Regional Carbon Policy in a Global Economy*

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Abstract

Climate policy by a coalition of countries can shift economic activity elsewhere via trade. We derive a coalition's optimal Pareto-improving policy in such an environment. The policy can be implemented by: (i) taxing fossil-fuel extraction at a rate equal to the global marginal harm from CO_2 emissions, (ii) taxing imports of energy and goods, while rebating the tax on exports of energy, but not goods, at a lower rate per unit of carbon than the extraction tax rate, and (iii) subsidizing exports of goods to expand the export margin. The optimal policy generates first-order welfare improvements over current and proposed climate policies.

Keywords: carbon taxes, border adjustments, leakage, climate change
JEL Codes: F18, H23, Q54

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1 Introduction

Current approaches to addressing climate change vary widely by country or region and are likely to do so for the indefinite future. Widely varying climate policies, however, may create incentives to shift the location of taxed or regulated activities to jurisdictions with lax policies. Often expressed in terms of leakage–the increase in emissions abroad because of climate policies at home–these effects have the potential to undermine domestic climate policies and possibly deter countries from enacting climate policies in the first place.

To understand the design of regionally differentiated climate policies, we consider a general equilibrium model of trade and climate change that captures the core elements of the problem but is still simple enough to provide analytical insights. Two countries extract and trade fossil fuels, which are combusted to produce goods, creating a global externality via CO_2 emissions. They trade goods based on comparative advantage, as in Dornbusch, Fisher, Samuelson (1977, henceforth DFS). Consumers in each country purchase and consume goods and energy. We solve the model following Costinot, Donaldson, Vogel, and Werning (2015, henceforth CDVW) to find the optimal allocation when one region of the world imposes a climate policy and the rest of the world is passive, and then find taxes and subsidies that implement the optimal allocation in a decentralized market.

The optimal unilateral policy has three components. First, it imposes carbon prices on both the supply of fossil-fuels and the demand for fossil fuels or for goods produced with fossil fuels. This mix of taxes balances supply-side and demand-side responses in foreign energy markets, thereby controlling what is sometimes called *indirect* leakage.[1] Second, the optimal policy imposes a border tax on the carbon content of imported goods that leaves the extensive margin of imports the same as in the business as usual world. The optimal policy does not, however, include a rebate of taxes for exports of goods that would leave the extensive margin of exports unchanged. Instead, the third component is a subsidy for exports that expands the export margin. The border tax on imports combined with the subsidy for exports more than eliminate *direct* leakage, instead shifting production of goods onshore.

[1]The literature on carbon leakage, for example Böhringer, Lange, and Rutherford (2014) and Fontagné and Schubert (2023), has distinguished two channels of leakage. The first, referred to as the competitiveness channel or *direct* leakage, refers to the change in the location of production due to the change in the relative price of carbon emissions. The second, referred to as the fuel price effect or *indirect* leakage, is the change in foreign emissions due to the change in the price of energy.

To compare the optimal policy to existing or commonly proposed policies, we solve the model with restrictions on the choice of instruments, so that the constrained optimum mimics those policies (e.g., a constraint that makes the solution be a price on emissions from domestic production as in the EU Emissions Trading System). We then calibrate a version of the model to compute quantitative differences between the optimal and the constrained policies. In our base calibration, OECD countries impose a climate policy and the rest of the world does not. We find substantial gains from imposing the optimal policy, or close variants, over more traditional policies. To test the robustness of these results, we consider a number of other coalitions as well as alternative parameter values. Finally, to understand how renewables might change our results, we extend the model to include many types of energy, and compute a quantitative version of the extended model.

The paper proceeds as follows. The remainder of this section describes our approach as it relates to the prior literature and our results as they relate to existing and proposed policies. Section 2 lays out the model. Section 3 solves the primal problem of a planner designing an optimal unilateral carbon policy. Section 4 derives a set of taxes and subsidies that implement this policy. Section 5 derives the policies that the planner would impose when further constrained in the activities it can control. We explore the quantitative implications of these policies in Section 6, using a calibrated version of the model. Section 7 extends the analysis to include many types of fuels, and renewable energy. Section 8 concludes.

1.1 Model Structure and Prior Literature

Markusen (1975) considers a two-country model where pollution by one country harms both. While Markusen was concerned with local pollution, we interpret his model as one of extraction and consumption of fossil fuels, the use of which generates CO_2 emissions, harming both countries. One country, Home, imposes a policy to address the CO_2 emissions, taking into account that fossil fuels are traded. The other country, Foreign, is passive.

Home's optimal policy in this setting is a Pigouvian tax on the extraction of fossil fuels at a rate equal to the domestic marginal harm from emissions (that is, the domestic social cost of carbon). This tax is combined with either a tariff on imports of fossil fuels (if Home is an importer) or a partial tax rebate on exports (if Home is an exporter), which together constitute a border adjustment. The border adjustment shifts a portion

of the tax downstream from extraction of fossil fuels to their consumption. A key but often overlooked aspect of Markusen's result is that the border adjustment is typically at a lower rate than the underlying Pigouvian tax, leaving some of the tax on the supply of fossil fuels.[2]

A limitation of Markusen's model for studying climate policy is that with no explicit representation of how fossil fuels are used to produce tradable goods, it cannot capture direct leakage caused by the shifting of such production to regions with lax policies. Direct leakage, however, is thought to be central to the design of climate policy.[3]

To understand how policies contend with direct leakage, we incorporate production of goods using fossil fuels. These goods are traded based on comparative advantage following a DFS structure. As a result, a tax on the use of fossil fuels in production can lead to shifts in comparative advantage, generating direct leakage. To steer clear of terms-of-trade considerations unrelated to climate, we restrict policies to those that do not make Foreign worse off, as in Böhringer, Lange, and Rutherford (2014).

Hoel (1996), Keen and Kotsogiannis (2014), Staiger (2022), and Kruse-Andersen and Sørensen (2024) also include some of these features in more stylized settings. There are two key differences between these studies and ours. First, we add additional structure, including trade driven by comparative advantage (DFS), to develop sharper results. Second, some of these models restrict the choice of policies the planner is allowed to consider. In particular, except for Kruse-Andersen and Sørensen (2024), the models do not allow the planner to control emissions intensity, a common feature of environmental policies throughout the world (e.g., the Corporate Average Fuel Economy standards, appliance efficiency standards, and many building codes).[4]

There is also a large body of work using CGE models to study regionally-differentiated

[2]The intuition for this result, developed in Hoel (1994) in the climate context, is that by choosing the mix of supply-side and demand-side taxes, Home is able to control the price of fossil fuels in Foreign to limit indirect leakage. Keen and Kostsogiannis (2014), Fæhn et al. (2017), and Weisbach et al. (2023) extend this result to more general settings.

[3]Typical estimates of leakage (both direct and indirect) are in the range of 5% to 25% on an economy-wide basis, as a fraction of policy-induced reductions at Home. For example, Böhringer et al. (2012) commissioned 12 modeling groups to study leakage using common datasets and scenarios. They find leakage in the range of 5% to 19% for a tax in Kyoto Protocol Annex B countries that reduces emissions by about 9.5%. A number of studies examine energy-intensive and trade-exposed industries, where leakage is expected to be the highest (e.g., Fowlie et al (2016)).

[4]Kruse-Andersen and Sørensen (2024), written contemporaneously with this paper, consider a model where firms can relocate abroad to avoid domestic carbon policies, focusing on the case where Home cannot impose border adjustments (for example because of legal restrictions on trade barriers). Some of their results parallel those found here, including a location subsidy that is similar to our export subsidy.

carbon taxes.[5] These models include a high level of detail and allow the modeler to consider many different policies and outcomes. They require, however, that the modeler choose the policies to study, which means that they cannot tell us which policies are optimal, nor do they provide transparent intuitions for their results. To our knowledge, all of these models constrain the set of policy choices under consideration. Most consider taxes on production, sometimes in combination with border adjustments that fully shift those taxes downstream to consumption. We are not aware of any that examine Markusen's recommendation to combine prices on both sides of the market by taxing extraction as well as production and consumption.

In a recent contribution, Farrokhi and Lashkaripour (2025) consider optimal policies within a model sharing some of the richness of CGE models. A key contribution of their analysis is to endogenize the size of the coalition implementing climate policy, thus building on the climate-clubs idea of Nordhaus (2015).

1.2 Key Results

We solve our model in the primal using CDVW. We give the planner control over all activities in Home including domestic energy extraction, the energy intensity of production of goods, imports and exports (including both the intensive and extensive margins of trade in goods), and domestic consumption. The planner cannot directly control Foreign's extraction, Foreign's production of goods for consumption there, and Foreign's choice of what exports to buy from Home.

Because the planner takes climate externalities into account and Foreign does not, the planner's valuation of the extraction and use of energy will be different from Foreign's. These differences generate three wedges, all defined to be positive: (i) the *extraction wedge* between the value that the planner and Foreign place on extracting a unit of energy, (ii) the *consumption wedge* between the value that the planner and Foreign place on using a unit of energy, and (iii) the *export wedges* between the shadow cost to the planner of goods produced in Home and delivered to Foreign and their marginal utility to Foreign consumers. The extraction wedge and the consumption wedge sum to the global marginal harm from emissions, or the *Pigouvian wedge* between the value the planner places on using and on extracting a unit of energy. The relative magnitude of the extraction and consumption wedges depends on the price of energy

[5] Branger and Quirion (2014), Elliott et al. (2013), Zhang (2012), and Metz et al. (2007) all provide surveys of these studies.

seen by Foreign.

Home's optimal policy has three components, reflecting these wedges.

1. Similar to Markusen (1975), the planner sets Home's net exports of energy, and hence the global price of energy, to balance the extraction wedge on the supply side and the consumption and export wedges on the demand side, taking account of Foreign responses to a change in the energy price. By balancing supply and demand-side effects this way, the planner reduces the cost of indirect leakage.

2. Because of the consumption wedge, the planner requires Foreign producers supplying imports to use the same low energy intensity as Home producers. As a result, Home's extensive margin of imported goods remains unchanged from the no-policy equilibrium, eliminating direct leakage from increased imports by Home.

3. Because of the export wedges, Home expands the extensive margin of exported goods relative to the no-policy equilibrium, crowding out Foreign production (for consumption there) and replacing it with goods produced with lower energy intensity in Home. This policy more than offsets direct leakage from reduced exports by Home.

There are a number of taxes and subsidies that implement this policy in a decentralized equilibrium and that match up with these wedges. The simplest and most intuitive is as follows: (i) a domestic carbon tax on the extraction of energy at a *nominal* rate equal to the Pigouvian wedge; (ii) a border adjustment on imports and exports of energy, at a rate equal to the consumption wedge (which we call a "partial border adjustment" because it is at a lower rate than the underlying nominal extraction tax); (iii) the same partial border adjustment on the energy content of imports (but leaving the tax on exports); and (iv) subsidies to expand the range of low-carbon exports from Home, equal to the export wedges.[6] While the nominal extraction tax is at the Pigouvian rate, the partial border adjustment shifts a portion of it equal to the consumption wedge downstream to production or consumption, leaving the *effective* extraction tax equal to the extraction wedge.

[6]The subsidy for exports is reminiscent of the export policy suggested by Fisher and Fox (2012) as it offers export rebates without removing the domestic carbon tax. It differs from Fisher and Fox, however, in that the policy seeks to expand the export margin rather than merely to maintain it.

1.3 Comparison to Existing and Proposed Policies

Although our results emerge from optimality conditions in a stylized model, they connect surprisingly closely to actual or proposed policies. For example, the EU ETS has been augmented with a border tax on imports (the Carbon Border Adjustment Mechanism or CBAM) but does not remove the carbon price on exports. In this respect, it mimics the optimal policy. The EU does not, however, directly subsidize exports as in the optimal policy, but it approximates this policy by freely allocating permits to producers in energy-intensive, trade-exposed industries (although this policy is being phased out as CBAM is implemented).

The California Cap-and-Trade Program does not impose an import tariff but does provide a free allocation of permits that has elements of the export subsidy seen in the optimal policy. It provides permits to producers based on an industry-wide benchmark multiplied by their output level. While not tied to exports or comparative advantage, this allocation effectively removes the carbon price on average but leaves it on the margin, a feature of the optimal export subsidy.

While we are not aware of actual policies that split the carbon price between the supply and demand for fossil fuel, doing so requires only ministerial changes to many carbon tax proposals. In particular, many carbon tax bills in U.S. Congress impose the carbon price on domestic extraction and include border adjustments on imports and exports of energy to shift the tax downstream to production. Lowering the border adjustment rate—that is changing a single number—would leave a portion of the price on extraction, as in the optimal policy.

2 Basic Model

We divide the world into separate regions, Home and Foreign, treated like two countries. A planner optimizes Home's carbon policy knowing that Foreign responds to market prices with no policy of its own.

Regions are endowed with energy deposits, E and E^*, and labor, L and L^* ($*$ means Foreign). Production takes place in two stages. First, energy is extracted from deposits using labor and is traded at a global price p_e. Second, final goods are produced by combining labor and energy and are then traded subject to frictions. Services, the numéraire, are provided with labor and freely traded. Labor is perfectly mobile across

sectors within a region.[7] Energy is used in production and also consumed directly.

As in DFS, goods come in a continuum, $j \in [0,1]$, with regions specializing in production based on comparative advantage. Welfare in each region is increasing in consumption of energy, goods, and services while decreasing in global energy use, the source of the global externality motivating Home's carbon policy.

2.1 Preferences

Home welfare is additively separable in consumption of services, C_s, consumption of individual goods, c_j, direct consumption of energy, C_e^d, and a climate externality:

$$U = C_s + \int_0^1 u(c_j)dj + v(C_e^d) - \varphi Q_e^W, \tag{1}$$

with u and v increasing concave functions. The parameter φ governs the cost to Home of damages from global carbon emissions, Q_e^W. Foreign preferences, U^*, take the same form, with u^*, v^*, and φ^*.[8] The global social cost of carbon is $\varphi^W = \varphi + \varphi^*$.

2.2 Technology

Deposits of energy differ by the labor required to extract the fossil fuel, with quantity $E(a)$ attainable in Home at a unit labor requirement below a. Tapping all deposits with $a \leq a(Q_e)$ yields $Q_e = E(a(Q_e))$. Foreign extraction from deposits $E^*(a)$ follows the same principle, with $Q_e^W = Q_e + Q_e^*$.[9] Energy is either consumed directly or used as an intermediate input by the goods sector.

Any good j can be produced in quantity q_j by combining energy E_j and labor L_j in a standard production function with constant-returns, so that:

$$q_j = \frac{1}{a_j} f(k_j) L_j, \tag{2}$$

[7] What we call labor should be interpreted as a combination of labor and capital, employed in each of the three sectors.

[8] Our assumption of quasi-linear preferences greatly simplifies the analysis of trade policy, as in Grossman and Helpman (1994). To ensure that the marginal utility of income is 1 we assume $C_s > 0$ and $C_s^* > 0$, a condition that is easily checked.

[9] We equate energy with a homogeneous fossil fuel measured by its carbon content. All energy that is extracted is combusted, so that global carbon emissions equal global extraction. (The exception is in Section 7 where we introduce multiple energy sources, including renewables.) Since energy is costly to extract, we set $E(0) = E^*(0) = 0$. For analytical tractability we assume that $E(a)$ is differentiable, with $E'(a) > 0$ and $E^{*\prime}(a) > 0$.

where a_j (a_j^* in Foreign) is the unit input requirement, $k_j = E_j/L_j$ is energy intensity, and $f(k)$ is the intensive form of the production function, increasing and concave. While k_j may vary, we treat f as common across goods and regions.

