

CAN TRADE POLICY MITIGATE CLIMATE CHANGE?

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Trade policy is often cast as a solution to the free-riding problem in international climate agreements. This paper examines the extent to which trade policy can deliver on this promise. We incorporate global supply chains of carbon and climate externalities into a multi-country, multi-industry general equilibrium trade model. By deriving theoretical formulas for optimal carbon and border taxes, we quantify the maximum efficacy of two trade policy solutions to the free-riding problem. Adding optimal *carbon border taxes* to existing tariffs proves largely ineffective, delivering only 3.4% of what could be achieved under globally optimal carbon pricing. In contrast, Nordhaus's (2015) *climate club* framework, in which border taxes are used as contingent penalties to deter free-riding, can achieve 33–68% of the globally optimal carbon reduction, depending on the initial coalition (EU, EU + US, or EU + US + China). In all cases, the climate club ensures universal compliance, thereby preserving free trade.

KEYWORDS: Climate change, international climate agreements, free riding, trade policy, carbon border taxes, climate clubs, general equilibrium, optimal policy.

1. INTRODUCTION

CLIMATE CHANGE is accelerating at an alarming rate, yet governments have been unsuccessful in forging an agreement to effectively tackle this pressing issue. Major climate agreements, like the 1997 KYOTO PROTOCOL and the 2015 PARIS CLIMATE ACCORD, have failed to deliver a meaningful reduction in global carbon emissions. This failure is often attributed to the *free-riding* problem: Countries have an incentive to free-ride on the rest of the world's reduction in carbon emissions without undertaking proportionate abatement themselves.

The shortcoming of existing climate agreements has led experts to propose alternative solutions that are resistant to free-riding. Two canonical trade policy proposals have emerged:

PROPOSAL 1: Climate-conscious governments use *carbon border taxes* as a second-best policy to curb untaxed carbon emissions beyond their jurisdiction.

PROPOSAL 2: Climate-conscious governments form a *climate club*, using collective and contingent trade penalties to incentivize climate cooperation by reluctant governments.

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While both proposals combine carbon pricing with trade policy, they differ starkly in their approach. Proposal 1 is grounded in unilateralism. It presumes that global climate cooperation is improbable, but unilateral policies can serve as a viable second-best solution. Proposal 2 relies on the premise that unilateral action is insufficient and that the failure of past multilateral agreements could be reversed through better institutional design.

The maximal efficacy of these proposals remains unclear due to the challenges in characterizing their *optimal* design within *quantitative* frameworks. Traditional theories of optimal trade and environmental policy are limited to stylized models that preclude quantitatively important considerations. Existing quantitative studies examine simplified variants of these proposals that are not optimal, sidestepping the computational challenges associated with optimal policy analysis. Thus, they reveal only a fraction of what these proposals could potentially achieve.

We overcome these challenges by combining optimal policy analysis with quantitative general equilibrium modeling. First, we incorporate global carbon supply chains and climate externalities into a multi-country, multi-industry general equilibrium trade model. Second, we derive theoretical formulas for optimal carbon border taxes and climate club penalties that internalize climate damage from carbon emissions and terms-of-trade effects under rich general equilibrium considerations. Third, we map our model and optimal policy formulas to data on trade, production, and emissions to evaluate the maximal effectiveness of carbon border taxes and climate clubs.

Section 2 presents our theoretical framework, that is a general equilibrium semi-parametric model of international trade with many countries and industries. Our framework incorporates production, distribution, and utilization of fossil fuel energy, which gives rise to international climate externalities. The resulting framework is particularly attractive as it tractably combines the carbon externality and terms-of-trade rationales for policy intervention. Section 3 derives theoretical formulas for optimal carbon and border taxes in our general equilibrium framework. Our optimal policy formulas represent a notable advance over traditional theories. In addition to internalizing multilateral leakage and ripple effects through carbon supply chains, our formulas pave the way for an in depth quantitative analysis of the above canonical climate policy proposals.

We derive computationally efficient formulas for optimal policy using a dual decomposition method that breaks down the general equilibrium optimal policy problem into independent sub-problems. Specifically, the optimal policy problem consists of a system of first-order conditions involving complex derivatives, representing the general equilibrium response of nonpolicy variables to policy. These derivatives are challenging to characterize, making optimal policy derivation difficult in general equilibrium settings. Our decomposition method simplifies this by dividing the problem into independent subproblems that can be solved without calculating such complex derivatives.¹ This approach mirrors the logic of the envelope theorem, in which the optimal policy for each instrument sets the marginal effect of a subset of variables to zero, making changes in those variables irrelevant when optimizing across other instruments.

Our analytical formulas indicate that the *unilaterally* optimal domestic carbon tax equals the disutility from carbon emissions for domestic households. This policy choice is inefficient from a global standpoint as it does not internalize the home country's carbon externality on foreign residents. Unilaterally optimal import tariffs and export subsidies are

¹Our decomposition method relies on the simplifying assumption that policy-induced changes to relative wages among foreign countries have no first-order effect on domestic welfare.

composed of two components: a conventional terms-of-trade-driven component and carbon border adjustments. Relevant to Proposal 1, these carbon adjustments impose a tax on imported goods based on the carbon content per dollar value and provide a subsidy to exported goods based on the carbon intensity of competing foreign varieties. Relevant to Proposal 2, the unilaterally optimal border taxes represent the trade penalties that maximize welfare transfers from free-riders to climate club members.

To better understand these noncooperative policy choices and elucidate the free-riding problem, we compare them with optimal policy under global cooperation. The first-best policy from a global standpoint features zero border taxes/subsidies and a globally optimal carbon tax that equals the *global* disutility from carbon emissions. Importantly, the globally optimal carbon tax rate greatly exceeds the unilaterally optimal rate as it penalizes a country's carbon externality on not only its own residents but also foreign households. Governments acting in their own self-interest, therefore, have incentives to deviate from the globally optimal rate, thus perpetuating the free-riding problem in climate action.

Sections 4 and 5 leverage our optimal tax formulas for counterfactual analysis to determine the maximal efficacy of carbon border taxes and the climate club proposal in reducing carbon emissions. The required data for counterfactual policy analysis are obtained as follows: First, observable shares are constructed from national and environmental accounts data. Second, the governments' perceived disutility from climate change is inferred from their applied environmentally-related taxes. Third, structural parameters including the industry-level trade elasticities and the energy demand elasticity are estimated using cross-sectional tax and expenditure data, utilizing conventional identification strategies. The required data on trade, production, carbon emissions, and taxes are primarily taken from the GTAP Database for 2014 augmented by several auxiliary data sources. Our final database covers 18 broadly defined industries, including energy, representing the entire vector of production across 13 major countries, the European Union, and five aggregate regions containing neighboring blocs of countries.

Our analysis reveals that adding border taxes to unilaterally optimal domestic carbon taxes yields limited carbon reduction. Introducing optimally-designed border taxes reduces global emissions by an additional 1.3%—addressing merely 3.4% of the excess emissions caused by free-riding behavior. Border taxes' inefficacy as an indirect form of carbon taxation stems from three factors. First, carbon border taxes fail to incentivize abatement among foreign firms because they tax firms based on industry-wide national averages rather than the firm-specific carbon intensity. Since individual firms cannot meaningfully influence these broad averages, they have no incentive to reduce their carbon intensity in response to these taxes. Second, carbon border taxes cannot target emissions from nontraded goods, which account for a significant share of global emissions. Third, carbon border taxes cannot prevent carbon leakage through general equilibrium price changes. As pretax energy prices fall in response to border taxes, energy use, and carbon emissions tend to increase in countries without a domestic carbon tax.

To examine the climate club, we solve a sequential game where *core* members move first, followed by other countries. Core members and noncore countries that join the club abide by the rules of membership: they impose unilaterally optimal trade penalties against nonmembers and commit to free trade among members. Furthermore, they raise domestic carbon prices to meet a specified *carbon tax target*. Nonmembers can use their trade taxes to retaliate against club members but keep their other taxes unchanged. When con-

sidering joining the club, countries weigh the cost of higher domestic carbon taxes against the benefits of evading the climate club's collective trade penalties.²

In setting the climate club's carbon tax target, we balance two considerations. The first is a trade-off reminiscent of the *Laffer* curve. Higher taxes encourage greater emission cuts per member, but also discourage participation—yielding an inverted U-shape relationship between global carbon reduction and the carbon tax target. The second consideration is upholding free trade. Trade penalties against nonmembers are intended as deterrent threats, so the ideal target must be set at a level that elicits universal participation, rendering the imposition of such penalties unnecessary. Considering these dual objectives, our analysis sets the carbon tax target at the maximal rate that results in an inclusive club of all nations.

The climate club framework can effectively reduce global carbon emissions, but its success hinges on the makeup of core members. If the EU and US initiate a climate club as core members, universal participation will be attained at a maximal carbon tax target of 53 (\$/tCO₂), yielding a 18.6% reduction in global carbon emissions. Though substantial, the EU-US alliance lacks the necessary market power to elicit a higher tax target. However, by incorporating China as a core member, the maximal carbon tax target can be raised to 89 (\$/tCO₂) leading to a 28.0% reduction in global carbon emissions. This figure represents 68% of the emissions reduction achievable under globally first-best carbon taxes, based on a social cost of carbon of 156 (\$/tCO₂). Overall, the climate club's efficacy in mitigating climate change relies on assembling an influential group of core members and setting an appropriate carbon tax target. Moreover, comparing the efficacy of the climate club to carbon border taxes reveals that trade policy is more effective when used as a contingent penalty for deterring free-riding than an indirect mechanism for carbon taxation.

Climate clubs outperform noncoordinated, unilateral policies for two reasons. First, they employ trade penalties as an enforcement tool rather than a means of indirect carbon taxation. These penalties are specifically designed to compel governments to increase their domestic carbon taxes. Domestic taxes are more effective than indirect border taxes because they induce abatement among local firms and can cover both traded and non-traded goods. Second, the multilateral structure of climate clubs amplifies the impact of trade penalties compared to unilateral measures. By leveraging their collective market power, club members can impose more consequential penalties on free-riders, generating stronger pressure for compliance.

Related Literature

Our work contributes to several areas of literature. First, we contribute to *theoretical* analyses of trade and environmental policy. Early works such as [Markusen \(1975\)](#), [Copeland \(1996\)](#), [Hoel \(1996\)](#), use partial equilibrium or two-country models to study how unilaterally-applied trade taxes can mitigate transboundary environmental damages. More recent research by [Kortum and Weisbach \(2021\)](#) and [Weisbach, Kortum, Wang,](#)

²Analyzing the climate club proposal quantitatively poses two major challenges. First, computing optimal trade penalties in a strategic game involving many players is practically infeasible with numerical optimization methods. We circumvent this issue by leveraging our theoretical formulas for optimal trade penalties. Second, solving the climate club game suffers from the curse of dimensionality, requiring that one searches over an excessively large number of possible outcomes. To overcome this challenge, we shrink the space of possible outcomes using a procedure that closely mimics the iterative elimination of dominated strategies.

and Yao (2023) characterizes unilaterally-optimal carbon policy in a two-country Dornbusch, Fischer, and Samuelson (1977) model, emphasizing the effectiveness of combining supply and demand-side carbon taxes. Another body of literature examines international agreements that link trade and climate policy, wherein free trade is *contingent* on climate action (Barrett (1997), Nordhaus (2015), Maggi (2016), Nordhaus (2021), Harstad (2024), Iverson (2024)). Our work advances this literature by characterizing optimal policy in a multi-country and multi-industry general equilibrium model amenable to rich quantitative analysis.

Second, our analysis is related to *quantitative* examinations of environmental and energy-related policies in open economies, for example, Babiker (2005), Elliott, Foster, Kortum, Munson, Perez Cervantes, and Weisbach (2010), Taheripour, Hertel, and Ramankutty (2019), Farrokhi (2020). Our paper is especially relevant to studies analyzing the efficacy of carbon border adjustment policies, including Böhringer, Carbone, and Rutherford (2016), Larch and Wanner (2017), Shapiro (2021). Although these studies feature rich specifications of the global economy, they lack a concept of optimal policy design. Consequently, they do not reveal the full potential of trade policy for reducing carbon emissions. We complement this literature by utilizing optimal policy formulas to uncover the frontier of trade and climate policy outcomes.

Third, our work relates to an emerging literature characterizing optimal policy in modern quantitative trade models, for example, Costinot, Donaldson, Vogel, and Werning (2015), Bartelme, Costinot, Donaldson, and Rodríguez-Clare (2021), Beshkar and Lashkaripour (2020), Lashkaripour (2021), Caliendo and Parro (2022), Lashkaripour and Lugovskyy (2023). These studies have bridged a longstanding divide between classic partial equilibrium trade policy frameworks and modern general equilibrium trade theories. Our dual decomposition technique advances this effort towards closing the gap. It shows that optimal policy formulas can be derived without characterizing complex general equilibrium elasticities, removing a primary impediment to general equilibrium optimal policy analysis. This particular result sharpens and extends the result in Lashkaripour and Lugovskyy (2023) to settings with global carbon supply chains and international consumption externalities, an example of which is climate change damage.

Lastly, we contribute to research on trade and the environment by examining trade policy as a tool to mitigate climate change. This literature incorporates environmental issues, from local pollution to global deforestation, into trade models, for example, Shapiro and Walker (2018) and Farrokhi, Kang, Pellegrina, and Sotelo (2023), with key advances reviewed by Desmet and Rossi-Hansberg (2024). For broader reviews, see Copeland and Taylor (2004) and Copeland, Shapiro, and Taylor (2021), and for a discussion on integrating climate change into the existing world trade system, see Staiger (2021).

2. THEORETICAL FRAMEWORK

The global economy consists of multiple countries indexed by $i, j, n \in \mathbb{C} \equiv \{1, \dots, N\}$ and multiple industries indexed by $k, g \in \{0, 1, \dots, K\}$. Each country i is endowed by \bar{L}_i workers and \bar{R}_i carbon reserves. Workers are perfectly mobile across industries but immobile across countries, and each worker supplies one unit of labor inelastically. Production in the global economy can be thought of as a two-stage process. First, each country's energy industry (indexed by $k = 0$) employs labor and carbon reserves—as a specific input—to produce energy. Second, other industries (indexed by $k = 1, \dots, K$) employ labor and

energy to produce final goods. Markets are perfectly competitive³ and goods in all industries are internationally traded.

We denote quantities of energy in terms of their CO₂ emission content. Along the carbon supply chain, we count CO₂ emissions when energy is used by final good producers and households. Since every individual producer or consumer is infinitesimally small, they do not internalize the impact of their production or consumption choices on CO₂ emissions.⁴

2.1. Prices and Tax Instruments

Subscript (ji, k) indexes a variety corresponding to *origin j-destination i-industry k*, that is, a variety of industry k that is produced in origin j and shipped to destination i . Country i 's government has access to the following tax instruments:

1. Import tax, $t_{ji,k}$, applied to imported variety ji, k ($t_{ii,k} = 0$ by design);
2. Export subsidy, $x_{ij,k}$, applied to exported variety ij, k ($x_{ii,k} = 0$ by design);
3. Carbon tax, $\tau_{i,k}$, applied to the carbon content of energy use;

Border taxes/subsidies create a wedge between the after-tax consumer price, $\tilde{P}_{ji,k}$, and the before-tax producer price, $P_{ji,k}$, of each variety (ji, k) ,

$$\tilde{P}_{ji,k} = \frac{(1 + t_{ji,k})}{(1 + x_{ji,k})} \times P_{ji,k}, \quad k = 0, 1, \dots, K. \quad (1)$$

A representative “energy distributor” in country i purchases varieties of energy from international suppliers $j = 1, \dots, N$, at prices $\{\tilde{P}_{ji,0}\}_j$, and aggregates them into a composite energy bundle with price $\tilde{P}_{i,0} = \tilde{P}_{i,0}(\tilde{P}_{1i,0}, \dots, \tilde{P}_{Ni,0})$. This bundle is sold to domestic producers after the inclusion of an end-use-specific carbon tax, which creates a wedge between $\tilde{P}_{i,0}$ and the final price paid by producers for use in industry k :

$$\tilde{P}_{i,0k} = \tilde{P}_{i,0} + \tau_{i,k}, \quad k = 1, \dots, K; \quad (2)$$

where $\tilde{P}_{i,0k}$ denotes the price of energy input for use in industry $k = 1, \dots, K$ (after the inclusion of all taxes) and $\tau_{i,k}$ is the carbon tax. The above-listed tax instruments are sufficient for obtaining the first-best policy outcome under cooperative and noncooperative scenarios. Additional tax instruments (e.g., production or consumption taxes) are redundant as their effects can be perfectly mimicked with the appropriate choice of existing instruments.

