Pollution Taxes and Clean Subsidies in an Open Economy

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Abstract

In open economies, the effectiveness of taxing a global pollutant is diminished by "pollution leakage," where some polluting activity shifts abroad as a result of the tax. This paper shows that the same economic conditions that lead to pollution leakage enhance the efficacy of clean subsidies. As a result, the optimal policy in an open economy is a combination of a pollution tax and a clean subsidy, the balance of which depends on the leakage rate. Furthermore, efficient corrective policy sets the sum of the tax and subsidy rates, a measure of policy ambition, equal to the marginal damages from pollution, and therefore does not depend on the leakage rate.

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1 Introduction

Climate change is an inherently global challenge. Individual countries' levels of greenhouse gas emissions and the damage they cause are inherently interconnected. Greenhouse gases are the classic example of a global pollutant: they have the same polluting effect regardless of where they are emitted and emissions released anywhere will impact all countries. Furthermore, different countries' emissions levels are interconnected, as the majority of greenhouse gases responsible for climate change are released by either the production or use of tradable goods. For many of these emissions sources, cleaner substitute goods have been developed. Renewable energy and electric vehicles are two prominent examples, but cleaner technologies to produce a number of industrial materials and fuels such as steel, concrete, fertilizer, and hydrogen are quickly emerging. Given the global nature of the production and the consequences of greenhouse gas pollution, it is critical to study climate policy in the context of an open economy.

Governments have adopted a variety of policies aimed at reducing greenhouse gas emissions. Many jurisdictions have adopted pollution taxes that price greenhouse gas emissions directly, while others have subsidized clean substitute goods, hoping to crowd out dirty production by encouraging substitution to a cleaner alternative.[1] Furthermore, some policies set very large tax and subsidy rates on broad tax bases, while others set much lower rates on narrow bases, indicating that the climate policy ambition of different countries, as measured by the combination of the effective pollution tax rate and clean subsidy rate, can vary dramatically as well. This paper investigates the policy incentives of an individual open economy trying to correct for a global pollutant, deriving an individual country's privately optimal choice of tax and subsidy instruments and level of policy ambition.

Policymakers interested in encouraging the transition to cleaner production processes and products can do so with a number of different policies. Clausing and Wolfram (2023) categorize policy instruments based on how ambitious they are and as either cost-imposing (taxes) or cost-reducing (subsidies). The European Union's emissions trading system and California's cap-and-trade law (AB32) are notable tax-like instruments. The United States' Inflation Reduction Act set high subsidy rates on a wide variety of clean industries, which are clear examples of high-ambition clean subsidies. State-level renewable portfolio standards for renewable electricity are additional examples of clean subsidy programs.

[1] Pollution taxes and clean subsidies are both examples of price instruments, which directly affect the price of emissions or clean production while allowing the quantities to fluctuate. Another set of policy tools include quantity instruments, which fix quantities while allowing prices to fluctuate. Quantity instruments include cap-and-trade programs and renewable portfolio standards. With full information, pricing instruments and quantity instruments can be used interchangeably. This paper refers to price instruments throughout, but its results equally apply to quantity instruments.

For a global policymaker, the targeting principle of optimal taxation provides a clear theoretical prescription for both the choice of policy instrument used and the level of policy ambition: the globally efficient policy is a pollution tax equal to the marginal global social cost of pollution, and there is no role for any additional tax or subsidy, if markets are otherwise undistorted. However, the incentives and tax instruments available to a policymaker in an individual open economy differ from those of a global policymaker.

An individual country is limited in which tax instruments it can use, as it cannot directly tax pollution emitted in a foreign jurisdiction. Thus, the targeting principle is not directly applicable. Analysis of an individual country's policy incentives will therefore be an analysis of second-best policy choices.

