economic Area (EEA).[3] We find the optimal combination of consumer taxes and producer taxes over time, and show that it is optimal to let the consumers carry the largest tax burden. Furthermore, we illustrate how a declining present value of the social cost of carbon over time supports a time path where the consumers' tax share of the total carbon tax also declines over time.

2 Theoretical analysis

In section 2.1, we present the model and derive how the climate coalition's demand-side and supply-side policies affect emissions from free riders (spatial and intertemporal leakages), as well as global emissions. In section 2.2, we find the optimal levels of the climate coalition's consumption and production of fossil fuels over time, and characterize the consumer and producer taxes which induce this outcome.

2.1 An intertemporal model for unilateral climate policy

We consider a climate coalition (”home country”) that aims to reduce damages from global emissions of greenhouse gases through a combination of domestic demand and supply-side policies. In this section, we simplify by considering two periods and one aggregate fossil fuel. Capital letters are assigned to the free-riders' (foreign's) variables and small letters are assigned to domestic variables. Let x_t and y_t (X_t and Y_t) denote production and consumption in period t, respectively. Furthermore, let $c_t(a_t)$ and $C_t(A_t)$ be convex and increasing functions that denote the coalition's and foreign's cost of producing fossil fuel as a function of aggregated production at time t (a_t and A_t). Fossil fuel is traded in the international market at price p_t. We normalize units such that consuming one unit of fossil fuel

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[3] The EEA brings together the EU Member States and the three EFTA States Iceland, Liechtenstein and Norway in a single market.

causes one unit of emissions. Market equilibrium requires global production to equal global consumption in each period. Market equilibrium and the above normalization w.r.t. emissions imply:

$$x_t + X_t = E_t = y_t + Y_t, \tag{1}$$

where E_t is global emissions. There is damage caused by the stock of carbon in the atmosphere (S_t) in each period ($Z_t(S_t)$). We simplify by assuming that a share given by $\alpha \in [0,1]$ of the emissions in period 1 remains in the atmosphere from one period to the next. In a two period model with $t \in T = \{1,2\}$ we have:

$$\begin{aligned} S_1 &= S_0 + E_1 = S_0 + x_1 + X_1, \\ S_2 &= \alpha S_1 + E_2 = \alpha S_0 + \alpha(x_1 + X_1) + x_2 + X_2, \end{aligned} \tag{2}$$

where S_0 is the initial stock of carbon in the atmosphere. The social cost of carbon at time t (v_t) is the marginal damage of one additional unit of emissions:

$$\begin{aligned} v_1 &= Z'_{S_1}(S_1) + \alpha\delta Z'_{S_2}(S_2), \\ v_2 &= Z'_{S_2}(S_2), \end{aligned} \tag{3}$$

where $\delta \in [0,1]$ is the discount factor.

We assume that the coalition can control domestic production and consumption of fossil fuels using taxes or other regulatory measures. Hence, we treat domestic production and consumption as exogenous. In the next section we will model taxes explicitly. In the following, we refer to reduced consumption (y_t) in the home country as demand-side policies, whereas reduced production (x_t) in the home country is coined supply-side policies.

Foreign consumption of fossil fuels in period t is a decreasing function of the price in that period $Y_t = D_t(p_t)$ (with $\partial D_t(p_t)/\partial p_t \equiv D'_t < 0$). We assume that foreign producers are competitive and maximize the present value of their income from fossil fuel production over both periods. In particular, this implies that the marginal discounted profits from the resource are equalized across time. Otherwise, the resource owners could increase the value of the resource by moving production from one period to the other. The foreign producer's extraction profile solves:

$$\underset{X_1, X_2}{\text{Max}}\ \Pi = \sum_{t \in T} \delta^{t-1} \left[p_t X_t - C_t(A_t) \right], \tag{4}$$

subject to the state variable equations $A_1=X_1$ and $A_2=X_1+X_2$. The first order conditions are given by:

$$\begin{aligned} &p_1 - C_1' - \delta C_2' = 0, \\ &p_2 - C_2' = 0. \end{aligned} \tag{5}$$

Note that the term $-\delta C_2'$ is the scarcity value (or shadow price) of the resource. It is negative because increased production in period 1 implies higher production cost and hence lower profit in period 2. The first order conditions in (5) and the state variable equations implicitly define the foreign supply functions for fossil fuels, $X_1(p_1,p_2)$ and $X_2(p_1,p_2)$, where (see Appendix A for calculations):

$$\begin{aligned} &\frac{\partial X_1}{\partial p_1} = \frac{1}{C_1''} > 0, \quad \frac{\partial X_1}{\partial p_2} = \frac{-\delta}{C_1''} < 0, \\ &\frac{\partial X_2}{\partial p_1} = \frac{-1}{C_1''} < 0, \quad \frac{\partial X_2}{\partial p_2} = \frac{C_1'' + \delta \cdot C_2''}{C_1'' \cdot C_2''} > 0. \end{aligned} \tag{6}$$

Inserting the functions for foreign demand and supply into the market equilibrium conditions (1) yields:

$$x_t + X_t(p_1, p_2) = y_t + D_t(p_t) = E_t, \quad t = 1,2. \tag{7}$$

We consider an equilibrium with strictly positive foreign production in both periods and unique market clearing prices such that (7) holds. These prices are functions of net demand from the home country in both periods:

$$p_t = p_t(y_1 - x_1, y_2 - x_2), \quad t = 1,2 \tag{8}$$

Increased net imports leads to higher international prices in both periods; i.e. we have:

$$\frac{\partial p_t}{\partial (y_s - x_s)} > 0, \quad t,s = 1,2 \tag{9}$$

The exact expressions for $\partial p_t / \partial (y_s - x_s)$ are given in Appendix A. The resource becomes scarcer if net domestic imports increases in at least one period. This increases the resource rent of foreign producers and, hence, the resource price is higher in both periods.

As international fossil fuel prices are functions of net import from the home country, both supply-side and demand-side policies will affect emissions abroad (carbon leakage). We define carbon leakage following from demand-side policies, L_{ts}, as the *increase* in emissions abroad at time *t* following from a unit *reduction* in domestic consumption at time *s*:

$$L_{ts} = \frac{\partial Y_t}{-\partial y_s} = -D_t' \frac{\partial p_t}{\partial\left(y_s - x_s\right)}, \quad t,s = 1,2 \tag{10}$$

Note that the production levels (x_s) are kept constant in (10). By keeping the consumption levels (y_s) constant, we find that the carbon leakages following from a unit reduction in domestic supply of fossil fuel are given by:

$$\frac{\partial Y_t}{-\partial x_s} = D_t' \frac{\partial p_t}{\partial\left(y_s - x_s\right)} = -L_{ts}, \quad t,s = 1,2 \tag{11}$$

As the international fuel prices are functions of net domestic demand, the carbon leakage following from demand-side policies and supply-side policies will have identical magnitudes, but opposite signs. We will refer to L_{tt} **(** $-L_{tt}$ **)** as *spatial carbon leakage*, that is, increased emissions abroad at time *t* following a unit reduction in domestic consumption (supply) at time *t*. Similarly, L_{ts} (- L_{ts}), $t \neq s$, is the *intertemporal carbon leakage*, that is, increased emissions abroad at time *t* following a unit reduction in domestic consumption (supply) at time *s*.

Proposition 1. *Consider a climate coalition that implements domestic measures to reduce global emissions. Then demand-side policies lead to positive intertemporal and spatial leakages, whereas supply-side policies lead to leakages of the same magnitudes, but with negative signs.*

Proof. *See Appendix A for proof that* $L_{ts} > 0$ and $L_{tt} > 0$.

Hence, if the coalition reduces future domestic demand for fossil fuels, foreign consumption of fossils fuels increases both now and in the future. On the other hand, if the coalition reduces future domestic supply of fossil fuels, foreign consumption decreases both today and in the future.

A decrease in domestic *consumption* in period *t* reduces the price in that period, implying more foreign consumption and emissions in period *t*. A decrease in domestic consumption in period *t* also decreases the residual demand faced by foreign producers in that period. Therefore, foreign production decreases in period *t*, implying that more resource is available for production in the other period *s*.[4] This

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[4] The shift in foreign production across periods can also be seen from equation (5): if domestic consumption in period 2 decreases, the equilibrium price and foreign production in period 2 decreases, implying a lower absolute value resource rent $\delta C_2'$ (for any given X_1) and, hence, more foreign production in period 1. Conversely, if domestic consumption in period 1 decreases, foreign firms will produce less in period 1. Thus, marginal production cost C_2' in period 2 decreases (for any given X_2) , implying higher foreign production in period 2. The argument is similar for supply side policies.

decreases the world market price in period *s*; i.e. domestic demand-side measures in period *t* induce lower prices and higher foreign consumption and emissions in both periods (positive leakage).

On the other hand, a decrease in domestic *production* in period *t* increases the price in that period, implying less foreign consumption and emissions in period *t*. A decrease in domestic production also increases the residual demand faced by foreign producers in that period. Therefore, foreign production increases in period *t*. Increased foreign production in period *t* implies that less resource is available for production in the other period *s*. This entails reduced foreign production and hence a higher world market resource price also in period *s*. The higher fuel prices reduce foreign emissions from consumption in both periods (negative leakage).

Note that supply-side policies within the coalition do not reduce emissions from the coalition, but reduces global emissions through the responses from the free-riders. Demand-side polices reduce emissions from the coalition in the period the policy is undertaken, but the impact on global emissions is dampened by leakage from the free-riders.

We have the following results regarding the global impact of unilateral policies:

Proposition 2. *Consider a climate coalition that implements domestic measures to reduce global emissions. Then we have the following:*

- i. *If both domestic consumption and production is reduced by one unit in period t, global emissions are reduced by one unit in that period, and are unaffected in the other period.*
- ii. *Both demand and supply-side policies in period t lead to lower global emissions in period t.*
- iii. *Demand-side policies in period t lead to higher global emissions in period s, whereas supply-side policies in period t lead to lower global emissions in period s* ($t \neq s$)*.*
- iv. *Both demand and supply-side policies in period t induce lower total accumulated emissions* ($E_1 + E_2$)

Proof. *See Appendix A.*

The first part of Proposition 1 holds because the world market price is unaffected if both domestic production and domestic consumption is reduced by the same amount in period *t*. Hence, there is no leakage if domestic supply and consumption is reduced by the same amount.[5] This result show that an important result from the static model in Bohm (1993) also holds in an intertemporal setting.