2.2. Consumption

The representative household in country i maximizes a nonparametric utility function $U_i(C_i)$ by choosing the vector of consumption quantities, $C_i = \{C_{ji,k}\}_{j,k \geq 1}$, subject to the budget constraint,

$$E_i = \sum_{j=1}^N \sum_{k=1}^K \tilde{P}_{ji,k} C_{ji,k}, \quad (3)$$

³In Section 6.3, we consider a more general case with monopolistic competition and firm entry.

⁴Throughout the paper, we use “energy” as a shorthand for “fossil fuel energy” and we use “carbon emissions” interchangeably with “CO₂ emissions.”

where E_i denotes national household expenditure, and $\tilde{P}_{ji,k}$ is the consumer price index of variety ji, k (Equation (1)). Let $\tilde{P}_i = \{\tilde{P}_{ji,k}\}_{j \in C, k \geq 1}$ denote the entire vector of consumer prices in country i . The household's utility maximization implies an indirect utility function, $V_i(E_i, \tilde{P}_i)$, and a Marshallian demand function for each variety ji, k ,

$$C_{ji,k} = D_{ji,k}(E_i, \tilde{P}_i), \quad k = 1, \dots, K. \tag{4}$$

We denote the elasticity of demand for variety (ji, k) with respect to the price of variety (ni, g) by

$$\varepsilon_{ji,k}^{(ni,g)} \equiv \frac{\partial \ln D_{ji,k}(E_i, \tilde{P}_i)}{\partial \ln \tilde{P}_{ni,g}}, \quad \varepsilon_{ji,k} \sim \varepsilon_{ji,k}^{(ji,k)}; \tag{5}$$

with the *own* price elasticity of demand compactly denoted as $\varepsilon_{ji,k} \sim \varepsilon_{ji,k}^{(ji,k)} \leq -1$.

We use β and λ to denote household expenditure shares. The within-industry expenditure share on variety ji, k (origin j -destination i -industry k) is denoted by $\lambda_{ji,k}$, and the overall expenditure share of country i on industry $k \neq 0$ is denoted by $\beta_{i,k}$,

$$\lambda_{ji,k} \equiv \frac{\tilde{P}_{ji,k} C_{ji,k}}{\sum_{n=1}^N \tilde{P}_{ni,k} C_{ni,k}}, \quad \beta_{i,k} \equiv \frac{\sum_{n=1}^N \tilde{P}_{ni,k} C_{ni,k}}{\sum_{n=1}^N \sum_{g=1}^K \tilde{P}_{ni,g} C_{ni,g}} = \frac{\sum_{n=1}^N \tilde{P}_{ni,k} C_{ni,k}}{E_i}. \tag{6}$$

A familiar special case is the Cobb–Douglas–CES form, where a constant fraction of expenditure, $\beta_{i,k}$, is spent on industry k whose varieties are differentiated by source countries under a constant elasticity of substitution, σ_k . The demand function in this special case is

[special case: Cobb–Douglas–CES]
$$D_{ji,k}(E_i, \tilde{P}_i) = \frac{b_{ji,k} \tilde{P}_{ji,k}^{-\sigma_k}}{\sum_n b_{ni,k} \tilde{P}_{ni,k}^{1-\sigma_k}} \beta_{i,k} E_i,$$

where $b_{ji,k}$ is an exogenous demand shifter and demand elasticities are given by $\varepsilon_{ji,k}^{(ni,k)} = -\sigma_k \mathbb{1}_{n=j} + (\sigma_k - 1)\lambda_{ni,k}$ and $\varepsilon_{ji,k}^{(ni,g)} = 0$ if $g \neq k$.

2.3. Production

Energy Extraction. The extraction industry ($k = 0$) in each country j produces energy by employing exogenously-given carbon reserves, \bar{R}_j , as a specific input and labor, $L_{j,0}$, as a variable input under a Cobb–Douglas technology:

$$Q_{j,0} = \bar{\varphi}_{j,0} \left(\frac{L_{j,0}}{1 - \phi_j} \right)^{1-\phi_j} \left(\frac{\bar{R}_j}{\phi_j} \right)^{\phi_j}. \tag{7}$$

Here, $\bar{\varphi}_{j,0}$ is an exogenous productivity parameter and $Q_{j,0}$ is the output quantity of energy, which can be thought of as *carbon supply* from each economy j . Extracted energy varieties are traded internationally subject to border taxes but *without* incurring iceberg

trade costs. The producer price of the energy variety extracted in country j equalizes across destinations i ,⁵

$$P_{ji,0} = P_{jj,0} = \frac{1}{\bar{\varphi}_{j,0}} w_j^{1-\phi_j} r_j^{\phi_j}. \tag{8}$$

Here, w_j is the wage rate in country j , and r_j represents the rental rate of carbon reserves in that country. Similar to other goods, energy varieties are subject to border taxes, resulting in a destination-specific consumer price, $\tilde{P}_{ji,0} = \frac{1+t_{ji,0}}{1+x_{ji,0}} P_{jj,0}$.

Energy Distribution. A representative energy distributor in each country i purchases varieties of energy $\{C_{ji,0}\}_i$ from international suppliers $j = 1, \dots, N$, aggregates them into a bundle of energy, $Z_i = Z_i(C_{1i,0}, \dots, C_{Ni,0})$, and sells this energy bundle to domestic final-good producers. The price of the energy bundle, $\tilde{P}_{i,0}$, is determined by a homogeneous-of-degree-one aggregator:

$$\tilde{P}_{i,0} = \tilde{P}_{i,0}(\tilde{P}_{1i,0}, \dots, \tilde{P}_{Ni,0}). \tag{9}$$

The energy price aggregator, $P_{i,0}(\cdot)$, is implied by a homothetic demand system for international energy varieties. The distributor’s demand for variety $(j, 0)$ is a function of total expenditure on energy varieties, $E_{i,0} = \sum_j \tilde{P}_{ji,0} C_{ji,0}$, and the vector of energy prices, $\tilde{P}_{i,0} = \{\tilde{P}_{1i,0}, \dots, \tilde{P}_{Ni,0}\}$, which includes border taxes but excludes the carbon tax applied post-distribution. Namely,

$$C_{ji,0} = D_{ji,0}(E_{i,0}, \tilde{P}_{i,0}). \tag{10}$$

As earlier, we use $\varepsilon_{ji,0}^{(ni,0)} = \partial \ln D_{ji,0}(\cdot) / \ln \tilde{P}_{ni,0}$ as the price elasticity of demand for energy varieties. A special case of the above specification is the CES aggregator, which implies the following price and quantity equations:⁶

$$[\text{special case: CES}] \quad \tilde{P}_{i,0}(\tilde{P}_{i,0}) = \left[\sum_j b_{ji,0} \tilde{P}_{ji,0}^{1-\sigma_0} \right]^{\frac{1}{1-\sigma_0}}; \quad D_{ji,0}(E_{i,0}, \tilde{P}_{i,0}) = \frac{b_{ji,0} \tilde{P}_{ji,0}^{-\sigma_0} E_{i,0}}{\sum_n b_{ni,0} \tilde{P}_{ni,0}^{1-\sigma_0}}.$$

Note that $\tilde{P}_{ji,0}$ includes border taxes on energy but not the carbon tax. The latter is applied after bundling of energy varieties, so that the final price of the energy bundle paid by final-good producers k is $\tilde{P}_{i,0k} = \tilde{P}_{i,0} + \tau_{i,k}$.

Household Energy Consumption. Our setup accommodates energy use by households, which we model by making use of a fictitious industry $k_0 \in \{1, \dots, K\}$ that purchases the energy bundle, at price $\tilde{P}_{i,0} + \tau_{i,k_0}$, and converts it without generating any value added into a final good of the same price. This fictitious industry is nontradeable and sells ex-

⁵This specification implies an energy supply curve, $P_{jj,0} = \bar{p}_{j,0} \times w_j \times Q_{j,0}^{\phi_j}$, where $\bar{p}_{j,0} = (\bar{\varphi}_{j,0} \times [\bar{R}_j / \phi_j]^{\phi_j})^{-1/(1-\phi_j)}$ is an exogenous shifter and $\bar{\phi}_j \equiv \phi_j / (1 - \phi_j) > 0$ is the inverse energy supply elasticity.

⁶The finite elasticity of substitution between energy sources, as shown in Farrokhi (2020), can be micro-founded via aggregation over sourcing choices of input-users who face variability in transport costs vis-a-vis exporters.

clusively to domestic households.⁷ Therefore, households' consumption of final good k_0 corresponds to their energy consumption and their associated CO₂ emission.

Production of Final Goods. Production of final good $k = 1, \dots, K$ in country i is conducted by symmetric competitive firms that combine labor and the energy input. Total production in each industry is represented by an aggregate constant-returns-to-scale production function:

$$Q_{i,k} = \bar{\varphi}_{i,k} F_{i,k}(L_{i,k}, Z_{i,k}). \quad (11)$$

The arguments $L_{i,k}$ and $Z_{i,k}$ denote the quantity of labor and energy inputs, and $\bar{\varphi}_{i,k} > 0$ is a Hicks-neutral productivity shifter. International trade in final goods is subject to iceberg trade costs, $\bar{d}_{in,k} \geq 1$, with $\bar{d}_{ii,k} = 1$. Per cost minimization, the competitive producer price of variety in, k is

$$P_{in,k} = \frac{\bar{d}_{in,k}}{\bar{\varphi}_{i,k}} \times c_{i,k}(w_i, \tilde{P}_{i,0k}), \quad (12)$$

where $c_{i,k}(\cdot)$ is a homogeneous-of-degree-one aggregator of input prices: the wage rate, w_i , and the after-tax price of the energy, $\tilde{P}_{i,0k} = \tilde{P}_{i,0} + \tau_{i,k}$. Assuming that the demand for inputs is homothetic, the cost share of energy, $\alpha_{i,k} \equiv \tilde{P}_{i,0k} Z_{i,k} / Y_{i,k}$, is also fully-determined by w_i and $\tilde{P}_{i,0k}$, with $Y_{i,k} = P_{ii,k} Q_{i,k}$ denoting the total value of sales of origin i -industry k .

A canonical special case of our setup is the case of CES production function, with

$$F_{i,k}(L_{i,k}, Z_{i,k}) = \left[(1 - \bar{\kappa}_{i,k})^{\frac{1}{\varsigma}} L_{i,k}^{\frac{\varsigma-1}{\varsigma}} + (\bar{\kappa}_{i,k})^{\frac{1}{\varsigma}} Z_{i,k}^{\frac{\varsigma-1}{\varsigma}} \right]^{\frac{\varsigma}{\varsigma-1}},$$

where $\bar{\kappa}_{i,k} \in [0, 1]$ represents exogenous energy intensity, and $\varsigma > 0$ is the elasticity of substitution between labor and energy inputs. In this special case, the input cost aggregator becomes

$$[\text{special case: CES}] \quad c_{i,k} = c_{i,k}(w_i, \tilde{P}_{i,0k}) \equiv \left[(1 - \bar{\kappa}_{i,k}) w_i^{1-\varsigma} + \bar{\kappa}_{i,k} \tilde{P}_{i,0k}^{1-\varsigma} \right]^{\frac{1}{1-\varsigma}};$$

where ς regulates the “energy demand elasticity,” implying $\alpha_{i,k} = \bar{\kappa}_{i,k} (\tilde{P}_{i,0k} / c_{i,k})^{1-\varsigma}$.

2.4. CO₂ Emissions

Aggregate CO₂ emissions from each industry $k = 1, \dots, K$ can be decomposed as

$$Z_{i,k} = z_{i,k} Q_{i,k}, \quad (13)$$

where $z_{i,k}$ represents the emissions per unit quantity and $Q_{i,k}$ is output quantity.⁸ The emission per quantity is determined by the after-tax energy input price, $\tilde{P}_{i,0k}$, and the wage rate:

$$z_{i,k} = z_{i,k}(\tilde{P}_{i,0k}, w_i).$$

⁷This is equivalent to the standard specification where households buy energy directly from the energy distributor, subject to a household-specific carbon tax, τ_{i,k_0} .

⁸In Copeland and Taylor (2004) terminology, $z_{i,k}$ represents *technique*, $Q_{i,k}$ is *scale*, and $\{Z_{i,k}\}_k$ represents *composition*.

A carbon tax, $\tau_{i,k}$, raises the consumer price of energy, $\tilde{P}_{i,0k}$, resulting in a lower energy use $Z_{i,k}$ per unit of final good production. Country i 's total CO₂ emissions, Z_i , and the distributor's total energy expenditure, $E_{i,0}$, are

$$Z_i = \sum_{k=1}^K Z_{i,k}, \quad E_{i,0} = \tilde{P}_{i,0} Z_i. \tag{14}$$

Under the special case with CES production, the emission per quantity takes the following parametric representation:

$$[\text{special case: CES}] \quad z_{i,k}(\tilde{P}_{i,0k}, w_i) = \bar{z}_{i,k} \left[\frac{\bar{\kappa}_{i,k} \tilde{P}_{i,0k}^{1-s}}{(1 - \bar{\kappa}_{i,k}) w_i^{1-s} + \bar{\kappa}_{i,k} \tilde{P}_{i,0k}^{1-s}} \right]^{\frac{s}{s-1}},$$

where $\bar{z}_{i,k} \equiv \bar{\kappa}_{i,k}^{\frac{1}{1-s}} / \bar{\varphi}_{i,k}$ is a constant shifter. Lastly, global CO₂ emissions can be calculated by summing over national CO₂ emissions:

$$Z^{(\text{global})} \equiv \sum_i Z_i. \tag{15}$$

2.5. General Equilibrium

Tax Revenues and National Income. We denote by T_i the tax revenues collected by country i 's government from imports, exports, and carbon taxes and rebated to consumers in that country,

$$T_i = \underbrace{\sum_{k=1}^K [\tau_{i,k} Z_{i,k}]}_{\text{carbon taxes}} + \underbrace{\sum_{k=0}^K \sum_{n \neq i} \left[\frac{t_{ni,k}}{1 + t_{ni,k}} \tilde{P}_{ni,k} C_{ni,k} \right]}_{\text{import taxes}} - \underbrace{\sum_{k=0}^K \sum_{n \neq i} \left[\frac{x_{in,k}}{1 + t_{in,k}} \tilde{P}_{in,k} C_{in,k} \right]}_{\text{export subsidies}}.$$

Let $Y_{i,k}$ denote sales of country i -industry k ,

$$Y_{i,k} = P_{ii,k} Q_{i,k}. \tag{16}$$

Industry sales, on aggregate, generate an income level of $\sum_{k=0}^K Y_{i,k} = w_i \bar{L}_i + r_i \bar{R}_i$ in each country i . We assume trade is balanced, so that national income is the sum of the wage bill, rental payments to carbon reserves, and tax revenues:

$$Y_i = w_i \bar{L}_i + \Pi_i + T_i, \quad \text{where } \Pi_i = r_i \bar{R}_i. \tag{17}$$

General Equilibrium. For a given set of taxes $\{t_{ji,k}, x_{ij,k}, \tau_{i,k}\}$, a *general equilibrium* is a vector of consumption, production and input use, $\{C_{ji,k}, Q_{i,k}, L_{i,k}, Z_{i,k}\}$, final goods and energy input prices, $\{P_{ji,k}, \tilde{P}_{ji,k}, \tilde{P}_{i,0}, \tilde{P}_{i,0k}\}$, wage and rental rates, $\{w_i, r_i\}$, and income, sales, and expenditure levels, $\{Y_i, Y_{i,k}, E_i, E_{i,0}\}$, such that Equations (1)–(17) hold; goods market clear, equating national consumption expenditure with income, $E_i = Y_i$, and each industry's total output with demand,

$$Q_{i,k} = \sum_{n=1}^N \bar{d}_{in,k} C_{in,k} \tag{18}$$

and the factor markets clear according to

$$w_i \bar{L}_i = \sum_{k=1}^K [(1 - \alpha_{i,k}) Y_{i,k}] + (1 - \phi_i) Y_{i,0}, \quad \Pi_i \equiv r_i \bar{R}_i = \phi_i Y_{i,0}; \quad (19)$$

where the wage rate in each country clears the labor market and the rental rate of carbon reserves clears the market for energy extraction.

3. OPTIMAL POLICY AND THE FREE-RIDING PROBLEM

Our analysis builds on the realization that the globally optimal climate outcome is politically infeasible due to free-riding incentives, but climate-conscious countries can use trade policies to target global emissions. In this section, we first characterize the unilaterally optimal carbon and border taxes, elucidating two rationales for policy intervention from a unilateral standpoint. Next, we characterize the globally optimal policy to highlight the free-riding problem in climate agreements. Finally, we discuss two trade policy remedies for the free-riding problem: carbon border taxes and the climate club. We explain how our theoretical optimal policy results provide the groundwork for quantitatively evaluating these policies. To set the stage, we begin with a formal definition of policy objectives.