Domestic policymakers' objectives typically differ from those of a global social planner. An individual country considers domestic welfare and is apt to discount or ignore the costs and benefits of its policies that are borne by other countries. For a global pollutant such as greenhouse gas emissions, this will lead to climate policy free riding. One ton of carbon dioxide has the same climatic warming effect regardless of where it is emitted and affects countries all over the world. However, an individual country that considers only the damages occurring domestically from its greenhouse gas emissions will set insufficiently ambitious climate policy.

Furthermore, in an open economy, trade creates linkages between economies, policies, and environmental outcomes. Changes in policies or economic conditions in one country impact world prices and trade flows, affecting economic activity and the effectiveness of policy abroad. In addition, openness to trade causes pollution leakage, where polluting industries move from jurisdictions with high pollution taxes to jurisdictions with low pollution taxes. Pollution leakage will impact the effectiveness of climate policies intended to reduce greenhouse gas emissions. As emissions are a global pollutant, the geographic source of the emissions is irrelevant. All that matters is the total quantity of emissions.

This paper presents a model of the domestically optimal tax and subsidy policy for an individual open economy attempting to correct for a global pollutant emitted through the production of a globally tradable good. Crucially, the tradable good can be produced using either a "clean" or a "dirty" production process, but each process produces a homogeneous output and is traded on a single global market. Local policymakers can tax or subsidize either production process domestically, but cannot directly tax foreign dirty production.[2]

The first set of results detail the optimal policy considerations for a local policymaker

[2]Attempts to tax foreign production through import tariffs (such as a border-carbon adjustment) are discussed in Appendix A. However, these policies still have no taxing jurisdiction to tax dirty goods that are both produced and consumed abroad.

that takes foreign tax and subsidy policies as given. The policy choices faced by a local policymaker will be impacted by free-riding and pollution leakage. The domestic policymaker free rides by setting environmental policy proportional only to the local costs of pollution rather than the global cost of pollution. This is true regardless of whether the economy is open to trade.

In addition, openness to trade affects the choice of policy instruments through pollution leakage. Trade rationalizes the use of a clean subsidy in addition to a pollution tax on efficiency grounds. When foreign dirty production is very responsive to changes in the world price, the marginal rate of pollution leakage will be high, making a domestic pollution tax less effective. However, these conditions also make a clean subsidy more effective. In an open economy, the clean subsidy can be used to flood the world market with the clean good, lowering the world price and crowding out dirty production abroad. The domestic policymaker in an open economy will therefore optimally use both a pollution tax and a clean subsidy, and the marginal leakage rate will determine whether pollution taxes or clean subsidies should be used more prominently. When the leakage rate is high, the policymaker will set a low pollution tax rate but a high clean subsidy rate.

These results also emphasize that the domestically optimal tax and subsidy rates depend on the *world* supply and demand elasticities rather than local elasticities. Therefore, even a very small open economy would choose to implement a positive carbon tax and clean subsidy. A small open economy should still use a clean subsidy even though doing so creates only a very small change in the world price of the tradable good, and therefore sends only a small price signal to dirty producers. Intuitively, this is because the price signal creates a very small change among a very large number of foreign dirty producers, and the aggregate change in environmental benefits remains on the same order of magnitude as the domestic distortions induced by the subsidy.

This paper's second set of results considers properties of the multi-country equilibrium when countries set policies competing in a Nash game. These results characterize when there will be climate policy interactions where changing policy in one country causes another country to change their policy. In this equilibrium characterization, policy interactions occur when changing domestic environmental policy impacts the marginal effectiveness of environmental policy abroad. When pollution taxes and clean subsidies are used only to correct for environmental policy (rather than redistributing income or manipulating terms-of-trade), this interaction occurs exclusively through changing the marginal rate of pollution leakage. Although local policy will affect the level of foreign welfare through other mechanisms (such as tax exporting), the foreign marginal policy incentives, and therefore the pollution tax and clean subsidy rate, are only impacted through changes in the rate of pollution leakage.