Services, in quantitites Q_s and Q_s^*, are provided in both regions at a unit labor requirement of 1.[10]

2.3 International Trade

Home and Foreign can trade services for energy at price p_e (quantity of services per unit of energy). Trade in manufactured goods follows DFS. Goods are ordered by Home comparative advantage:

$$\frac{a_j^*}{a_j} = A(j), \tag{3}$$

with $A(j)$ continuous and strictly decreasing, $A(0)$ arbitrarily large, and $A(1) = 0$.[11] Goods trade incurs iceberg costs $\tau \geq 1$ and $\tau^* \geq 1$ so that the overall unit input requirement is τa_j if Home exports good j and $\tau^* a_j^*$ if Home imports it.

2.4 Labor and Energy Requirements

Energy intensity may depend on where a good is produced and on where it will be shipped. We therefore distinguish Home exports, x_j, Home production for domestic consumption, y_j, Home imports, m_j, and Foreign production for domestic consumption, y_j^*, delivering $c_j = y_j + m_j$ and $c_j^* = y_j^* + x_j$. The corresponding energy intensities are k_j^i, for $i \in \{x, y, m, y^*\}$.[12]

At energy intensity k, the production function (2) gives Home's unit labor and energy requirements for good j:

$$l_j(k) = a_j/f(k); \qquad e_j(k) = kl_j(k) = \frac{a_j k}{f(k)}. \tag{4}$$

[10]We assume that labor endowments in Home and Foreign are each large enough to guarantee an active services sector so that Q_s and Q_s^* are strictly positive. Since services are the numéraire, the competitive-equilibrium wage in Foreign is $w^* = 1$.

[11]These assumptions on $A(j)$ simplify the analysis of goods trade. To simplify aggregation across goods, we assume that a_j and a_j^* are also continuous functions.

[12]Because Foreign can set k_j^{y*} independently from how it sets k_j^m, we do not include a so-called Brussels effect, as suggested by Bradford (2020).

Replacing a_j with a_j^* we get Foreign's unit input requirements, $l_j^*(k)$ and $e_j^*(k)$.[13] These unit labor and energy requirements scale with trade costs for goods shipped abroad.

2.5 Carbon Accounting

Energy embodying carbon is extracted in one or both regions and possibly traded. Carbon is released when the energy is directly consumed (say, heating a house) or used to produce a good. Goods embodying carbon are also traded before the carbon is consumed indirectly by households. We can trace carbon from where it's extracted, to where it's released into the atmosphere, and to where it's directly or indirectly consumed.

We define G_e as direct consumption of energy in Home plus intermediate demand for energy by Home goods producers. Home net exports of energy (Foreign net imports), which may be positive or negative, are $Q_e - G_e = G_e^* - Q_e^*$, accounting for the first level of trade in carbon.

The second level of trade in carbon is embodied in goods. The 2×2 matrix in the upper left of Table 1 depicts the implicit bilateral flows of carbon. Rows indicate the location of consumption and columns the location of production. For example, indirect consumption of carbon in Home is the sum of carbon released by producers in Home serving the local market, C_e^y, and carbon released by Foreign producers in supplying Home imports, C_e^m. The first row of the middle column constructs C_e^m by aggregating over goods the product of (i) the quantity imported by Home, (ii) the unit energy requirement (a function of energy intensity), and (iii) the trade cost. Adding direct consumption, C_e^d, to indirect consumption gives overall consumption, C_e, in Home, shown in the upper right. Just below is overall consumption of carbon in Foreign, C_e^*.

2.6 Efficient Production

Let p denote either the global price of energy p_e or the planner's shadow value of energy λ_e (introduced below). The optimal energy intensity for good j is then:

$$k(p) = \arg\min_k \{l_j(k) + pe_j(k)\} = \arg\min_k \left\{ \frac{1}{f(k)} + p\frac{k}{f(k)} \right\}, \tag{5}$$

[13] Since emissions are proportional to energy use, our *unit energy requirement* is sometimes called *emissions intensity* in the environmental economics literature, e.g. Shapiro and Walker (2018). We instead use the terms *energy intensity* or *carbon intensity* for energy per worker, k, by analogy to *capital intensity* for capital per worker in the macroeconomics literature.

Table 1: Carbon Account

	Home	Foreign	Total
Home	$C_e^y = \int_0^1 e_j(k_j^y) y_j dj$	$C_e^m = \int_0^1 \tau^* e_j^*(k_j^m) m_j dj$	$C_e = C_e^y + C_e^m + C_e^d$
Foreign	$C_e^x = \int_0^1 \tau e_j(k_j^x) x_j dj$	$C_e^{y*} = \int_0^1 e_j^*(k_j^{y*}) y_j^* dj$	$C_e^* = C_e^x + C_e^{y*} + C_e^{d*}$
Total	$G_e = C_e^y + C_e^x + C_e^d$	$G_e^* = C_e^m + C_e^{y*} + C_e^{d*}$	$G_e^W = C_e^W = Q_e^W$

with $k(p)$ decreasing in p. Given p, the same $k(p)$ applies to all goods j in Home and Foreign since, aside from a_j and a_j^*, the production function is everywhere the same.[14] Unit shadow costs of production are $a_j g(p)$ and $a_j^* g(p)$, where $g(p) = (1+pk(p))/f(k(p))$. By Shepard's lemma, unit energy requirements are $e_j = a_j g'(p)$ and $e_j^* = a_j^* g'(p)$. Energy cost as a share of production costs is thus $\epsilon_g(p) = pg'(p)/g(p)$, or the elasticity of $g(p)$.[15]

2.7 Business as Usual

The competitive equilibrium of the basic model with no carbon policy, *business as usual* or BAU, is a reference point for the planning problem that follows. In BAU, the relative wage is 1 and the global price of energy is $\bar{p}_e$ (our convention throughout is that $\bar{x}$ is the BAU value of any variable x). Specialization in goods production mimics DFS. Good j is produced at cost $a_j g(\bar{p}_e)$ in Home and $a_j^* g(\bar{p}_e)$ in Foreign so that Foreign's relative cost is $A(j)$. Home consumers buy goods $j < \bar{j}_m$ from local producers and import goods $j > \bar{j}_m$, where $A(\bar{j}_m) = 1/\tau^*$. Foreign consumers buy goods $j > \bar{j}_x$ from local producers and import goods $j < \bar{j}_x$, where $A(\bar{j}_x) = \tau$. Analogs of these import and export thresholds, $\bar{j}_m$ and $\bar{j}_x$, play a key role in the planning problem.

[14] In their analysis of trade and the environment Copeland and Taylor (1994, 1995) also build on DFS, but make a restriction opposite to ours. Expressed in the notation here, they set $a_j = a$ and $a_j^* = a^*$ while allowing $f_j(k) = k^{\alpha(j)}$ to vary across goods. A hybrid of these two approaches (allowing both efficiency and energy intensity of production to vary across goods) could lead to additional insights but appears intractable.

[15] Given p, this share doesn't vary by good or by where a good is produced. Furthermore, for any good j that is traded, the fraction of energy used in transport is pinned down by iceberg costs only. For a good that Home exports, energy per unit is $\tau a_j g'(\lambda_e)$ with a fraction $(\tau - 1)/\tau$ due to transport. For a good that Home imports, energy per unit is $\tau^* a_j^* g'(p_e)$ with a fraction $(\tau^* - 1)/\tau^*$ due to transport.

3 Unilateral Planning Problem

A planner allocates the resources that it controls to maximize Home's welfare. Outcomes in Foreign (such as how much energy it extracts) are dictated by market prices. The planner is subject to three constraints: (i) labor employed in the three sectors of the economy can't exceed global labor supply; (ii) energy directly consumed plus energy used to produce goods can't exceed global energy supply; and (iii) Foreign can't be made worse off than in BAU.[16] We consider market outcomes in Foreign and the planner's constraints before stating the planning problem.

3.1 Foreign Outcomes

Energy extractors in Foreign hire labor at wage $w^* = 1$ and sell energy at price p_e. They therefore tap all energy deposits with a labor requirement below p_e:

$$Q_e^* = E^*(p_e). \tag{6}$$

Consumers in Foreign buy energy at price p_e, equating their marginal utility from direct consumption of energy to that price:

$$v^{*\prime}(C_e^{d*}) = p_e. \tag{7}$$

Goods producers in Foreign purchase energy at price p_e and hire labor at wage 1. They produce for the domestic market at energy intensity $k_j^{y*} = k(p_e)$, from (5). They can supply good j to consumers there at price $p_j^* = a_j^* g(p_e)$. This price sets an upper bound on the marginal utility of good j in Foreign:

$$u^{*\prime}(c_j^*) \leq a_j^* g(p_e) = p_j^*. \tag{8}$$

[16]This constraint on Foreign welfare requires the planner to search for a Pareto improvement over BAU. We introduce it so that the optimal unilateral policy doesn't manipulate the terms of trade. To satisfy this constraint, the planner can adjust transfers of services from Home to Foreign, subject to $C_s + C_s^* = Q_s + Q_s^*$. The planner is not constrained by trade balance.

3.2 Constraints

The global labor constraint, given the endowment $L^W = L + L^*$, is:

$$L_e^W + L_g^W + L_s^W = L^W. \tag{9}$$

Expressions for sectoral employment are in Table 2.

Table 2: Labor Account

	Home	Foreign	Total
Energy	$L_e = \int_0^{a(Q_e)} aE'(a)da$	$L_e^* = \int_0^{p_e} aE^{*\prime}(a)da$	L_e^W
Goods	$L_g = \int_0^1 \left(l_j(k_j^y)y_j + \tau l_j(k_j^x)x_j \right) dj$	$L_g^* = \int_0^1 \left(l_j^*(k_j^{y*})y_j^* + \tau^* l_j^*(k_j^m)m_j \right) dj$	L_g^W
Services	$L_s = Q_s$	$L_s^* = Q_s^*$	L_s^W
Total	$L = L_e + L_g + L_s$	$L^* = L_e^* + L_g^* + L_s^*$	L^W

The global energy constraint, given Q_e^* from (6), is:

$$G_e + G_e^* \leq Q_e + Q_e^* = Q_e^W. \tag{10}$$

Expressions for G_e and G_e^* are in Table 1. The Foreign welfare constraint, given BAU welfare of $\bar{U}^*$, is:

$$C_s^* + \int_0^1 u^*(c_j^*)dj + v^*(C_e^{d*}) - \varphi^* Q_e^W \geq \bar{U}^*. \tag{11}$$

3.3 Planner's Lagrangian

The planner seeks to maximize Home's welfare subject to Foreign outcomes and the constraints (9), (10), and (11). In effect, it maximizes global welfare, $U^W = U + U^*$, transferring services between Home and Foreign to satisfy (11). We use (9) to substitute out $C_s^W = Q_s^W = L_s^W$, apply a Lagrange multiplier λ_e to the global energy constraint (10), and drop the constants L^W and $\bar{U}^*$ to write the planner's Lagrangian as:

$$\begin{aligned} \mathcal{L} = &\int_0^1 u(c_j)dj + \int_0^1 u^*(c_j^*)dj + v(C_e^d) + v^*(C_e^{d*}) - \varphi^W Q_e^W \\ &- (L_e^W + L_g^W) - \lambda_e \left(C_e^y + C_e^m + C_e^x + C_e^{y*} + C_e^d + C_e^{d*} - Q_e^W \right). \end{aligned} \tag{12}$$

Elements of L_e^W and L_g^W are in Table 2 while elements of C_e^y, C_e^m, C_e^x, and C_e^{y*} are in Table 1. Foreign outcomes impose (6), (7), (8), and $k_j^{y*} = k(p_e)$.

For the *unilateral* optimum, the planner chooses the quantities of each good that Home consumes and each good that it exports, $\{y_j\}$, $\{m_j\}$, $\{x_j\}$, their energy intensities, $\{k_j^y\}$, $\{k_j^m\}$, $\{k_j^x\}$, energy extraction Q_e, direct consumption of energy C_e^d, and the price of energy, p_e. Choosing p_e amounts to choosing net exports of energy, $Q_e - G_e$, positive or negative. (A lower price p_e corresponds to higher net energy exports by Home.)

The Lagrangian also encompasses a number of other cases, which are determined by the resources that the planner is assumed to control. To derive the *global* optimum, we enlarge the planner's choices to include $\{y_j^*\}$, $\{k_j^{y*}\}$, Q_e^*, and C_e^{d*}.[17] Restricting the planner's choices allows us to derive simpler policies, which we explore in Section 5 and in our simulations.

We solve the unilateral optimum, starting with what CDVW call the *inner problem*, involving optimality conditions for an individual good given values for Q_e, C_e^d, p_e, and λ_e. We then solve for Q_e, C_e^d, and p_e in what they call the *outer problem*. The Lagrange multiplier adjusts to satisfy the global energy constraint.

The solution can be characterized with various wedges (defined to be non-negative) between how the planner values things relative to their market price in Foreign. For example, $\lambda_e - p_e$ is the *consumption wedge* in valuing energy, which is positive since the planner wants energy to be used sparingly. If $\varphi^W = 0$ then wedges vanish and the planner's problem matches BAU.

3.4 Inner Problem

The inner problem, for any arbitrary good j, is to maximize:

$$\begin{aligned}\mathcal{L}_j = {} & u\left(y_j + m_j\right) + u^*(y_j^* + x_j) \\ & - \left(l_j(k_j^y) + \lambda_e e_j(k_j^y)\right) y_j - \tau^* \left(l_j^*(k_j^m) + \lambda_e e_j^*(k_j^m)\right) m_j \\ & - \tau \left(l_j(k_j^x) + \lambda_e e_j(k_j^x)\right) x_j - \left(l_j^*(k(p_e)) + \lambda_e e_j^*(k(p_e))\right) y_j^*,\end{aligned}$$

subject to (8). Note that energy intensities, $k_j^i \quad i \in \{y, m, x\}$, enter the inner problem as in (5), replacing p with λ_e. It follows that the optimal values are:

$$k_j^i = k(\lambda_e), \quad i \in \{y, m, x\}.$$

[17] Of course p_e drops out of the problem in this case. Appendix A provides a step-by-step solution.

The planner chooses the same energy intensity for production of any good consumed in Home (whether produced in Home or Foreign) and for production of any good in Home (whether serving consumers in Home or Foreign). Due to the consumption wedge, it's lower than the energy intensity $k(p_e)$ used by Foreign to serve its own consumers.

The associated unit shadow costs to produce and deliver y_j, m_j, and x_j are $a_j g(\lambda_e)$, $\tau^* a_j^* g(\lambda_e)$, and $\tau a_j g(\lambda_e)$, so that the inner problem simplifies to:

$$\begin{aligned}\mathcal{L}_j = & \, u\left(y_j + m_j\right) + u^*(y_j^* + x_j) \\ & - a_j g(\lambda_e) y_j - \tau^* a_j^* g(\lambda_e) m_j \\ & - \tau a_j g(\lambda_e) x_j - a_j^* \left(g(p_e) + (\lambda_e - p_e) g'(p_e)\right) y_j^*,\end{aligned} \tag{13}$$

with $a_j^* g'(p_e)$ replacing $e_j^*(k(p_e))$. We maximize (13) to solve for y_j and m_j, and then x_j after imposing (8).