Social Welfare With Climate Damage. The welfare of the representative consumer in country i is the utility from consumption net of the disutility from CO₂ emissions.⁹ Namely,

$$W_i = V_i(E_i, \tilde{P}_i) - \delta_i \times Z^{(\text{global})}. \quad (20)$$

The first component represents the indirect utility from consumption and the second component is the disutility from global CO₂ emissions. δ_i is a parameter that represents the disutility per unit of CO₂ emissions for country i 's residents. However, since individual producers or consumers take $Z^{(\text{global})}$ as given, they do not internalize the associated externality in their energy consumption decisions. Governments, meanwhile, can influence CO₂ emissions and internalize them in their policy choice. So, for all practical purposes, δ_i hereafter represents the disutility from CO₂ emissions as *perceived* by governments—meaning that our analysis does not rule out that δ_i may be disconnected from the actual climate cost facing country i 's residents.¹⁰ With this in mind, we turn to characterizing optimal policy under various scenarios.

3.1. Unilaterally Optimal Policy Problem

Unilaterally optimal policies apply to noncooperative settings, where governments choose policies to maximize national welfare as specified by Equation (20) without considering effects on foreign households. The government in country i can utilize a comprehensive set of tax instruments denoted by $\mathbb{I}_i \equiv \{t_{ji,k}, x_{ij,k}, \tau_{i,k}\}_{j,k}$. The unilateral optimal

⁹We exclude political economy factors for two reasons. First, they predominantly influence the within-national rather than cross-national distribution of welfare or rents, which is not the focus of our analysis; see Ossa (2016). Second, quantifying political economy weights is infeasible due to overidentification issues. For any hypothetical tax schedule, there exists a set of political weights that would rationalize it as optimal.

¹⁰We also examine an alternative specification where δ_i maps to estimates of country-level climate change damage.

policy choice is formally defined below, with an expansive formulation of the optimal problem provided in Supplemental Appendix B.1 (Farrokhi and Lashkaripour (2025)).

DEFINITION: The *Unilaterally Optimal Policy* for country i consists of taxes, $\mathbb{I}_i^* \equiv \{t_{ji,k}^*, x_{ij,k}^*, \tau_{i,k}^*\}_{j,k}$, that maximize country i 's welfare in general equilibrium:

$$\mathbb{I}_i^* = \arg \max W_i(\mathbb{I}_i, \bar{\mathbb{I}}_{-i}) \text{ subject to general equilibrium Equations (1)–(19);}$$

where W_i is described by Equation (20) and $\bar{\mathbb{I}}_{-i}$ denotes policy choices in the rest of the world, which country i takes as given.

The unilaterally optimal policy seeks to correct the two sources of inefficiency in the decentralized equilibrium from country i 's *unilateral* standpoint: First, private energy production and consumption decisions fail to internalize the associated climate externality on country i 's residents (as measured by δ_i). Second, country i 's producers fail to internalize their collective market power when pricing the goods, so there is unexploited market power which country i 's government can exploit to improve its terms of trade vis-a-vis the rest of the world.¹¹

The *targeting principle* provides guidance on the unilaterally optimal policy choices. Domestic carbon taxes are the first-best remedy for correcting carbon emissions from domestic economic activity. Border taxes (based on the carbon content of goods) are the unilaterally optimal instrument for correcting foreign emissions. And border taxes (based on national-level market power) are the first-best instrument for manipulating the terms-of-trade. However, characterizing the optimal policy is complicated in multi-country, multi-industry general equilibrium models. Below, we introduce a method to bypass some of these complexities.

Before beginning our analysis, it is useful to conceptualize an equilibrium under optimal policy as the joint solution to two mappings: (a) the equilibrium allocation given optimal taxes, and (b) the optimal taxes given an equilibrium allocation. The following section provides a unique representation for mapping (b), with Section 4.1 detailing how we jointly solve (a) and (b).¹²

3.2. Dual Decomposition Technique for Optimal Policy Derivation

To derive the unilaterally optimal policy, we first reformulate the problem of selecting taxes, $\mathbb{I}_i \equiv \{t_{ji,k}, x_{ij,k}, \tau_{i,k}\}_{j,k}$, into an equivalent problem where the government directly selects after-tax prices: $\mathbb{P}_i = \{\tilde{P}_{ji,k}, \tilde{P}_{ij,k}, \tau_{i,k}\}_{j,k}$. Optimal import tariffs and export subsidies can be derived from optimal prices, \mathbb{P}_i^* , using $1 + t_{ji,k}^* = \frac{\tilde{P}_{ji,k}^*}{P_{ji,k}}$ and $(1 + x_{ij,k}^*)^{-1} = \frac{\tilde{P}_{ij,k}^*}{P_{ij,k}}$. The reformulated optimal policy problem can be expressed as

$$\max_{\mathbb{P}_i} V_i(E_i, \tilde{\mathbf{P}}_i) - \delta_i Z^{(\text{global})}.$$

¹¹Similarly, domestic consumers fail to internalize their collective monopsony power when buying foreign varieties.

¹²Note that mapping (b) is unique up to the multiplicity introduced by the Lerner symmetry. Moreover, if mapping (a) admits multiple solutions, this multiplicity will extend to the joint solution of (a) and (b). In the presence of multiple equilibria, our optimal policy results do not offer guidance on how to choose between the multiple joint solutions.

The first-order condition (FOC) *w.r.t.* to a generic policy instrument $\tilde{P} \in \tilde{\mathbb{P}}_i$ is

$$\frac{\partial V_i(\cdot)}{\partial E_i} \frac{\partial E_i}{\partial \tilde{P}} + \frac{\partial V_i(\cdot)}{\partial \tilde{P}} - \delta_i \frac{\partial Z^{(\text{global})}}{\partial \tilde{P}} = 0.$$

A critical aspect of our approach is specifying E_i and $Z^{(\text{global})}$ as functions of select variables and expressing $\frac{\partial E_i}{\partial \tilde{P}}$ and $\frac{\partial Z_{n,k}}{\partial \tilde{P}}$ in terms of their derivatives. Total expenditure is equal to national income, given by the following function:

$$E_i = Y_i = Y_i(\mathbb{P}_i, \mathbf{w}, \mathbf{C}, \mathbf{Z}_i, \mathbf{P}_0).$$

The function, $Y_i(\cdot)$, is a unique mapping *from* policy \mathbb{P}_i , wages $\mathbf{w} \equiv [w_i, \mathbf{w}_{-i}]$, consumption quantities $\mathbf{C} \equiv [C_i, \mathbf{C}_{-i}, C_{i,0}, \mathbf{C}_{-i,0}]$, local emissions \mathbf{Z}_i , and energy producer prices \mathbf{P}_0 to national income, Y_i , which is the sum of factor rewards and tax revenues. Using the vector notation for compactness, the function $Y_i(\cdot)$ is defined as

$$\begin{aligned} Y_i(\mathbb{P}_i, \mathbf{w}, \mathbf{P}_0, \mathbf{C}, \mathbf{Z}_i) &= w_i L_i + \Pi_i([P_{in,0}]_n, w_i) + \boldsymbol{\tau}_i^\top \mathbf{Z}_i \\ &+ (\tilde{P}_{i,0} - P_{i,0})^\top C_{i,0} + (\tilde{P}_{-i,0} - P_{-i,0})^\top C_{-i,0} \\ &+ (\tilde{P}_i - P_i(\cdot))^\top C_i + (\tilde{P}_{-i} - P_{-i}(\cdot))^\top C_{-i}. \end{aligned}$$

Here, $\Pi_i([P_{in,0}]_n, w_i)$ is a function that maps wage and producer prices in the energy extraction sector to the surplus, Π_i , paid to fixed reserves, following cost minimization. The column vector $\mathbf{Z}_i = [Z_{i,k}]_k$ contains *local* industry-level emissions and $\boldsymbol{\tau}_i^\top = [\tau_{i,k}]_k^\top$ is the corresponding row vector of carbon taxes. $C_{i,0} \equiv [C_{ni,0}]_n$ denotes *local* energy consumption quantities with corresponding after- and pre-tax prices $\tilde{P}_{i,0}$ and $P_{i,0}$; $C_{-i,0} \equiv [C_{in,0}]_{n \neq i}$ denotes energy *export* quantities with corresponding prices $\tilde{P}_{-i,0}$ and $P_{-i,0}$. Similarly, C_i and \tilde{P}_i denote the consumption quantity and after-tax price of *locally-consumed* final goods, and C_{-i} and \tilde{P}_{-i} denote the quantity and after-tax price of *exported* final goods. The functions $\mathbf{P}_i(\cdot) = [P_{ni,k}(\cdot)]_{n,k>0}$ and $\mathbf{P}_{-i}(\cdot) = [P_{in,k}(\cdot)]_{n \neq i, k>0}$ represent the producer prices of locally-consumed and exported final goods, where $P_{in,k}(\mathbb{P}_i, w_i)$ for all n and $P_{ni,k}(\mathbb{P}_i, P_{-in,0}, w_n)$ for $n \neq i$ (where $P_{-in,0} \equiv [P_{jn,0}]_{j \neq i}$), map policy, wages, and energy prices to producer prices that satisfy cost minimization.

Global emissions are the sum of domestic and foreign emissions, $Z^{(\text{global})} = \sum_k Z_{i,k} + \sum_k \sum_{n \neq i} Z_{n,k}$, where emissions for home (i) and foreign countries ($n \neq i$) are described by

$$Z_{i,k} = z_{i,k}(\mathbb{P}_i, w_i) Q_{n,k}, \quad Z_{n,k} = z_{n,k}(\tilde{P}_{in,0}, P_{-in,0}, w_n) Q_{n,k}.$$

The functions $z_{i,k}(\cdot)$ and $z_{n,k}(\cdot)$ for $n \neq i$ map input prices to the intensity of energy use (i.e., carbon emission per unit of output) as implied by cost minimization.¹³ Total output $Q_{n,k}$ is given by the function $Q_{n,k}(\cdot)$, which maps demand quantities for country n 's

¹³Recall that carbon emission intensities are fully determined by energy and labor input prices: $z_{n,k} = z_{n,k}(\tilde{P}_{n,0k}, w_n)$ for all n . The energy price, $\tilde{P}_{i,0k} = \tilde{P}_{i,0}(\{\tilde{P}_{ji,0}\}_j) + \tau_{i,k}$, in home country i is fully determined by policy, $\{\{\tilde{P}_{ji,0}\}_j, \tau_{i,k}\} \in \mathbb{P}_i$. In foreign country $n \neq i$, the energy price is determined by foreign energy prices, $P_{-in,0} \equiv [P_{jn,0}]_{j \neq i}$, and price of home's energy variety, $\tilde{P}_{in,0}$, which is set by home's export policy. So, we can reformulate the emission intensity function as

$$z_{n,k}(\tilde{P}_{n,0k}, w_n) = \begin{cases} z_{n,k}(\tilde{P}_{in,0}, P_{-in,0}, w_n) & n \neq i, \\ z_{i,k}(\mathbb{P}_i, w_i) & n = i. \end{cases}$$

varieties in industry k to total output:

$$Q_{n,k} = Q_{n,k}([C_{nj,k}]_j) \equiv \sum_{j=1}^N \bar{d}_{nj,k} C_{nj,k}.$$

Generic First-Order Condition. For expositional purposes, we present the logic of our dual decomposition method disregarding foreign energy price effects, $\frac{\partial [P_{-in,0}]_n}{\partial \tilde{P}}$. However, our actual derivation in the Supplemental Appendix accounts for these effects. Under this simplification, the FOC with respect to policy instrument $\tilde{P} \in \tilde{\mathbb{P}}_i$, can be expanded as¹⁴

$$\begin{aligned} \frac{\partial V_i(\cdot)}{\partial E_i} & \underbrace{\left(\frac{\partial Y_i(\cdot)}{\partial \tilde{P}} + \frac{\partial Y_i(\cdot)}{\partial \mathbf{w}} \frac{\partial \mathbf{w}}{\partial \tilde{P}} + \frac{\partial Y_i(\cdot)}{\partial [P_{in,0}]_n} \frac{\partial [P_{in,0}]_n}{\partial \tilde{P}} + \frac{\partial Y_i(\cdot)}{\partial \mathbf{C}} \frac{\partial \mathbf{C}}{\partial \tilde{P}} + \frac{\partial Y_i(\cdot)}{\partial \mathbf{Z}_i} \frac{\partial \mathbf{Z}_i}{\partial \tilde{P}} \right)}_{\partial E_i / \partial \tilde{P}} + \frac{\partial V_i(\cdot)}{\partial \tilde{P}} \\ & - \delta_i \underbrace{\left(\frac{\partial \mathbf{Z}_i}{\partial \tilde{P}} \mathbf{1} + \mathbf{z}_{-i} \frac{\partial \mathbf{Q}_{-i}}{\partial \tilde{P}} + \sum_{n \neq i} \left(\frac{\partial \mathbf{z}_n(\cdot)}{\partial \tilde{P}} + \frac{\partial \mathbf{z}_n(\cdot)}{\partial w_n} \frac{\partial w_n}{\partial \tilde{P}} \right) \mathbf{Q}_n \right)}_{\partial Z^{(global)} / \partial \tilde{P}} = 0. \end{aligned} \tag{21}$$

Terms such as $\frac{\partial V_i(\cdot)}{\partial \tilde{P}}$, $\frac{\partial Y_i(\cdot)}{\partial \tilde{P}}$ and $\frac{\partial \mathbf{z}_n(\cdot)}{\partial \tilde{P}}$ represent the partial derivative of known functions with respect to a specific argument. In contrast, $\frac{\partial \mathbf{w}}{\partial \tilde{P}}$, $\frac{\partial [P_{in,0}]_n}{\partial \tilde{P}}$, $\frac{\partial \mathbf{C}}{\partial \tilde{P}}$, $\frac{\partial \mathbf{Z}_i}{\partial \tilde{P}}$, and $\frac{\partial \mathbf{Q}_{-i}}{\partial \tilde{P}}$ are general equilibrium (GE) derivatives, which are difficult to characterize. They result from the implicit differentiation of a complex and interdependent system of equilibrium conditions. Traditionally, optimal policy formulas are either presented in terms of these complex derivatives (Dixit (1985)) or they are simplified through strong parametric assumptions that remove equilibrium interdependencies, reducing the noted derivatives into partial equilibrium objects.¹⁵ Our method takes a different approach. We use less restrictive assumptions, which allow us to bypass the task of calculating complex GE derivatives while maintaining the model’s rich GE structure.¹⁶

ASSUMPTION 1: *Policy-induced changes to relative wages between foreign countries (w_n/w_j , for all $n, j \neq i$) and changes to the fraction of wage to total income in foreign countries ($w_n L_n/Y_n$ for all $n \neq i$) have no first-order effect on country i ’s welfare in the neighborhood of the optimum.*

A similar consideration applies to the above definition of producer prices of final goods ($k > 0$), $P_{in,k}(\mathbb{P}_i, w_i)$ for all n and $P_{ni,k}(\mathbb{P}_i, P_{-in,0}, w_n)$ for $n \neq i$.

¹⁴To maintain compact notation, we omit the transpose sign hereafter, with the understanding that each product in the FOC represents compatible row and column vectors, for example, $\frac{\partial Y_i(\cdot)}{\partial \mathbf{w}} \frac{\partial \mathbf{w}}{\partial \tilde{P}} = \sum_n \frac{\partial Y_i(\cdot)}{\partial w_n} \frac{\partial w_n}{\partial \tilde{P}}$.

¹⁵For instance, consider a quasilinear and separable utility function, $U = C_0 + \sum_k u(C_k)$, where $u(C_k) = \frac{\eta}{\eta-1} (C_k^{\frac{\eta-1}{\eta}} - 1)$ for each good k . Here, $C_k = D_k(\tilde{P}_k) = \tilde{P}_k^{-\eta}$ depends only on the own price \tilde{P}_k , given the choice of numeraire, $\tilde{P}_0 = 1$. In particular, the GE elasticity $\frac{\partial C_k}{\partial \tilde{P}}$ reduces to a constant parameter, $-\eta$, if $\tilde{P} = \tilde{P}_k$ and is zero otherwise.

¹⁶Our approach advances the dual technique from Lashkaripour and Lugovskyy (2023) in two ways. First, we enhance their approach by recasting it as a dual decomposition method that partitions the optimal policy problem into independent subproblems. This reformulation enables standardized application across a broad range of optimal policy problems. Second, we extend their approach by incorporating international externalities, such as climate change, that operate through cross-border consumption and production effects, independently of terms-of-trade externalities. Our analysis introduces new lemmas (E1, E2, and E3, in Supplemental Appendix B) that characterize endogenous energy price changes throughout the global carbon supply chain.

Normalizing the wage rate in one of the foreign countries per Walras' law, we can invoke Assumption 1 (henceforth, A1) to solve the FOCs, disregarding changes to wages and income in the rest of the world. In other words, A1 effectively converts the generic system of FOCs into one that can be solved as if there is a single foreign wage. Quantitatively, we confirm in Supplemental Appendix D that A1 provides an accurate approximation and relaxing it has a negligible effect on optimal policy outcomes.¹⁷ The reason is that each country's policy exerts a negligible influence on relative foreign wages. Additionally, changes to relative foreign wages have an insignificant effect on home's welfare, as they represent transfers between foreign nations. Likewise, changes in foreign wage-to-income ratios represent transfers between agents within those countries, with minimal consequences for country i 's welfare. A1 becomes redundant in a standard trade policy framework, involving two countries, a single production factor, and a laissez-faire foreign country.