Furthermore, whether taxes and subsidies in different countries are strategic complements or substitutes does not depend on whether countries compete in pollution taxes or clean substitutes. In the political and policy discourse surrounding the interdependence of climate change policy, clean subsidy races are sometimes framed as a mechanism to overcome policy free-riding while pollution leakage is often framed as creating a race to the bottom in carbon tax rates.[3] However, the analysis of the multi-country equilibrium suggests that considering policy interdependence does not favor the use of one tax policy instrument over another. The conditions that make policy rates strategic complements when all countries only use a clean subsidy would also lead to carbon taxes being strategic complements were all countries to only use pollution taxes. Finally, if all countries optimally use both a pollution tax and clean subsidy, any policy interdependence will simply shift the focus from one instrument to the other rather than increasing the overall level of climate policy ambition.

The final section illustrates the implications of the model using US electricity markets, calibrating the optimal pollution tax to clean subsidy ratio in each state. The US electricity grid is split into three major interconnections, segmenting the grid into separate geographic markets, and therefore serves as a natural setting for studying the model implications. Estimating the long-run supply elasticities and marginal pollution leakage rate for different states, these calibrations show that the rate of pollution leakage is lower in markets that are already predominately clean. Given that the long-run forecasts predict that the electric grid will be supplied mostly by clean sources under current trends, states enacting additional policies should rely primarily on pollution taxes rather than clean subsidies. This is especially true in the cleaner Western Interconnection compared to the relatively dirty Eastern Interconnection.

This research contributes to several lines of literature at the intersection of public finance and environmental economics. First, this research contributes to a significant literature on the choice of environmental tax instruments in the closed economy. A long targeting literature has shown that if all units of the externality producing good are taxable, the externality produced can be corrected for separately with a tax on the externality producing good (Sandmo, 1975; Dixit, 1985; Kopczuk, 2003). However, recent literature has focused on other domestic distortions in the closed economy that may complicate this logic for real world policy. Borenstein and Kellogg (2023) discuss policy instruments in the closed economy, pointing out that market power in electricity markets makes retail electricity priced above marginal cost, potentially negating the advantage of using a carbon tax over a clean subsidy. In political discourse, clean subsidies are often deemed to be a politically feasible

[3]See the comments by John Podesta (Senior Advisor for International Climate Policy for President Biden) discussing a race to the bottom and race to the top in climate policy (Podesta, 2024).

second best policy and academic work has documented the political unpopularity of carbon taxes (Anderson, Marinescu and Shor, 2023). Finally, clean subsidies can also be justified in models with endogenous growth paths and learning spillovers (Acemoglu et al., 2012, 2016; Xiang, 2023).

This paper shows that openness to trade creates an efficiency rationale for subsidizing clean substitute goods in addition to taxing pollution, even without other economic distortions present. This finding can be reconciled with the targeting literature by considering domestic dirty production and foreign dirty production as separate externalities. Domestic pollution can be directly taxed, and is therefore entirely corrected for with the pollution tax. Foreign dirty production cannot be directly taxed. Instead, both the pollution tax and clean subsidy influence foreign production through the world price, so both instruments are modified accordingly.

This paper also contributes to a significant literature studying pollution leakage. This literature examines how local pollution taxes and regulations can shift polluting production abroad to less stringently regulated jurisdictions (notably in Copeland and Taylor (1995, 2004) and more comprehensively reviewed in Copeland, Shapiro and Taylor (2022)) or empirically measuring pollution leakage either in specific industries (Fowlie, Reguant and Ryan, 2016; Fowlie, Petersen and Reguant, 2021; Domınguez-Iino, 2023; Hsiao, 2024) or systematically across many industries (Fowlie and Reguant, 2018; Fischer and Fox, 2018).