Part *ii* reflects that the spatial leakage must be less than unity in the partial equilibrium framework employed in this paper.[6] Reduced domestic consumption induces lower equilibrium prices and increased consumption abroad. However, the increase in foreign consumption must be less than the domestic reduction due to downward sloping demand functions.

Part *iii* follows directly from the sign of the intertemporal leakages derived in Proposition 1.

The last part *iv* holds because the sum of spatial and intertemporal leakages is less than unity; i.e., total emissions decline if the climate coalition implements supply or demand-side policies to reduce carbon emissions. Table 1 summarizes the results from Proposition 1 and Proposition 2.

	Demand-side policy period t	*Supply-side policy period t*
Change in foreign emissions in same period *t*	$\frac{\partial Y_t}{-\partial y_t} = L_{tt} > 0$	$\frac{\partial Y_t}{-\partial x_t} = -L_{tt} < 0$
Change in foreign emissions in other period *s*	$\frac{\partial Y_s}{-\partial y_t} = L_{st} > 0$	$\frac{\partial Y_s}{-\partial x_t} = -L_{st} < 0$
Change in world emissions in same period *t*	$\frac{\partial E_t}{-\partial y_t} = -1 + L_{tt} < 0$	$\frac{\partial E_t}{-\partial x_t} = -L_{tt} < 0$
Change in world emissions in other period *s*	$\frac{\partial E_s}{-\partial y_t} = L_{st} > 0$	$\frac{\partial E_s}{-\partial x_t} = -L_{st} < 0$
Change in world emissions over both periods	$\frac{\partial E_t}{-\partial y_t} + \frac{\partial E_s}{-\partial y_t} = -1 + L_{tt} + L_{st} < 0$	$\frac{\partial E_t}{-\partial x_t} + \frac{\partial E_s}{-\partial x_t} = -L_{tt} - L_{st} < 0$

Table 1. Changes in emissions following domestic supply and demand-side policies in period *t* ($t,s = 1,2$, $t \neq s$).

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[5] Remember that domestic production and consumption are regulated in both time periods.

[6] See Karp (2010) for a discussion about carbon leakage using partial versus general equilibrium models.

Proposition 2 has some implications for welfare. Gerlagh (2010) distinguishes between a weak and a strong kind of green paradox. The weak green paradox arises when early emissions increase because fossil fuel owners anticipate bleaker future market conditions (e.g., because of lower fuel demand in the future) and therefore accelerates production. The strong green paradox arises when the intertemporal adjustment of the resource owners not only increases early emissions, but the present value of total environmental damages increases as well. Proposition 1 and 2 have the following corollary:

Corollary 1. *Consider a climate coalition that regulates domestic production and consumption in both time periods. Then we have the following:*

i. *A credible announcement of increased future unilateral supply-side policies reduces early emissions (opposite of green paradox).*

ii. *A credible announcement of increased future unilateral demand-side policies always induces the weak green paradox. This is also a strong green paradox on the margin if*

$$v_1 L_{12} + \delta v_2 \left(L_{22} - 1 \right) > 0$$

Proof. *The corollary follows directly from Part iii in proposition 2 and eq.(3).*

Intuitively, there can be no green paradox related to supply-side policies, because emissions decline in both periods (cf. Proposition 2). Indeed, the intertemporal leakages that cause the green paradox with demand-side policies actually work in favor of the climate coalition in the case of supply-side policies. That is, intertemporal leakages cause emissions to decline even before the environmental policy is implemented. In the case of future demand-side policies, however, we know that early emissions will increase and induce a weak green paradox. Even though we know from Proposition 2 that total emissions decline, a marginal increase in demand-side policies in the future may lead to an increase in the present value of total environmental damages. This effect (a strong green paradox) may occur if the present value of the social cost of carbon declines fast and intertemporal leakage is large.[7] See further discussion of this issue in Section 2.2 below.

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[7] Note that the green paradox is not an argument against current demand-side policies per se. On the contrary, the paradox arises from more stringent future environmental policy and thus, if anything, constitutes an argument for introducing stringent current environmental policy today.

2.2 Optimal unilateral supply and demand-side climate policy measures

In this section we discuss the implications Propositions 1 and 2 have for the optimal mix of demand and supply-side policies. Let the coalition's benefit from consumption of carbon be given by $B_t(y_t)$. We assume the climate coalition maximizes domestic welfare (*W*):[8]

$$\underset{y_1,y_2,x_1,x_2}{\text{Max}} \; W=\sum_{t\in T}\delta^{t-1}\left[B_t\left(y_t\right)-c_t\left(a_t\right)-p_t\left(\cdot\right)\left(y_t-x_t\right)-Z_t\left(S_t\right)\right] \tag{12}$$

We find the optimal quantities of production and consumption over both periods from the first order conditions associated with (12) (see Appendix A). We use these first order conditions to derive the optimal consumer taxes (τ_t^y) and the optimal producer taxes (τ_t^x) in a competitive fossil fuel market. The optimal consumer taxes are defined as the wedges between marginal utility of consumption and the resource price. Similarly, the optimal producer taxes are defined as the wedges between the resource price and the marginal production cost.[9]

$$\begin{aligned}
&\tau_1^y \equiv B_1'-p_1=R_{11}+\delta R_{21}+(1-L_{11})v_1-\delta L_{21}v_2,\\
&\tau_1^x \equiv p-c_1'-\delta c_1'=-R_{11}-\delta R_{21}+L_{11}v_1+\delta L_{21}v_2,\\
&\delta\tau_2^y \equiv \delta B_2'-\delta p_2=R_{12}+\delta R_{22}-v_1L_{12}+\delta(1-L_{22})v_2,\\
&\delta\tau_2^x \equiv \delta p_2-\delta c_2'=-R_{12}-\delta R_{22}+v_1L_{12}+\delta L_{22}v_2.
\end{aligned} \tag{13}$$

Here, R_{ts} denotes the marginal increase in the import bill in period *t* following from a unit increase in net demand in period *s*:

$$R_{ts}=\frac{\partial p_t}{\partial\left(y_s-x_s\right)}\cdot\left(y_t-x_t\right),\quad t,s=1,2 \tag{14}$$

We henceforth coin R_{ts} optimal tariff. A tariff on net import leads to lower domestic demand and higher domestic production, which contributes to lower international prices, and thus gain a fossil fuel importer. Hence, R_{ts} is positive if the coalition is a net importer of fossil fuels.

From (13), we see that:

$$\tau_t^y+\tau_t^x=v_t. \tag{15}$$

We have the following result:

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[8] For simplicity, we use the same discount factor for foreign producers as in calculation of the coalition's social welfare.
[9] The equalities in (13) follows directly from rearranging the first order conditions associated with (12).

Proposition 3: *Consider a climate coalition that implements domestic measures to reduce global emissions. Then we have:*

- *i.* *The sum of the optimal demand and supply side taxes on carbon in period t equals the social cost of carbon in period t.*
- *ii.* *Optimal climate policy implies a combination of demand and supply-side policies within the coalition.*

Proof: *Part i follows directly from (15). Regarding Part ii, competitive markets and no climate policy yield* $B_1' = p_1 = c_1' + \delta c_1'$ *and* $B_2' = p_2 = c_2'$. *The right hand side of the four equations in (13) will in general differ from zero (except by coincidence).*

Remember that the social cost of carbon at time *t* includes both present and future marginal damages following one additional unit of carbon emissions in period *t* (cf. (3)). Proposition 3 implies that combining demand and supply-side measures induce improved welfare, as compared with pure demand-side or pure supply-side policies. The intuition behind this result is straightforward: if the regulator has two instruments available (demand and supply side taxes), it is typically best to use them both. Further, whereas the total tax is always positive, given a positive social cost of carbon, it is possible that either the demand or the supply-side tax is negative (i.e., a subsidy). If we add the constraint that the tax shares are bounded in the interval $[0,1]$, however, a corner solution is fully possible. Proposition 3 generalizes the conclusions from the static model considered in Hoel (1994) to the dynamic case, where resource exhaustibility is taken into account.

In Corollary 1 we stated that a future marginal increase in demand-side policies induce a strong green paradox if and only if $v_1 L_{12} + \delta v_2 \left(L_{22} - 1\right) > 0$. Disregarding the optimal tariffs, we see from (13) that if $v_1 L_{12} + \delta v_2 \left(L_{22} - 1\right) > 0$, it is optimal to subsidize future consumption ($\delta \tau_2^y$<0). This suggests that the green paradox is not necessarily a problem per se: if the environmental and economic conditions are such that a strong green paradox arises, the regulator should consider subsidizing future consumption in order to reduce current emissions.

We see from (13) that the larger spatial and intertemporal leakages, the lower is the consumer tax, and the higher is the producer tax in each period. Large leakages make supply-side polices more efficient in terms of reducing global emissions, whereas large leakages dampen the global emission reductions following from demand-side policies. Furthermore, due to the terms of trade effects, the larger net import of fossil fuel in each period, the larger is the consumer tax and the smaller is the producer tax in each period. The impact of the social cost of carbon on the producer and consumer taxes is less straight forward. We see that the larger cost of carbon in period 1 (v_1), the larger is the consumer tax in period 1, but the smaller is the consumer tax in period 2. Similarly, the larger cost of carbon in period 2 (δv_2), the larger is the consumer tax in period 2, but the smaller is the consumer tax in period 1. In contrast, an increase in the social cost of carbon in one of the periods, leads to larger producer taxes in both periods. In the next section we discuss in more detail how the development of the social cost of carbon over time influences the optimal combination of consumer and producer taxes over time.