3.4.1 Goods for Home Consumers

The pair of first-order conditions for y_j and m_j are: (i) $u'(y_j + m_j) - a_j g(\lambda_e) \leq 0$, with equality if $y_j > 0$ and (ii) $u'(y_j + m_j) - \tau^* a_j^* g(\lambda_e) \leq 0$, with equality if $m_j > 0$. We define j_m as the good for which these two conditions hold with equality. Using (3), this import threshold satisfies:

$$A(j_m) = \frac{1}{\tau^*}. \tag{14}$$

The import threshold separates goods that Home produces for itself from those that it imports. If $j < j_m$, Home has a lower shadow cost of production, (ii) holds with a strict inequality (so that $m_j = 0$), and (i) holds with equality to determine $y_j > 0$. If $j > j_m$, Foreign has a lower shadow cost of production, (i) holds with a strict inequality (so that $y_j = 0$), and (ii) holds with equality to determine $m_j > 0$. Although Home's imports are produced in Foreign, their shadow cost depends on λ_e, not p_e. Hence, j_m equals $\bar{j}_m$, the BAU import threshold.

3.4.2 Goods for Foreign Consumers

Unlike goods for Home consumers, in which the planner chooses both y_j and m_j, for Foreign consumers the planner chooses only x_j subject to the constraint (8).

If this constraint is not binding then $y_j^* = 0$ and x_j solves $u^{*\prime}(x_j) = \tau a_j g(\lambda_e)$. This solution applies to any $j < j_s$, where j_s is the good that Home and Foreign can supply

at equal cost to Foreign consumers when energy used by Foreign producers is valued at its market price of p_e. Using (3), this threshold good satisfies:

$$A(j_s) = \tau \frac{g(\lambda_e)}{g(p_e)}. \tag{15}$$

It is apparent (by comparing to BAU) that $j_s \leq \bar{j}_x$, with a strict inequality if $\lambda_e > p_e$.

For any good $j \geq j_s$ the constraint (8) is binding so that Foreign consumption is set by $u^{*\prime}(c_j^*) = a_j^* g(p_e)$. The planner can choose $x_j = c_j^*$ thereby crowding out Foreign production. This solution applies to any $j < j_x$, where j_x is the good that Home and Foreign producers can supply at equal cost to Foreign consumers if energy used by Foreign producers is valued at the planners shadow cost of λ_e. Using (3) and the formulation of cost in the last line of (13), this threshold good satisfies:

$$A(j_x) = \tau \frac{g(\lambda_e)}{g(p_e) + (\lambda_e - p_e) g'(p_e)}. \tag{16}$$

For goods $j > j_x$ the planner chooses $x_j = 0$ with $y_j^* = c_j^*$.[18]

As illustrated in Figure 1, the thresholds j_s and j_x divide the continuum of goods into three intervals. Interval 1 is goods $j < j_s$ where Home's comparative advantage is strongest. Home exports these goods in quantities that equate Foreign's marginal utility to Home's shadow cost of supply. Interval 2 is goods $j_s \leq j < j_x$ for which Home's comparative advantage is moderate. Home exports these goods at the minimum quantities sufficient to deter Foreign from producing them for itself. Interval 3 is goods $j > j_x$ for which Home's comparative advantage is weakest. Foreign produces these goods for itself.

Interval 2 implies a set of *export wedges*, $s_j = \tau a_j g(\lambda_e) - a_j^* g(p_e)$, between the shadow cost of Home producing and delivering these goods and Foreign's own cost, equal to its marginal utility of consuming them. The export wedge, relative to Foreign

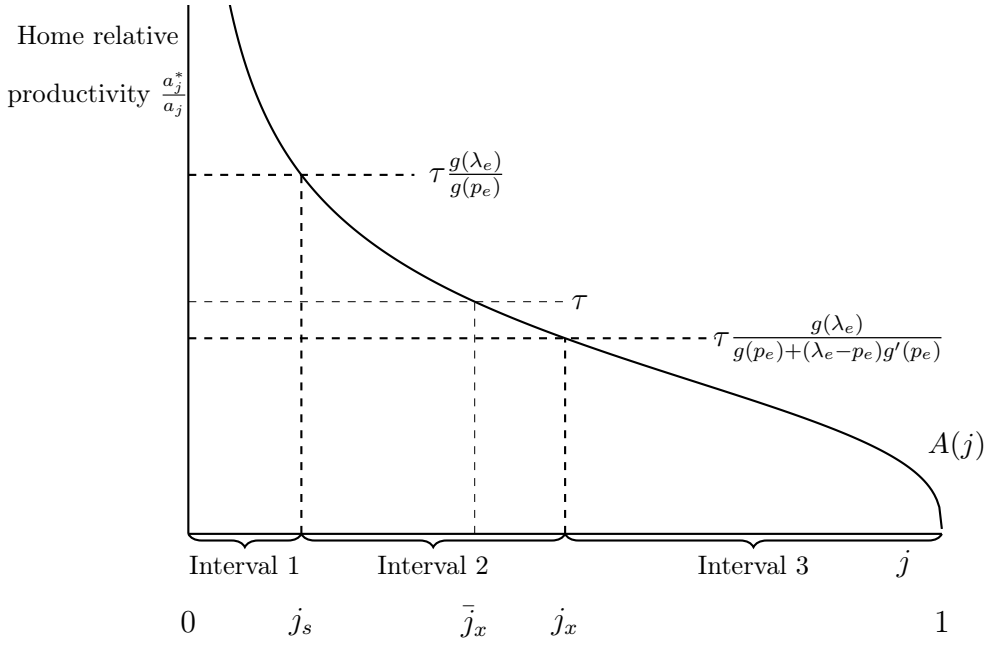
[18] More formally, when (8) is binding, the derivative of (13) with respect to x_j becomes:

$$\partial \mathcal{L}_j / \partial x_j = -\tau a_j g(\lambda_e) + a_j^* g(p_e) + (\lambda_e - p_e) a_j^* g'(p_e),$$

which is positive at $j = j_s$. This derivative is decreasing in j and hits zero when j reaches j_x. Therefore, the inner Lagrangian is maximized at the corner solutions $x_j = c_j^*$ (with $y_j^* = 0$) for $j \in [j_s, j_x)$ and $x_j = 0$ (with $y_j^* = c_j^*$) for $j > j_x$. If $\lambda_e = p_e$ then j_s and j_x both converge to the BAU export threshold of $\bar{j}_x$. Otherwise, for $\lambda_e > p_e$: (i) $(\lambda_e - p_e) g'(p_e) > 0$, which implies $A(j_x) < A(j_s)$ and hence $j_x > j_s$ and (ii) the denominator of (16) exceeds $g(\lambda_e)$, because $g(p)$ is concave, which implies $A(j_x) < \tau = A(\bar{j}_x)$ and hence $j_x > \bar{j}_x$.

production cost, is strictly increasing in j over Interval 2, starting at zero for good j_s.[19] Interval 2 disappears if the consumption wedge is zero. It emerges for a strictly positive consumption wedge, $\lambda_e > p_e$, because the planner wants these goods to be produced with energy intensity $k(\lambda_e)$ rather than with the higher value $k(p_e)$ that Foreign producers would choose. Since the planner can't specify energy intensity in Foreign, it has Home export these goods instead. As a result Home expands its range of exports to j_x, which is beyond j_s and even beyond the BAU export threshold of $\bar{j}_x$.

Figure 1: Goods for Foreign Consumers



This figure illustrates the determination of export thresholds. The y-axis is Home's relative productivity. On the x-axis, interval 1 is the set of goods that Home exports at its cost. Interval 2 is the set of goods that Home exports at Foreign's cost. Interval 3 is the set of goods that Foreign supplies to itself.

Summary Table 3 displays the quantities of goods produced and traded, as determined by the inner problem, with rows indicating the location of consumption and columns

[19]The export wedge relative to Foreign's cost, for $j \in [j_s, j_x]$, is:

$$\frac{s_j}{a_j^* g(p_e)} = \frac{\tau g(\lambda_e)}{A(j) g(p_e)} - 1,$$

which is strictly increasing in j since $A(j)$ is strictly decreasing in j. Equation (15) implies that this ratio is 0 for good j_s. Equation (16) implies that its maximum value (for good j_x) is $(\lambda_e/p_e - 1)\epsilon_g(p_e)$, the product of the ad-valorem consumption wedge and the share of energy in Foreign's production cost for its domestic market.

Table 3: Solution to Inner Problem (Goods-Sector Outcomes)

	Home		Foreign	
Home	$u'(y_j) = a_j g(\lambda_e)$	$j < j_m$	$u'(m_j) = \tau^* a_j^* g(\lambda_e)$	$j > j_m$
Foreign	$u^{*\prime}(x_j) = \begin{cases} \tau a_j g(\lambda_e) \\ a_j^* g(p_e) \end{cases}$	$j \leq j_s$ $j_s \leq j < j_x$	$u^{*\prime}(y_j^*) = a_j^* g(p_e)$	$j > j_x$

The thresholds, j_m, j_s, and j_x, are given by equations (14), (15), and (16), with $m_j = 0$ for $j < j_m$, $y_j = 0$ for $j > j_m$, $y_j^* = 0$ for $j < j_x$, and $x_j = 0$ for $j > j_x$. Good $j = j_m$ may be either imported by Home or produced domestically while good $j = j_x$ may be either exported by Home or produced by Foreign. Aggregate outcomes are invariant to this ambiguity.

indicating the location of production as in Table 1. The terms on the diagonal depend on preferences and costs as expected, but those for Home's imports in the upper right and for Home's exports in the lower left are unexpected: (i) while Home's imports are produced in Foreign, with energy price p_e, the quantity is set as if producers there faced the same shadow cost of energy as producers in Home and (ii) while goods in Interval 2 are produced in Home, the quantities demanded by Foreign's consumers depend on what it would cost to produce them in Foreign. In both cases the planner dictates the energy intensity to produce goods based on its shadow value of energy rather than letting them be produced with the higher energy intensity that Foreign's producers would have chosen in the absence of the policy.[20]

3.5 Outer Problem

The outer problem is to maximize the Lagrangian (12) with respect to Q_e, C_e^d, and p_e, given the solution to the inner problem.

[20]If the consumption wedge is strictly positive, $\lambda_e > p_e$, any good $j \leq j_x$ is produced by Home and exported to Foreign using less energy than if it were produced in Foreign. It's sufficient to demonstrate this result for good j_x. By the concavity of $g(p)$ we have $g(p_e) + g'(\lambda_e)(\lambda_e - p_e) < g(\lambda_e)$. Since $g'(\lambda_e) < g'(p_e)$ we have $g(p_e)g'(\lambda_e)/g'(p_e) + g'(\lambda_e)(\lambda_e - p_e) < g(\lambda_e)$. Hence $g'(\lambda_e)/g'(p_e) < g(\lambda_e)/(g(p_e) + g'(p_e)(\lambda_e - p_e))$. Multipling both sides by τ implies $\tau g'(\lambda_e)/g'(p_e) < A(j_x)$. Cross multiplication then gives the result that $a_{j_x}\tau g'(\lambda_e) < a_{j_x}^* g'(p_e)$.

3.5.1 Extraction and Direct Consumption

The first-order condition for Q_e is:

$$\frac{\partial \mathcal{L}}{\partial Q_e} = -\varphi^W - \frac{\partial L_e}{\partial Q_e} + \lambda_e \leq 0,$$

with equality if $Q_e > 0$. The extra labor to extract a bit more energy, $\partial L_e/\partial Q_e$, is the labor requirement for Home's marginal energy deposit, $a(Q_e)$. Applying this result, the first-order condition simplifies to:

$$Q_e = E\left(\lambda_e - \varphi^W\right), \tag{17}$$

for $\lambda_e - \varphi^W \geq 0$, with $Q_e = 0$ otherwise. This condition mimics (6), with $\lambda_e - \varphi^W$ in place of p_e. This gap, $p_e - (\lambda_e - \varphi^W)$, is the *extraction wedge*.

The first-order condition for C_e^d is:

$$v'(C_e^d) = \lambda_e. \tag{18}$$

This condition mimics (7), with λ_e in place of p_e due to the *consumption wedge*.

3.5.2 Energy Price

The first-order condition for p_e is more intricate:

$$\frac{\partial \mathcal{L}}{\partial p_e} = \int_0^1 \frac{\partial u^*(c_j^*)}{\partial p_e} dj + \frac{\partial v^*(C_e^{d*})}{\partial p_e} - \varphi^W \frac{\partial Q_e^*}{\partial p_e} - \frac{\partial L_e^*}{\partial p_e} - \frac{\partial L_g^W}{\partial p_e} - \lambda_e \left(\frac{\partial C_e^*}{\partial p_e} - \frac{\partial Q_e^*}{\partial p_e} \right) = 0,$$

where terms optimized in the inner problem dropped out due to the envelope condition. As shown in Appendix B the first-order condition simplifies to:

$$\left[p_e - (\lambda_e - \varphi^W)\right] \frac{\partial Q_e^*}{\partial p_e} + \left[\lambda_e - p_e\right] \frac{\partial C_e^{\tilde{y}*}}{\partial p_e} + \int_{j_s}^{j_x} \left[s_j\right] \frac{\partial x_j}{\partial p_e} dj = 0, \tag{19}$$

where $C_e^{\tilde{y}*} = C_e^{y*} + C_e^{d*}$.

Equation (19) balances the extraction, consumption, and export wedges introduced above (in square brackets), taking account of Foreign responses to a change in p_e of energy supply ($\partial Q_e^*/\partial p_e > 0$), energy demand ($\partial C_e^{\tilde{y}*}/\partial p_e < 0$), and export demand ($\partial x_j/\partial p_e < 0$). Wedges capture the welfare consequences of each Foreign response: (i)

the extraction wedge between the value that the planner and Foreign's market place on extracting a unit of energy, (ii) the consumption wedge between the value that the planner and Foreign's market place on using a unit of energy, and (iii) the export wedges between the shadow cost to the planner and the cost to Foreign's producers of supplying each good in Interval 2 to Foreign's consumers. If the planner raises the energy price (by reducing Home's net exports of energy) the extraction wedge rises and the consumption and export wedges fall. Therefore, if the left side of (19) is negative, the planner increases p_e to rebalance it. If the left side of (19) is positive, the planner reduces p_e to rebalance it. When (19) is balanced, the energy price lies in the interval $(\lambda_e - \varphi^W, \lambda_e]$, with $p_e < \lambda_e$ if $\varphi^W \partial Q_e^*/\partial p_e > 0$.[21]

3.6 Properties of the Solution

Taking stock: (i) the inner problem gives C_e^y, C_e^m, C_e^x, and C_e^{y*} in terms of p_e and λ_e; (ii) equations (6) and (17) give Q_e^* and Q_e as functions of p_e and λ_e; (iii) equations (7) and (18) give C_e^{d*} and C_e^d as functions of p_e and λ_e; and (iv) equation (19) and (10) nail down p_e and λ_e. We now turn to the optimal wedges that characterize the solution.

Pigouvian Wedge Adding the extraction and consumption wedges yields the Pigouvian wedge, φ^W, i.e. the global social cost of carbon. It's the wedge between the value the planner places on using energy and its valuation on extracting energy. If the planner could control outcomes in Foreign, it would impose this Pigouvian wedge there too (see Appendix A). But, a unilateral policy can't achieve a globally harmonized wedge. Instead, the planner splits the Pigouvian wedge into extraction and consumption wedges based on Foreign demand and supply responses to the global energy price.