As climate policies have become more prominent, a large literature has studied how the leakage effect impacts the optimal level and design of carbon taxes in an individual open economy (Markusen, 1975; Hoel, 1994; Fischer and Fox, 2012; Böhringer, Rosendahl and Storrøsten, 2017; Weisbach et al., 2023; Böhringer et al., 2022; Kortum and Weisbach, 2022; Grubb et al., 2022; Kotchen and Maggi, 2024). This literature has focused on modifying the design of a pollution tax to include either a border carbon adjustment or an output-based subsidy to account for pollution leakage. The border carbon adjustment is an import tax and export subsidy set at the pollution tax rate intended to put domestic dirty producers on an equal footing with foreign producers. Output-based subsidies are per-unit output subsidies designed to support domestic industry. Both of these policies are designed to prevent carbon taxes from making domestic firms less competitive with foreign competition. Kortum and Weisbach (2022) also consider how openness to trade impacts domestic policy with multiple tax instruments, but focus instead on production and consumption taxes. They show the optimal domestic policy is to include a combination of both supply-side and demand-side policies, showing that the optimal border adjustment should not fully compensate for the supply-side tax.

Most of this literature does not model subsidies for clean substitute goods. Kotchen and

Maggi (2024), developed concurrently with this paper, is an exception. Kotchen and Maggi (2024) consider a model where fossil fuel energy and green energy are used as inputs for a homogeneous final consumption good and present similar results showing that an open economy provides an efficiency rationale to subsidize green energy and the subsidy operates through a pollution leakage channel.[4] They use this framework to analyze the impact of political lobbying and the properties of international cooperative agreements.

In addition, this paper contributes to a literature on interdependent climate policy in the international setting. In their article, Clausing and Wolfram (2023) consider environmental policies in an international context, discussing how pollution leakage, free-riding, and subsidy races can influence the policy ambition and instrument choice of individual economies. This paper takes many of these ideas and embeds them into a formal framework, incorporating ideas both from optimal taxation and non-cooperative game theory. Doing so illustrates that pollution leakage impacts the choice of tax and subsidy instruments and that this decision is largely separable from the level of policy ambition, which is impacted by free riding.

Hoel (1994); Nordhaus (2015); Kotchen (2018); Baksi and RayChaudhuri (2024); Farrokhi and Lashkaripour (2024) all look at international coalitions of countries that agree to set policy more ambitiously than the domestic cost of carbon emission. Farrokhi and Lashkaripour (2024) also look at how policy choice can impact international equilibrium outcomes in climate policy. However, they consider the choice between a carbon tax with a border adjustment and the carbon club (which requires some cooperation as proposed by Nordhaus (2015)) rather than a choice between a pollution tax and clean subsidy. They use a general equilibrium trade model which allows them to model economy-wide taxes, but requires them to compute multi-country equilibrium numerically. In contrast, this paper models the domestic economy in a sector-specific way, focusing on one policy targeted to one polluting industry and interactions in output markets (rather than factor markets). These simplifications allow for an explicit comparison with a clean subsidy and an analytical analysis of the multi-country equilibrium.

The remainder of the paper proceeds as follows. Section 2 presents the baseline model and domestic optimal policy. Section 3 discusses optimal policy in a small open economy. Section 4 extends the baseline model to allow for the emissions intensity of dirty production to vary between countries. Section 5 presents analytical results for policy interdependence in the multi-country equilibrium. Section 6 presents calibrations to US state electricity policy, and Section 7 concludes.

[4]Proposition 4 and 5 in Section 2 below—developed independently from Kotchen and Maggi (2024)—carry similar implications. The analysis in Section 2 explicitly models leakage, showing how it affects both tax and subsidy rates; and the analysis in Section 5 considers the implications for non-cooperative international equilibrium.

2 Baseline Model

This section presents the setup for the base model and solves for the policy incentives of a domestic social planner. Before presenting the main results for the open economy, I present two benchmark policy problems, one for a global policymaker and one for a closed economy. The global policymaker's problem illustrates the first-best policy that maximizes global social welfare. The closed economy policymaker's problem serves as a useful intermediate benchmark illustrating which frictions arise specifically due to openness to trade and which are simply the result from a domestic policymaker ignoring costs and benefits to other countries.