2.3 Time paths for producer and consumer taxes

We now examine how the optimal supply and demand-side shares of the total tax develop over time. The difference between the consumption tax's share of the total tax in periods 2 and 1 is given by (see Appendix A):

$$\frac{\tau_2^y}{v_2} - \frac{\tau_1^y}{v_1} = \underbrace{\left(L_{11} - L_{22}\right)}_{\text{Spatial leakage}} + \underbrace{\left(\frac{\delta v_2}{v_1} L_{21} - \frac{v_1}{\delta v_2} L_{12}\right)}_{\text{Intertemporal leakage}} + \underbrace{\left(\frac{R_{12} + \delta R_{22}}{\delta v_2} - \frac{R_{11} + \delta R_{21}}{v_1}\right)}_{\text{Terms of trade}} \tag{16}$$

If the expression in (16) is positive (negative), the optimal consumption tax's share of the total tax is increasing (decreasing) over time. We observe that the optimal consumption tax's share of the total carbon tax can increase or decrease over time, depending on the development of spatial leakage, intertemporal leakage, terms of trade effects and the social cost of carbon. We have the following result regarding the impact of the social cost of carbon time trajectory:[10]

Proposition 4. *Consider a climate coalition that implements domestic measures to reduce global emissions. Assume that the social cost of carbon is not too small in any of the periods. Then, the optimal consumption tax's share of the total carbon tax decreases (increases) over time for a sufficiently large decline (increase) in the present value of the social cost of carbon over time.*

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[10] The condition in Proposition 4 (i.e., that the social cost of carbon is not too small) ensures that the intertemporal leakage effects dominate the terms of trade effects. The terms of trade effects in (16) pulls in the direction of a larger consumption tax share if the climate coalition's net import increases over time.

Proof. *The present value of the social cost of carbon declines over time if* $v_1 / \delta v_2 > 1$ *. We see that (16) is negative for sufficiently large absolute value* $\left|-v_1 L_{12} / \delta v_2\right|$*, unless* $v_2 \to 0$*. Similarly, (16) is positive for sufficiently large value of* $\delta v_2 L_{21} / v_1$*, unless* $v_1 \to 0$*.*

The key to understanding Proposition 4 is that supply-side policy in period *t* decreases emissions in both periods, whereas demand-side policy in period *t* decreases emissions in period *t*, but also increases emissions in period $s \neq t$ (cf. Proposition 2). If the social cost of carbon declines over time it is more valuable to reduce present emissions than future emissions. It is then better with a relatively large supply-side tax share in the future, because that also reduces harmful emissions today. Conversely, it is better with a relatively large supply-side tax share today if the social cost of emissions increases substantially over time, as that also reduces the very harmful emissions in the future.

We stress that Proposition 4 only regards the supply and demand-side *shares* of total taxation. The sum of these shares, i.e., the optimal total tax on carbon, equals the social cost of carbon (cf. Proposition 3).

We see from (16) that the time paths of supply and demand-side policies also depend on spatial leakage. Relatively large future spatial leakage pulls in the direction of lower future demand-side taxation. The explanation is that, whereas emissions reductions caused by demand-side policies are dampened through spatial leakage, supply-side policies work through higher world prices on fossil fuels that reduce foreign consumption (negative spatial leakage), see Table 1.

3 Numerical illustration

In this section we substantiate our theoretical results on supply versus demand-side policies along the optimal time trajectory using the numerical model PetroHead. We assume that the climate coalition is the European Economic Area (EEA), which maximizes domestic welfare. This is done implementing a carbon tax satisfying the optimal demand and supply-side tax trajectories given in (13).

The present paper deals with environmental policy, and we therefore omit terms of trade effects from the analysis. There are two main reasons for this choice: first, the EEA is a large net importer of fossil fuels and use the consumption tax to improve their terms of trade (lower import bill). It then turns out to be optimal to levy the tax almost fully on the demand side.[11] While this result is in itself of some interest, it does not facilitate a good numerical illustration of the theory section in this paper. Second, the carbon tax induced by terms of trade considerations in (13) is not an environmental tax per se, as it would be optimal to levy it even if climate change was absent.

We first give a brief heuristic account of the model PetroHead. Then we present the numerical results, focusing on the oil market (presenting results from all fossil fuel markets is space consuming and not necessary to illustrate our theoretical results).[12] For details including exact functional forms and parameter values we refer to Appendix B, which also shows the model's goodness of fit in the period 1991 to 2013 and selected results from the gas and coal markets.

3.1 Heuristic model summary

PetroHead is a dynamic partial equilibrium model for the world oil, gas and coal markets. Its main outputs are figures for yearly regional consumption, production, prices and emissions associated with oil, gas and coal for the time span from 2013 to 2100. The model also includes biofuels, which we model as a perfect substitute for oil. Both production and consumption feature dynamic elements. The oil and gas producers maximize the present value of their resource, implying that oil and gas prices contain scarcity rents. In addition, the supply-side features sluggish production capacity. This is implemented such that current production capacity increases in past production levels. The demand side also features sluggishness in the sense of habit formation. That is, present demand for one type of fuel depends positively on past consumption of that fuel. This allows the model to differentiate between short and long run elasticities.

3.1.1 Demand for fossil fuels

PetroHead features six regions that demand oil, gas and coal: The European Economic Area (EEA), OECD America, Rest Europe and Eurasia, OECD Asia and Oceania, Non-OECD Asia, and Rest of world.[13] The demand functions are log-linear with endogenous region-specific prices. The fuels are imperfect substitutes for each other. Regional demand functions change exogenously over time due to

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[11] More precisely, the model simulation with terms of trade suggests that the optimal demand-side tax shares for oil and gas associated with the IWG SCC (see figure 1) are 1, whereas the demand-side tax share for coal varies around 0.6.

[12] A detailed numerical analysis of spatial and intertemporal leakage following demand and supply side policies is the topic in a forthcoming companion paper.

[13] Except for the EEA, we follow the geographical definitions used in IEA (2014) for consumer and producer regions. The choice of regions is a trade-off with transparence and computational ease on the one side, and a detailed description of the world fossil fuels market on the other. For example, the need for modelling several regional suppliers is larger for gas than for oil and coal, e.g., because of the relatively large costs of transporting gas.

changes in regional GDP and energy efficiency. The demand functions have an autoregressive distributive lags structure which yields sluggish demand. Demand functions are estimated using yearly figures from 1990 to 2012.[14] The resulting absolute value long run producer price demand elasticities range from 0.1 to 0.76, see Appendix B.[15] Future demand is calibrated to match the projections in the International Energy Agency (IEA) World Energy Outlook 2014 (IEA, 2014).

3.1.2 Supply of fossil fuels

Producers maximize the present value of their resource. This implies that the increase in total discounted profit from extracting one additional unit of the resource must be equalized across time along the optimal extraction path. Whereas this yields positive resource rents in the oil and gas markets, coal is available in abundance implying close to zero resource rents.[16] All producers are competitive with a yearly real discount rate equal to 5 percent. The exception is OPEC, which is modelled as a weak cartel in the oil market.[17]

Unit production costs increase in cumulative production and decrease in time. This means that production costs can rise or fall over time, depending on the resource depletion versus technology growth effect. Further, it is costly to produce at levels high above installed production capacity. We model this using increasing marginal production cost within a given time period (in addition to depletion cost from accumulative production). Production capacity evolves as a differential equation depending on previous production and an exogenous element calibrated after IEA (2014). Transport costs between regions are very small and constant in the oil market, higher and constant in coal market and increase in traded quantities in the gas market. This implies that the regional oil and biofuel prices are almost equal, whereas we have bilateral trade between interdependent regional markets for gas and coal. Cost functions and transport costs are calibrated using yearly data from IEA (2012, 2014).

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[14] Consumption and prices are from the “IEA extended energy balances” database, visited October 2014. Regional emissions due consumption are from “IEA CO2 emissions from fuel combustion” database, visited June 2015. GDP figures are from “IMF World Economic Outlook database”, visited October 2014.

[15] The literature on fuel price elasticities gives a wide range of estimates, inter alia depending on methodology, prices used in the estimations and regions included. IEA (2007) estimates of long-run crude oil price elasticities range from -28 (Latin America) to -0.01 (Africa). The World Bank (2008) estimates long-run price elasticities for gasoline and diesel at -0.61 and -0.67, respectively. Fournier et al. (2013) estimate the average medium to long-run price elasticity in OECD and BRIICS (Brazil, Russia, India, Indonesia, China and South Africa) countries to be around -0.2. Askari and Krichene (2010) estimate long-run demand elasticities to be around -0.01.

[16] Model generated shadow prices for coal are close to zero and have negligible effect on production. It is therefore set equal to zero to ease numerical computation.

[17] OPEC behaves roughly in the middle between Cournot and competitive behavior and use a price elasticity equal to -0.5 for all regions, see Appendix B for details.

Regional emissions from extraction of fossil fuels are fetched from the International Association of Oil & Gas Producers (OGP).[18]

The model features four oil suppliers: OECD America, EEA, OPEC, and Rest of world; five gas suppliers: OECD America, EEA, Rest Europe and Eurasia, Asia pacific, and Rest of world; two coal suppliers: EEA and Rest of world; and one global biofuels producer with learning by doing and zero transport costs.

3.1.3 Equilibrium

We use optimal control theory to derive the conditions for producer profit maximum, given the regional fuel demand functions. Fuel suppliers perceive the elements of sluggishness as exogenous in the current model version; i.e., they do not increase current production in order to increase future demand and production capacity. We solve the resulting system of equations as a mixed complementarity problem using numerical programming software (GAMS). All regional markets clear each period (year) with equilibrium prices so that consumption and production are equal. In the model runs we use forecast figures from the New Policies Scenario (i.e., the reference scenario) in the IEA World Energy Outlook 2014 (IEA, 2014), and gas transport capacities (for gas transport costs) from IEA World Energy Outlook 2012 (IEA 2012).[19] This version of PetroHead is therefore best suited to examine model runs that do not deviate too much from this scenario. This is no problem in the present paper.

3.1.4 Welfare

In this paper we use PetroHead to illustrate the optimal mix between supply and demand-side policies. Thus we need a measure for comparing welfare across the different tax trajectories. We approximate changes in welfare, as compared with a business as usual simulation (BaU, no EEA action to reduce global warming), using yearly changes in consumer surplus, producer surplus and environmental damage associated with the fuels.[20] We then calculate the present value of these changes over the time

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[18] Regional supply and fuel prices are from the IEA extended energy balances" database, visited October 2014. Information about present and future gas pipelines and LNG capacities are from IEA (2012). Regional emissions caused by fossil fuel production are from OGP (2013). The current model version simplifies by assuming no carbon emissions from biofuels.

[19] We extrapolate the trends given in the projections in IEA (2014) into the future to derive figures for the years after 2040. Whereas these figures are highly uncertain and appropriate for illustrative purposes only, the problem is somewhat ameliorated by the discounting which dramatically reduces the weight of changes far into the future, and that our results are based on comparative statistics using different model runs. The model runs for 100 years in this paper, but we stop calculating welfare in 2100. The model is not sensitive to time horizon length.