Balancing Extraction and Consumption Wedges The planner chooses a consumption wedge, $\lambda_e - p_e$, in the interval $[0, \varphi^W)$. This wedge approaches φ^W if $\partial Q_e^*/\partial p_e$ is large relative to $\left|\partial C_e^{\tilde{y}*}/\partial p_e\right|$ resulting in a low value of p_e to limit Foreign's extraction of energy. The extraction wedge, $p_e - (\lambda_e - \varphi^W) = \varphi^W - (\lambda_e - p_e)$, then approaches

[21] If $\varphi^W > 0$ then equation (19) can't be satisfied by $p_e \leq \lambda_e - \varphi^W$ as then the sum of the left-hand-side terms would be strictly negative. Likewise, if $p_e > \lambda_e$ then the inner problem would give $j_s = j_x < \bar{j}_x$, eliminating the integral in (19), so that all terms on the left side of (19) would be strictly positive. Hence, a solution to (19) implies $p_e \in (\lambda_e - \varphi^W, \lambda_e]$. If $\varphi^W \partial Q_e^*/\partial p_e = 0$ then $p_e = \lambda_e$ solves (19), with $j_s = j_x = \bar{j}_x$. If $\varphi^W \partial Q_e^*/\partial p_e > 0$, then balancing (19) requires at least one strictly negative term, hence $p_e < \lambda_e$.

0. At the other extreme, with perfectly inelastic Foreign supply, the planner chooses a high price to limit Foreign's energy demand. The extraction wedge then equals the Pigouvian wedge and the consumption wedge is 0. In this case, the unilateral policy achieves the global optimum.[22]

Export Wedges and Crosshauling The export threshold, j_x, is greater than in BAU when $\lambda_e > p_e$. With energy highly valued by the planner, global resources are saved by having goods in Interval 2 produced in Home rather than in Foreign. Export wedges emerge since these goods must be delivered to Foreign's consumers at a price no higher than if they were produced in Foreign. Under the optimal policy there may be a set of goods that Home simultaneously imports and exports. Such crosshauling always occurs in the absence of trade costs as then $A(j_m) = 1/\tau^* = 1$ and $A(j_x) < 1$ implying $j_x > j_m$. With high enough trade costs, however, $A(j_x) > A(j_m)$ so that $j_x < j_m$. The inherent inefficiency of crosshauling then outweighs its advantage in crowding out Foreign production.

4 Optimal Taxes and Subsidies

We can now describe a set of taxes and subsidies that deliver the optimal unilateral policy as the outcome of a competitive equilibrium. In the resulting market economy, recall that services are the numéraire and the labor requirement for services pins the wage to 1 in both regions.

4.1 A Simple Implementation

We consider implementing the unilaterally optimal policy with three interventions, which correspond to different wedges:

1. Tax energy extraction in Home at *nominal* rate $t_e^N = \varphi^W$ (Pigouvian wedge).

2. Impose border adjustments on Home's energy trade, and on energy embedded in Home's imports of goods, at rate $t_b = \lambda_e - p_e$ (consumption wedge).

3. Subsidize Home's exports of each good in Interval 2 at rate s_j (export wedges).

[22]Following this logic, Harstad (2012) makes a case that the policy maker buy marginal energy deposits from Foreign to create a locally vertical Foreign supply curve. We have ruled out such an international market in Foreign's energy deposits in our analysis here.

There are three *effective* carbon taxes implicit in this policy. The first is a tax on Home's extraction, $t_e = t_e^N - t_b = \varphi^W - (\lambda_e - p_e)$ (extraction wedge). The second is a tax t_c on carbon embodied in Home's consumption, including imports, $t_c = t_b = \lambda_e - p_e$ (consumption wedge). The third is a tax t_p on carbon used in Home's production, including exports, $t_p = t_b = \lambda_e - p_e$ (consumption wedge). (Home's production and consumption overlap when Home produces for itself, in which case only one tax is applied.) The per-unit subsidy to exports in Interval 2 is layered on top of these three carbon taxes.[23] This set of taxes and subsidies is not the only way to implement the unilaterally optimal policy, but we find it the easiest to interpret.[24]

4.2 After-Tax Prices

Net prices faced by the various agents in the global economy are as follows:

1. The global price of energy, p_e, is paid by users of energy in Foreign and is received by energy extractors in Foreign.

2. If energy is imported by Home, it is subject to a border adjustment t_b, raising the price of energy for users in Home to $p_e + t_b$.

3. Energy extractors in Home sell energy domestically at price $p_e + t_b$, so after paying the extraction tax they net $p_e + t_b - t_e^N = p_e - t_e$.

4. Extractors in Home export energy at price p_e and get a rebate of t_b on the nominal extraction tax, so also net $p_e - t_e^N + t_b = p_e - t_e$.

5. Goods $j < j_m$ are produced in Home, using energy costing $p_e + t_b$, so that local consumers pay $p_j = a_j g(p_e + t_b)$.

[23] This policy differs from that discussed in Staiger (2022) for three reasons. First, we assume that Foreign has no carbon policy. Second, we force Home's policy to generate a global Pareto improvement. Third, and more subtle, in our model carbon intensity is endogenous. As a consequence, border adjustments on goods must be imposed per unit of embodied carbon. Furthermore, this carbon tax is imposed on Home's exporters so that they choose the optimal carbon intensity. The per-unit subsidy for exporters doesn't undo this incentive, a result reminiscent of Fischer and Fox (2012).

[24] We can also implement the unilaterally optimal policy starting from a tax on emissions rather than a tax on extraction: (1) tax energy used for production of goods in Home (and on direct consumption of energy in Home) at *nominal* rate $t_p^N = \varphi^W$ (Pigouvian wedge); (2) impose border adjustments on energy embodied in Home's imports of goods at rate $t_c = t_b = \lambda_e - p_e$ (consumption wedge); and (3) subsidize energy imports and tax energy exports at rate $t_e = t_p^N - t_b$ (extraction wedge). The export subsidy for goods in Interval 2 remains s_j (export wedge). This policy works because the subsidy to energy imports and tax on energy exports act as a tax on Home's extractors. The resulting *effective* production tax is $t_p = t_p^N - t_e = t_b = \lambda_e - p_e$ (consumption wedge).

6. Goods $j > j_m$ are imported by Home. Anticipating the border adjustment, Foreign produces these goods with energy intensity $k(p_e + t_b)$. The production cost, including the trade cost, is $\tau^* l_j^*(k(p_e + t_b)) + p_e \tau^* e_j^*(k(p_e + t_b))$. With the border adjustment, $t_b \tau^* e_j^*(k(p_e + t_b))$, consumers pay $p_j^m = \tau^* a_j^* g(p_e + t_b)$.

7. Goods $j < j_s$ in Interval 1 are produced in Home and exported. The producers use energy costing $p_e + t_b$, with no border adjustment for exports. The price in Foreign, including the trade cost, is $p_j^x = \tau a_j g(p_e + t_b)$.

8. Goods $j \in [j_s, j_x)$ in Interval 2 are also exported by Home. The producers use energy costing $p_e + t_b$, with no border adjustment for exports. They sell at price $p_j^* = a_j^* g(p_e)$ in Foreign. These producers get a subsidy of s_j per unit, so they net $p_j^* + s_j = \tau a_j g(p_e + t_b)$, which covers their cost.

9. Goods $j > j_x$ in Interval 3 are produced in Foreign, using energy at price p_e. They are sold to local consumers at price $p_j^* = a_j^* g(p_e)$.

5 Constrained Optimal Policies

As shown above, the optimal unilateral policy can be implemented by combining carbon taxes on Home extraction, consumption, and production, together with subsidies for a range of goods (Interval 2) that Home exports. To assess this policy, we compare it to more conventional polices that involve some subset of these taxes with no subsidy for exports. We solve for the optimal version of each constrained policy following the approach we took for the optimal unilateral policy (there are seven constrained policies, one for each subset of the three types of taxes).[25]

For constrained policies involving an extraction tax, the tax rate on extraction equals the extraction wedge, $t_e = \varphi^W - (\lambda_e - p_e)$. For constrained policies involving a consumption tax, the tax rate on consumption equals the consumption wedge, $t_c = \lambda_e - p_e$. These results mimic the optimal unilateral policy. For constrained policies involving a production tax, the tax rate t_p is below the consumption wedge, unlike

[25]We provide additional intuition for these conventional policies in Weisbach et al. (2023). There we solve the dual problem to get conditions for optimal tax rates directly (given the taxes allowed in each case). Here, to facilitate comparison to the optimal unilateral policy, we solve the primal problem to characterize the constrained-optimal allocation and then derive conditions for taxes that implement each allocation. Full solutions to the Lagrangian for each case are shown in Appendix C.

the optimal unilateral policy. With no export subsidy, a production tax induces direct leakage (increased energy use by Foreign) which reduces its efficacy.

Consider a constrained policy that includes a production tax but not a consumption tax. Let $v_e = p_e + t_p$ be the cost of energy to producers in Home. Raising v_e causes consumers in Home and in Foreign to substitute away, on both the extensive and intensive margins, from goods produced in Home. The extensive-margin response is governed by the slope of the comparative advantage curve, $A(j)$, near the trade thresholds, with a flatter slope implying more leakage. Figure 2 illustrates the leftward shift in the two extensive margins. Relative to BAU, both j_m and j_x decline, in contrast to the optimal unilateral policy in which j_m doesn't change and j_x rises.

Leakage, on the margin, is (minus) the increase in emissions (here, energy use) in Foreign, relative to the decrease in Home, from a change in v_e:

$$\Lambda = -\frac{\partial G_e^*/\partial v_e}{\partial G_e/\partial v_e}.$$

The planner optimizes, accounting for leakage, by setting the cost of energy in Home to $v_e = \Lambda p_e + (1-\Lambda)\lambda_e$, closer to p_e if leakage is higher, and closer to λ_e if leakage is lower. The resulting production tax is therefore $t_p = (1-\Lambda)(\lambda_e - p_e)$. The production tax rate, with no leakage, is equal to the consumption wedge. But, it declines linearly with leakage, and with 100% leakage the optimal production tax is 0. These results continue to apply if the production tax is combined with an extraction tax.[26]

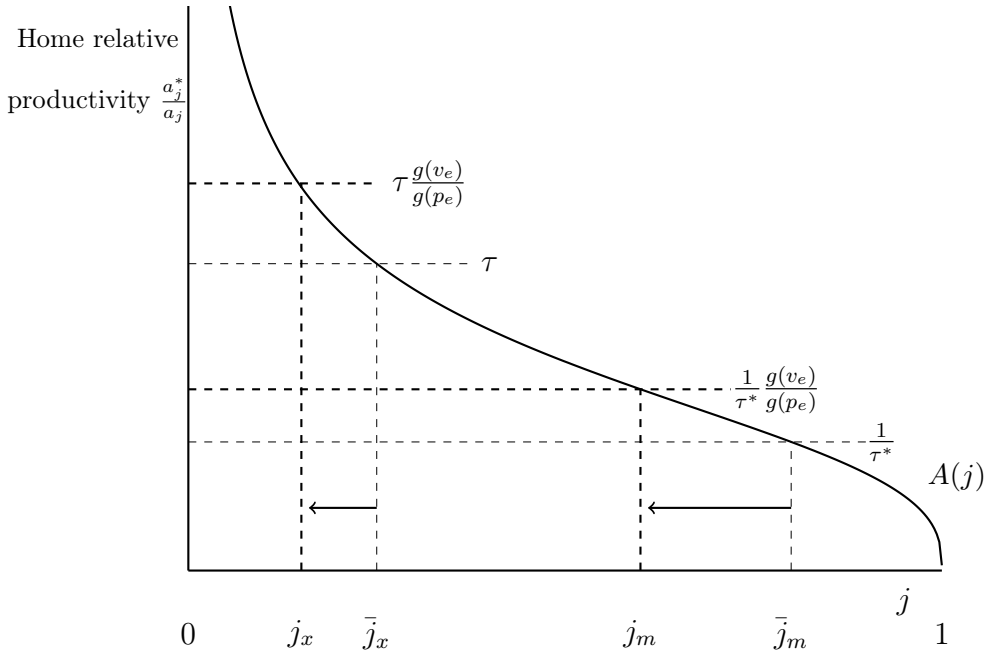
If the constrained policy includes a consumption tax then v_e applies only to Home production for export. Leakage takes place only via Foreign consumers substituting (on both the extensive and intensive margins) away from goods produced in Home. The expression for leakage becomes:

$$\Lambda^* = -\frac{\partial C_e^{y*}/\partial v_e}{\partial C_e^x/\partial v_e},$$

which we call "foreign leakage" to distinguish it from Λ. Foreign leakage does not include substitution by Home consumers away from Home production (since the cost of energy

[26]While an extraction/production hybrid tax must contend with direct leakage, it has an offsetting advantage over other policies: it can be implemented simply and accurately. To implement this tax, Home could impose a nominal extraction tax of $t_e^N = t_e + t_p = \varphi^W - \frac{\Lambda}{1-\Lambda}t_p$ and border adjustments on energy (but not on goods) at rate $t_b = t_p$. By avoiding border adjustments on goods, the tax avoids the need to measure the marginal emissions from the production of goods in foreign countries, which is the key problem in imposing border adjustments, see Kortum and Weisbach (2016).

Figure 2: Import/Export Thresholds under Pure Production Tax



This figure illustrates the determination of import and export thresholds with a production tax. The axes are as in Figure 1. For a policy that includes a production tax but not a consumption tax, both the import and export thresholds decrease, as shown. If a consumption tax is also part of the policy, the import threshold remains unchanged at $j_m = \bar{j}_m$.

to supply Home, whether by domestic producers or imports, is $\lambda_e = p_e + t_c$). In this scenario, Figure 2 would show $j_m = \bar{j}_m$ since $(1/\tau^*)g(v_e)/g(p_e)$ would be replaced by $(1/\tau^*)g(\lambda_e)/g(\lambda_e) = 1/\tau^*$ to determine the import threshold. The planner optimizes, taking account of foreign leakage, by setting the cost of energy for Home exports to $v_e = \Lambda^* p_e + (1 - \Lambda^*)\lambda_e$. The resulting production tax, now applying only to energy used in Home exports, becomes: $t_p = (1 - \Lambda^*)(\lambda_e - p_e)$.

We have explained how each tax rate is set for each of the seven constrained policies, given the extraction wedge, the consumption wedge, and the appropriate leakage rate. The consumption wedge itself is based on the first-order condition for p_e, analogous to equation (19), but without export wedges, which are absent in all the constrained policies. The consumption wedge adjusts based on the supply and demand responses to the energy price. Supply and demand responses vary with the constrained policy being considered, hence so do the associated consumption wedges. Appendix C provides all derivations, with results summarized in Appendix Table 6.

6 Quantitative Illustration

We now calibrate the model, compute the optimal unilateral policy, explore its quantitative implications, and compare it to constrained optimal policies. Our computational strategy exploits convenient functional forms and conditions on observed global carbon flows in 2018, which we interpret as BAU outcomes.

Preferences We assume constant-elasticity demand:

$$u(c_j) = \eta^{1/\sigma} \frac{c_j^{1-1/\sigma} - 1}{1 - 1/\sigma},$$

where η governs demand for goods and σ is the elasticity of substitution between goods. In aggregate, $\int_0^1 u(c_j)dj = u(C_g)$, where $C_g = \left(\int_0^1 c_j^{(\sigma-1)/\sigma} dj\right)^{\sigma/(\sigma-1)}$ is total goods consumption. Foreign demand takes the same form, with parameters η^* and $\sigma^* = \sigma$.[27]

Demand for direct consumption of energy, based on $v(C_e^d)$, takes the same form, with parameters η_e and σ_e (in Foreign η_e^* and $\sigma_e^* = \sigma_e$).