Beyond a two-country model, A1 simplifies the generic first-order condition (21) in two ways. First, the terms including foreign wage effects, $\frac{\partial Y_i(\cdot)}{\partial w_{-i}} \frac{w_{-i}}{\partial P} - \delta_i \sum_{n \neq i} \frac{\partial E_n(\cdot)}{\partial w_n} \frac{\partial w_n}{\partial P} Q_n$, can be disregarded at the optimum. Second, the GE derivatives of foreign demand with respect to policy reduce to Marshallian price elasticities of demand, $\frac{\partial C_{-i}}{\partial P} = \frac{\partial D_{-i}(\cdot)}{\partial P}$, which are easier to characterize.¹⁸ Nevertheless, the FOCs still involve the GE derivatives of local variables, such as $\frac{\partial w_i}{\partial P}$, $\frac{\partial C_i}{\partial P}$, $\frac{\partial Z_i}{\partial P}$, $\frac{\partial [P_{in,0}]_n}{\partial P}$, and $\frac{\partial Q_{-i}}{\partial P}$, which remain the main obstacles to deriving streamlined optimal policy formulas.

Building on several intermediate results, we demonstrate that the optimal policy problem can be decomposed into *independent subproblems* and solved without characterizing these GE derivatives.¹⁹ The first intermediate result (Lemma 1) shows that the terms containing the GE derivatives of local wage and energy producer prices, $\frac{\partial w_i}{\partial P}$, and $\frac{\partial [P_{in,0}]_n}{\partial P}$ drop out of the first-order condition:

$$\frac{\partial Y_i(\cdot)}{\partial w_i} = \frac{\partial Y_i(\cdot)}{\partial [P_{in,0}]_n} = 0. \quad [\text{Lemma 1}]$$

Based on the above result, the optimal policy could be derived without specifying the GE derivatives, $\frac{\partial w_i}{\partial P}$, and $\frac{\partial [P_{in,0}]_n}{\partial P}$. The logic is that any welfare gains from perturbing local wage or energy producer prices will be fully internalized by the price instruments in \mathbb{P}_i . Conditional on \mathbb{P}_i , changing local factor or producer prices merely redistributes income

¹⁷In Supplemental Appendix D, we validate the accuracy of our optimal policy formulas through extensive numerical testing, focusing particularly on the implications of A1. First, we show that the welfare gains predicted by our formulas are almost identical to those from numerical optimization. Second, we show that A1 provides an accurate approximation: perturbing a country's taxes around their optimal levels, has negligible effects on relative wages among foreign countries and their wage-to-income ratios. Importantly, our method offers substantial computational advantages: while direct numerical optimizations require 108 minutes to find a country's optimal unilateral policy, our algorithm accomplishes this in just 3.5 seconds. This dramatic improvement in computational speed is crucial for conducting our climate club analysis.

¹⁸The derivative of demand in foreign location $n \neq i$ can be expressed as $\frac{\partial C_n}{\partial P} = \frac{\partial D_n(\cdot)}{\partial P} + \frac{\partial D_n(\cdot)}{\partial E_n} \frac{\partial E_n}{\partial P}$, where by invoking A1 the second term can be disregarded near \mathbb{P}_i^* . The reason is that changes in $E_n = (\frac{Y_n}{w_n L_n}) w_n L_n$ are driven solely by changes in country n 's wage (w_n) and wage-to-income ratio ($w_n L_n / Y_n$), neither of which has first-order effects on country i 's welfare around the optimum, per A1. However, in the general case considered in the Supplemental Appendix, we also account for GE effects related to foreign energy prices, that is, $\frac{\partial C_n}{\partial P} = \frac{\partial D_n(\cdot)}{\partial P} + \frac{\partial D_n(\cdot)}{\partial P_{-in}} \frac{\partial P_{-in}(\cdot)}{\partial [P_{-in,0}]_m} \frac{\partial [P_{-in,0}]_m}{\partial P}$.

¹⁹Supplemental Appendix B contains the details of these intermediate results and their proofs.

between primary factors and government revenues, leaving total expendable income, Y_i , unchanged.

Optimal Local Prices. The FOC with respect to local consumer prices, $\tilde{P} \in \{\tilde{P}_i, \tau_i\}$, can be simplified by appealing to utility maximization and cost minimization—namely, Roy’s identity and Shephard’s lemma. This point constitutes our second intermediate result (Lemma 2):²⁰

$$\frac{\partial V_i(\cdot)}{\partial E_i} \frac{\partial Y_i(\cdot)}{\partial \tilde{P}} + \frac{\partial V_i(\cdot)}{\partial \tilde{P}} = 0, \quad \forall \tilde{P} \in \{\tilde{P}_i, \tau_i\}. \quad [\text{Lemma 2}]$$

Moreover, local prices do not directly enter the functions that regulate foreign emissions and demand, indicating that $\frac{\partial z_n(\cdot)}{\partial \tilde{P}} = 0$ and $\frac{\partial C_{-i}}{\partial \tilde{P}} = \frac{\partial D_{-i}(\cdot)}{\partial \tilde{P}} = 0$ for all $\tilde{P} \in \{\tilde{P}_i, \tau_i\}$. Considering this point and Lemma 2, and invoking A1 to discard the terms involving foreign wages, the first-order condition (Equation (21)), reduces to

$$\left[\frac{\partial Y_i(\cdot)}{\partial C_i} - \tilde{\delta}_i z_{-i} \frac{\partial Q_{-i}(\cdot)}{\partial C_i} \right] \frac{\partial C_i}{\partial \tilde{P}} + [\tau_i - \tilde{\delta}_i \mathbf{1}] \frac{\partial Z_i}{\partial \tilde{P}} = 0,$$

where $\tilde{\delta}_i \equiv \delta_i \tilde{P}_i$ is the carbon disutility adjusted for the consumer price index, $\tilde{P}_i \equiv (\frac{\partial V_i(\cdot)}{\partial E_i})^{-1}$. In the above equation, the terms in the bracket are easy to evaluate as they involve the derivative of known functions w.r.t. specific arguments. The GE derivatives, $\frac{\partial C_i}{\partial \tilde{P}}$, and $\frac{\partial Z_i}{\partial \tilde{P}}$, however, are difficult to characterize. But as hinted above, they need not be characterized to obtain the optimal policy formulas. This point is formalized by another intermediate result (Lemma 3), which states that local price optimality entails that

$$\frac{\partial Y_i(\cdot)}{\partial C_i} - \tilde{\delta}_i z_{-i} \frac{\partial Q_{-i}(\cdot)}{\partial C_i} = 0, \quad \tau_i - \tilde{\delta}_i \mathbf{1} = 0. \quad [\text{Lemma 3}]$$

The above result decomposes the optimal *local* price problem into independent subproblems that merely involve the derivative of functions, $Q_{-i}(\cdot)$ and $Y_i(\cdot)$ with respect to specific arguments. As we elaborate shortly, Lemma 3 also serves as an envelope-like result that simplifies the characterization of optimal export prices.

Optimal Export Prices. Now, consider the policy instrument, $\tilde{P} \in \tilde{P}_{in} \subset \tilde{P}_{-i}$, which regulates export prices to country $n \neq i$. Notice that $\frac{\partial V_i(\cdot)}{\partial \tilde{P}} = 0$, since \tilde{P} is not a local price. Moreover, $\tilde{P} \in \tilde{P}_{in}$ influences demand in foreign market n through $\frac{\partial C_n}{\partial \tilde{P}} = \frac{\partial D_n(\cdot)}{\partial \tilde{P}}$, and demand and emissions in the local market i through general equilibrium effects, that is, $\frac{\partial C_i}{\partial \tilde{P}} \sim \frac{\partial D_i(\cdot)}{\partial E_i} \frac{\partial E_i}{\partial \tilde{P}}$. Considering these points, the FOC w.r.t. $\tilde{P} \in \tilde{P}_{in}$ becomes

$$\begin{aligned} & \frac{\partial Y_i(\cdot)}{\partial \tilde{P}} + \left[\frac{\partial Y_i(\cdot)}{\partial C_n} - \tilde{\delta}_i z_{-i} \frac{\partial Q_{-i}(\cdot)}{\partial C_n} \right] \frac{\partial D_n(\cdot)}{\partial \tilde{P}} - \tilde{\delta}_i \frac{\partial z_n(\cdot)}{\partial \tilde{P}} Q_n \mathbf{1}(\tilde{P} = \tilde{P}_{in,0}) \\ & + \left[\frac{\partial Y_i(\cdot)}{\partial C_i} - \tilde{\delta}_i z_{-i} \frac{\partial Q_{-i}(\cdot)}{\partial C_i} \right] \frac{\partial C_i}{\partial \tilde{P}} + [\tau_i - \tilde{\delta}_i \mathbf{1}] \frac{\partial Z_i}{\partial \tilde{P}} = 0. \end{aligned}$$

²⁰For instance, consider the imported price of industry k from origin j , $\tilde{P} = \tilde{P}_{ji,k}$. When i ’s government raises $\tilde{P}_{ji,k}$, i ’s income increases proportional to its imported quantity $\frac{\partial Y_i(\cdot)}{\partial \tilde{P}_{ji,k}} = C_{ji,k}$, whereas Roy’s identity implies $\frac{\partial V_i(\cdot)}{\partial \tilde{P}_{ji,k}} = -\frac{\partial V_i(\cdot)}{\partial E_i} \times C_{ji,k}$. Together $\frac{\partial V_i(\cdot)}{\partial \tilde{P}_{ji,k}} + \frac{\partial V_i(\cdot)}{\partial E_i} \frac{\partial Y_i(\cdot)}{\partial \tilde{P}_{ji,k}} = 0$.

Following Lemma 3, the second line collapses to zero if local prices are set optimally. This makes Lemma 3 akin to an *envelope* result, allowing us to solve for the optimal export prices without considering their impact on local consumption and emissions. In other words, the export price problem simplifies into another independent subproblem.

Altogether, our dual approach breaks down the initial optimal policy problem into a set of independent subproblems that are free from GE derivatives (e.g., $\frac{\partial C_i}{\partial \tilde{P}}$, $\frac{\partial Z_i}{\partial \tilde{P}}$, $\frac{\partial [P_{in,0}]_n}{\partial \tilde{P}}$, $\frac{\partial w_i}{\partial \tilde{P}}$).²¹ We present this result under the following proposition.

PROPOSITION 1: *Country i 's unilaterally optimal policy can be obtained by solving three independent sub-problems:*

$$\begin{cases} \boldsymbol{\tau}_i - \tilde{\delta}_i \mathbf{1} = \mathbf{0} & \text{[SP 1]} \\ \frac{\partial Y_i(\cdot)}{\partial C_i} - \tilde{\delta}_i \mathbf{z}_{-i} \frac{\partial \mathbf{Q}_{-i}(\cdot)}{\partial C_i} = \mathbf{0} & \text{[SP 2]} \\ \frac{\partial Y_i(\cdot)}{\partial \tilde{P}} + \left[\frac{\partial Y_i(\cdot)}{\partial C_n} - \tilde{\delta}_i \mathbf{z}_{-i} \frac{\partial \mathbf{Q}_{-i}(\cdot)}{\partial C_n} \right] \frac{\partial \mathbf{D}_n(\cdot)}{\partial \tilde{P}} - \tilde{\delta}_i \frac{\partial \mathbf{z}_n(\cdot)}{\partial \tilde{P}} \mathbf{Q}_n \mathbf{1}(\tilde{P} = \tilde{P}_{in,0}) = 0 & \text{[SP 3]} \end{cases}$$

Solving these subproblems involves taking partial derivatives of known functions w.r.t. to their arguments, without specifying complex general equilibrium derivatives such as $\frac{\partial C_i}{\partial \tilde{P}}$, $\frac{\partial Z_i}{\partial \tilde{P}}$, $\frac{\partial [P_{in,0}]_n}{\partial \tilde{P}}$, and $\frac{\partial w_i}{\partial \tilde{P}}$.

As mentioned earlier, our presentation here abstracted away from foreign energy price effects, $\frac{\partial [P_{in,0}]_n}{\partial \tilde{P}}$. Our main derivation in Supplemental Appendix B accounts for these effects showing that these energy price effects can be specified as the product of a matrix of equilibrium variables and demand effects $\frac{\partial C}{\partial \tilde{P}}$ (Lemmas E1, E2, and E3 in the Supplemental Appendix). This result allows absorbing the energy price effects into subproblems 2 and 3, while preserving the modularity and independence of these subproblems.

3.3. Unilaterally Optimal Policy Formulas

We build on Proposition 1 to derive the unilaterally optimal policy formulas. To present our formulas, we denote by $v_{n,k}$ the CO₂ emission per unit value of output in country n -industry k , and let $\rho_{ni,k}$ denote market i 's share from that industry's total sales, $Y_{n,k}$,

$$v_{n,k} = \frac{Z_{n,k}}{Y_{n,k}}, \quad \rho_{ni,k} = \frac{P_{ni,k} C_{ni,k}}{Y_{n,k}} \tag{22}$$

Additionally, we denote the elasticities of demand for the composite energy input (equivalently, CO₂ emissions) with respect to the energy input price at the industry and national

²¹Costinot et al. (2015) present an alternative method for optimal policy derivation in a general equilibrium Ricardian model. Their primary approach breaks down the optimal policy problem into an inner problem involving good-specific and independent cell problems, and an outer problem that determines the economy-wide wage rate.

levels as²²

$$\zeta_{n,k} \equiv \frac{\partial \ln Z_{n,k}(\cdot)}{\partial \ln \tilde{P}_{n,0k}}, \quad \zeta_n \equiv \frac{\partial \ln \sum_{k \neq 0} Z_{n,k}(\cdot)}{\partial \ln \tilde{P}_{n,0k}} = \sum_{k \neq 0} \left(\frac{Z_{n,k}}{Z_n} \right) \zeta_{n,k}. \quad (23)$$

In the special case with CES production functions, $\zeta_{n,k} = -s(1 - \alpha_{n,k})$, with (s) as the elasticity of substitution between energy and labor inputs. Below, we present formulas for the unilaterally optimal policy, which, by the Lerner symmetry, is unique up to an arbitrary tax shifter.²³

PROPOSITION 2: *Country i 's unilaterally optimal policy consists of (i) uniform carbon taxes ($\tau_{i,k}^* = \tau_i^*$),*

$$\tau_i^* = \tilde{\delta}_i \equiv \delta_i \tilde{P}_i,$$

(ii) import tariffs and export subsidies on final goods ($k \geq 1$) that are unique up to a uniform and arbitrary tax-shifter, $\bar{t}_i \geq 0$, augmented by a carbon border adjustment based on the CO₂ content per unit value of imported goods $v_{n,k}$ (Equation (22)),

$$1 + t_{ni,k}^* = (1 + \bar{t}_i) + \tau_i^* v_{n,k},$$

$$1 + x_{in,k}^* = \frac{1 + \varepsilon_{in,k}}{\varepsilon_{in,k}} \sum_{j \neq i} \left[(1 + t_{ji,k}^*) \frac{\lambda_{jn,k}}{1 - \lambda_{in,k}} \right],$$

(iii) import tariffs and export subsidies on energy,

$$1 + t_{ni,0}^* = (1 + \bar{t}_i)(1 + \omega_{ni,0}) + \tau_i^* \sum_{\ell \neq i} \sum_{j \neq i} \left[\tilde{\psi}_{jn}^{(i,0)} \rho_{j\ell,0} \frac{\zeta_\ell}{\tilde{P}_{\ell,0}} \right],$$

$$1 + x_{in,0}^* = \frac{1 + \varepsilon_{in,0}}{\varepsilon_{in,0}} \sum_{j \neq i} \left[(1 + t_{ji,0}^*) \frac{\lambda_{jn,0}}{1 - \lambda_{in,0}} \right] - \left(\Lambda_{in,0} + \tau_i^* \frac{\zeta_n}{\tilde{P}_{n,0}} \right) \frac{(1 + \bar{t}_i)}{\varepsilon_{in,0}},$$

where $\Lambda_{in,0} = \frac{\sum_k \alpha_{n,k} Y_{n,k} \rho_{ni,k}}{\sum_k \alpha_{n,k} Y_{n,k}}$ is the fraction of energy exports reimported via the carbon supply chain; $\omega_{ni,0} = \sum_{j \neq i} \tilde{\psi}_{jn}^{(i,0)} \rho_{ji,0}$ is the inverse export supply elasticity of energy (for flows from n to i), where $\tilde{\psi}_{jn}^{(i,0)} \equiv \frac{\phi_j}{1 - \phi_j} \psi_{jn}^{(i,0)} \frac{Y_{j,0}}{Y_{n,0}}$ represents backward linkages in the energy sector;²⁴ λ and ρ represent international expenditure and sales shares (Equations (6) and (22)); ζ is the demand elasticity of composite energy input (Equation (23)), and ε denotes the Marshallian demand elasticities (Equation (5)).