[20] More precisely, the BaU simulation is the "New Policies Scenario" in IEA (2014). Hence, EEA unilateral climate action modelled here is in addition to the climate policies implemented in that scenario.

span 2013-2100, using a yearly social discount rate equal to 3 percent and linear approximations to the regional demand and supply functions around optimum. The optimal tax trajectory is the one that maximizes the increase in this welfare measure as compared to BaU.

Whereas the total tax on carbon is changed each year (cf. (15)), the demand versus supply side tax shares are only allowed to be updated in the years 2013, 2030, 2040, 2050 and 2060 (to simplify solving the model). Hence, (13) is only approximately satisfied in this numerical illustration.

3.2 Numerical results

Figure 1 shows the present value of the social cost of carbon (SCC) suggested by the Interagency Working Group on the Social Cost of Carbon (IWG),[21] and the associated optimal demand-side carbon tax share trajectory in the oil market.

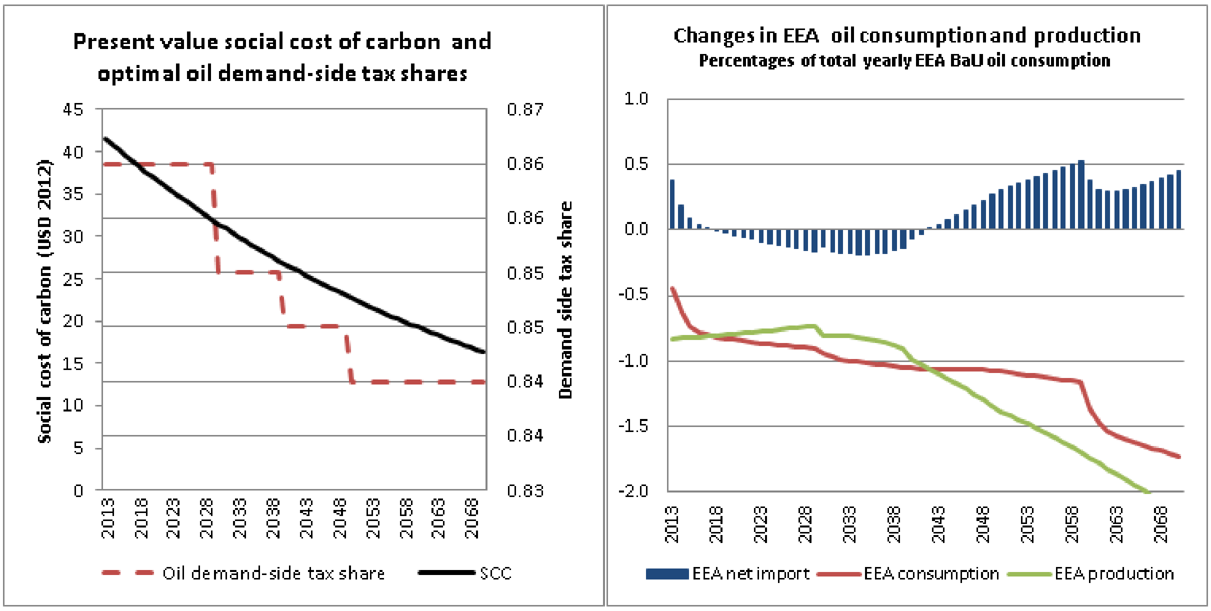

Figure 1. The present value SCC from IWG and the associated demand-side tax trajectories from 2013 to 2070. The right picture shows changes in yearly EEA oil consumption, production and net oil import following this tax trajectory (relative to BaU).

The declining demand-side tax share in Figure 1 follows from interaction between the two first mechanisms in (16): Firstly, the potential for oil market *spatial leakage* is relatively constant over time (levying the tax fully on the demand side induces a oil leakage rate that varies around 3-4 percent in the time interval from 2013 2070). Secondly, *intertemporal leakage* causes a decline in the present value of the SCC to imply a declining optimal demand-side tax share over time, see Proposition 4.

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[21] See http://costofcarbon.org/faq.

Figure 1 also shows that oil consumption and oil production declines in EEA, as compared with the BaU simulation. Even though the demand-side tax share is higher than the supply side tax share, the outcome is an increase in net import over about half of the time horizon. The oil consumption reductions become larger over time. [22] There are two reasons for this: Firstly, it takes time for the consumers to adjust demand to the higher oil prices. While the first years reflect adaptation captured by short run price elasticities, the later years are closer to new consumption habits governed by the long run price elasticity adaptation. Secondly, whereas the present value of the SCC declines in this simulation, the undiscounted SCC increases, implying a higher oil tax level in the future. On the supply-side, the oil tax causes EEA oil production to decline over time, with gradually increasing reductions relative to BaU. The reductions grow over time because the producer oil tax increases due a higher (running value) SCC and a larger supply-side share of the total tax. In addition, lower production levels reduce the EEA oil production capacity relative to BaU over time, which further reduces EEA oil production.

Another notable feature in Figure 1 is the time trajectory for EEA net oil imports. We see that the optimal tax trajectory features reductions in EEA oil production and consumption, which causes the optimal tax trajectory to induce completely different leakage rates as compared with a pure demand-side tax.[23] Indeed, a pure demand side tax would induce an average leakage rate equal to 3 percent over the time horizon 2013 to 2070, whereas the optimal tax trajectory induces an average leakage rate equal to -7 percent over the same time horizon. The leakage is negative whenever the change in EEA net oil demand is positive in Figure 1. The explanation is that increased EEA net demand for oil increases the global equilibrium oil price. The higher global oil price reduces oil consumption outside of the EEA.

The oil market welfare gain following the optimal tax trajectory in Figure 1 is 20 percent larger than the welfare gain following a pure demand side tax. That is, increasing the supply-side oil tax share from 0 percent to around 15 percent increases oil market welfare gains from the environmental policy by 20 percent (omitting terms of trade).

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[22] The sharper decline in oil consumption starting in 2060 occurs because the optimal demand-side tax share on coal declines substantially in 2060, with associated lower coal consumer prices (the supply-side coal tax forces EEA coal production to a halt 2060 in the simulation with the IWG SCC, see Appendix B4).

[23] In the theory section we differentiated spatial and intertemporal mechanisms for leakage. The leakage rate in the numerical section is caused by both these mechanisms. It is defined as the number of units of increased carbon emissions in the rest of the world (non-EEA) in year *t* per unit of decreased emissions in the EEA in year *t*.

3.2.1 Trajectories for the social cost of carbon: implications for demand versus supply-side policies.

We now compare the optimal supply versus demand-side tax mix associated with the SCC from IWG with two stylized time trajectories for the present value of the SCC: one time neutral and one increasing.[24] Figure 2 illustrates these SCC trajectories and their associated optimal demand-side share of the total oil market carbon tax. Note that Figure 2 shows the demand-side shares relative to the tax trajectory associated with the time neutral path.

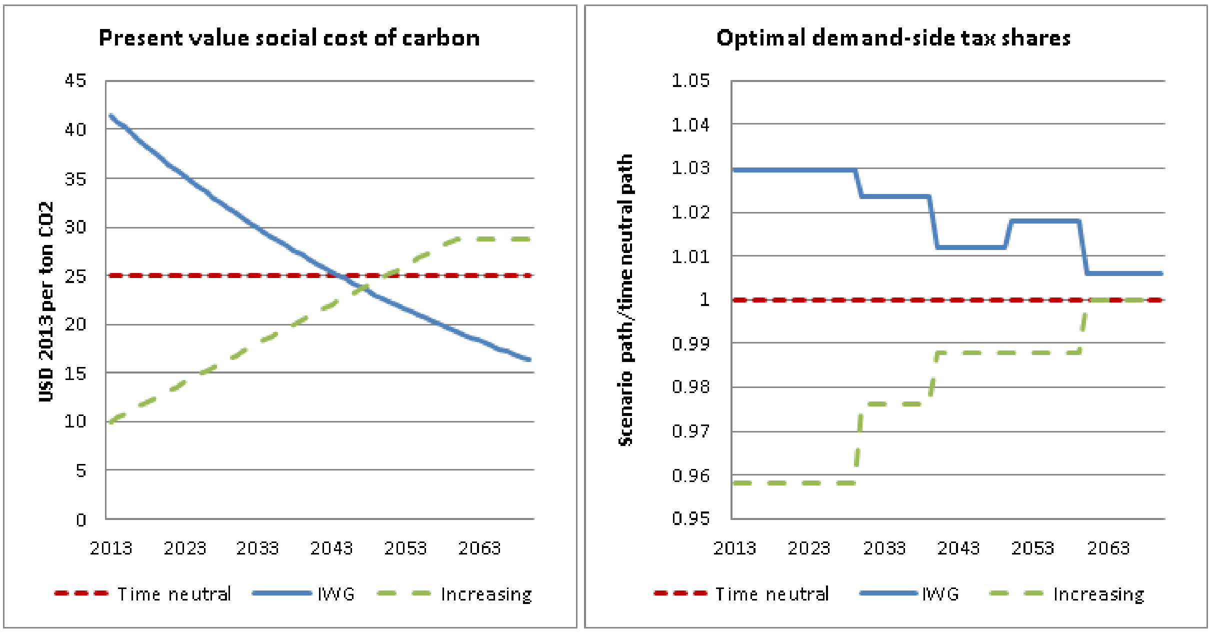

Figure 2. Three scenarios for the SCC with associated demand-side shares of the total oil tax along the optimal time trajectory.

We know from Proposition 4 that the optimal consumption tax's share of the total carbon tax decreases (increases) over time for a sufficiently large decline (increase) in the present value of the social cost of carbon over time (from intertemporal leakage effects). We observe that the simulation runs yield consistent results. Nevertheless, the differences between the demand-side shares are modest, suggesting that spatial leakage is a more important factor for the optimal tax trajectory.

Additional numerical model runs indicate that our qualitative results are robust to alternative values for the discount rate, time horizon, the social cost of carbon and EEA oil demand price elasticities. In particular, increasing the absolute value of the EEA long run oil and gas price elasticities from 0.1 to

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[24] The time neutral path is time neutral for the social planner (discount rate 0.03).

0.5 only increased the optimal oil tax demand share with 1-2 percent. On the other hand, the oil market leakage was positive during the whole time horizon in the simulation with these elasticities.