2.1 Model Setup

Consider a model with a homogeneous tradable final good and a separate numeraire good. The tradable good can be produced using either a "dirty" or a "clean" production process, but the output from the two production processes are identical from the perspective of the consumer. Dirty production produces a global externality, where the externality depends on the total quantity of worldwide dirty production, regardless of where it occurs.

2.1.1 Consumer Demand

There are N countries and demand for the tradable good and numeraire good is given by a country i representative consumer. The tradable good, x_i, is sold on a worldwide market and there is a single market clearing price p. Consumers have exogenous endowed income y_i and receive profits from the firm, π_i and lump-sum government transfers T_i that they spend on x_i and numeraire good z_i. Demand is given by a standard quasi-linear utility maximization problem

$$\begin{aligned} &\max_{x_i, z_i} u_i(x_i) + z_i \\ &\quad \text{s.t. } y_i + \pi_i + T_i = p x_i + z_i \end{aligned} \tag{1}$$

where $u_i(x_i)$ is twice continuously differentiable and concave. Consumer demand for good x_i in country i is therefore simply a function of p, $x_i(p)$, and does not depend on income, profits, or transfers.

2.1.2 Supply

There are two production technologies for producing good x, a clean process and a dirty process that produces an environmental externality. Country i produces $x_{i,c}$ units using the clean process and $x_{i,d}$ units using the dirty production process. It costs $C_{i,d}(x_{i,d})$ and $C_{i,c}(x_{i,c})$ units of the numeraire good to produce $x_{i,c}$ and $x_{i,d}$ respectively. Finally, the government of country i can impose production taxes $\tau_{i,c}$ and $\tau_{i,d}$ on the two production processes (with negative values corresponding to subsidies). The representative firms produce to maximize after-tax profits taking prices as given.

$$\max_{x_{i,c}} \pi_{i,c} = \max_{x_{i,c}} (p - \tau_{i,c}) x_{i,c} - C_{i,c}(x_{i,c}) \tag{2a}$$

$$\max_{x_{i,d}} \pi_{i,d} = \max_{x_{i,d}} (p - \tau_{i,d}) x_{i,d} - C_{i,d}(x_{i,d}) \tag{2b}$$

Total costs $C_{i,c}$ and $C_{i,d}$ are increasing and convex. Markets are perfectly competitive and firms are price-takers, but strictly convex costs imply that there will be non-zero profits. Note that the cost functions depend only on the quantity produced using that production process. This is consistent with an economic environment where there is scarcity among technology specific input factors, but the industries are small enough not to impact prices of the shared input factors (capital and labor). Solving the representative firm problem shows that supply of the tradable good using either the clean or dirty production technologies are simply functions of the after-tax price, $x_{i,c}(p - \tau_{i,c})$ and $x_{i,d}(p - \tau_{i,d})$.

2.1.3 Market Clearing

The market clearing condition states that the total worldwide demand for good x has to equal the total worldwide supply from the clean and dirty production processes

$$\sum_i x_i(p) = \sum_i x_{i,c}(p - \tau_{i,c}) + \sum_i x_{i,d}(p - \tau_{i,d}). \tag{3}$$

2.1.4 Policymaker's Problem

The policymaker in country i sets tax/subsidy rates, $\vec{\tau}_i$, to maximize country i welfare. In addition to utility, welfare is impacted by an externality related to total dirty production, $\Gamma_i(X_d)$ where $X_d = \sum_{j=1}^{N} x_{j,d}$. The government transfers any tax revenue back to the consumer in a lump sum fashion $T_i = \tau_{i,c} x_{i,c} + \tau_{i,d} x_{i,d}$.