²²The function $Z_{n,k}(\cdot)$ is defined based on Equation (13) as $Z_{n,k} = Z_{n,k}(\tilde{P}_{n,0k}, w_n, Q_{n,k}) \equiv z_{n,k}(\tilde{P}_{n,0k}, w_n) Q_{n,k}$.

²³For a clearer presentation, the export subsidy formulas are reported for additively separable preferences across industries and generalized separability within industries. General formulas are provided in Supplemental Appendix B.7.

²⁴Specifically, $\psi_{jn}^{(i,0)}$ is entry (j, n) of matrix $\Psi^{(i,0)} \equiv \text{inv}(\mathbf{I}_N - [\mathbf{1}_{j \neq i} \sum_{\ell \neq i} \frac{\phi_n}{1 - \phi_n} \rho_{j\ell,0} \varepsilon_{j\ell,0}^{(n\ell,0)}]_{j,n})$, measuring the exposure of country j 's energy output to demand for country n 's energy, as detailed in Supplemental Appendix B.

Proposition 2 characterizes the unilaterally optimal policy as a function of nonpolicy variables, such as demand elasticities (ε) and trade shares (λ). Section 4.1 explains how to solve for equilibrium under the optimal policy, accounting for the dependence of nonpolicy variables on the policy itself.

The unilaterally optimal carbon tax, τ_i^* , corrects only the carbon externality imposed on households in country i .²⁵ Specifically, it equals the welfare cost per unit of CO₂ emissions to residents of country i adjusted for the consumer price index, that is, $\tilde{\delta}_i \sim \delta_i \tilde{P}_{i,0}$. The unilaterally optimal border taxes, however, pursue two objectives. First, they seek to manipulate the terms of trade in country i 's favor. Second, they include a carbon border tax component that indirectly taxes the carbon externality of foreign production and consumption.

To better understand carbon border taxes, it is helpful to examine a small open economy under Cobb–Douglas CES preferences.²⁶ Under the CES assumption, the import demand elasticity takes the form $\varepsilon_{in,k} = -\sigma_k + (\sigma_k - 1)\lambda_{in,k}$. The small open economy assumption sets $\lambda_{in,k} \approx \rho_{ni,k} \approx 0$. Plugging these into our general optimal policy formulas yields a simplified representation:

$$\left\{ \begin{array}{ll} \tau_i^* = \tilde{\delta}_i \sim \delta_i \tilde{P}_i & \text{[carbon tax],} \\ t_{ni,k}^* = \bar{t}_i + \tau_i^* v_{n,k} \quad t_{ni,0}^* = \bar{t}_i & \text{[import tax],} \\ 1 + x_{in,k}^* = (1 + \bar{t}_i) \frac{\sigma_k - 1}{\sigma_k} + \tau_i^* \sum_{j \neq i} [\lambda_{jn,k} v_{j,k}] \frac{\sigma_k - 1}{\sigma_k} & \text{[export subsidy (nonenergy)],} \\ 1 + x_{in,0}^* = (1 + \bar{t}_i) \frac{\sigma_0 - 1}{\sigma_0} + \tau_i^* \frac{1}{\sigma_0} \frac{\zeta_n}{\tilde{P}_{n,0}} & \text{[export subsidy (energy)].} \end{array} \right.$$

The optimal import tax on final-good variety ni, k , which is *unaffected* by the CES and small open economy simplification, can be decomposed as

$$t_{ni,k}^* = \bar{t}_i + \underbrace{\tau_i^* \times v_{n,k}}_{\text{Carbon Border Tax}}. \quad (24)$$

The uniform tariff component \bar{t}_i reflects the standard terms-of-trade rationale for import taxation.²⁷ The carbon border tax component mimics the unilaterally-optimal domestic carbon tax. It taxes the carbon content per dollar value of imports, $v_{n,k}$, at the unilaterally optimal rate, τ_i^* . Remarkably, the unilaterally optimal border tax rate coincides with the accounting border adjustment that neutralizes the domestic cost disadvantage caused by

²⁵Alternatively, the carbon tax could be applied at the point of energy extraction with appropriate adjustments to energy border taxes. See Supplemental Appendix E.3 for optimal policy formulas featuring an explicit extraction tax. In our framework, extraction taxes are nonessential due to product differentiation in energy markets, where border taxes serve as a more direct instrument for regulating foreign emissions. However, when energy is a homogeneous commodity, there is no strict independence between border and extraction taxes, making extraction taxes an essential component of the optimal policy schedule, as in Kortum and Weisbach (2021).

²⁶Our definition of a small open economy differs from the conventional definition, which is based on a lack of influence over world prices. Instead, we define a country as a small open economy if it accounts for a vanishingly small share of foreign sales and expenditure (see also Caliendo and Feenstra (2024)).

²⁷This element of our formula echoes the familiar result that, absent climate externalities, optimal tariffs are uniform across differentiated constant-returns to scale industries.

carbon-pricing. Our formula presents a welfare rationale for these widely used border adjustment schemes.²⁸

The unilaterally optimal export subsidy on final-good variety in, k can be decomposed as

$$1 + x_{in,k}^* = (1 + \bar{t}_i) \frac{\sigma_k - 1}{\sigma_k} + \underbrace{\tau_i^* \times \sum_{j \neq i} [\lambda_{jn,k} v_{j,k}]}_{\text{Carbon Border Subsidy}} \frac{\sigma_k - 1}{\sigma_k}, \tag{25}$$

where the first component corresponds to the optimal markup on exports from the terms-of-trade standpoint.²⁹ The carbon border subsidy depends on the average carbon intensity of competing foreign varieties in market n , namely $\sum_{j \neq i} [\lambda_{jn,k} v_{j,k}]$. This differs from accounting border adjustment schemes that simply rebate the carbon taxes toward exports. The optimal carbon border subsidy seeks to mimic a carbon tax, τ_i^* , on foreign varieties sold to market $n \neq i$. It accomplishes this by subsidizing the price of domestically produced exports varieties. Since domestically produced and foreign varieties are substitutable, the subsidy lowers demand for foreign goods in market $n \neq i$, imitating the demand drop if those goods were taxed directly.

Turning to border taxes on energy varieties, the uniform tariff, \bar{t}_i , on energy imports is motivated by terms-of-trade considerations.³⁰ Since imported energy varieties, after bundling and distribution, are subjected to a domestic carbon tax τ_i^* , no additional import duty on energy is needed. The optimal policy, however, includes a carbon-based tax on energy exports equal to $\tau_i^* \times \frac{1}{\sigma_0} (\zeta_n / \bar{P}_{n,0})$. The rationale is that country i would ideally levy a tax on country n 's composite energy input at an ad valorem rate of $\tau_i^* / \bar{P}_{n,0}$. This policy is infeasible, but the energy export tax is passed on to foreign's energy price, imitating this intended tax. Echoing this logic, the optimal export tax rate depends on the magnitude of tax pass-through, which is determined by the foreign countries's energy input demand elasticity, $\zeta_n \equiv \frac{\partial \ln \sum_k Z_{n,k}(\cdot)}{\partial \ln \bar{P}_{n,0}} < 0$, and the elasticity of substitution between international energy varieties, σ_0 .

Building on the intuition from the small open economy case, let us revisit the general formulas presented under Proposition 2. The optimal export subsidy for nonenergy goods depends on foreign demand elasticity ε , which is determined by structural parameters (like σ in the case of CES) and endogenous expenditure shares. The optimal border taxes on energy, meanwhile, account for GE linkages, which are nontrivial for large economies (as shown by lemmas E1, E2, E3 in Supplemental Appendix B). Import taxes on energy contract export supply and increase the marginal cost of energy extraction abroad. This triggers price changes that alter global energy demand, prompting further energy

²⁸The above carbon border tax configuration does not account for origin country carbon tax rates, therefore risking double taxation. This is due to the noncooperative nature of these taxes since governments may doubly tax the carbon externality to generate revenue. As shown in Supplemental Appendix C, double taxation is avoided in a cooperative setting. The optimal cooperative carbon border tax is $(\tau^* - \tau_n) \times v_{n,k}$, taxing the difference between the globally optimal rate τ^* and the rate applied in the origin country, thus preventing double taxation.

²⁹Since $\frac{\sigma_k - 1}{\sigma_k} < 1$, the optimal export policy in the absence of climate externalities would involve an export tax under the normalization $\bar{t}_i = 0$.

³⁰A small open economy's optimal energy import tax has no climate-driven element, since imported energy varieties face a carbon tax after bundling and distribution. However, for a large economy, the optimal energy import tax internalizes climate impacts arising from general equilibrium linkages, as Proposition 2 indicates. We elaborate on these general equilibrium linkages in the next paragraph.

price shifts worldwide. These GE ripple effects are captured by the backward linkage matrix, $\Psi^{(i,0)}$, whose elements determine the optimal import tariff. Energy export subsidies meanwhile influence the cost of foreign goods using the subsidized or taxed input. Some of these goods are imported by country i and face a carbon border tax upon importation. The optimal energy export subsidy is, thus, adjusted to prevent double marginalization. The optimal adjustment depends on the fraction $\Lambda_{in,0}$ of energy exports reimported via the energy supply chain.

3.4. Globally Optimal Carbon-Pricing and Free-Riding

This section characterizes the optimal carbon policy from a global standpoint. Comparing the globally optimal policy with the unilaterally optimal policy, derived earlier, elucidates the free-riding problem that impedes cooperation on climate action. We obtain the globally optimal policy by solving a *global* planning problem, where the planner selects tax instruments $\mathbb{I} \equiv \{\mathbb{I}_i\}_{i \in \mathbb{N}}$ and lump-sum international transfers, $\mathbb{\Delta} \equiv \{\Delta_i\}_i$, to maximize an internationally representative social welfare function. Letting $\tilde{\mathbb{I}} \equiv \{\mathbb{I}, \mathbb{\Delta}\}$ denote the policy set, the planning problem can be formulated compactly as

$$\max_{\tilde{\mathbb{I}}} \sum_i \vartheta_i \ln W_i(\tilde{\mathbb{I}}) \text{ subject to general equilibrium Equations (1)–(19),}$$

where $W_i \sim V_i(E_i + \Delta_i, \tilde{P}_i) - \delta_i \times Z^{(\text{global})}$ is country i 's climate-adjusted welfare under policy, with $\sum_i \Delta_i = 0$, and ϑ_i is country i 's weight in the planner's problem. The inclusion of income transfers is essential, as it separates redistribution, addressed via transfers, from climate-related externalities, addressed via taxes.

Capitalizing on a variation of Proposition 2, we derive the globally optimal policy in Supplemental Appendix C. The optimal policy from a global perspective involves carbon taxes that correct the worldwide externality of carbon emissions, along with zero trade taxes:³¹

$$\tau_{i,k}^* = \sum_i \tilde{\delta}_i \sim \tau^*, \quad t_{ij,k}^* = x_{ij,k}^* = 0 \quad (\forall i, j, k). \tag{26}$$

The globally optimal border taxes are zero because border taxes are an inefficient policy for reducing carbon emissions compared to directly targeted carbon taxes. In the unilateral case, carbon border taxes were justified since country i 's government could not directly tax foreign carbon inputs. This missing policy limitation no longer applies in the globally optimal context.

The *free-riding problem* stems from the gap between the unilaterally optimal and globally optimal carbon tax rates. Specifically,

$$\tau_i^* = \tilde{\delta}_i < \tau^* = \sum_n \tilde{\delta}_n.$$

This means that if all other countries commit to τ^* , country i 's welfare-maximizing government will be inclined to lower its carbon tax rate from τ^* to τ_i^* . Strategic behavior by all governments in this manner triggers a race to the bottom in climate action. In the next section, we discuss two potential solutions to the free-riding problem.

³¹Transfers, $\Delta_i = (\pi_i \times \sum_i E_i) - E_i$, are pinned down by the optimal income shares: $\pi_i^* = (\vartheta_i \frac{V_i}{W_i}) / (\sum_n [\vartheta_n \frac{V_n}{W_n}])$.

3.5. Two Remedies for the Free-Riding Problem

Two types of policies can mitigate the free-riding problem, both involving border tax measures:

PROPOSAL 1: Governments use border taxes as a *second-best* policy to correct the climate externality of foreign emissions on their citizens. The maximal efficacy of this proposal will be realized if carbon border tax rates are set to the optimal rate specified by Proposition 2.

PROPOSAL 2: Climate-conscious governments forge a climate club and leverage *contingent* trade penalties to deter free-riding. The maximal efficacy of this proposal will be realized if the trade penalties are applied based on the unilaterally optimal import and export tax rates (t^* and x^*) specified by Proposition 2.

While Proposal 1 is rooted in unilateral action Proposal 2 seeks to revive multilateral climate efforts through better policy design. In theory, Proposal 2 could achieve first-best carbon pricing together with free trade. However, poorly-designed trade penalties and carbon tax targets for club members could decouple the climate club from the rest of the world. Here, our notion of optimal trade penalties refers to penalties that maximize welfare transfers from free-riders to climate club members, that coincide with the unilaterally optimal trade tax/subsidies specified by Proposition 2. In Section 6.2, we discuss policy designs when free-riding is not a concern or trade penalties are chosen differently.

4. MAPPING THEORY TO DATA

This section describes how our model is mapped to data to simulate counterfactual policy outcomes. We first outline our strategy for computing counterfactual optimal policy outcomes, followed by a discussion of our data and estimation. For our quantitative analyses, we assume that the production function of final goods and the energy distributor has a CES form and the households' demand function takes a Cobb-Douglas-CES form. The *baseline equilibrium*, to which we introduce the optimal policy interventions, corresponds to the status quo in 2014, as explained in Section 4.2. We are interested in counterfactual outcomes when taxes are revised from their applied levels to their optimal rates under the noncooperative and climate club scenarios.

4.1. Quantitative Strategy

Required Data and Parameters. The baseline equilibrium under the status quo is characterized by the following statistics: expenditure shares $\{\lambda_{ni,k}, \beta_{i,k}\}$ and employment shares $\{\ell_{i,k}\}$, where $\ell_{i,k} \equiv L_{i,k}/\bar{L}_i$ is country i 's share of employment in industry k ; CO₂ emissions, energy input cost shares, and CO₂ intensity values, $\{Z_{i,k}, \alpha_{i,k}, v_{i,k}\}$; pre-carbon-tax price of energy $\{\tilde{P}_{i,0}\}$; and national income accounting variables, $\{w_i \bar{L}_i, r_i \bar{R}_i, Y_i\}$.

Let \mathcal{B}^V stack the above-mentioned *baseline* variables, and let $\mathcal{B}^T \equiv \{x_{m,k}, t_{ni,k}, \tau_{i,k}\}$ contain the applied policy variables—both of which are observable. Also, let $\mathcal{B}^\Theta = \{\tilde{\delta}_i, \phi_i, s, \sigma_k\}$ denote the carbon disutility parameters, cost share of carbon reserves, energy input demand elasticity, and trade elasticities; with $\mathcal{B} \equiv \{\mathcal{B}^V, \mathcal{B}^T, \mathcal{B}^\Theta\}$ denoting the required set of observable data and estimable parameters for conducting counterfactual policy analyses.

Counterfactual Policy Scenarios. Counterfactual outcomes under each policy scenario solve a system of equations consisting of equilibrium conditions and optimal tax formulas. The joint solution to this system determines optimal policy, $\mathcal{R}^T = \{x'_{in,k}, t'_{ni,k}, \tau'_{i,k}\}$, as well as *changes* to nonpolicy variables, $\mathcal{R}^V = \{\hat{\lambda}_{ni,k}, \hat{\ell}_{i,k}, \hat{Z}_{i,k}, \hat{\alpha}_{i,k}, \hat{v}_{i,k}, \hat{P}_{i,0}, \hat{P}_i, \hat{w}_i, \hat{r}_i, \hat{Y}_i\}$. The prime notation denotes variables in the counterfactual equilibrium, with $\hat{z} \equiv z'/z$ denoting the change in a generic variable z .