4 Concluding remarks

In this paper we have showed analytically and numerically that unilateral climate policy combining demand and supply-side measures improves welfare, as compared with pure demand or supply-side policies. Demand-side policies lead to positive intertemporal and spatial leakages, whereas supply-side policies lead to leakages of the same magnitudes, but with negative signs. In particular, intertemporal leakages, which cause the green paradox with demand-side policies, actually work in favor of the climate coalition in the case of supply-side policies. That is, intertemporal leakages cause foreign emissions to decline even before the environmental policy is implemented. Further, the optimal unilateral carbon tax equals the social cost of carbon and its distribution across consumers and producers differs over time, depending on environmental damages, spatial leakages, intertemporal leakages and terms of trade effects. For example, a declining social cost of carbon over time supports a time path where the consumer tax’s share of the total carbon tax also declines over time.

In order to derive our results, we have assumed full information about current and future market conditions. This is a strong but standard assumption in the economic literature of exhaustible resources (Hotelling, 1931; Sinn, 2008; Hoel 2013). The full information assumption also removes challenges related to commitment to future environmental policy. Note that the assumption about perfect foresight is only crucial for the intertemporal mechanisms we have examined. As such, the result that welfare can be improved by combining demand and supply-side policies is robust to less demanding assumptions about information.

Numerical model runs indicate that the optimal oil market demand-side tax share (excluding terms of trade) fluctuates around 85 percent of the total carbon tax in the case of unilateral climate policy implemented by the European Economic Area (EEA). Although the consumption tax is much higher than the production tax, the outcome is an increase in net import over about half of the time horizon.

Unilateral policies for reducing greenhouse gas emissions have so far typically targeted consumption of fossil fuels only. The take-home message from the present paper is that welfare gains may be achieved by considering long term environmental policies that also include supply-side measures.

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Appendix A: Calculations and proofs

Calculation of equation (6):

Totally differentiating the first order conditions (5) we get:

$$\begin{pmatrix} C_1'' + C_2'' & \delta C_2'' \\ C_2'' & C_2'' \end{pmatrix} \begin{pmatrix} dX_1 \\ dX_2 \end{pmatrix} = \begin{pmatrix} dp_1 \\ dp_2 \end{pmatrix},$$

with solution:

$$\begin{pmatrix} dX_1 \\ dX_2 \end{pmatrix} = \frac{1}{C_1''C_2''} \begin{pmatrix} C_2''\left(dp_1 - \delta p_2\right) \\ \left(C_1'' + \delta C_2''\right) dp_2 - C_2'' dp_1 \end{pmatrix}.$$

The equations follow (divide with the relevant price and use partial derivatives; i.e. the other price is constant).

Calculation of the price effects in (9):

Total differentiation of equation (7) yields (omitting E_t):

$$\begin{pmatrix} \partial X_1 / \partial p_1 - D_1' & \partial X_1 / \partial p_2 \\ \partial X_2 / \partial p_1 & \partial X_2 / \partial p_2 - D_2' \end{pmatrix} \begin{pmatrix} dp_1 \\ dp_2 \end{pmatrix} = \begin{pmatrix} dz_1 \\ dz_2 \end{pmatrix}.$$

with $z_1 \equiv y_1 - x_1$. Using Cramer's rule we get the solution:

$$\begin{pmatrix} dp_1 \\ dp_2 \end{pmatrix} = \frac{1}{M} \begin{pmatrix} dz_1\left(\partial X_2 / \partial p_2 - D_2'\right) - dz_2 X_1 / \partial p_2 \\ dz_2\left(\partial X_1 / \partial p_1 - D_1'\right) - dz_1 X_2 / \partial p_1 \end{pmatrix}$$

where $M \equiv \left(D_1' - \partial X_1 / \partial p_1\right)\left(D_2' - \partial X_2 / \partial p_2\right) - \left(\partial X_2 / \partial p_1\right)\left(\partial X_1 / \partial p_2\right) > 0$ by the foreign firms' second order conditions. Using partial derivatives we find:

$$\frac{\partial p_1}{\partial\left(y_1 - x_1\right)} = \frac{1}{M}\left(\frac{\partial X_2}{\partial p_2} - D_2'\right) > 0, \quad \frac{\partial p_1}{\partial\left(y_2 - x_2\right)} = \frac{-1}{M}\frac{\partial X_1}{\partial p_2} > 0,$$

$$\frac{\partial p_2}{\partial\left(y_1 - x_1\right)} = \frac{-1}{M}\frac{\partial X_2}{\partial p_1} > 0, \quad \frac{\partial p_2}{\partial\left(y_2 - x_2\right)} = \frac{1}{M}\left(\frac{\partial X_1}{\partial p_1} - D_1'\right) > 0.$$

Inserting from (6):

$$\frac{\partial p_1}{\partial\left(y_1-x_1\right)}=\frac{1}{M}\left(\frac{C_1''+\delta\cdot C_2''}{C_1''\cdot C_2''}-D_2'\right)>0,\quad \frac{\partial p_1}{\partial\left(y_2-x_2\right)}=\frac{\delta}{MC_1''}>0,$$
$$\frac{\partial p_2}{\partial\left(y_1-x_1\right)}=\frac{1}{MC_1''}>0,\quad \frac{\partial p_2}{\partial\left(y_2-x_2\right)}=\frac{1}{M}\left(\frac{1}{C_1''}-D_1'\right)>0.$$

Proof of Proposition 1:

We have $0<L_{ts}$ because $L_{ts}=-D_t'\left(p_t\right)\cdot\left(\partial p_t\left(\cdot\right)/\partial\left(y_s-x_s\right)\right)>0$ from equation (9), and $D_t'\left(p_t\right)$ <0 ($t,s=1,2$).

Proof of Proposition 2:

We find from (7) and (9) to (11) that:

$$\begin{aligned}&\frac{\partial E_t}{-\partial y_t}=-1+L_{tt},\ \frac{\partial E_t}{-\partial x_t}=-L_{tt},\ \frac{\partial E_s}{-\partial y_t}=L_{st},\ \frac{\partial E_s}{-\partial x_t}=-L_{st},\\&\frac{\partial E_t}{-\partial y_t}+\frac{\partial E_s}{-\partial y_t}=-1+L_{tt}+L_{st},\quad \frac{\partial E_t}{-\partial x_t}+\frac{\partial E_s}{-\partial x_t}=-L_{tt}-L_{st},\quad t,s=1,2,t\neq s.\end{aligned}\tag{17}$$

To prove part *i*), we observe that $\frac{\partial E_t}{-\partial y_t}+\frac{\partial E_t}{-\partial x_t}=-1+L_{tt}-L_{tt}=-1$; i.e. one unit reduction in domestic production and reduction in period *t* yields one unit reduction in global emissions in period *t*. Further, we see that global emissions in the other period *s* equal $\frac{\partial E_s}{-\partial y_t}+\frac{\partial E_s}{-\partial x_t}=L_{st}-L_{st}=0$.

We observe from (17) that Part *ii*) is satisfied for $0<L_{tt}<1$. In the proof of proposition 1 we proved that $0<L_{tt}$. It remains to prove $L_{tt}<1$. We begin with spatial leakage in period 1:

$$\begin{aligned}L_{11}&=\frac{\partial Y_1}{-\partial y_1}=\frac{\partial(X_1+x_1-y_1)}{-\partial y_1}=1-\left[\frac{\partial X_1}{\partial p_1}\frac{\partial p_1}{\partial\left(y_1-x_1\right)}+\frac{\partial X_1}{\partial p_2}\frac{\partial p_2}{\partial\left(y_1-x_1\right)}\right]\\&=1-\frac{1}{MC_1''}\left(\left(\frac{C_1''+\delta\cdot C_2''}{C_1''\cdot C_2''}-D_2'\right)-\frac{\delta}{C_1''}\right)\\&=1-\frac{1}{MC_1''}\left(\frac{1}{C_2''}-D_2'\right)\end{aligned}$$

which proves that $L_{11}^D<1$ as $M,C_t'',-D_t'>0$. By similar reasoning, we have:

$$L_{22}=\frac{\partial Y_2}{-\partial y_2}=\frac{\partial\left(X_2+x_2-y_2\right)}{-\partial y_2}=1-\frac{\partial X_2}{\partial p_1}\frac{\partial p_1}{\partial\left(y_2-x_2\right)}+\frac{\partial X_2}{\partial p_2}\frac{\partial p_2}{\partial\left(y_2-x_2\right)}$$

$$=1-\frac{1}{MC_1''}\left(\frac{-\delta}{C_1''}+\frac{C_1''+\delta\cdot C_2''}{C_2''}\left(\frac{1}{C_1''}-D_1'\right)\right)$$

$$=1-\frac{1}{MC_1''}\left(\frac{-\delta C_2''}{C_1''C_2''}+\frac{C_1''+\delta\cdot C_2''}{C_1''C_2''}-\frac{C_1''+\delta\cdot C_2''}{C_2''}D_1'\right)$$

$$=1-\frac{1}{MC_1''}\left(\frac{1}{C_2''}-\frac{C_1''+\delta\cdot C_2''}{C_2''}D_1'\right)$$

which proves that $L_{22}^D<1$ as $M,C_t'',\delta,-D_t'>0$.

Part *iii*) holds as $L_{st}>0$, see proof of proposition 1 and (17).

To prove part *iv*), we first observe from (17) that:

$\frac{\partial E_t}{-\partial x_t}+\frac{\partial E_s}{-\partial x_t}<0$ as $L_{st}>0$, see proof of proposition 1 and (17).

To determine the sign of $\frac{\partial E_t}{-\partial y_t}+\frac{\partial E_s}{-\partial y_t}$, it remains to derive the expressions for L_{ts} (see eq. (17)) :

$$L_{12}=\frac{\partial Y_1}{-\partial y_2}=\frac{\partial(X_1+x_1-y_1)}{-\partial y_2}=-\frac{\partial X_1}{\partial p_1}\frac{\partial p_1}{\partial\left(y_2-x_2\right)}-\frac{\partial X_1}{\partial p_2}\frac{\partial p_2}{\partial\left(y_2-x_2\right)}$$

$$=-\frac{1}{C_1''}\frac{\delta}{MC_1''}+\frac{\delta}{C_1''}\frac{1}{M}\left(\frac{1}{C_1''}-D_1'\right)=\frac{-\delta D_1'}{MC_1''}$$

$$L_{21}=\frac{\partial Y_2}{-\partial y_1}=\frac{\partial(X_2+x_2-y_2)}{-\partial y_1}=-\frac{\partial X_2}{\partial p_1}\frac{\partial p_1}{\partial\left(y_1-x_1\right)}-\frac{\partial X_2}{\partial p_2}\frac{\partial p_2}{\partial\left(y_1-x_1\right)}$$

$$\frac{1}{C_1''}\frac{1}{M}\left(\frac{C_1''+\delta\cdot C_2''}{C_1''\cdot C_2''}-D_2'\right)-\frac{C_1''+\delta\cdot C_2''}{C_1''\cdot C_2''}\frac{1}{MC_1''}=\frac{-D_2'}{MC_1''}$$

From the expressions of L_{tt} and L_{ts} derived above, we find that:

$$\frac{\partial E_1}{-\partial y_1}+\frac{\partial E_2}{-\partial y_1}=\frac{-1}{MC_1''C_2''}<0,\quad \frac{\partial E_1}{-\partial y_2}+\frac{\partial E_2}{-\partial y_2}=\frac{1}{MC''C_2''}\left(D_1'C_1''-1\right)<0$$

This completes the proof.