Energy Supply We assume constant extraction elasticities, ϵ_S and ϵ_S^*, so that:

$$E(a) = Ea^{\epsilon_S}; \qquad E^*(a) = E^* a^{\epsilon_S^*},$$

where the parameters E and E^* govern the mass of energy deposits in each region.

Goods Production We assume a CES production function:

$$f(k) = (1 - \alpha + \alpha k^{(\rho-1)/\rho})^{\rho/(\rho-1)},$$

with elasticity of substitution ρ and energy shift parameter α.[28]

Comparative Advantage We parameterize input requirements for goods production in each region by:

$$a_j = \left(\frac{j}{A}\right)^{1/\theta}; \qquad a_j^* = \left(\frac{1-j}{A^*}\right)^{1/\theta},$$

[27] If $\sigma \to 1$ we get $u(C_g) = \eta \ln C_g = \eta \int_0^1 \ln c_j dj$ (and likewise in Foreign).

[28] If $\rho \to 1$ we get a Cobb-Douglas production function, $f(k) = k^\alpha$, with fixed energy share $\epsilon_g(p) = \alpha$.

where A and A^* govern absolute advantage and θ comparative advantage. Hence:

$$A(j) = \frac{a_j^*}{a_j} = \left(\frac{A}{A^*}\frac{1-j}{j}\right)^{1/\theta}.$$

This formulation has the convenient property that in BAU, the share of spending on imported goods equals the measure of goods imported.

Carbon Embodied in Goods The carbon embodied in a good j is the product of the quantity produced and the unit energy requirement. Demand for the good depends on the after-tax energy price p (either p_e or $p_e + t_b$) via the term $g(p)^{-\sigma}$ (recall that $a_j g(p)$ is the unit cost function in Home). The unit energy requirement depends on the energy price via the term $g'(p)$. Combining these two terms, the energy embodied in any good depends on the after-tax energy price via $D(p) = g(p)^{-\sigma}g'(p)$. The elasticity of this expression, how carbon consumption responds to the carbon price, is:

$$\epsilon_D(p) = -pD'(p)/D(p) = \epsilon_g(p)\sigma + (1-\epsilon_g(p))\rho. \tag{20}$$

The first term on the right hand side of (20) is the effect of the carbon price in reducing the quantity of the good demanded, which is increasing in the elasticity of substitution in consumption, σ. The second is its effect in reducing carbon per unit produced, which is increasing in the elasticity of substitution in production, ρ.[29]

6.1 Counterfactual Policies

We capture the key counterfactual outcomes under the optimal unilateral policy in the vector $\boldsymbol{z}$. Its elements include carbon flows (energy extraction and the elements of Table 1), energy cost shares (which depend on the carbon price), and carbon-price variables (p_e and t_b). The structure of the model delivers these counterfactual outcomes

[29] From (5), and imposing the CES production function, we get:

$$g(p) = (1-\alpha)^{\rho/(1-\rho)}\left(1 + (\alpha/(1-\alpha))^{\rho}p^{1-\rho}\right)^{1/(1-\rho)}.$$

The energy share, and hence the elasticity of $g(p)$, is thus:

$$\epsilon_g(p) = \frac{pg'(p)}{g(p)} = \frac{\alpha^{\rho}p^{1-\rho}}{(1-\alpha)^{\rho} + \alpha^{\rho}p^{1-\rho}}.$$

Using these results it is straightforward to derive $\epsilon_D(p)$.

succinctly in terms of their BAU values, $\bar{\boldsymbol{z}}$, so that:

$$\boldsymbol{z} = F(\bar{\boldsymbol{z}}; \boldsymbol{\Theta}),$$

where $\boldsymbol{\Theta}$ is a vector of parameters.[30] We describe the mapping F in what follows, with some details relegated to Appendix D.1.

Energy extraction is particularly simple to compute given carbon-price variables:

$$Q_e = \left(\frac{p_e + t_b - \varphi^W}{\bar{p}_e}\right)^{\epsilon_S} \bar{Q}_e; \qquad Q_e^* = \left(\frac{p_e}{\bar{p}_e}\right)^{\epsilon_S^*} \bar{Q}_e^*,$$

where $Q_e = 0$ if $p_e + t_b - \varphi^W \leq 0$. The parameters E and E^* disappear.

Given p (either p_e or $p_e + t_b$) we can use results in footnote 29 to compute the energy cost share in terms of its BAU value, $\bar{\epsilon}_g = \epsilon_g(\bar{p}_e)$:

$$\epsilon_g(p) = \frac{(p/\bar{p}_e)^{1-\rho}\bar{\epsilon}_g}{(p/\bar{p}_e)^{1-\rho}\bar{\epsilon}_g + (1-\bar{\epsilon}_g)}. \tag{21}$$

The parameter α disappears.

The optimal export threshold can also be expressed in terms of its BAU value:

$$j_x = \frac{\hat{g}(p_e + t_b)^{-\theta}\bar{j}_x}{\hat{g}(p_e + t_b)^{-\theta}\bar{j}_x + \hat{g}(p_e)^{-\theta}\left(1 + (t_b/p_e)\epsilon_g(p_e)\right)^{-\theta}(1 - \bar{j}_x)},$$

where $\hat{g}(p) = g(p)/g(\bar{p}_e) = \left(\bar{\epsilon}_g(p/\bar{p}_e)^{1-\rho} + 1 - \bar{\epsilon}_g\right)^{1/(1-\rho)}$. In BAU every good is produced with the same energy share $\bar{\epsilon}_g$ so that, exploiting the special property of $A(j)$, the BAU export threshold is simply $\bar{j}_x = \bar{C}_e^x/(\bar{C}_e^x + \bar{C}_e^{y*})$. Similarly, the BAU import threshold satisfies $1 - \bar{j}_m = \bar{C}_e^m/(\bar{C}_e^y + \bar{C}_e^m)$, with $j_m = \bar{j}_m$.[31] The A's and τ's disappear.

[30] The strategy follows Dekle, Eaton, and Kortum (2007). For any individual outcome (or function of outcomes) x we let $\bar{x}$ be its value in BAU, x its value under a counterfactual carbon policy, $\hat{x} = x/\bar{x}$, and $\Delta x = x - \bar{x}$. In this application, by matching the BAU value of key outcomes to data, we ignore any existing carbon policies. Such policies were quite limited as of 2018, our base year for the calibration.

[31] The mapping from BAU trade thresholds to observed carbon flows would be more intricate if we introduced intermediate goods. Suppose composite intermediates for Home and Foreign production, constructed like C_g, entered goods production with a Cobb-Douglas share α_n. We would then have:

$$(1 - \bar{j}_m) = [1 - \alpha_n(\bar{j}_m - \bar{j}_x)]\,\frac{\bar{C}_e^m}{\bar{C}_e^y + \bar{C}_e^m}; \quad \bar{j}_x = [1 - \alpha_n(\bar{j}_m - \bar{j}_x)]\,\frac{\bar{C}_e^x}{\bar{C}_e^x + \bar{C}_e^{y*}},$$

where $\alpha_n(\bar{j}_m - \bar{j}_x)$ is the share of endogenously non-traded intermediates embodied in the production of Home's imports and exports. Since the data in Table 4 account for carbon embodied in intermediates,

Consumption of carbon in Foreign from Foreign production is given by:

$$C_e^{y*} = \hat{D}(p_e)\left(\frac{1-j_x}{1-\bar{j}_x}\right)^{1+(1-\sigma)/\theta}\bar{C}_e^{y*},$$

where $\hat{D}(p) = D(p)/D(\bar{p}_e) = \hat{g}(p)^{\rho-\sigma}(p/\bar{p}_e)^{-\rho}$.[32] Direct consumption of carbon in Foreign is $C_e^{d*} = (p_e/\bar{p}_e)^{-\sigma_e}\bar{C}_e^{d*}$, with elasticity σ_e. In all such expressions for energy demand (a complete list is in Appendix Table 10) the η's and η_e's disappear.

Equation (19) delivers an expression for the border adjustment (consumption wedge). Observing that constant-elasticity preferences imply $\partial x_j/\partial p_e = -\sigma x_j \epsilon_g(p_e)/p_e$, defining $S = \int_{j_s}^{j_x} s_j x_j dj$, and employing elasticities introduced above, it simplies to:

$$t_b = \frac{\varphi^W \epsilon_S^* Q_e^* - \sigma \epsilon_g(p_e) S}{\epsilon_S^* Q_e^* + \epsilon_D(p_e) C_e^{y*} + \sigma_e C_e^{d*}}. \tag{22}$$

The optimal border adjustment along with the energy price jointly satisfy (22) and clear the global energy market, $C_e^W = Q_e^W$.

All the expressions for computation shown above are designed for the unilaterally optimal policy. The minor modifications required to compute constrained optimal policies are described in Appendix D.2.

Home's welfare gain under an optimal policy (either the unilaterally optimal policy or a constrained optimal policy) can be measured as equivalent variation. Starting from BAU, raising income in Home by $EV = \Delta U = U - \bar{U}$ (which would be spent on consumption of services) delivers the same welfare gain as implementing the optimal policy. Since Foreign's welfare is fixed, we can compute EV as the increase in global welfare, as shown in Appendix D.1, from elements of $\boldsymbol{z}$.

For a high-level perspective on the counterfactual results in Section 6.3, we will illustrate the trade-off between global emissions reductions ($-\Delta Q_e^W$) and reductions in global consumption, measuring the change in global consumption from an optimal policy as $\Delta C^W = EV + \varphi^W \Delta Q_e^W$ (where $\Delta C^W < 0$ if $\varphi^W > 0$). For a given policy, and fixed φ^W, we can plot $-\Delta Q_e^W$ on the vertical axis and ΔC^W on the horizontal. Varying φ^W traces out the frontier of possibilities for global emissions reductions and associated declines in global consumption for a given policy. The slope of this frontier is $-1/\varphi^W$

generalizing the model along these lines is a priority for future work.

[32] By the envelope condition $\epsilon_D(p_e)$ is the price elasticity of C_e^{y*}, since j_x can be treated as fixed with respect to small deviations of p_e from its optimum.

at the optimum. The frontier for a constrained optimal policy will, by definition, lie below the frontier for the optimal unilateral policy.

6.2 Calibration

We calibrate $\bar{\boldsymbol{z}}$ to the data shown in Table 4, a measure of the BAU energy price, and a measure of energy as a share of production costs in BAU. The carbon flow data for 2018 come from two sources. Energy extraction is from the International Energy Agency World Energy Statistics Database. We use emissions factors to convert units of fuels of different types to gigatons of CO_2. Indirect and direct consumption is from the Trade Embodied in CO_2 ($TECO_2$) database, made available by the OECD.[33] For most of our results, members of the OECD form the taxing region, or Home, and non-OECD countries are Foreign, as in Table 4. By this CO_2 metric the OECD represents about one-third of the world. It represents a smaller share of extraction and a larger share of implicit consumption, nearly twenty percent of which is imported.

We take the BAU energy price to be $\bar{p}_e = \$167$ per ton of CO_2.[34] The definition of BAU implies $\bar{t}_b = 0$. We compute the BAU energy share in cost to be $\bar{\epsilon}_g = 0.22$.[35]

In addition to $\bar{\boldsymbol{z}}$ we need values for $\boldsymbol{\Theta} = \left\{\varphi^W, \theta, \sigma_e, \sigma, \rho, \epsilon_S, \epsilon_S^*\right\}$ in order to compute model outcomes $\boldsymbol{z}$. We calibrate these seven parameters from a variety of sources.

Under the optimal unilateral policy the sum of the extraction tax and the border adjustment equals the global social cost of carbon φ^W. We consider a range of values from \$0 to \$400 per ton of CO_2 (hence billions of dollars per gigaton). The Environmental Protection Agency, EPA (2023), applied a value of \$190 for CO_2 emissions in 2020 (for discounting at 2%).

A higher θ eases substitution between Home and Foreign production, raising the potential for carbon leakage. We take $\theta = 4$ based on the preferred estimate in Simonovska and Waugh (2014). We also consider a much higher value of $\theta = 16$ to see how export subsidies under the optimal unilateral policy respond to higher potential

[33]The values that we take from $TECO_2$ are broadly consistent with those available from the Global Carbon Project. Further details on the data construction are described in Appendix E.

[34]The Federal Reserve Economic Data (FRED) reports the 2018 global price per barrel of Brent Crude as \$71.6. The EPA Greenhouse Gases Equivalencies Calculator reports 0.43 metric tons of CO_2 per barrel of crude oil. Hence, $\bar{p}_e = 71.6/0.43 = 166.5$.

[35]The United Nations National Accounts reports a world total value added in agriculture plus manufacturing (what we consider the goods sector) of \$17,364 billion in 2018. From Table 4, total energy used in production is 28.9 gigatons of CO_2. Pricing it at \$167 per ton gives a value of \$4812 billion. Hence, $\bar{\epsilon}_g = 4812/(17,364 + 4812) = 0.217$.

Table 4: Carbon Flows: Home as the OECD

	Home	Foreign	Direct	Total
Home	$\bar{C}_e^y = 8.7$	$\bar{C}_e^m = 2.5$	$\bar{C}_e^d = 2.5$	$\bar{C}_e = 13.7$
Foreign	$\bar{C}_e^x = 1.0$	$\bar{C}_e^{y*} = 16.7$	$\bar{C}_e^{d*} = 2.2$	$\bar{C}_e^* = 19.9$
Direct	$\bar{C}_e^d = 2.5$	$\bar{C}_e^{d*} = 2.2$		
Total	$\bar{G}_e = 12.2$	$\bar{G}_e^* = 21.4$		$\bar{C}_e^W = 33.6$
Extraction	$\bar{Q}_e = 9.3$	$\bar{Q}_e^* = 24.3$		$\bar{Q}_e^W = 33.6$

The table shows carbon flows in 2018 from OECD countries (Home) to all other countries (Foreign), measured as gigatons of CO_2. Data construction is described in more detail in Appendix E.

leakage.

The parameter σ_e is the elasticity of demand for direct consumption of energy. Most studies find this elasticity to be quite small. Addressing the endogeneity of energy prices, that bias estimates toward zero, Davis and Kilian (2011) use state-level variation in gas taxes to estimate $\sigma_e = 0.7$. They acknowledge that the long-run elasticity is likely larger, so we choose a slightly higher value of $\sigma_e = 1$. This value is also in line with estimates from Metcalf and Stock (2023) using time-series variation in carbon taxes.[36]

The parameter σ is both the elasticity of substitution across goods and the elasticity of demand for aggregate goods consumption, C_g. Using both individual and aggregate data while taking account of non-homothetic demand for goods relative to services, estimates by Boppart (2014) imply $\sigma = 0.6$. This value is unusually small for the elasticity of substitution between goods, but that implication will hardly matter because, with our specification of $A(j)$, trade substitution is driven primarily by θ.