We evaluate Proposal 1 by simulating the *noncooperative* equilibrium in which each country adopts its unilaterally-optimal policy. Under this scenario, country i 's policy, $\mathcal{R}_i^T \equiv \{x'_{in,k}, t'_{ni,k}, \tau'_{i,k}\}$ is determined by the optimal policy formulas presented under Proposition 2. These formulas express $\mathcal{R}^T = \{\mathcal{R}_i^T\}_i$ as a function of \mathcal{B} and \mathcal{R}^V , which we refer to as $\mathcal{R}^T = f(\mathcal{R}^V; \mathcal{B})$ or mapping (b). In turn, the change in nonpolicy variables, \mathcal{R}^V , is described by general equilibrium conditions as a function of \mathcal{R}^T and \mathcal{B} , as outlined in Supplemental Appendix G.1. We refer to this relationship as $\mathcal{R}^V = g(\mathcal{R}^T; \mathcal{B})$ or mapping (a). Jointly solving mappings (a) and (b), $\mathcal{R}^V = g(\mathcal{R}^T; \mathcal{B})$ and $\mathcal{R}^T = f(\mathcal{R}^V; \mathcal{B})$, determines optimal policy \mathcal{R}^T and counterfactual nonpolicy outcomes \mathcal{R}^V as a function of the data and parameters in \mathcal{B} . Supplemental Appendix G.2 details the numerical algorithm used to solve this system, which starts with a guess of \mathcal{R}^T and iterates between $\mathcal{R}^V = g(\mathcal{R}^T; \mathcal{B})$ and $\mathcal{R}^T = f(\mathcal{R}^V; \mathcal{B})$ to find a joint solution. While we have not been able to prove convergence properties of this algorithm, it performs quickly in all the settings where we have examined, as reported in Supplemental Appendix D.2.³² Likewise, our analysis of the climate club uses the unilaterally optimal trade taxes described by Proposition 2 as contingent trade penalties, and simulates counterfactual policy outcomes using the same logic.³³

4.2. Data and Parameters

In this section, we describe the required data and parameters for conducting counterfactual policy analysis, which include data on trade, production, and CO₂ emissions (labeled as \mathcal{B}^V), applied taxes (\mathcal{B}^T), and the structural parameters of our model (\mathcal{B}^θ).

Trade, Production, and Expenditure. We use data on international trade and production from the Global Trade Analysis Project (GTAP) database (Aguiar, Chepeliev, Corong, McDougall, and Van Der Mensbrugge (2019)), which provides international trade flows by country-industry origin and destination for 2014. We consolidate our sample into $(K + 1 = 18)$ “industries,” comprising $K = 17$ nonenergy ISIC-level industries and one composite energy industry, and $(N = 19)$ “countries,” consisting of the 13 countries with the largest GDP plus 6 aggregate regions. Tables I and II list the industries

³²The resulting equilibrium constitutes the Nash equilibrium of a one-shot game, wherein every country selects their best policy response given policies in the rest of world. Lashkaripour (2021) and Lashkaripour and Lugovskyy (2023) use a similar logic to quantify the counterfactual impact of noncooperative trade policies.

³³Two clarifications are needed for interpreting our counterfactual policy outcomes. First, our counterfactual analyses measure long-run outcomes based on whether governments maintain a noncooperative policy stance or form a climate club. Proposal 1 examines outcomes if heightened climate concerns lead governments to abandon shallow trade cooperation while raising domestic carbon taxes to the unilaterally optimal rate. Proposal 2 evaluates outcomes when climate considerations are integrated into free trade agreements. Second, the goal of our optimal policy framework is to outline the policy outcome frontier, not to necessarily explain government behavior. Actual policies often fall short of this frontier due to various obstacles, but it remains a useful tool for assessing long-term policy efficacy—a point we come back in Section 6.2 when discussing the EU's unilateral policy frontier.

and countries in our sample, along with their key characteristics. Our final sample forms a $19 \times 19 \times 18$ matrix of free-on-board flows, with element $X_{ij,k}^{(fob)} = \tilde{P}_{ji,k} C_{ji,k} / (1 + t_{ij,k})$ corresponding to origin j -destination i -industry k .³⁴

CO₂ Emissions and Carbon Accounting. We obtain CO₂ emissions associated with use of fossil fuels from the GTAP database, counting CO₂ emissions at the location of energy use by end-users (i.e., nonenergy industries and households). All energy types are consolidated into a composite energy industry, denoted as industry “0,” with CO₂ emissions calculated from both direct and indirect purchases of energy. Supplemental Appendix F.1 details our carbon accounting procedure. Table A.2 reports total emissions (as the sum of direct and indirect emissions from use of energy) by industries and households.

Let us highlight key statistics that will help interpret our quantitative results in Section 5. First, emissions from production constitute three-fourths of global CO₂ emissions, with the remaining one-fourth generated by households (Supplemental Appendix Table A.2). Second, most production-related CO₂ emissions are embedded in goods that never cross international borders (Supplemental Appendix Figure A.2). For instance, highly tradeable industries like electronics and machinery, textiles, and motor vehicles collectively account for only 6% of global CO₂ emissions from production (Table I). Lastly, low and middle-income countries are largest contributors to global CO₂ emissions, with China alone accounting for over a quarter of these emissions. This proportion reaches 60% when considering all non-OECD countries (Table II).

Input Cost Shares. We construct energy input cost shares for final-good industries, $\alpha_{n,k}$, using data on their sales and energy input expenditures, with global averages shown in Table I. For the energy extraction industry, the carbon reserve cost share, ϕ_i , is determined based on the value-added share of natural resources in each country’s primary energy sector, which has an average of 0.37. See Supplemental Appendix F.2 for more details.

Baseline Taxes. We use 2014 tariff data from the GTAP database, accessed through the Market Access Map of the International Trade Center, and set energy import tariffs to zero in the baseline. Consistent with World Trade Organization rules, we assume export subsidies are negligible and set $x_{ij,k} = 0$ in the baseline. Carbon taxes, which are negligible in most countries in 2014, are derived from the World Bank’s Carbon Pricing Dashboard. See Supplemental Appendix F.3 for more details.

Perceived Disutility From Carbon Emissions. We recover the perceived national disutility from CO₂ emissions ($\tilde{\delta}_i$) through governments’ revealed preferences for tackling environmental issues. Specifically, we postulate that $\tilde{\delta}_i$ is proportional to applied environmentally-related taxes per unit of CO₂ emissions, adjusted for country size. If perceptions of climate damage were symmetric across governments, $\tilde{\delta}_i$ would scale solely with country size. To account for the size effect, we impose $(\tilde{\delta}_i / \tilde{\delta}_j) \propto (L_i / L_j)$, where L_i is country i ’s population. However, governments’ attitudes towards climate change are markedly diverse—even after accounting for size effects. These considerations lead to

³⁴To be consistent with our framework, we purge the data from trade imbalances following Ossa (2016).

TABLE I
INDUSTRY-LEVEL STATISTICS.

| Industry | CO ₂ Emission (% of Total) | Trade-to-GDP Ratio | Carbon Intensity (<i>v</i>) | Energy Cost Share (<i>α</i>) | Trade Elasticity (<i>σ</i> - 1) |
|---------------------------|---|-----------------------|-------------------------------------|--------------------------------------|--|
| Agriculture | 4.2% | 8.9% | 100.0 | 0.030 | 3.80 |
| Other Mining | 1.9% | 28.9% | 183.0 | 0.055 | 10.16 |
| Food | 3.3% | 8.0% | 45.9 | 0.015 | 3.80 |
| Textile | 1.9% | 22.8% | 59.7 | 0.021 | 4.25 |
| Wood | 0.5% | 8.4% | 61.0 | 0.026 | 6.50 |
| Paper | 2.1% | 8.9% | 125.9 | 0.061 | 6.55 |
| Chemicals | 9.5% | 21.9% | 179.5 | 0.062 | 8.60 |
| Plastics | 1.8% | 13.5% | 89.1 | 0.056 | 8.60 |
| Nonmetallic Minerals | 8.6% | 6.0% | 458.4 | 0.121 | 5.27 |
| Metals | 14.7% | 14.6% | 205.2 | 0.066 | 5.99 |
| Electronics and Machinery | 3.0% | 30.0% | 42.0 | 0.022 | 3.98 |
| Motor Vehicles | 1.2% | 23.3% | 34.0 | 0.014 | 4.88 |
| Other Manufacturing | 0.6% | 21.5% | 42.0 | 0.032 | 4.80 |
| Construction | 1.5% | 0.6% | 59.2 | 0.025 | 5.94 |
| Wholesale and Retail | 3.6% | 2.4% | 34.7 | 0.017 | 5.94 |
| Transportation | 27.3% | 10.5% | 498.3 | 0.171 | 5.94 |
| Other Services | 14.5% | 3.1% | 26.7 | 0.012 | 5.94 |

Note: This table shows for every of the 17 nonenergy industries the share from world industrial CO₂ emission (not including households' emission), world-level trade-to-GDP ratio, global average carbon intensity (CO₂ emissions per dollar of output) normalized by that of agriculture, energy cost shares reported as unweighted mean across countries within each industry, and estimated trade elasticities.

the following proportionality condition:

$$(a) \quad \frac{\tilde{\delta}_i/L_i}{\tilde{\delta}_j/L_j} = \frac{T_i^{(env)}/Z_i}{T_j^{(env)}/Z_j},$$

where $T_i^{(env)}$ is the environmentally-related taxes collected by country i , sourced from OECD-PINE. Moreover, the sum of disutility from CO₂ emissions equates the global Social Cost of CO₂:

$$(b) \quad \sum_i \tilde{\delta}_i = \text{SC-CO}_2.$$

We calibrate SC-CO₂ based on the latest release of the United States Environmental Protection Agency (EPA)'s Final Report on the Social Cost of Greenhouse Gases. From this report, we adopt the middle scenario discount rate, yielding a SC-CO₂ of \$156.2 per tonne of CO₂ in 2014.³⁵ By consolidating conditions, (a) and (b), we recover the CPI-adjusted disutility from carbon emissions, $\tilde{\delta}_i$. Table II reports our calibrated values of $\tilde{\delta}_i$ for each country in the sample.³⁶

³⁵Table A.5 of the EPA's publication reports 193 (\$/tCO₂) for 2020 and 230 (\$/tCO₂) for 2030, in dollars of 2020, based on a 2% annual discount rate. Using a linear projection to the year 2014, and adjusting for the inflation, we obtain a SC-CO₂ of 156.2 (\$/tCO₂) for 2014 in terms of dollars of 2014.

³⁶We alternatively calibrate $\tilde{\delta}_i$ based on country-level social costs of carbon (see Figure A.5 and Section 6.1).

TABLE II
COUNTRY-LEVEL STATISTICS.

| Country | Share from World | | | Carbon | |
|---------------------|------------------|--------------------------|------------|-------------------|-------------------------|
| | Output | CO ₂ Emission | Population | Intensity (v) | Disutility (δ) |
| Australia | 1.8% | 1.2% | 0.3% | 147.5 | 1.5 |
| EU | 25.9% | 12.3% | 7.5% | 100.0 | 53.2 |
| Brazil | 2.8% | 1.6% | 2.8% | 135.3 | 6.0 |
| Canada | 1.9% | 1.6% | 0.5% | 176.1 | 1.2 |
| China | 17.8% | 26.7% | 18.9% | 378.1 | 20.9 |
| Indonesia | 1.0% | 1.5% | 3.5% | 302.0 | 0.5 |
| India | 2.4% | 6.4% | 17.9% | 620.4 | 12.5 |
| Japan | 6.2% | 3.6% | 1.8% | 127.6 | 6.0 |
| Korea | 2.2% | 1.7% | 0.7% | 188.7 | 3.2 |
| Mexico | 1.4% | 1.4% | 1.7% | 218.8 | 0.3 |
| Russia | 1.9% | 4.4% | 2.0% | 436.5 | 0.2 |
| Saudi Arabia | 0.4% | 1.5% | 0.4% | 752.4 | 0.0 |
| Turkey | 1.0% | 1.1% | 1.1% | 245.5 | 4.9 |
| USA | 20.4% | 17.2% | 4.4% | 162.0 | 6.8 |
| Africa | 2.6% | 3.6% | 15.9% | 285.3 | 22.2 |
| RO Americas | 3.0% | 2.7% | 4.1% | 194.7 | 9.8 |
| RO Asia and Oceania | 5.1% | 5.5% | 11.8% | 253.0 | 6.6 |
| RO Eurasia | 0.7% | 2.2% | 1.9% | 671.6 | 0.1 |
| RO Middle East | 1.6% | 3.9% | 2.8% | 494.9 | 0.3 |

Note: This table shows for every of the 19 regions (13 countries + the EU + Africa + 4 “Rest Of” regions as collection of neighboring countries), their share from world output, CO₂ emissions, and population, and carbon intensity (CO₂ emissions per dollar of output) normalized by that of the EU, and CPI-adjusted disutility from one tonne of CO₂ emission, which sum to the social cost of carbon.

Trade Elasticities. We estimate the industry-level trade elasticities, $(\sigma_k - 1)$, using an identification strategy resembling that of [Caliendo and Parro \(2015\)](#). Our estimation procedure is reported in Supplemental Appendix F.4, with point estimates replicated in Table I.³⁷

Energy Demand Elasticity. The following equation describes the quantity of energy inputs relative to total input cost, $Z_{i,k}/TC_{i,k}$, in country i -industry k :

$$\ln\left(\frac{Z_{i,k}}{TC_{i,k}}\right) = -\varsigma \ln \tilde{P}_{i,0k} + \underbrace{(1 - \varsigma) \ln mc_{i,k} + \ln \bar{\kappa}_{i,k}}_{=\phi_i^{(energy)} + \phi_k^{(energy)} + \epsilon_{i,k}^{(energy)}}. \quad (27)$$

The right-hand side variables include the after-tax price of energy, $\tilde{P}_{i,0k}$,³⁸ the marginal cost, $mc_{i,k}$, and the exogenous input demand parameter, $\bar{\kappa}_{i,k}$. We allow the combined effect of the latter two terms to systematically vary by country and industry through the

³⁷The table does not list the energy industry, as CO₂ emissions are assigned to energy consumption rather than production. The global energy trade-to-GDP ratio is 24.6%, with an energy trade elasticity of $(\sigma_0 - 1) = 10.16$, estimated by pooling energy flow observations with Other Mining.

³⁸The after-tax price of energy which we use here includes fuel taxes that are not related to climate change. In our quantitative analysis, these nonclimate-related fuel taxes are captured by exogenous energy demand shifters.

fixed effects, $\Phi_i^{(energy)}$ and $\Phi_k^{(energy)}$, with $\epsilon_{i,k}^{(energy)}$ denoting the unobserved energy demand residual.

Our identification strategy relies on two assumptions. First, an individual industry's energy demand residual in a given country has a negligible effect on global pre-tax energy prices, as each industry is small relative to the global energy market. Second, the unobserved energy demand residual is assumed to be uncorrelated with energy tax rates after accounting for country and industry fixed effects. Table A.4 reports our estimation results, with our preferred specification in column (3) showing an energy demand elasticity of 0.65³⁹

Magnitudes of Optimal Border Taxes. To evaluate Proposals 1 and 2, we calculate unilaterally optimal border policies (which combine import tariffs and export subsidies) in our calibrated model. Absent climate externalities, these policies are driven solely by terms-of-trade considerations. Per Lerner's symmetry, only the ratio of the optimal tariff (t^*) to export subsidy (x^*) is determined, with a median of 17% across nonenergy product varieties, i.e., $(1 + t^*)/(1 + x^*) \simeq 0.17$. The 10th and 90th percentiles of these ratios are 12% and 26%, respectively. These ratios vary inversely with the industry-level trade elasticity but modestly across countries.⁴⁰ Carbon border taxes/subsidies represent a modest share of the optimal border tax/subsidy rate and vary significantly across countries, reflecting each country's unilaterally optimal carbon tax, $\tau_i^* = \tilde{\delta}_i$. They also differ across industries, being more punitive in sectors with higher carbon intensities.⁴¹

5. QUANTITATIVE ASSESSMENT OF CLIMATE PROPOSALS 1 AND 2

In this section, we provide a quantitative assessment of two prominent climate proposals that combine carbon taxes with border measures to address the free-riding problem. We examine the efficacy of each proposal by reporting the changes in carbon emissions and welfare resulting from these policies, compared to the status quo.

5.1. Proposal 1: Noncooperative Carbon Border Taxes

Under Proposal 1, border taxes are employed as a second-best policy to cut (undertaxed) carbon emissions by noncooperative trading partners. To gauge maximal efficacy, we simulate a noncooperative Nash equilibrium in which each government enacts its best policy response consisting of unilaterally optimal border and carbon taxes. The resulting change in CO₂ emissions (Z), real consumption (V), and climate-adjusted welfare (W) are reported in Table III.

³⁹Our elasticity parameters align with the *long-run* estimates in the literature, reflecting our focus on long-term outcomes. Labandeira, Labeaga, and López-Otero (2017) report an average long-run energy demand elasticity of 0.59, compared to our 0.65. Our calibration implies a greater-than-one energy supply elasticity consistent with the literature review in Kotchen (2021). Lastly, our trade elasticity, ranging between 3.8 and 8.6 across manufacturing industries, is in line with larger and long-run estimates in the literature (Alessandria, Khan, Khederlarian, Ruhl, and Steinberg (2021)).