First order conditions following from (12):

$$
\begin{aligned}
&B_1' = p_1 + R_{11} + \delta R_{21} + (1 - L_{11})v_1 - \delta L_{21} v_2,\\
&c_1' + \delta c_1' = p_1 + R_{11} + \delta R_{21} - L_{11} v_1 - \delta L_{21} v_2,\\
&\delta B_2' = \delta p_2 + R_{12} + \delta R_{22} - v_1 L_{12} + \delta(1 - L_{22})v_2,\\
&\delta c_2' = \delta p_2 + R_{12} + \delta R_{22} - v_1 L_{12} - \delta L_{22} v_2.
\end{aligned}
$$

***Derivation of equation (16)*:**

From (13) we find:

$$
\begin{aligned}
\frac{\tau_2^y}{v_2} - \frac{\tau_1^y}{v_1} &= \frac{R_{12} + \delta R_{22} - v_1 L_{12} + \delta(1 - L_{22})v_2}{\delta v_2} - \frac{R_{11} + \delta R_{21} + (1 - L_{11})v_1 - \delta L_{21} v_2}{v_1}\\
&= \frac{R_{12} + \delta R_{22}}{\delta v_2} - \frac{v_1 L_{12}}{\delta v_2} + 1 - L_{22} - \frac{R_{11} + \delta R_{21}}{v_1} - (1 - L_{11}) + \frac{\delta L_{21} v_2}{v_1}\\
&= \left[L_{11} - L_{22}\right] + \left[\frac{\delta v_2}{v_1} L_{21} - \frac{v_1}{\delta v_2} L_{12}\right] + \frac{R_{12} + \delta R_{22}}{\delta v_2} - \frac{R_{11} + \delta R_{21}}{v_1}
\end{aligned}
$$

which is equation (16).

Appendix B: PetroHead

In this appendix we present an algebraic model summary, parameter values and model fit to history for the PetroHead version used in this paper.

B1. Algebraic model summary

B1.1 The demand-side

Let the consumer price of fuel $f, ff \in F = \left\{1,...,n^f\right\}$ in region $j \in J = \left\{1,...,n^j\right\}$ at time $t \in T = \left\{1,...,n^j\right\}$ be given by $\tilde{P}_t^{fj} = (P_t^{fj} + v_t^{fj})$ (*ff* is alias). Here P_t^{fj} is the producer price of fuel and v_t^{fj} denotes region specific costs like taxes, regional transportation, distribution and refining of fuel.[25] Demand for fossil fuels is modelled using log-linear demand functions:

$$(18) \qquad D_t^{fj} = \beta_0^{fj}\left(G_t^j\right)^{\beta_y^j}\left(D_{t-1}^{fj}\right)^{\beta_d^{fj}}\prod_{f \in F}\left(\tilde{P}_t^{fj}\right)^{\beta^{fj}}, \quad \forall f, \forall j, \forall t,$$

where the β's are constants and G_t^j is a parameter that accounts for total energy demand growth (i.e., GDP growth and energy efficiency).[26] With $i \in I = 1,...,n^i$ fuel producers with access to region *j*, market clearing requires:

$$(19) \qquad \sum_{i \in I} x_t^{fij} = D_t^{fj} \quad ,\forall f, \forall j, \forall t,$$

where x_t^{fij} denotes fuel *f* extracted by producer *i* and sold in region *j* at time *t*. The demand function (18) and the equilibrium condition (19) imply the following equilibrium producer fuel price in region *j*:

---

[25] To simplify language, we do not explicitly refer to indexes denoting fuel $f \in F$, region $j \in J$, time $t \in T$ and firm $i \in I$ in the text, unless this is convenient for understanding.

[26] We use total primary energy demand from the IEA database as a proxy for G_t^j in the estimation (and instrumental variables using GDP, time and lags when the statistical software Stata's tests for endogeneity suggests that to be required).

$$(20) \qquad P_t^{fj} = \left(\frac{\sum_{i\in I} x_t^{fij} + \zeta_t^{fj}}{\beta_0^{fj} (\mathrm{G}_t^j)^{\beta_y^j} (D_{t-1}^{fj})^{\beta_d^{fj}} \prod_{ff\in F\setminus\{f\}} (\square P_t^{fj})^{\beta^{fj}}} \right) - v_t^{fj} \quad ,\forall f, \forall j, \forall t .$$

Here ζ_t^{fj} is a small positive constant included to ensure that price is bounded above.[27]

B1.2 The supply-side

Each fuel producer supplies one type of fuel and have access to all markets $j \in J$, at given transport costs w_t^{ij} (e.g., LNG transport).[28] Producer *i*'s total production at time *t* is then $x_t^i = \sum_{j\in J} x_t^{ij}$. Let the unit cost function of fuel producer $i \in I$ be given by:

$$(21) \qquad \begin{aligned} & C_t^i\left(x_t^i, A_i^i, \bar{x}_t^i, t\right) = c_1^i\left(1 + c_2^i \frac{x_t^i - \bar{x}_t^i}{\bar{x}_t^i} + c_3^i A_t^i\right)\exp\left(c_3^i\left(t-1\right)\right), \quad \forall i, \forall t \\ & \text{st.} \quad \bar{x}_t^i = \left(1-\psi\right)\hat{x}_{t-1}^i + \alpha x_{t-1}^i, \end{aligned} \quad ,$$

where the *c*'s are constants, $\hat{x}_t^i$ is a proxy for the exogenous part of production capacity, A_t^i is accumulated production and $\psi \in \left[0,1\right)$. The proxy for the exogenous part in the differential equation for capacity $\hat{x}_t^i$ is calibrated using the production projections given in the new policies scenario in IEA's World Economic Outlook (IEA, 2014). Firms take capacity x_t^i as given in the model version of PetroHead utilized in the present paper: i.e. they do not increase current production in order to increase future production capacity and hence reduce production costs.[29] An exhaustible resource owner has $c_3^i > 0$, while learning by doing is characterized by $c_3^i < 0$ (biofuels).

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[27] We also use ζ_t^{fj} to account for structural changes in future demand in some regions. For example, the link between GDP and coal demand in China is changing rapidly (see e.g. figures in EIA 2014).

[28] The analysis easily generalizes to competitive firms producing several types of fuel, given that the cost function of producing different fuel types are independent of each other. In the case of oligopolistic firms, the current model setup does not allow consideration of potential cross price effects of production decisions regarding fuel f on prices of other fuels ff the oligopolistic firm also produce (which are probably rather small in any case).

[29] Model experimentation suggests that this effect is small for our value of $\psi = 1/4$ and substantially increase computational complexity.

Whereas unit transport costs are constant in the oil and coal markets, unit gas transport costs increase in supply from producer *i* to region *j*, with fixed time dependent transport capacities $\tilde{x}_t^{ij}$ between producers and regions:

$$\begin{aligned} &w_t^{ij} = c_5^{ij}, \quad \forall i \in I \setminus \left\{ I^{gas} \right\}, \forall j, \forall t, \\ &w_t^{ij} = \frac{c_5^{ij}}{\tilde{x}_t^{ij}} x_t^{ij}, \quad \forall i \in \left\{ I^{gas} \right\}, \forall j, \forall t, \end{aligned} \tag{22}$$

where I^{gas} is the subset of *I* consisting of all the gas producers and $\tilde{x}_t^{ij}$ is a proxy for exogenous transport capacity. Transport costs are calibrated to roughly match observed transport costs and quantities in WEO (2012, 2014). Gas transport capacity from producer *i* to region *j* is approximated using figures for current and future pipeline and LNG capacities in WEO (2012).

The state variables for accumulated production are governed by the following differential equation:

$$A_{t+1}^i = A_t^i + \sum_{j \in J} x_t^{ij}, \quad A_t^i \geq 0, \forall i, \forall t. \tag{23}$$

Each firm $i \in I$ maximizes the sum of discounted profits from sales in all regions $j \in J$ w.r.t. extraction profiles $\left\{ x_t^{fij} \right\}_{t=1}^{t=T}$:

$$\max_{x_t^{fij}} \left[\sum_{t \in T} \left(\delta^i \right)^{t-1} \left(\sum_{j \in J} \left(\left(P_t^{fj}(\cdot) - w_t^{ij} \right) x_t^{fij} \right) - C_t^i(\cdot) x_t^{fi} \right) \right], \quad \forall i, \forall f, \tag{24}$$

subject to (20) to (23). Here $\delta^i \in [0,1)$ is the discount factor. To simplify the formulation of the numerical model, define a constant $\theta_i \in [0,1]$ such that $\theta_i = 0$ indicates that firm *i* is perfectly competitive and $\theta_i = 1$ refer to a Cournot firm. The objective function (24) gives the following Hamiltonians for each firm $i \in I$:

$$H_t^i(\cdot) = \left(\delta^i \right)^{t-1} \left(\sum_{j \in J} \left(\left(P_t^{fj}(\cdot) - w_t^{ij} \right) x_t^{fij} \right) - C_t^{fi}(\cdot) x_t^{fi} \right) + \lambda_t^{fi} A_{t+1}^{fi}, \quad \forall i, \forall f, \forall t$$

with $x_t^{fi} = \sum_{j \in J} x_t^{fij} = \sum_{j \in J} x_t^{ij}$. This is valid also for $t = T$ because the transversality conditions with free endpoints A_T^i are $\lambda_T^i = 0$ (see below). Firms take demand (18) as given in the model version of PetroHead utilized in the present paper; i.e., they do not increase current production in order to increase future demand.[30]

The optimal extraction path must satisfy the following necessary conditions:

(i) The Hamiltonians for each firm $i \in I$ are maximized w.r.t. x_t^{ij} for all *t*. The Hamiltonians are concave in x_t^{ij}, so x_t^{ij} solves:

$$(25) \qquad \left(\delta^i\right)^{t-1} \left(P_t^{fj}(\cdot) + \theta_i \frac{\partial P_t^{fj}(\cdot)}{\partial x_t^{ij}} x_t^{ij} - w_t^{ij} - \left(1 + \frac{\partial C_t^i(\cdot)}{\partial x_t^{ij}} \right) C_t^i \right) + \lambda_t^i \frac{\partial A_{t+1}^i}{\partial x_t^{ij}} \leq 0, \quad \forall i, \forall j, \forall f, \forall t$$

with = (<) for $x_t^{ij} > (=) 0$.