The elasticity of demand for energy by goods producers, $\epsilon_D(p)$, is increasing in ρ and σ, given the energy share, as shown in equation (20). The magnitude of ρ (relative to 1) determines whether $\epsilon_g(p)$ itself is increasing or decreasing in p, as shown in equation (21). Antoszewski (2019) estimates industry-level elasticities of substitution between energy and value added using panel data across countries. The average over agriculture

[36]They consider only carbon taxes (not carbon prices from the EU ETS) that cover mostly transportation and buildings. They find a 4 to 6% decline in emissions from a \$40 per ton tax covering 30% of all emissions. Our parameterization would predict $\hat{C}^d = 0.7 + 0.3((167 + 40)/167))^{-1} = 0.942$, or just less than a 6% decline.

and manufacturing industries is 0.45, which we approximate as $\rho = 0.5$. Since long-run substitution possibilities could be much larger, making energy demand more elastic, we also consider $\rho = 2$. This larger value is consistent with firm-level estimates from Colmer, Martin, Muûls, and Wagner (2025), based on evidence from the EU ETS.[37]

Prior studies, such as Elliott et al. (2010), show that the foreign elasticity of energy supply, ϵ_s^*, is the key parameter affecting leakage and the effectiveness of a production tax. We calibrate $\epsilon_S = \epsilon_S^* = 0.5$ using data in Asker, Collard-Wexler, and De Loecker (2018), by fitting the slope of $E(a)$ and $E^*(a)$ among oil deposits with costs above the median (see Appendix E). Based on a literature review, Kotchen (2021) uses much higher values for the United States, with a point estimate for coal, 1.9, for natural gas, 1.6, and for gasoline, 2.0. Hence, we also consider a Foreign supply elasticity of $\epsilon_s^* = 2.0$.

In summary, our baseline parameter values are $\theta = 4$, $\sigma_e = 1$, $\sigma = 0.6$, $\rho = 0.5$, $\epsilon_S = 0.5$, $\epsilon_S^* = 0.5$, and a range for φ^W from 0 to 400. Alternative parameter values, considered one at a time, are $\theta = 16$, $\rho = 2$, and $\epsilon_S^* = 2$. Appendix E provides additional details on our data and on our calibration of the supply elasticities. For a given φ^W, our program uses a built-in solver to compute $F(\bar{\boldsymbol{z}}; \boldsymbol{\Theta})$.[38]

6.3 Results

We begin by computing the optimal policy (Home is OECD) as it varies with the global social cost of carbon, φ^W. Figure 3 shows, from left to right (top to bottom): (i) global

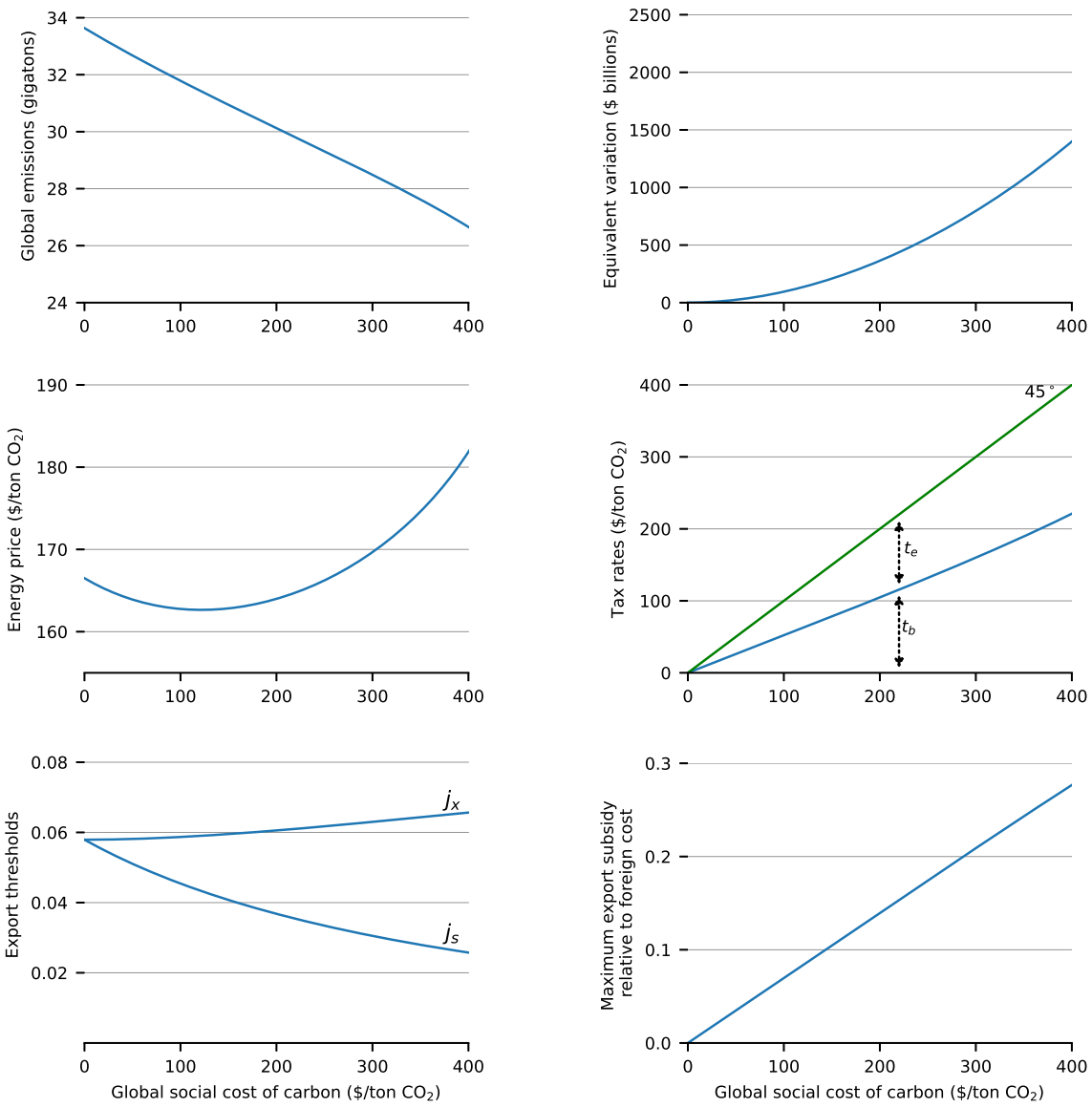
[37]To interpret this evidence through the lens of our model, we take a firm to be the unique producer of a particular good on the unit continuum, and rewrite equation (20) as:

$$\epsilon_D(p) = \epsilon_g(p)(\sigma - 1) + [(1 - \epsilon_g(p))\rho + \epsilon_g(p)] .$$

The first term is now the effect of the carbon price on a firm's value added (measured in terms of the numéraire). The term in square brackets is its effect on the firm's use of carbon per unit of value added. In phase II of the EU ETS (from 2008-2012), a firm subject to the regulation faced a carbon price that was higher (relative to an unregulated firm) by the factor $p/\bar{p}_e = (156.0 + 15.5)/156.0 = 1.10$, where 156.0 is the average euro price of Brent Crude from 2008-2012 translated into euros per ton of CO_2 (as in footnote 34) and 15.5 is the average emissions allowance price during phase II. Colmer et. al. (2025) estimate that a firm subject to the regulation reduced energy use by about 16 percent relative to a matched firm not subject to the regulation. The model nearly matches that 16 percent response with $\rho = 2$, $\sigma = 0.6$, and $\epsilon_g(p)$ computed from (21). Also in line with Colmer et. al.'s evidence, the model predicts that essentially all of the reduction is due to the term in square brackets. The effect on the firm's nominal value added would only be substantial if σ were much greater than 1.

[38]As a check on our solution, which is based on first order conditions, we also directly maximize the planner's Lagrangian numerically. For the parameters discussed in the following subsection, we obtain nearly identical results. Our script is in Python and uses the built-in solver fsolve from Scipy. Our code is available at `https://github.com/dweisbach/Optimal-Unilateral-Carbon-Policy`.

Figure 3: Optimal Policy in the OECD



emissions, (ii) Home's equivalent variation, (iii) the energy price, (iv) optimal taxes, (v) Home's export thresholds, and (vi) the maximum export subsidy normalized by the cost of the good in Foreign.[39]

[39]Using a result from footnote 19, this normalized maximum export subsidy can be expressed as $\frac{s_{j_x}}{a^*_{j_x} g(p_e)} = \frac{t_b}{p_e}\epsilon_g(p_e)$, the product of the ad-valorem border adjustment and the energy share in Foreign's production for its domestic market.

Starting in the upper left, global emissions go down by ⅕ as φ^W rises to \$400, a substantial reduction given that emissions in the OECD are only about ⅓ of global emissions (as reflected in the value of $\bar{G}_e$ in Table 4). Note that the substantial reduction from the OECD policy does not mean that the OECD's emissions are near zero. Some of the reductions arise in other parts of the world because of how the optimal policy expands the carbon price to trading partners. Notably, the OECD would choose to impose a significant carbon policy even when the rest of the world does not, delivering gains (equivalent variation) of nearly \$1.5 trillion as φ^W hits \$400.

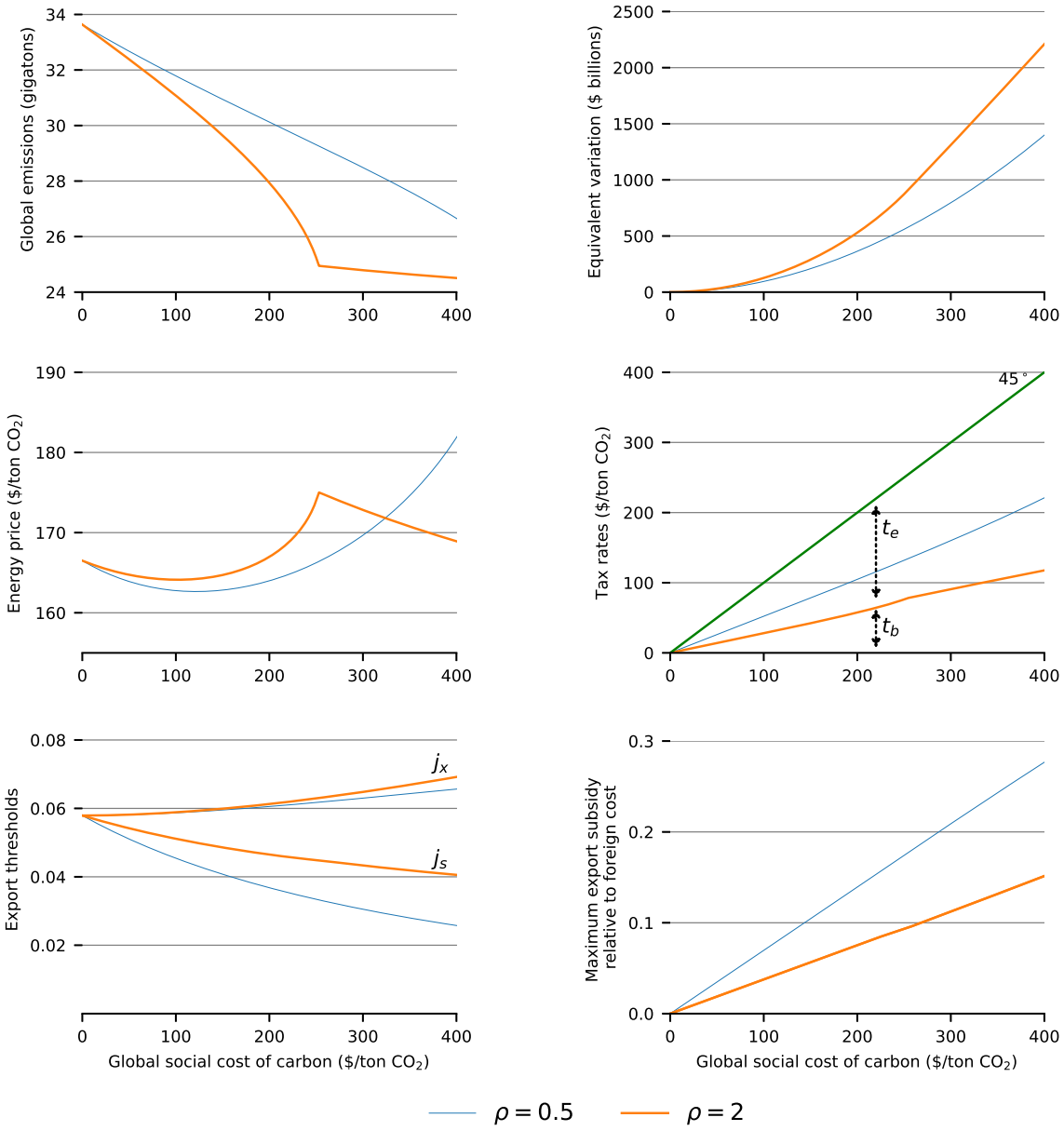
The OECD policy relies about evenly on an effective extraction tax (taxing supply) and a border adjustment (taxing demand), as shown in the middle right panel. The net effect keeps the global energy price below its BAU level for φ^W up to \$260 and above the BAU level at higher values. The extraction tax rises faster than the energy price as φ^W goes up. The two are nearly equal at $\varphi^W = \$400$ so that energy extractors in Home receive an after-tax price approaching zero.

Examining the lower left panel of Figure 3, we can see that Home expands the range of goods it exports as φ^W increases. By increasing its export threshold, Home is able to broaden the application of its carbon policy, which becomes more beneficial at a high global social cost of carbon. The vertical distance between the lower line and the upper line is the range of exported goods that Home subsidizes. These subsidies can become costly, reflected by the maximum subsidy (relative to Foreign's price) shown in the lower-right panel, which rises with φ^W.

Recall that a higher value of the elasticity of substitution between labor and energy is consistent with the evidence in Colmer et al (2025) reviewed above. In Figure 4 we illustrate how the optimal unilateral policy would be effected if $\rho = 2$ (shown with thick orange lines) in comparison to the baseline value of 0.5 as in the previous figure (shown in thin blue lines). With a higher ρ, energy demand by Foreign's producers is more elastic, tilting the optimal policy toward taxing supply rather than demand, and hence pushing up the energy price. This shift is clear in the middle right panel. For larger values of φ^W the net price received by energy extractors in the OECD, $p_e - t_e$, becomes negative and extraction in the OECD hits zero for φ^W approaching \$230. Extraction in Home remains at zero for higher values of φ^W, causing a kink in the energy price line as energy supply no longer declines with higher taxes.[40]

[40]Once $t_e \geq p_e$, so that $Q_e = 0$, the exact value of the t_e becomes irrelevant (for convenience, however, we show t_e continuing to rise with φ^W even beyond that point).

Figure 4: Optimal Policy in the OECD with Higher ρ



With a high elasticity of substitution, global emissions fall more sharply and are reduced at lower cost, yielding greater policy gains as measured by equivalent variation. A more subtle change is that the greater reliance on the extraction tax reduces distortions in the export market. The range of exported goods that are subsidized declines and the

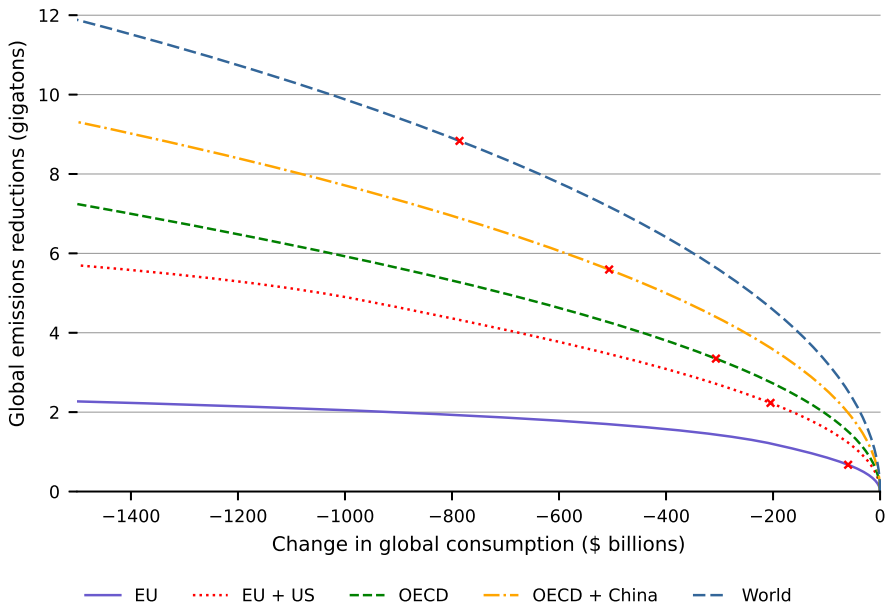
normalized maximum export subsidy is smaller.