⁴⁰Our optimal border taxes are broadly consistent with, but on the lower side of existing estimates obtained from models without carbon externalities, for example, Ossa (2014), Lashkaripour (2021). The terms-of-trade component of optimal border taxes largely depend on the industry-level trade elasticity, $(\sigma_k - 1)$, with a higher trade elasticity implying a lower degree of national-level market power. Our estimates of trade elasticity are on average 5.9, which is higher than the estimates of trade elasticity in Ossa (2014), Lashkaripour (2021).

⁴¹Supplemental Appendix Figure A.3 illustrates this in the case of the EU's unilaterally optimal carbon import taxes.

The first panel (titled “Noncooperative: Carbon + Border Tax”) reports changes in outcomes relative to the status quo when all governments adopt their unilaterally optimal carbon and border tax measures noncooperatively. To understand these results, note that domestic carbon taxes are small or virtually zero under the status quo. Therefore, the carbon reduction reported in this panel represents the combined reduction from both elevating the domestic carbon tax and border tax rates to their unilaterally optimal rates.

To isolate the net contribution of border taxes, the middle panel in Table III (titled “Noncooperative: Carbon Tax”) reports outcomes under unilaterally optimal domestic carbon taxes that are not supplemented with any carbon border taxes. The difference between the numbers presented in the first and middle panels represents the net contribution of noncooperative border taxes. To put the noncooperative outcomes in perspective, the panel “Globally Cooperative” presents the effects of globally optimal (first-best) carbon taxes.⁴²

The results in Table III suggest that optimally-designed noncooperative border taxes deliver a 1.3% reduction in global CO₂ emissions (i.e., $(1 - 0.066)/(1 - 0.054) - 1 = 1.3\%$), complementing the 5.4% reduction attained through unilaterally optimal domestic carbon taxes.⁴³ This stands in contrast to the additional 37.6% reduction in global CO₂ emissions when domestic carbon prices are elevated to their first-best level (i.e., $(1 - 0.410)/(1 - 0.054) - 1 = 37.6\%$). To rephrase, noncooperative border taxes replicate only 3.4% of the potential CO₂ reduction under global cooperation (i.e., $1.3/37.6 = 3.4\%$)—highlighting the limited effectiveness of noncontingent carbon border taxes at addressing the free-riding problem.

The inefficacy of carbon border taxes at mitigating the free-riding problem stems from three factors. First, they fail to incentivize abatement by individual firms because the taxes are based on the average carbon intensity of all firms within a country and industry, rather than the firm-specific carbon intensity. As individual firms cannot meaningfully influence these broad averages, they have no motivation to reduce their carbon inputs and emissions in response to the taxes.

Second, border taxes cannot cut the CO₂ emissions from nontraded goods, which constitute a significant portion of worldwide emissions. The “transportation” sector, for example, is responsible for over 25% of global industrial CO₂ emissions, yet it has a trade-to-GDP ratio of just 0.10 (see Table I). Supplemental Appendix Figure A.2 compares the tradeability of industries to their global emissions share. Notably, the industries that have a trade-to-GDP ratio below 0.15 are responsible for over 80% of global CO₂ emissions from production.

Third, border taxes are not immune to leakage via general equilibrium energy price adjustments. They reduce global demand for energy, which leads to lower pre-tax energy prices worldwide. This in turn causes a drop in the after-tax price of energy in countries like Russia and Saudi Arabia, which have lesser care for climate change. As a result, their CO₂ emissions rise with carbon border taxes, dampening the overall reduction in global emissions.⁴⁴

⁴²The outcomes presented in the last panel exclude the lump-sum intercountry transfers necessary for ensuring Pareto improvements. The country weights in the global planner’s problem could be chosen to ensure such Pareto improvements. Here, we simply set these weights based on GDP share of countries in status quo.

⁴³Let $\Delta x_A = (\hat{x}_A - 1)$ be the percent change in x under policy “ A ,” where $\hat{x}_A \equiv x_A/x$. The percent change from counterfactual policy A to B is $(\hat{x}_B/\hat{x}_A - 1) = ([1 + \Delta x_A]/[1 + \Delta x_B] - 1)$.

⁴⁴Our carbon border tax specification exhibits similarities and differences with the EU’s carbon border adjustment mechanism (CBAM). Both unilaterally levy duties on the carbon content of imports. However, the CBAM aims to target firm-level emissions when possible, exempting exporters who demonstrate abatement

TABLE III
THE IMPACT OF NONCOOPERATIVE AND COOPERATIVE TAX POLICIES.

| Country | Non-Cooperative | | | | | | Globally Cooperative | | |
|----------------|---------------------|------------|------------|---------------------|------------|------------|----------------------|------------|------------|
| | Carbon + Border Tax | | | Carbon Tax | | | ΔCO_2 | ΔV | ΔW |
| | ΔCO_2 | ΔV | ΔW | ΔCO_2 | ΔV | ΔW | | | |
| Australia | 0.3% | -0.6% | -0.5% | 1.9% | -0.0% | 0.1% | -39.6% | -1.2% | -0.4% |
| EU | -22.2% | -0.3% | -0.0% | -21.2% | -0.0% | 0.2% | -38.5% | -0.4% | 1.7% |
| Brazil | -1.5% | -0.1% | 0.3% | -1.0% | 0.0% | 0.3% | -39.4% | 0.3% | 2.6% |
| Canada | 8.1% | -1.6% | -1.5% | 3.5% | -0.1% | 0.0% | -42.6% | -1.2% | -0.6% |
| China | -9.8% | -0.1% | 0.1% | -8.3% | 0.0% | 0.1% | -39.0% | -1.7% | -0.6% |
| Indonesia | 1.2% | -0.2% | -0.1% | 2.4% | -0.0% | 0.1% | -42.9% | -3.1% | -2.7% |
| India | -6.9% | -0.3% | 0.5% | -5.3% | 0.0% | 0.7% | -44.0% | 4.5% | 10.8% |
| Japan | -2.1% | -0.3% | -0.1% | -0.6% | 0.0% | 0.1% | -39.1% | -1.5% | -0.5% |
| Korea | 0.5% | 0.3% | 0.6% | 0.9% | 0.0% | 0.2% | -39.9% | 1.6% | 3.2% |
| Mexico | 4.3% | -1.3% | -1.2% | 3.0% | -0.0% | 0.0% | -41.5% | -1.3% | -1.1% |
| Russia | 7.1% | -1.4% | -1.3% | 3.5% | -0.2% | -0.2% | -43.8% | -0.0% | 0.1% |
| Saudi Arabia | 11.5% | -3.9% | -3.9% | 4.8% | -0.6% | -0.6% | -45.8% | -0.6% | -0.5% |
| Turkey | -4.6% | -0.5% | 0.3% | -0.0% | 0.1% | 0.8% | -39.1% | 1.9% | 7.6% |
| USA | -4.0% | -0.3% | -0.3% | -1.9% | 0.0% | 0.0% | -43.0% | -1.7% | -1.3% |
| Africa | -12.8% | -1.2% | 0.1% | -10.2% | -0.1% | 1.1% | -41.7% | 8.4% | 20.6% |
| RO Americas | -5.3% | -0.7% | -0.2% | -3.4% | -0.0% | 0.4% | -41.5% | 2.0% | 5.6% |
| RO Asia | -5.5% | -1.0% | -0.9% | -0.9% | 0.0% | 0.2% | -40.6% | -0.9% | 0.4% |
| RO Eurasia | 2.0% | -1.1% | -1.1% | 3.6% | -0.1% | -0.1% | -44.2% | -2.2% | -2.1% |
| RO Middle East | 5.6% | -2.5% | -2.5% | 3.9% | -0.3% | -0.3% | -43.3% | 0.0% | 0.2% |
| Global | -6.6% | -0.5% | -0.2% | -5.4% | -0.0% | 0.2% | -41.0% | -0.6% | 1.1% |

Note: This table shows the change to CO₂ emissions, real consumption, and welfare for every country when moving from the baseline to noncooperative and cooperative equilibrium. In the baseline, each country's tariffs and carbon taxes are set at their applied rates in 2014 and export subsidies are zero. Optimal policy formulas for the noncooperative and cooperative outcomes are detailed in Sections 3.3 and 3.4 and our quantitative implementation is described in Sections 4.1 and 4.2.

The modest CO₂ reduction achieved with noncooperative border taxes is offset by sizable consumption losses in most countries. Overall, global real consumption declines by 0.5% under these taxes, yielding only a negligible benefit in terms of emissions reduction. By comparison, globally optimal carbon taxes deliver a 41.0% reduction in global CO₂ emissions, paired with a mere 0.6% loss to real consumption, which translates to a 1.1% increase in *climate-adjusted* welfare.

5.2. Proposal 2: Climate Club With Contingent Trade Penalties

Under Nordhaus's (2015) climate club proposal, border taxes are used as a *contingent* penalty device to deter free-riding. We begin by specifying the climate club as a sequential game. A group of "core" countries move first and all other countries simultaneously play afterwards. The game is characterized by a given set of core countries, denoted by $\mathbb{N}^{(\text{core})}$, and a "carbon tax target," denoted by $\tau^{(\text{target})}$. Given $(\mathbb{N}^{(\text{core})}, \tau^{(\text{target})})$, governments play according to the following rules:

through monitoring. Thus, while the CBAM faces the second and third limitations highlighted above, the extent to which the first limitation applies is unclear. Additionally, the CBAM allows deduction of carbon taxes already paid in the origin country. This bears similarity to the globally-optimal carbon border taxes analyzed in Supplemental Appendix E.1.

Members. A member country must raise its domestic carbon tax to $\tau^{(\text{target})}$, set zero border taxes against other members, and impose unilaterally optimal trade taxes, as penalty, against nonmembers. By design, core countries adhere to these rules, while others conform only if they opt to join the club.

Nonmembers. Nonmember nations retaliate by imposing their unilaterally optimal trade taxes against member countries. Other than this, nonmember countries retain their status quo tax policies—preserving existing tariffs against other nonmember countries and maintaining their zero or near-zero carbon taxes.

For a game $(\mathbb{N}^{(\text{core})}, \tau^{(\text{target})})$, a partitioning of countries into noncore club members $\mathbb{N}^{(\text{member})}$, and nonmembers $\mathbb{N}^{(\text{nonmember})}$ constitutes a Nash equilibrium if (i) No noncore country has an incentive to deviate from the partition to which it belongs. (ii) Each core country's welfare improves (compared to the baseline) under this partition

Quantitative Challenges. Analyzing the climate club game in-depth poses significant challenges for two main reasons. First, iteratively determining optimal trade penalties for various countries across all conceivable partitions is practically infeasible with brute-force numerical optimization techniques. Our formulas for optimal border taxes, however, offer an analytical representation of these penalties, effectively circumventing this issue. Second, identifying all possible equilibria of the climate club game is complicated by the curse of dimensionality. Without a technique to shrink the outcome space, our analysis would involve examining $2^{N-N^{(\text{core})}}$ combinations of national strategies.⁴⁵ We address this challenge by noting that the severity of climate club penalties increases with the club's size. Consequently, the pay-off from joining the club rises with size, allowing us to shrink the outcome space via iterative elimination of dominated strategies.⁴⁶

Carbon Tax Target. The selection of the carbon tax target $\tau^{(\text{target})}$ is based on two key considerations. First, there is an inverted U-shaped relationship between the club's emission reduction and the carbon tax target, akin to the *Laffer curve*. When weighing club membership, noncore countries compare the costs of raising their carbon tax against trade penalties from club members. While a higher carbon tax target prompts more emission reduction per member, it also deters participation due to higher costs. This creates a trade-off: an excessively high tax target reduces membership limiting global emission cuts, while an overly low target delivers a limited reduction in global emissions despite maximal participation. Second, the climate club's aim is to cut emissions without triggering decoupling between club members and the rest of the world. That is, trade penalties are

⁴⁵With nineteen countries in our sample and supposing one core member, we would be required to solve for 262 thousand general equilibrium outcomes. Each partitioning of noncore countries, $(\mathbb{N}^{(\text{member})}, \mathbb{N}^{(\text{nonmember})})$, maps to a different general equilibrium outcome, amounting to 2^{18} cases. Therefore, in total, there are $2^{18} \approx 262$ thousand general equilibrium outcomes to compute.

⁴⁶This procedure requires that the benefits of membership increase as the climate club grows larger. This typically holds since a bigger club can impose harsher trade penalties on nonmembers. However, the relationship may not hold universally due to a caveat: As the climate club expands, global energy demand decreases, lowering the pre-tax price of energy worldwide. These general equilibrium price effects can diminish the desirability of club membership by raising the opportunity cost of carbon pricing. We cannot theoretically preclude scenarios where these general equilibrium forces undermine the link between club size and membership benefits. Instead, in the spirit of irreversible actions in theories of gradual coalition formation (Seidmann and Winter (1998)), we assume that exiting the climate club damages reputation and carries a nonpecuniary cost that intensifies with the club's size. Therefore, even if escalating trade sanctions prove insufficient, the nonpecuniary cost of existing ensures that the benefits of maintaining membership rise as the club grows.

meant to deter free-riding without being exercised in equilibrium. To achieve this, $\tau^{(\text{target})}$ must be ideally set to the maximal carbon tax target that supports an inclusive club of all nations as the Nash equilibrium.⁴⁷

Solution Algorithm. We employ the following two-tier procedure to identify the maximal carbon tax target. In the inner tier, we use the following iterative procedure for a given carbon tax target: In the first iteration, climate club penalties are applied only by core members. We identify non-core countries that would benefit from unilaterally joining the club, adding them to the club in the subsequent rounds. In the second iteration, climate club penalties are applied by core members plus those added from the previous round. We re-evaluate the gains from unilateral club membership under the new penalties and update the club accordingly. We repeat this procedure until we achieve convergence. The resulting outcome is an equilibrium club of all nations if: (i) the converged set corresponds to the set of all noncore countries who have no incentive to unilaterally withdraw, (ii) the welfare of core countries has increased relative to the status quo.⁴⁸ In the outer tier, we incrementally increase the carbon tax target from a small initial value until we identify the maximum target at which the club of all nations is formed.

While we specify the climate club as a static one-shot game, our procedure offers a glimpse into the club's potential expansion trajectory. For example, consider a club with the EU and US as core members and a carbon tax target of 53 (\$/tCO₂), as detailed in Table IV. In Round 1, five countries with stronger trade ties to the EU and US find it beneficial to join. Given this outcome, two additional countries opt to join in Round 2 to evade penalties by the EU, US, and the five other members that joined in Round 1. Following this iterative process, the club eventually includes all noncore countries after six rounds. At this point, we assess the benefits for the first movers—the EU and US—and find that their core membership has improved their national welfare compared to the status quo. It is worth noting that this example uses the maximal carbon tax target of 53 (\$/tCO₂), as a higher target fails to deliver global participation.

The progression of country memberships in the above example reflects the *gravity* structure of trade relations. Nations like Turkiye and Canada join early, given their strong trade ties with the EU and US. As the club expands, it attracts more distant countries with strong trade connections with the evolving club's collective body. Accordingly, the club's expansion occurs by membership from the West toward the East.

Outcomes Under Various Makeup of Core Members. We analyze three climate club scenarios, each with a distinct composition of core countries. Initially, we consider the European Union (EU) as the sole core member, recognizing its status as a leader in environmental commitment. Subsequently, we explore a scenario where the United States joins

⁴⁷In our quantitative exercises, this maximal target typically aligns with the peak of the emission reduction along the Laffer curve. The maximum emission reduction can be attained only when large developing countries such as India or Indonesia are in the club. At the same time, these countries are nearly marginal in joining the club or staying out. As a result, although that is not theoretically the case, in practice aiming for an inclusive club of all nations typically aligns with achieving the maximum emission reduction.

⁴⁸The second stage among noncore countries constitutes a *coalition-proof* equilibrium under the assumption referenced in footnote 46. Specifically, suppose that once a country joins the club, the increasing costs of exiting prevent it from leaving in subsequent rounds. Under this assumption as a universal feature, our procedure coincides with the *iterative elimination of dominated strategies*, allowing us to narrow the set of potential outcomes. Moreover, the resulting outcome is a coalition-proof equilibrium provided that the iterative elimination of dominated strategies converges to a unique outcome, which is the case in our analysis (Moreno and Wooders (1996)). Lastly, we highlight that, for completeness, we always verify that the resulting outcome constitutes a Nash equilibrium even without the assumption in footnote 46.

TABLE IV
CLIMATE CLUB GAME WITH THE EU AND US AS CORE AND CARBON TAX
TARGET OF 53 (\$/tCO₂).

| | |
|---------|--|
| Core | EU, USA |
| Round 1 | Brazil, Canada, Korea, Turkiye, RO Eurasia |
| Round 2 | Russia, RO Americas |
| Round 3 | Africa |
| Round 4 | Japan, Mexico, Saudi Arabia |
| Round 5 | China, Indonesia, RO Asia, RO Middle East |
| Round 6 | Australia, India |

Note: This table shows the convergence of our solution method via successive rounds to a club of all nations, for the case in which the EU and US are core members and the carbon tax target is at its maximal value of 53 \$/tCO₂. A country unilaterally evaluates to join at each round given the club configuration at its previous round.