(ii) The adjoint functions solve the following equations for each firm $i \in I$:

$$(26) \qquad \lambda_{t-1}^i = \frac{\partial H_t^i}{\partial A_t^i} = -\left(\delta^i\right)^{t-1} \frac{\partial C_t^i(\cdot)}{\partial A_t^i} x_t^i + \lambda_t^i, \quad \forall i, \forall t$$

(iii) The transversality conditions with free A_T^i are:

$$(27) \qquad \lambda_T^i = 0, \quad \forall i$$

(iv) The extraction path must be admissible, i.e. $x_t^{ij} \geq 0$ and the state variable equations (23) holds.

The Hamiltonian is strictly concave in $\left(x_t^{ij}, \mathrm{A}_t^i\right)$. Thus, the solution satisfying conditions (25) to (27) solves the firms maximization problem (24).[31]

---

[30] Model experimentation suggests that this effect, relevant to firms with market power only, is very small and substantially increase computational complexity.

[31] The requirement that H(·) is concave in $\left(x_t^{ij}, \mathrm{A}_t^i\right)$ is stronger than necessary, see, e.g., Sydsæter et al (2008).

B1.3 Equilibrium

The full market equilibrium is the unique solution to equations (20) to (23) and (25) to (27). The solution is not sensitive to the number of periods $n^T\!=\!100$ used in the model run.

B2. Model estimation and calibration

The demand side in the numerical model is estimated in terms of natural logarithms:

$$\ln D_t^{fj} = \ln \beta_0^{fj} + \beta_y^{fj} \ln \mathrm{G}_t^j + \beta_d^{fj} \ln D_{t-1}^{fj} + \sum_{f \in F} \beta^{fj} \ln P_t^{fj}, \quad \forall f, \forall j, \forall t$$

This demand function is estimated for each fuel in each region using yearly prices and quantities from IEA (2014) for the period 1990 to 2013, see tables B1 to B4. The associated output from *Stata* (statistical software) is available on request. The Dickey-Fuller unit root test suggests that the residuals are stationary, suggesting that the non-stationary variables are cointegrated (as do the Johansen test for cointegration). Future demand is calibrated to match the projections in the International Energy Agency (IEA) World Energy Outlook 2014 (IEA, 2014).

We calibrate c_1^{fi} such that marginal costs (including approximate resource rent) equals price when price and production is the average of the year interval 2004-2013.[32] Further, c_2^i is calibrated such that unit cost doubles when production is 25 percent above capacity at $A_t^i = 0$. Last, we calibrate c_3^i such that unit cost doubles when accumulated production equals proven reserves (fetched from BP, 2014). The exogenous parts of future production and gas transport capacities are calibrated to match the projections in the IEA World Energy Outlooks from 2012 and 2014 (IEA, 2012, 2014). We set yearly exogenous technological growth c_4^i low because technology growth is captured by the exogenous part of yearly production capacity calibrated using IEA (2014).

The tables below use the following legend: demand side: R1 = OECD America, R2 = The European Economic Area (EEA), R3 = Rest Europe and Eurasia, OECD R4 = Asia and Oceania, R5 = Non-OECD Asia, R6 = Rest of world. Supply side oil: Oil1 = OECD America, Oil2 = EEA, Oil3 = OPEC, Oil3 = Rest of world; supply-side gas: Gas1 = OECD America, Gas2 = EEA, Gas3 = Rest Europe and

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[32] Supply cost is not equal to production cost in the calibration, because the resource rent is endogenous. Supply costs equal price perfectly in the model runs.

Eurasia, Gas4 = Asia pacific, Gas5 = Rest of world; supply-side coal: Coal1 = EEA, Coal 2 = Rest of world; supply-side biofuels: Bio = global biofuels producer.

Table B1. Constant term in fuel demand ($\ln \beta_0^{fj}$) *

	R1	R2	R3	R4	R5	R6
Oil	0.743	-1.657	-2.791	0.331	-0.176	1.156
Gas	-3.260	-7.271	0.514	-0.626	-0.874	-3.826
Coal	4.582	-1.901	-0.831	-0.574	-0.356	0.888

*Parameter values differ slightly from the empirically estimated coefficients for some regions to improve fit in model runs against history (with model generated endogenous prices).

Table B2. Primary energy demand (GDP*energy intensity) elasticity (β_y^{fj})

	R1	R2	R3	R4	R5	R6
Oil	0.483	0.699	1.188	0.218	0.121	0.318
Gas	0.876	1.235	0.182	0.139	0.237	0.992
Coal	0.266	0.395	0.530	0.277	0.160	0.291

Table B3. Demand elasticity in demand last year (autoregressive coefficient in demand function, β_d^{fj})

	R1	R2	R3	R4	R5	R6
Oil	0.396	0.499	0.082	0.732	0.905	0.522
Gas	0.473	0.684	0.711	0.972	0.849	0.461
Coal	0.000	0.851	0.462	0.696	0.887	0.337

Table B4. Short long run price elasticities (β^{fj})*

	R1	R2	R3	R4	R5	R6
Oil- Oil	-0.060	-0.050	-0.092	-0.035	-0.021	-0.048
Oil to Gas	0.006	0.005	0.009	0.003	0.001	0.005
Oil to Coal	0.006	0.005	0.009	0.003	0.001	0.005
Gas to Oil	0.045	0.003	0.003	0.000	0.002	0.005
Gas to Gas	-0.096	-0.032	-0.003	-0.022	-0.026	-0.054
Gas to Coal	0.005	0.024	0.003	0.000	0.002	0.005
Coal to Oil	0.010	0.001	0.005	0.003	0.001	0.007
Coal to Gas	0.010	0.035	0.005	0.134	0.001	0.036
Coal to Coal	-0.100	-0.086	-0.005	-0.096	-0.011	-0.066

*Some values have been increased relative to empirically estimated coefficients (the model needs strictly negative price elasticities in order to solve and/or produce reasonable results). We use -0.1 as an upper limit for long run own price elasticities in the numerical simulation, and 0.01 as a lower limit for the other price elasticities.

Table B5. Implied long run price elasticities.

	R1	R2	R3	R4	R5	R6
Oil to oil	-0.10	-0.10	-0.1	-0.13	-0.22	-0.1
Oil to Gas	0.01	0.01	0.01	0.01	0.01	0.01
Oil to Coal	0.01	0.01	0.01	0.01	0.01	0.01
Gas to Oil	0.08	0.01	0.01	0.01	0.01	0.01
Gas to gas	-0.18	-0.10	-0.1	-0.76	-0.17	-0.1
Gas to Coal	0.01	0.08	0.01	0.01	0.01	0.01
Coal to Oil	0.01	0.01	0.01	0.01	0.01	0.01
Coal to Gas	0.01	0.23	0.01	0.44	0.01	0.1
Coal to coal	-0.10	-0.58	-0.1	-0.32	-0.10	-0.1

Table B6. Parameters in producer cost functions.*

	Oil1	Oil2	Oil3	Oil4	Bio	Gas1	Gas2	Gas3	Gas4	Gas5	Coal1	Coal2
C_1	108.98	55.98	80.98	85.98	115.98	34.95	42.78	80.78	72.78	88.78	21.65	31.65
C_2	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
C_3**	0.06	0.95	0.01	0.06	-0.09	0.19	0.61	0.04	0.15	0.02	0.00	0.00
C_4**	-2.50	-2.50	-2.50	-2.50	-2.50	-2.50	-2.50	-2.50	-2.50	-2.50	-2.50	-2.50
ψ	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
δ	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
ϑ	0	0	0.5	0	0	0	0	0	0	0	0	0

*The $n^j \times n^i$ transport costs matrix (c_5) is omitted due space considerations. It is available from the authors on request.
**Divide by 1000 to get model value.

B3. Model fit to history

We test the model fit by running the model from 1991. This section presents figures showing model projections and historic figures for the period 1991 – 2012.

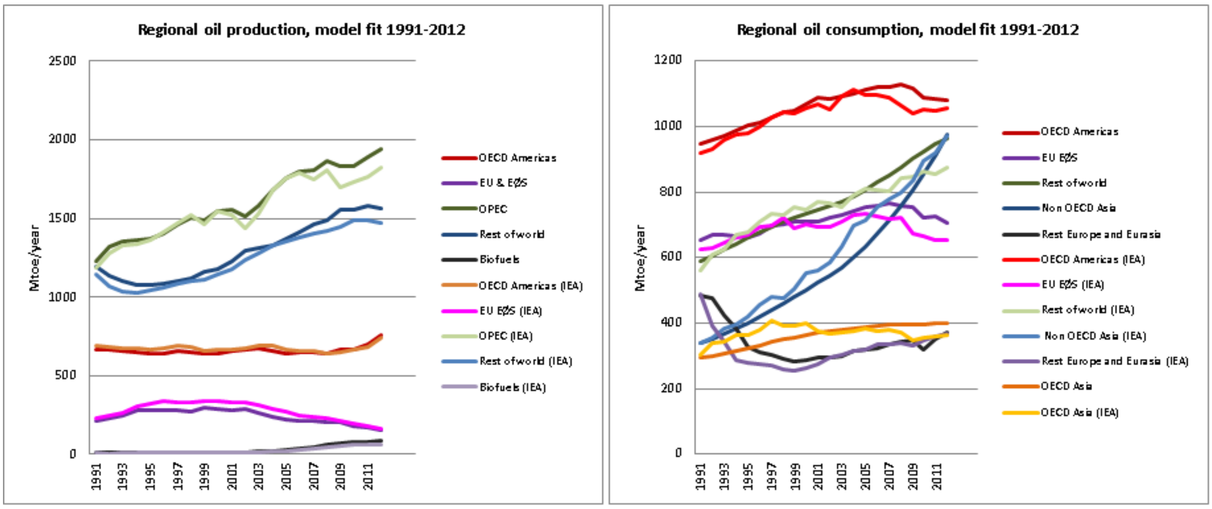

Figure B1. Model fit oil market: Endogenous paths against history figures (EIA extended energy balances database, visited October 2014) for the period 1992 to 2012.