6.3.1 Coalition Size

A key factor in global climate negotiations is the set of countries that will agree to emissions reductions. To examine the effects of coalition size, Figure 5 shows global emissions under optimal policies with five increasingly large coalitions, starting with just the EU and moving up to a global coalition.[41] Tables 16, 17 and 18 in the appendix provide the carbon flow data we calibrate to for the three new scenarios. Global emissions in BAU, the energy price and energy share in BAU, and the parameter vector $\boldsymbol{\Theta}$ remain the same across all these scenarios.

Figure 5, like a production possiblity frontier, shows the greater global emissions reductions (on the vertical axis) that can be achieved at the cost of ever greater declines in global consumption (on the horizontal axis), for a given scenario for Home. The red x's for each scenario indicate the optimal emissions reduction when $\varphi^W = 190$.

Figure 5: Coalition Size



The consistent story is that there are substantial gains from expanding the taxing coalition. The EU alone has almost no power to reduce global emissions. Adding the

[41]We treat the global case as the limit of our two-region model as Foreign becomes infinitesimally small. For the EU-only case, we treat the EU as having 28 members as it had, prior to Brexit, in 2015.

United States or the rest of the OECD countries helps significantly and increases the willingness of the coalition to incur costs to reduce emissions. Adding China to the taxing coalition leads to even greater emissions reductions for any given reduction in global consumption, and for $\varphi^W = \$190$ global emissions reductions are about ⅔ of what they would be for a global coalition.

Looking at the calibration tables, Appendix Tables 16 and 17, we can see that the size of the extraction base is the key difference between the EU and the coalition of the EU and the United States. Energy used in production and consumption is roughly double, reflecting the relative size of the two economies, but extraction is higher by a factor of more than 5. With almost no extraction, the EU on its own gets little advantage from the extraction tax portion of the optimal policy, which means that acting alone, it only slightly reduces global emissions. Adding the United States expands the extraction base and makes the policy more effective.

6.3.2 Choice of Tax

Figure 6: Choice of Tax in the OECD

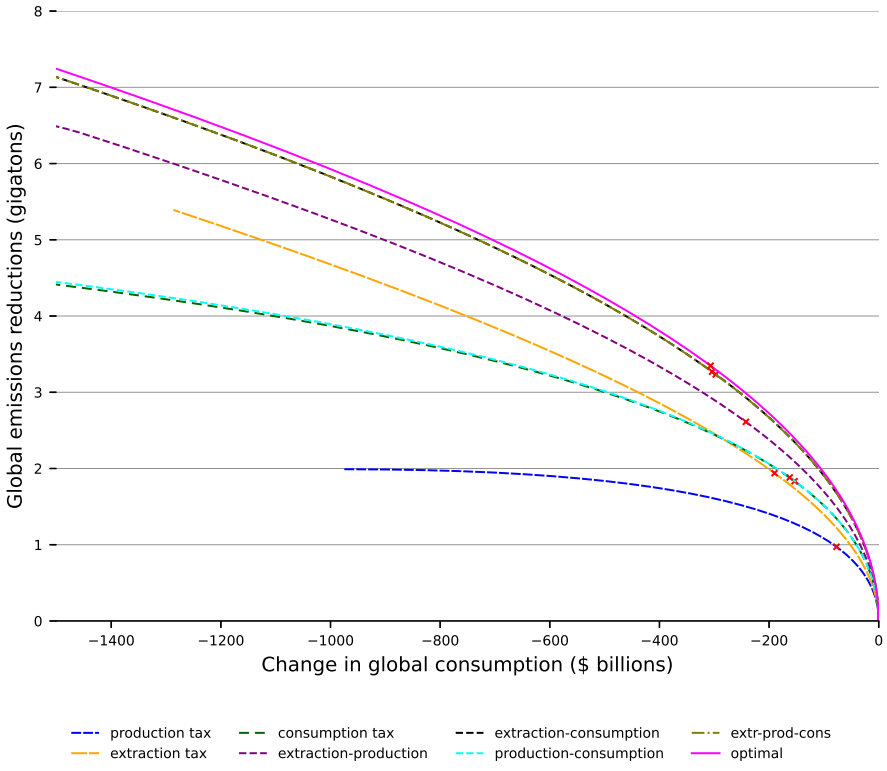


Figure 6 compares the set of taxes and subsidies that implement the optimal policy

to the seven constrained taxes (the three pure taxes and the hybrids of those taxes) with Home as the OECD.[42] A pure consumption tax significantly outperforms a pure production tax, confirming the widely-held view that adding border adjustments to a production tax (which shift the tax downstream to consumption) may be desirable. Hybrid taxes that combine demand-side and supply-side taxes, however, provide an even greater benefit. For example, the extraction-production hybrid substantially outperforms a pure consumption tax, and the extraction-consumption hybrid and the hybrid of all three taxes (which are nearly indistinguishable in the figure) come close to the optimal.

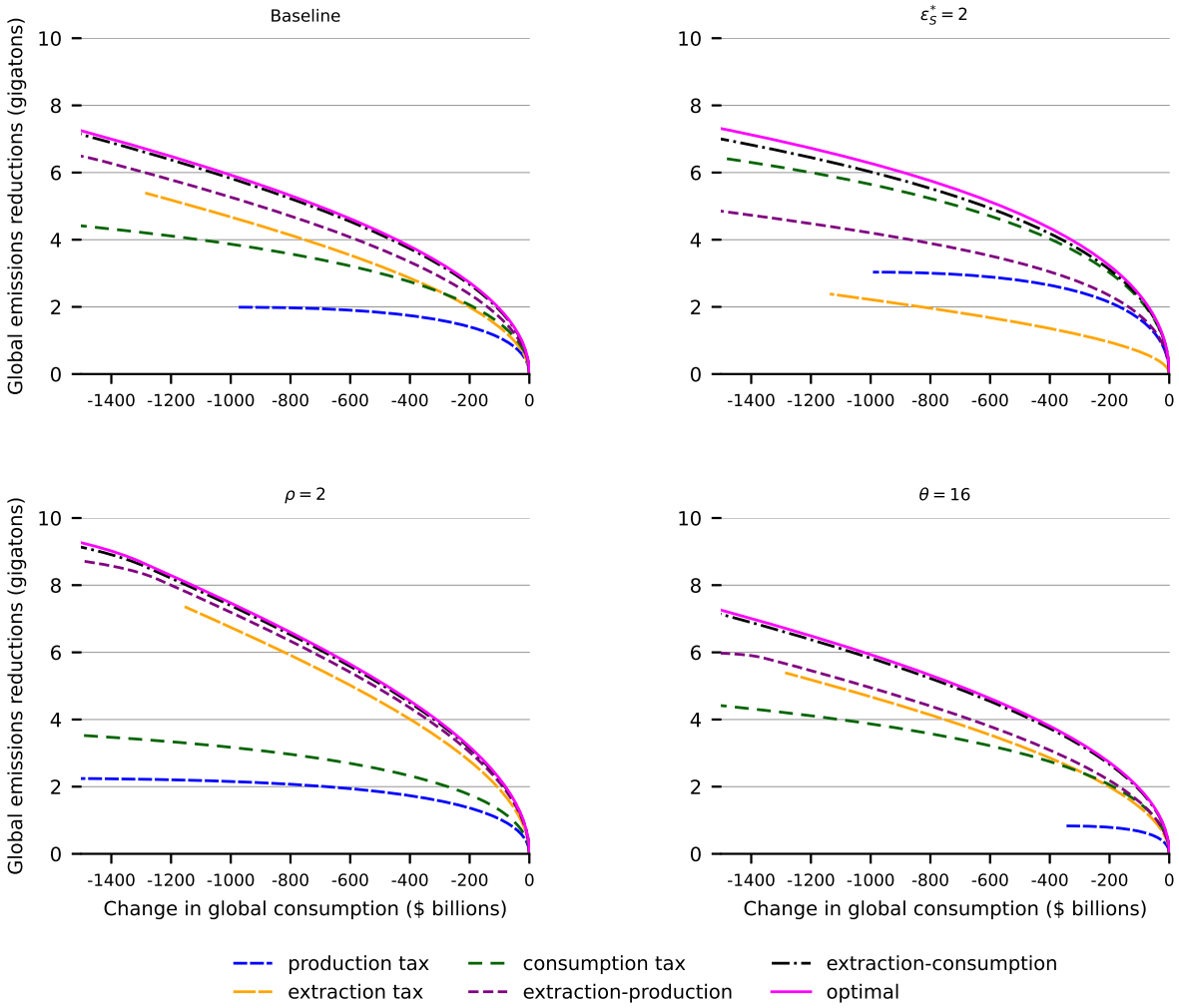
In our static model, the EU's emissions trading system is like a pure production tax, with a tax rate equal to the price of an emissions permit. Within the next few years, the EU CBAM will impose border taxes on imports (importers must purchase emissions permits) but will not rebate prior taxes paid (emissions permits purchased) on exports, which means that the EU CBAM is like a production-consumption tax, with $t_p = t_c$. Comparing a pure consumption tax to that hybrid tax (so adding export rebates to it) shows that the two systems perform almost identically. Full export rebates do not hurt the system's performance very much (at least with Home as OECD), notwithstanding that exported goods no longer bear a tax.

Figure 7 explores how the constrained policies perform under different parameter values (for legibility, we do not show the production-consumption hybrid and the hybrid of all three taxes). When ϵ_S^* is high (top right), the extraction tax no longer performs well. By raising p_e, it induces a large response in Foreign's extraction which offsets reductions in extraction in Home. Demand-side taxes, particularly a pure consumption tax, are correspondingly more effective because they lower p_e, causing a significant reduction in Foreign's extraction. Because the extraction tax now lacks power, combining it with a consumption tax does not significantly improve its performance.

When ρ is high (bottom left), the extraction tax performs better than baseline. It increases p_e which causes a large shift away from energy use in Foreign. Demand-side

[42]The frontiers for a pure extraction tax and a pure production tax in Figure 6 stop short on the left. For the extraction tax, Home extraction Q_e hits zero when the net price hits zero (at $p_e = t_e = \$224$) for sufficiently high φ^W. A higher extraction tax becomes irrelevant beyond that point. For a production tax, eventually leakage hits 100% (at $t_p = \$327$ with $p_e = \$147$) even as $\varphi^W \to \infty$. An optimal production tax wouldn't go above the value at which $\Lambda = 1$ (100% leakage), as a higher tax with lower global consumption no longer buys lower global emissions. For any policy that involves a consumption tax, global emissions continue to decline (with t_c ever higher) as $\varphi^W \to \infty$, even at a higher cost in global consumption.

Figure 7: Choice of Tax with Alternative Parameters



taxes lower p_e, and therefore, do not take advantage of the ability of Foreign to shift away from energy-intensive production. The extraction tax on its own in this scenario performs almost as well as the optimal policy, which itself relies heavily on an extraction tax (as seen in Figure 4, middle right panel).

Finally, when θ is high (bottom right), the production tax performs especially poorly. If θ is high, direct leakage will be more prevalent. The production tax doesn't control direct leakage and, therefore, is ineffective in this scenario. Policies other than a production tax, however, perform similarly to our baseline case even when θ is high, indicating that concerns about leakage can readily be addressed through a number of different policies.

Figure 8: Energy Price and Foreign Activities

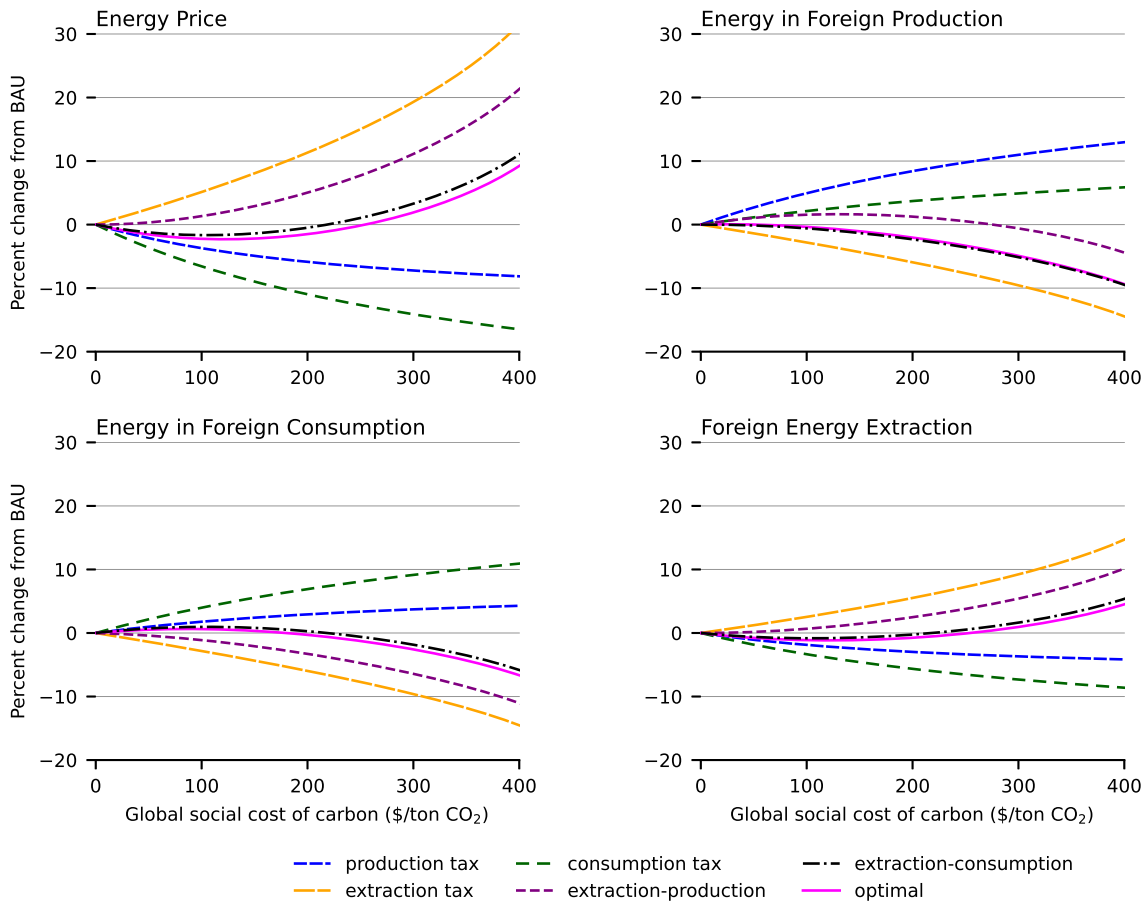


Figure 8 shows the effects of the same six policies (under our baseline calibration) on the price of energy and foreign extraction, production, and consumption, providing a visual sense of different types of leakage (both direct and indirect) caused by various policies. Demand-side policies, such as a production tax or a consumption tax, suppress p_e, while supply-side policies increase p_e. For values of the social cost of carbon below \$260, the optimal policy keeps p_e roughly level, as does the extraction-consumption hybrid.