TABLE V
CLIMATE CLUB OUTCOMES.

| Core | Max Carbon Target (\$/tCO ₂) | Reduction in Global CO ₂ |
|------------------|--|-------------------------------------|
| EU | 36 | -13.4% |
| EU + USA | 53 | -18.6% |
| EU + USA + China | 89 | -28.0% |

Note: This table shows the climate club outcomes of the maximal carbon price target and the corresponding reduction in global CO₂ emissions for each scenario of the core countries

the EU, forming a larger core. Our final scenario includes the EU, US, and China as the core members of the club.

For each scenario, Table V reports the maximal carbon tax target and the resulting global CO₂ reduction. With the EU as the only core member, the maximal carbon price target is 36 (\$/tCO₂), leading to a 13.4% decrease in global emissions. When the EU and US unite as core members, the maximal target rises to 53 (\$/tCO₂), delivering a 18.6% reduction in global emissions. The addition of China as a core member further amplifies the club's impact: it allows for a maximal carbon price target of 89 (\$/tCO₂), culminating in a 28.0% reduction in global emissions. This is substantial when contrasted with the 41.0%, obtainable under first-best carbon pricing.⁴⁹

These findings suggest that a well-structured climate club could achieve more than two-thirds of the first-best reduction in global carbon emissions ($28.0/41.0 \approx 0.68$). The extent of this success, however, hinges critically on the initial composition of core members and the appropriate selection of the carbon tax target.

6. DISCUSSIONS

In this section, we examine the robustness of our results to alternative parameterizations, characterize alternative policy designs, and discuss extensions to our framework.

⁴⁹Tables A.5 and A.6 in the Supplemental Appendix show the rounds of accession with the EU and EU + US + China as core members. In addition, Figure A.4 compares welfare gains between participation and withdrawal for noncore countries, and shows core members' welfare improvements relative to status quo.

6.1. Sensitivity Analysis and External Validity

We redo our analysis under five alternative specifications, with results reported in Tables A.7 and A.8. First, we set the social cost of carbon at 92 (\$/tCO₂) compared to 156 (\$/tCO₂) in our main analysis. This choice is consistent with the EPA's estimate under a 2.5% (instead of 2%) annual discount rate. Second, we leverage *country-level* estimates for the social cost of carbon from Ricke, Drouet, Caldeira, and Tavoni (2018) to recalibrate the carbon disutility parameters, $\tilde{\delta}_i$.⁵⁰ Third, we assign a common trade elasticity, $\sigma_k \equiv \sigma = 6.7$, to all industries, estimated using the pooled sample. In this case, export market power varies solely with export market share across industries. Fourth, we consider a Cobb–Douglas production function for final goods, representing a unitary substitution elasticity between energy and labor inputs (i.e., $\varsigma \rightarrow 1$), compared to $\varsigma = 0.65$ in our main specification. Lastly, we consider an alternative (inverse) energy supply elasticity by setting $\phi_i/(1 - \phi_i)$ to 2.0 for all countries, compared to an average of 0.6 in our main specification. Following Kortum and Weisbach (2021), this choice aligns with data on the distribution of extraction costs among oil fields.⁵¹ For each specification, Table A.7 reports the effects of noncooperative border taxes, while Table A.8 reports outcomes associated with the climate club. Across all scenarios tested, the qualitative results remain identical and quantitative results are similar to our main specification.

We additionally conduct two external validation checks on our model. First, we conduct an IV-based test in the spirit of Adao, Costinot, and Donaldson (2025). To this end, we use our model to simulate countries' emission response to *observed* changes in carbon taxes from 2014 to 2022, holding all parameters of the model constant at their 2014 values. We then check whether the difference between the vector of model-implied and observed emission changes is uncorrelated with the vector of carbon tax changes. Following Adao, Costinot, and Donaldson (2025), and provided that carbon tax changes are independent of other changes in model fundamentals, a significant nonzero correlation would suggest that our model is misspecified. Encouragingly, as Figure A.8 shows, the noted correlation is statistically indistinguishable from zero in our case.⁵² Second, we compare our model's predicted emissions reductions from globally-applied carbon taxes to estimates from other modeling approaches, including integrated assessment models, computable general equilibrium models, and ex post empirical studies. Figure A.9 plots our model's projected global emission reductions against the global carbon tax rate, benchmarked against projections from leading studies in the literature. Despite differences in underlying assumptions, our results fall within the range reported across these previous analyses, providing additional support for the credibility of our model.

⁵⁰Specifically, we calibrate the disutility parameters by assuming that the relative disutility is proportional to the country-level cost of carbon and that the disutility parameters add up to $SC\text{-}CO_2 = 156$.

⁵¹Our specification of energy production, Equation (7), is isomorphic to the one in Kortum and Weisbach (2021). The latter assumes a continuum of fields that are heterogenous in their extraction costs, as captured by the unit labor requirement, a . Let $Q_0 = E(\bar{a}) = \text{constant} \times \bar{a}^\epsilon$ represent the amount of energy that can be extracted with a unit labor requirement $a < \bar{a}$. This formulation is equivalent to the production function, $Q_0 = \text{constant} \times L_0^{1-\phi}$, assumed in this paper by setting $(1 - \phi) = \epsilon/(\epsilon + 1)$. The choice of $\epsilon = 0.5$ implied by the empirical distribution of extraction costs yields $\phi = 2/3$, which corresponds to an inverse energy supply elasticity of $\phi/(1 - \phi) = 2$.

⁵²We view the test outcome as merely suggestive since applying that procedure in this context, with only one policy shifter, requires (a) the assumption that countries are approximately independent markets and (b) the asymptotic formula provided by Adao, Costinot, and Donaldson (2025) may be inaccurate with our small number of countries ($N = 19$).

6.2. *Alternative Policy Designs*

Our main analysis focused on policies that address the *free-riding* problem. Our analysis of Proposal 1 considered the most effective carbon border tax design that is resilient to free-riding, as characterized by Proposition 2. For Proposal 2, we focused on optimal penalties that maximize welfare transfers from nonmembers to members of the climate club. However, border taxes can deliver even greater emission reductions when free-riding is *not* the main obstacle to carbon pricing. These taxes can also be more punitive than the unilaterally-optimal taxes used in our climate club analysis. Below, we explore alternative border tax designs, which are relevant when free-riding is less of a concern or when countries are willing to exert harsher sanctions on free-riders.

First, consider a global economy where governments are willing to cooperate on climate issues but face political pressures that prevent them from implementing *first-best* carbon taxes. In this scenario, border taxes could serve as a *second-best* cooperative solution. We characterize the globally optimal border taxes under this scenario in Supplemental Appendix C. Quantitatively, we find that this policy reduces global carbon emissions by only 0.9%, which is comparable to the noncooperative border taxes examined earlier. The main takeaway here is that carbon border taxes have limited efficacy in reducing global emissions regardless of whether they address international free-riding or domestic political constraints. Instead, their ineffectiveness stems from the three structural limitations discussed in Section 5.1.

Second, envision a scenario where the home country's government assigns a nonzero weight to foreign welfare when designing its policy. The resulting optimal policy choices in that case trace out the home country's *unilateral policy frontier*. Each point on this frontier corresponds to a specific set of weights assigned to foreign countries' welfare. As detailed in Supplemental Appendix C, placing more importance on foreign welfare dilutes the terms-of-trade component of the optimal border taxes. And when the weights on foreign welfare are sufficiently large, the home country's optimal policy has no negative externality on other countries—aligning with the optimal policy framework in Kortum and Weisbach (2021).

Figure A.6 in the Supplemental Appendix illustrates the EU's unilateral policy frontier. As the EU assigns a greater weight to non-EU countries, its optimal policy moves along the frontier to a point where it preserves non-EU's welfare. This policy, labeled "Externality-Free," elevates the EU's welfare by 0.19% compared to 0.32% under our baseline unilaterally-optimal policy. Moreover, global emissions drop by 3.4% under the Externality-Free policy compared to around 2% under the unilaterally-optimal policy. The Externality-Free policy, however, is difficult to implement due to free-riding incentives. It effectively raises non-EU welfare to the detriment of EU countries compared to other policies on the frontier (top panel of Figure A.7). Additionally, policies that assign a greater weight to non-EU welfare trigger more carbon leakage, as displayed in the bottom panel of Figure A.7. The reason is that a higher non-EU weight prompts the EU to raise its domestic carbon tax, bringing it closer to the social cost of carbon. This increase in tax reduces the EU's energy demand, and consequently lowers global pre-tax energy prices, prompting higher energy use and carbon emissions in non-EU regions.⁵³

⁵³The unilateral policy frontier, moreover, identifies the range of penalties a country could impose on its trade partners, for instance by assigning a negative weight to foreign welfare, as in Becko (2024). Under one such weighting scheme, a country could achieve the maximal reduction in foreign welfare without reducing its own welfare. The noted policy lies on the westernmost point of the frontier, labeled as "Maximal Sanction" in Figure A.6. In the context of a climate club, applying these extreme trade sanctions would have ambiguous ef-

Lastly, the unilateral policy frontier shows the limitations of unilateral policy, regardless of whether governments implement optimal policies or not. The frontier shown in Figure A.6 determines the range of potential welfare outcomes possible under unilateral policy. Suboptimal policy decisions would result in outcomes inside the frontier. The maximum welfare increase realizable for the EU under unilateral policy is less than 0.4%, contrasting with the 0.7% increase feasible under the climate club led by the EU. Similarly, emissions reductions are capped at around 5% under the EU's unilateral policy, compared to more than 13% with the climate club initiated by the EU (Figure A.7 and Table V). Essentially, even if governments do not optimize policies, the climate club's frontier remains far more promising.

6.3. Extensions to Richer Settings

(a) *Increasing-Returns to Scale.* We introduce increasing-returns to scale in final-good industries as in Krugman (1980), with details provided in Supplemental Appendix H.1. In this setting, scale economies arise from love-for-variety, governed by the elasticity of substitution, γ_k , between firm varieties.⁵⁴ Firms' entry decisions do not internalize the full benefits of introducing new varieties, leading to inefficient entry and output across industries. Consequently, optimal policy aims to address inter-industry scale distortions while also managing the terms of trade and reducing emissions. For a small open economy under Cobb-Douglas-CES preferences, the unilaterally optimal policy formulas become

$$\left\{ \begin{array}{ll} \tau_i^* = \tilde{\delta}_i \sim \delta_i \tilde{P}_i, & s_{i,k}^* = \frac{1}{\gamma_k - 1} & \text{[carbon tax and domestic subsidy]} \\ t_{ni,k}^* = \bar{t}_i + \frac{\gamma_k - 1}{\gamma_k} \tau_i^* v_{n,k} & t_{ni,0}^* = \bar{t}_i & \text{[import tax (energy and nonenergy)]} \\ 1 + x_{in,k}^* = (1 + \bar{t}_i) \frac{\sigma_k - 1}{\sigma_k} & & \text{[export subsidy (nonenergy)]} \\ & + \frac{\gamma_k - 1}{\gamma_k} \tau_i^* \sum_{j \neq i} [\lambda_{jn,k} v_{j,k}] \frac{\sigma_k - 1}{\sigma_k} & \\ 1 + x_{in,0}^* = (1 + \bar{t}_i) \frac{\sigma_0 - 1}{\sigma_0} + \tau_i^* \frac{1}{\sigma_0} \frac{\zeta_n}{\tilde{P}_{n,0}} & & \text{[export subsidy (energy)]} \end{array} \right. \quad (28)$$

The above policy differs from the constant-returns to scale variant in two ways. First, it includes production subsidies, denoted by $s_{i,k}$. The optimal production subsidy is carbon-blind and corrects scale distortions by favoring high-returns-to-scale (low- γ) industries. Second, carbon border taxes are adjusted to account for scale economies, as they exert two countervailing effects on foreign emissions: they lower emissions by reducing output (Q), but concurrently, raise the per-unit emissions (Z/Q). The latter effect occurs because per unit emissions decline with output scale at an elasticity, $(\gamma_k - 1)^{-1}$. To balance this trade-off, the optimal carbon border tax is revised downwards by a factor of $\frac{\gamma_k - 1}{\gamma_k}$. In the limit where $\gamma_k \rightarrow \infty$, industry k operates under constant-returns to scale, and the above formulas reduce to the baseline formulas presented earlier.

ffects on the club's efficacy. On one hand, the sanctions would make nonmembership more costly. On the other hand, they would dilute the benefits of membership by prioritizing harm to foreign countries over domestic welfare.

⁵⁴As shown in Supplemental Appendix H.1, this extended model is isomorphic to a setting with *external* economies of scale.

Tables A.9 and A.10 in the Supplemental Appendix show the impacts of Proposals 1 (non-cooperative carbon border taxes) and 2 (climate club) under increasing-returns to scale. The analysis uses scale elasticities derived from the estimates in [Lashkaripour and Lugovskyy \(2023\)](#).⁵⁵ The results indicate that carbon pricing policies deliver smaller reductions in *global* emissions due to the same trade-off highlighted earlier. Specifically, under increasing-returns to scale (IRS), contractions in output, Q , coincide with an increase in per-unit emissions (Z/Q). While this trade-off moderates the overall impact of policy on emissions, the relative efficacy of Proposals 1 and 2 is virtually unchanged compared to the baseline constant-returns-to-scale (CRS) scenario.⁵⁶

(b) *Firm Heterogeneity.* We consider two sources of firm heterogeneity: differences in (1) total factor productivity and (2) carbon intensity across firms. The Krugman extension of our framework can readily handle the former, but modeling heterogeneity in carbon intensity is more challenging due to data limitations. Specifically, the formulas described in Equation (28) remain valid if there is firm heterogeneity only in total factor productivity. The formulas apply without qualification if serving new markets does not require paying a fixed overhead cost. In the presence of fixed costs, however, the optimal policy must account for self-selection of the most productive firms into export markets, à la [Melitz \(2003\)](#). Following [Kucheryavyy, Lyn, and Rodriguez-Clare \(2023\)](#), it can be shown that the Krugman extension of our model is isomorphic to the Melitz model when firm-level productivity follows a Pareto distribution. See Supplemental Appendix H.2 for details. Therefore, Equation (28) describes optimal policy also in the Melitz–Pareto case, albeit with a reinterpretation of parameters—indicating our quantitative results would be unchanged.

A richer extension could incorporate firm heterogeneity in both productivity and carbon intensity (see [Cherniwchan, Copeland, and Taylor \(2017\)](#)). Here, border taxes could alter the average carbon intensity of exporting firms. This consideration lends itself to policy designs that target firm-level abatement, such as the Carbon Border Adjustment Mechanism (CBAM) referenced in footnote 44. But how this consideration affects optimal policy design depends on information asymmetry between governments and foreign firms. For instance, if governments know that more productive firms tend to be less carbon-intensive, they could set a higher carbon border tax to deter entry by small, carbon-intensive firms. Yet with only industry-level data on carbon intensities, governments may implement voluntary certification schemes that incentivize low-emissions firms to disclose their output and emission levels ([Cicala, Hémous, and Olsen \(2022\)](#)). Quantifying the global impacts of border taxes in either case requires international firm-level emissions data, which is presently unavailable.

7. CONCLUSION

We analyzed two major climate policy proposals that use trade policy to address free-riding in climate action. One involves carbon border taxes as a second-best tool to limit

⁵⁵In this extension of our model, a necessary condition for uniqueness is $\mu_k \equiv (\sigma_k - 1)/(\gamma_k - 1) \leq 1$. Therefore, we use the estimates of μ_k from [Lashkaripour and Lugovskyy \(2023\)](#), which guarantee $\mu_k \leq 1$, together with our estimates of trade elasticity σ_k to recover the love-of-variety parameters, γ_k .

⁵⁶Despite similar aggregate results, some differences are noticeable at the level of individual countries. For example, Figure A.10 compares the change in CO₂ emissions under Proposal 1 between our main model (CRS) and extended model (IRS). Under the IRS model, when firms are subjected to border tax hikes, they tend to relocate to larger markets to evade such taxes. These delocation effects can raise the scale of production and CO₂ emissions even in climate-conscious regions like the EU that charge a relatively high carbon tax.

transboundary emissions, while the other, the climate club, uses border taxes to incentivize cooperation from reluctant governments. Our results show that even optimally designed carbon border taxes achieve only modest global emissions reductions, whereas the climate club can be highly effective under an appropriate composition of core members and carbon tax target.

Our analysis puts forth methods with broader implications. For instance, carbon border taxes could target individual firms with proper monitoring, and collecting firm-level emissions data offers a promising research direction. Future work could also explore distributional considerations, such as international climate funds, technology transfers to developing nations, or supply-side carbon policies. Additionally, our analysis omits factors like adoption and innovation in renewable energy, which justify policies such as green technology subsidies.

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