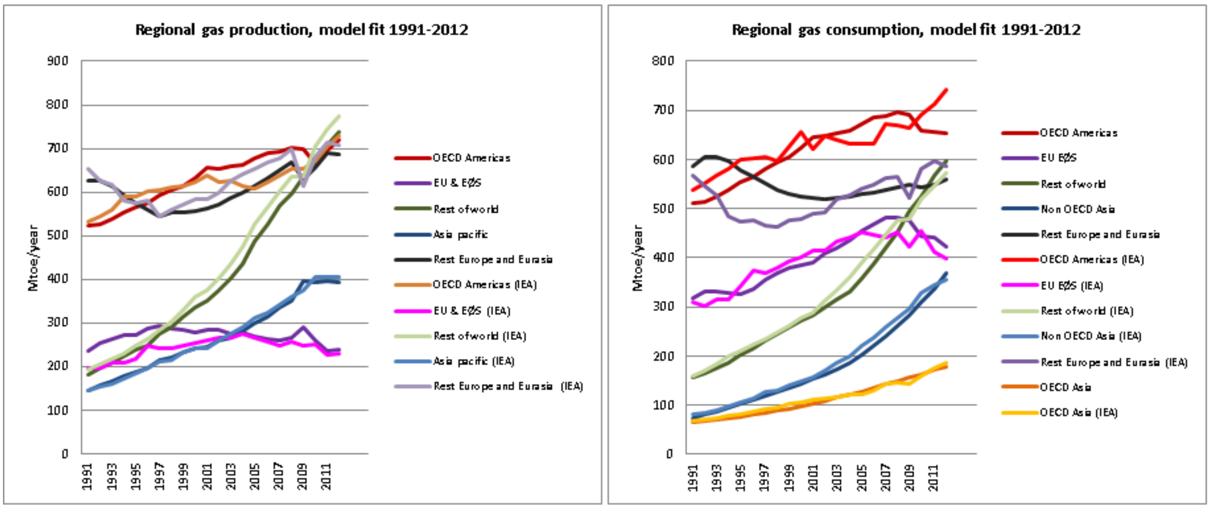

Figure B2. Model fit gas market: Endogenous paths against history figures (EIA extended energy balances database, visited October 2014) for the period 1992 to 2012.

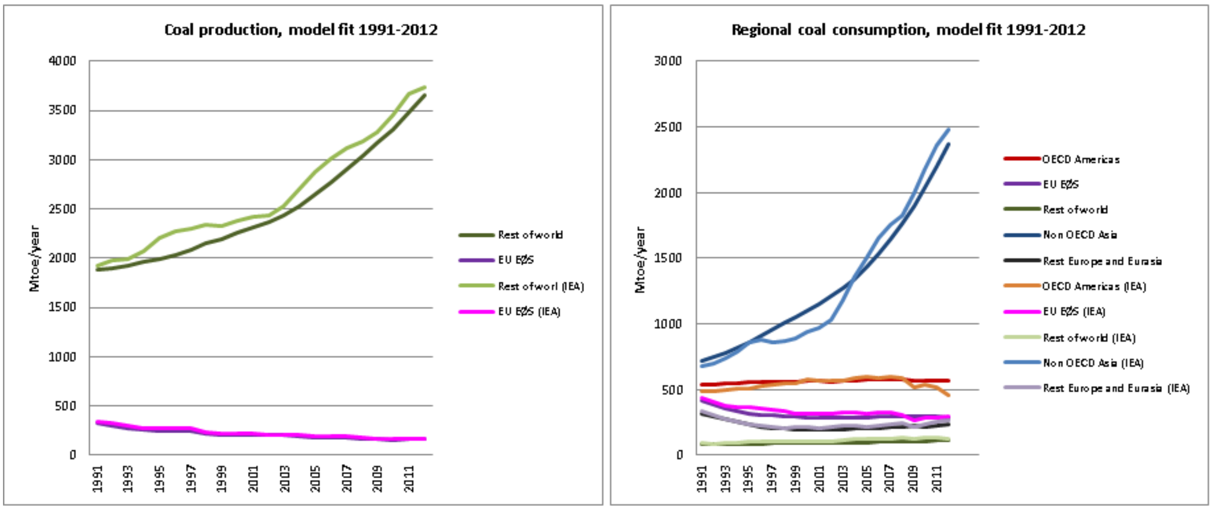

Figure B3. Model fit coal market: Endogenous paths against history figures (EIA extended energy balances database, visited October 2014) for the period 1992 to 2012.

B4. Selected results from gas and coal markets in IWG SCC simulation

In this appendix we briefly present results from the gas and coal markets. The climate policy has relatively large effect on the coal market because coal is very emissions intensive, implying higher taxes on coal per energy equivalent. Indeed, the coal tax forces EEA coal production to a halt in 2060 in the IWG simulation. Further, the relative price increase is much larger on coal than on gas, causing EEA consumers to substitute away from coal and to gas. That is, EEA gas consumption increases due the environmental policy (see Figure 5B).

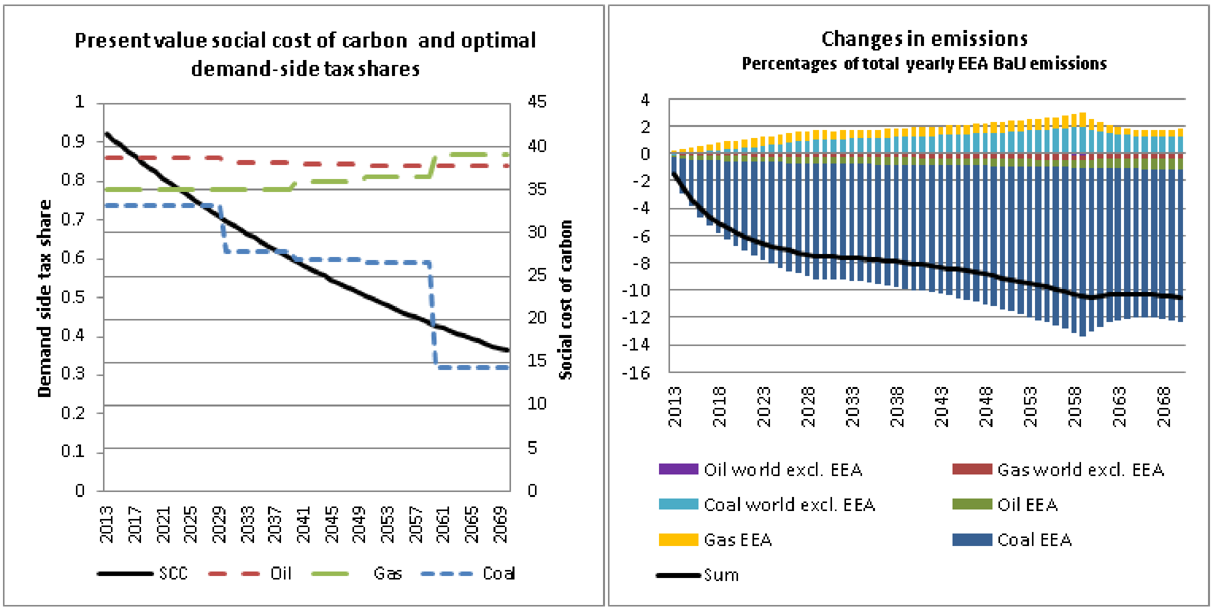

Figure B4. Optimal tax trajectories and the IWG social cost of carbon. The right hand picture shows changes in emissions relative to BaU.

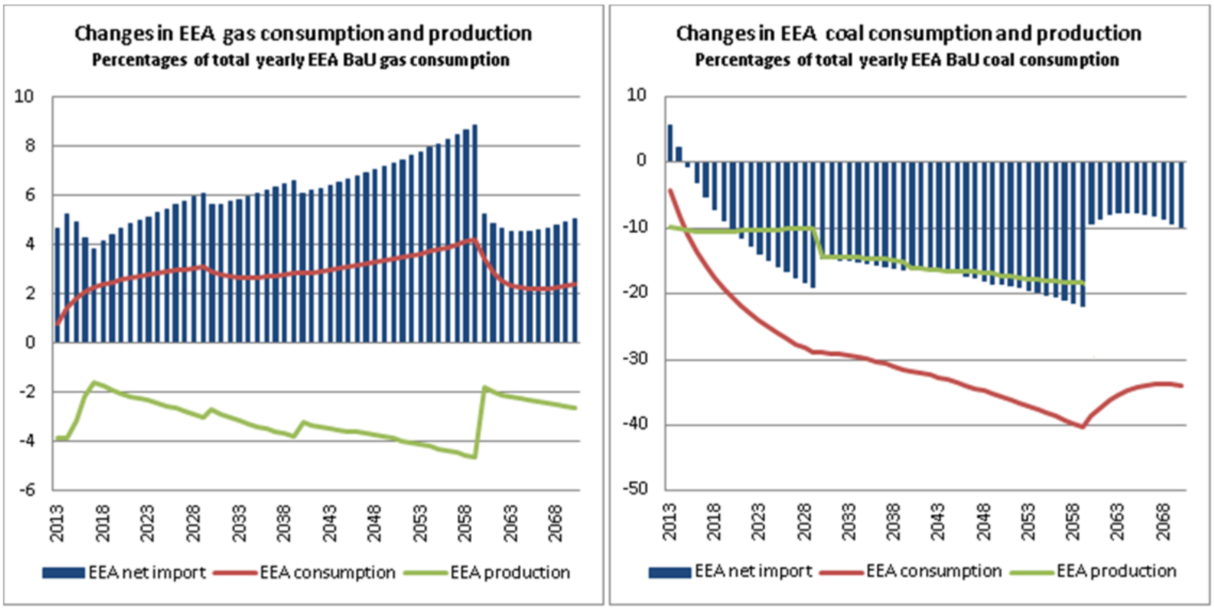

Figure B5. Changes in yearly EEA gas and coal consumption, production and net imports following the IWG tax trajectory (relative to BaU). EEA coal production ends in 2060 in the IWG simulation.

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