The effects on Foreign activities follow from the change in p_e. Because an extraction tax increases p_e, it causes Foreign to increase extraction and reduce production and consumption. The demand side policies, because they lower p_e, reduce Foreign's extraction but increase Foreign's production and consumption. The optimal policy

minimizes changes in Foreign's extraction and consumption, but causes a modest decline in Foreign's production, due to the rise in j_x.

Combined, Figures 6 through 8 show that the hybrid taxes generally perform better than the pure taxes and in some cases come close to the optimal tax.

7 Multiple Energy Sources

So far we have treated energy as a homogeneous fossil fuel measured in units of CO_2. Here we extend the analysis to accommodate $r = 1, 2, ..., R$ energy sources such as coal, natural gas, solar, and wind, which may differ in dirtiness, $d_r = CO_2$ per unit of energy. We take $r = 1$ to be oil, with $d_1 = 1$. If r is a renewable source then $d_r = 0$. Each source has a corresponding distribution of what we continue to call extraction costs, analogous to those for oil deposits, $E_r(a)$ in Home and $E_r^*(a)$ in Foreign.[43]

To keep this extension as simple as possible we take different sources of energy to be perfect substitutes for users. We continue to assume that oil is traded at price p_e, but again we simplify the analysis by treating other forms of energy as nontradeable.[44] The quantity of energy supplied by Home becomes $Q_e = \sum_{r=1}^{R} Q_{e,r}$, with CO_2 content $Q_c = \sum_{r=1}^{R} d_r Q_{e,r}$. Foreign supplies $Q_e^* = \sum_{r=1}^{R} Q_{e,r}^* = \sum_{r=1}^{R} E_r^*(p_e)$, with CO_2 content $Q_c^* = \sum_{r=1}^{R} d_r Q_{e,r}^*$. For $R = 1$ we return to our original analysis with no distinction between the quantity of energy and its carbon content.

7.1 Amendments to the Planning Problem

Incorporating multiple energy sources in this way requires only modest extensions to the unilaterally optimal solution presented in Section 3. Critically, $Q_c^W = Q_c + Q_c^*$ replaces Q_e^W as the source of the global externality, and hence the variable multiplying φ^W in the Lagrangian (12). The inner problem is unchanged since different sources of

[43]We assume that each of these distributions satisfies the conditions described in footnote 9. This formulation is plausible for renewables as well, although the term *generation* is then more appropriate than *extraction*. Generating energy from solar, wind, and water power is constrained, like extracting fossil fuels, by scarce geographic factors.

[44]With this assumption we rule out interventions by Home that could shift Foreign's extraction toward energy sources with lower CO_2 content. In contrast, Kotchen and Maggi (2025) consider trade in both "green energy" and fossil fuels in a simpler 2-country model with a climate externality. Their analysis can rationalize carbon policies that combine a subsidy to green energy with a tax on fossil-fuel extraction. The logic is related to why Home subsidizes exports of some goods in our paper, to crowd out dirty production in Foreign. While intriguing, a full analysis of such policies is beyond the scope of this paper.

energy are perfect substitutes in production, with the Lagrange multiplier λ_e applying to energy without regard to its carbon content.

In the outer problem, the first-order condition for Home extraction from a given source r implies:

$$Q_{e,r} = E_r \left(\lambda_e - d_r \varphi^W\right), \tag{23}$$

for $\lambda_e - d_r \varphi^W \geq 0$ and $Q_{e,r} = 0$ otherwise. This condition is like (17) but with the dirtiness of energy source r weighting the global social cost of carbon. The planner's choice of direct consumption of energy satisfies (18).

The first-order condition for the energy price is like (19) but with a separate extraction wedge, $p_e - (\lambda_e - d_r \varphi^W)$, for each energy source. Aggregating over energy sources, the first-order condition becomes:

$$\varphi^W \frac{\partial Q_c^*}{\partial p_e} - [\lambda_e - p_e] \frac{\partial Q_e^*}{\partial p_e} + [\lambda_e - p_e] \frac{\partial C_e^{\tilde{y}*}}{\partial p_e} + \int_{j_s}^{j_x} [s_j] \frac{\partial x_j}{\partial p_e} dj = 0. \tag{24}$$

The response of the carbon content of Foreign's extraction, $\partial Q_c^* / \partial p_e$, is a key determinate of the consumption wedge that balances (24). A higher Foreign response requires that Home increase net exports of energy, thereby lowering the global energy price and raising the consumption wedge. Foreign's *marginal* response is what matters. Even if most Foreign energy is from renewable sources, if coal is the dominant marginal source, the planner will maintain a larger consumption wedge to reduce Foreign's extraction of this carbon-intensive fossil fuel.

7.2 Amendments to Optimal Taxes

The optimal policy can be implemented as in Section 4.1, with a nominal extraction tax per unit of CO_2 (Pigouvian wedge), a border adjustment per unit of energy (consumption wedge), and a subsidy per unit of goods (in Interval 2) exported by Home (export wedges). With multiple sources of energy, however, energy and CO_2 are not functionally the same. The nominal extraction tax, φ^W, applies to the carbon content of each source of energy, at a common rate per unit of CO_2. The tax rate per unit of energy depends on the dirtiness of each source, $t_{e,r}^N = d_r \varphi^W$. The border adjustment, $t_b = \lambda_e - p_e$, on the other hand, applies per unit of energy, whether on energy itself or on energy

embodied in Home imports of goods.[45] The after-tax price of energy in Home, whether consumed directly or embodied in domestically produced or imported goods, is $p_e + t_b$ without regard to its source.

Combining the nominal extraction tax with the border adjustment, the effective tax per unit of energy supplied from source r is $t_{e,r} = t^N_{e,r} - t_b$, equal to the corresponding extraction wedge. Home's extractors receive $p_e - t_{e,r}$ per unit of energy extracted from source r, and therefore extract a quantity satisfying (23). The effective extraction tax will be positive for dirty sources (with $d_r \geq 1$), for which $t_{e,r} \geq \varphi^W - (\lambda_e - p_e)$, but negative for renewables (with $d_r = 0$), for which $t_{e,r} = p_e - \lambda_e < 0$. Under the optimal policy, extraction from a high-carbon source will shrink or even cease, while renewables will expand due to the implicit subsidy per unit of renewable energy generated. The policy, as implemented here, provides a supply-side incentive to generate clean energy rather than a demand-side incentive to use clean energy.

7.3 Quantitative Illustration

To assess the implications of these amendments to the optimal unilateral policy, we modify the procedure described in Section 6, in a minimal way, by including just renewable energy ($r = 2$) along with oil ($r = 1$). We assume that renewables supply has the same functional form as oil deposits. We calibrate the level of renewables supply to BAU, with renewables accounting for 13% of energy supply (based on the same IEA source that we use for fossil fuel extraction). We consider the case of both a low renewables supply elasticity in Home and Foreign (of 0.5) and a high elasticity (of 2). All other parameters are set to their baseline values from Section 6.2.

Global carbon flows in BAU remain as in Table 4 (taking Home to be the OECD), but we need to include the additional energy from renewables when we calibrate energy demand. To minimize deviations from Section 6, we calibrate direct consumption of energy in Home and Foreign (implicitly η_e and η^*_e) to absorb this extra energy in BAU.[46]

Figure 9 shows what renewables contribute to the optimal unilateral policy. The left panel compares global emissions reductions, relative to BAU, without renewables

[45]This result formalizes the argument made in Kortum and Weisbach (2017) that the border adjustment should not be based on the carbon content of the energy source used to produce a particular good. Instead, what matters is the carbon content of the marginal energy source (with respect to a change in p_e) for the region exporting the good, which enters into equation (24).

[46]This choice of calibration does not constrain where renewable energy is used under the optimal unilateral policy. Recall that for users of energy, oil and renewables are perfect substitutes.

and with renewables (under both a low and high renewables supply elasticity). At a social cost of carbon of $300, global emissions are reduced by an additional 1.5 gigatons due to renewables (in the low-elasticity case) and by 3.5 gigatons (in the high-elasticity case). The right panel shows that the welfare gains for the policy are substantially higher in the presence of renewables, particularly in the high-elasticity case.

Figure 9: Optimal Policy with Renewables

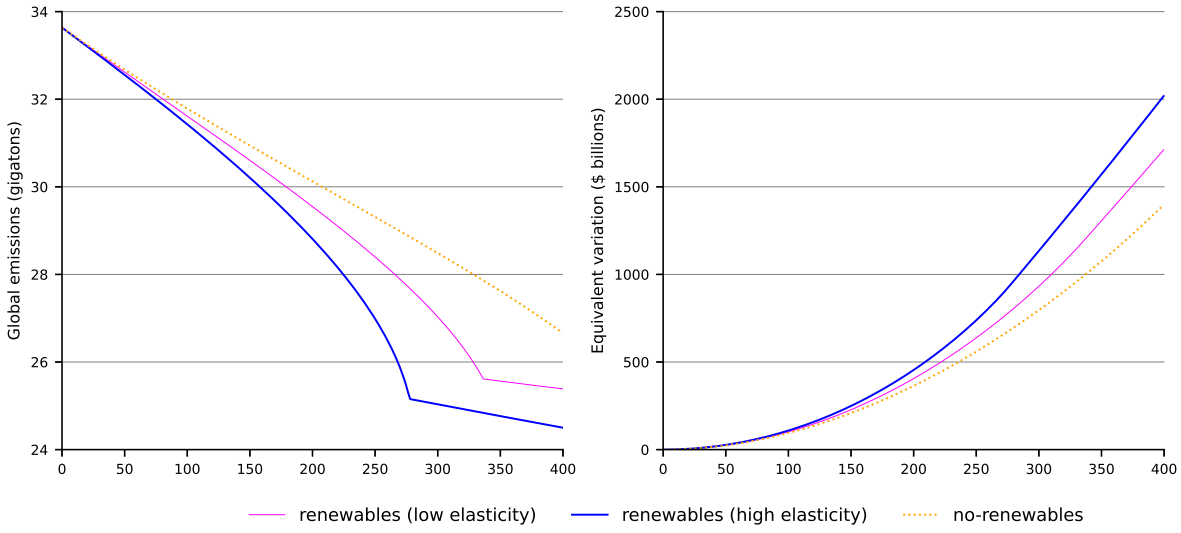
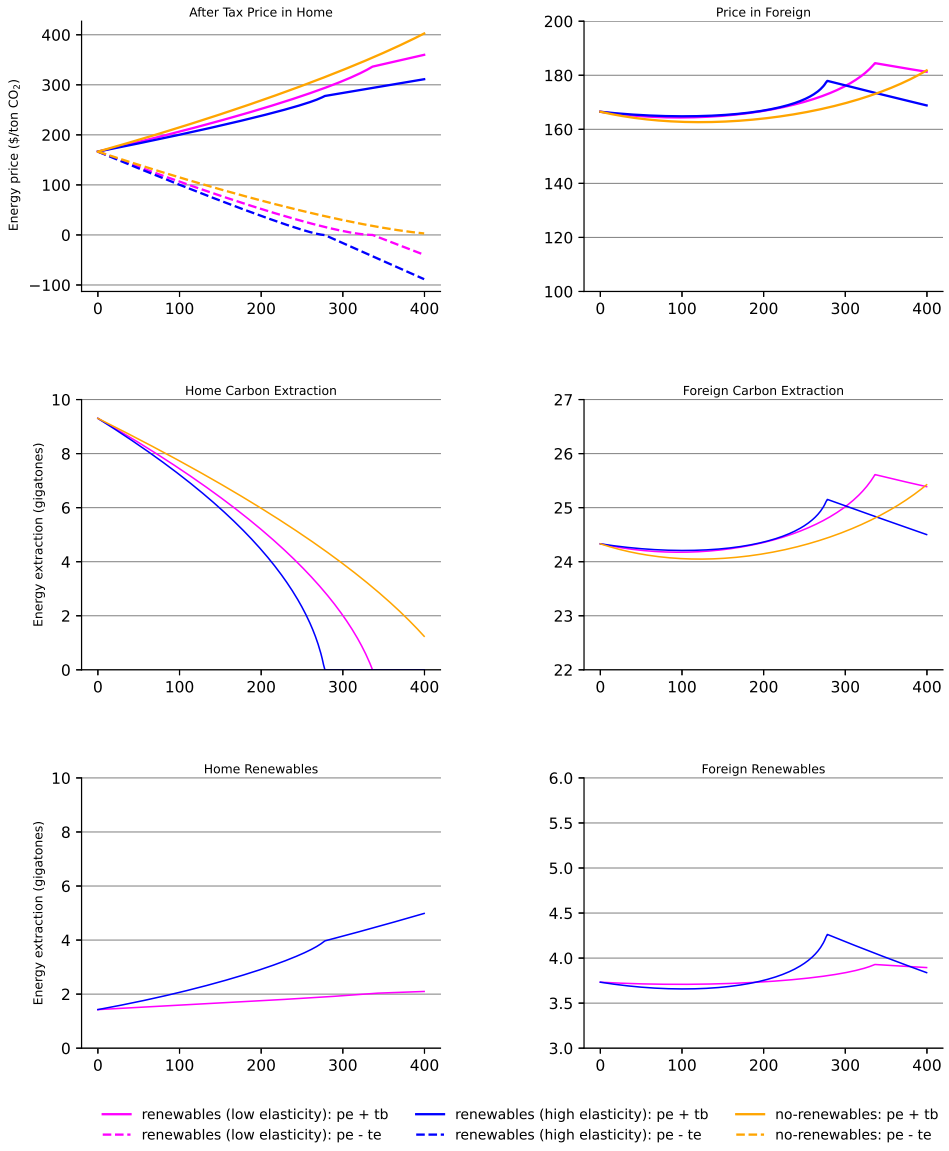


Figure 10 explores the mechanism behind these results. The upper left panel shows that in the presence of renewables, the optimal unilateral policy leads to a lower after-tax cost of energy for users in Home and a lower after-tax price for oil extractors in Home. The reason is that the policy tilts away from a border adjustment and toward a higher extraction tax when there is an alternative clean source of energy. This shift slightly raises the global energy price, relative to the scenario with no renewables, as shown in the upper right panel. Home's extraction of fossil fuel declines quite dramatically, as shown in the middle left panel, and shuts down completely when the social cost of carbon exceeds $340 (for the case of low renewables elasticity) or $275 (for the high-elasticity case). Renewables supply in Home expands, as renewables do not pay the extraction tax.

Figure 10: Energy Price and Supply in Home and Foreign



8 Conclusion

While the model in this paper is highly stylized, its simplicity yields analytical insights into the features of an optimal unilateral carbon policy. To go deeper requires pushing the analysis in a more quantitative direction, perhaps extending it to multiple countries, to multiple industries (with input-output linkages), or to multiple periods of time.[47] Another important extension, in a multi-country world, is to consider endogenizing the region we call Home. Our current approach follows Markusen (1975) and CDVW in assuming that Foreign is intransigent. Home's optimal policy will likely be different if it can entice (or coerce) other countries to join its coalition.[48]

[47] Barresi (2022) shows how our unilateral carbon policy fits into the multi-country trade model of Eaton and Kortum (2002), with coalitions of countries representing Home and Foreign. Larch and Wanner (2024) provide a natural multi-country analysis of the energy sector. Golosov, Hassler, Krusell, and Tsyvinski (2014) and Kotlikoff, Kubler, Polbin, Sachs, and Scheidegger (2021) are roadmaps for introducing dynamics.

[48] Promising steps in this direction have been taken by Nordhaus (2015) and Farrokhi and Lashkaripour (2025).

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