I explore the case where the policymaker is able to supplement production taxes with

a tax on the demand of x_i in Appendix A. Allowing for a tax on consumption allows for a direct comparison to border carbon adjustments, as the marginal incentives of tariffs can be recreated by a combination of production and consumption taxes (e.g. Kortum and Weisbach, 2022). However, this analysis only leads to minor modifications to the optimal tax and subsidy rates. Also, throughout the paper, I maintain the assumption that the numeraire good z_i will remain untaxed.[5]

The policymaker's problem is therefore stated formally as

$$\max_{\tau_{i,c},\tau_{i,d}} U_i(x_i(\vec{\tau}_i), z_i(\vec{\tau}_i)) - \Gamma_i(X_d(\vec{\tau}_i)) + \pi_i(\vec{\tau}_i) + \tau_{i,c}x_{i,c} + \tau_{i,d}x_{i,d} \tag{4}$$

The policymaker sets tax and subsidy rates accounting for consumer utility of the domestic consumer, profits of the domestic firms, the impact of global emissions on local economic activity, and tax revenues. Changing the tax rate for a production process $k \in \{c, d\}$ in country j has the effect of both creating a wedge between the price received by producers and the world price, as well as changing the world price of the tradable good, which in turn effects the quantity produced by suppliers in other industries and countries. The size of these two effects depends on the tax incidence of $\tau_{i,k}$, captured by how much the world price p changes when $\tau_{i,k}$ changes. The responsiveness of p to a change in $\tau_{i,k}$ can be calculated by differentiating Equation 3 and is given as

$$\frac{\partial p}{\partial \tau_{i,k}} = \frac{\alpha_{i,k}\eta_{i,k}}{\sum_n \alpha_{n,d}\eta_{n,d} + \sum_n \alpha_{n,c}\eta_{n,c} - \sum_n \beta_n \zeta_n} \tag{5}$$

where $\alpha_{n,k}$ is the world market share of country n production using technology k, $\eta_{n,k} = \frac{\partial x_{j,k}(p-\tau_{j,k})}{\partial (p-\tau_{j,k})}\frac{p}{x_{j,k}}$ is the price elasticity of supply for country i technology k production, β_n is the consumption share of country n and ζ_n is country n price elasticity of demand.

Before solving the policymaker's problem in the open economy, it is helpful to present the policy problem for two benchmark cases: the global policymaker and the policymaker in the closed economy. The global policymaker will provide an efficiency benchmark, showing the first-best policy the maximizes social welfare and the closed-economy policymaker's problem distinguishes between effects from maximizing domestic (rather than global) welfare and effects coming from openness to trade.

[5] If the numeraire good can be taxed or subsidized then there is an equivalence between the tax and subsidy as a tax on one good is equivalent to a subsidy on every other good in the economy (Corlett and Hauge, 1953).

2.2 Global Policymaker

Before deriving the optimal policy for an individual open economy, it is helpful to consider the optimal policy solutions for a global policymaker that is able to control all tax instruments in all countries. The global policymaker sets production tax and subsidy rates in every country to maximize the sum of global utility, serving as a useful illustration of the first-best globally efficient policy. Allowing the social planner to set all tax rates, the optimal tax rates are simply given by Proposition 1.

Proposition 1. The globally efficient tax and subsidy policy is to tax dirty production at the global social cost of pollution and to have no clean subsidies.

$$\begin{aligned} \tau_{i,d} &= \gamma^* \quad \forall i \\ \tau_{i,c} &= 0 \quad \forall i \end{aligned}$$

Proof in Appendix B.

As is well-known, the globally efficient policy is to impose a Pigouvian tax on dirty production everywhere. With a Pigouvian tax, there is no need to use a clean subsidy. Absent other frictions, clean production should not be taxed or subsidized. This well-known result is consistent with the targeting principle (Sandmo, 1975; Kopczuk, 2003).

The global policymaker chooses to use a clean subsidy only when it is prevented from using a tax on the dirty production process. Corollary 1 shows the optimal subsidy rates when the policymaker is restricted from taxing dirty production.[6]

Corollary 1. When the global policymaker is constrained to only use subsidies on the clean production process ($\tau_{i,d} = 0 \; \forall i$) the globally optimal subsidy rates are given as

$$\tau_{i,c} = -\gamma^* \left(\frac{\sum_{n=1}^{N} \alpha_{n,d} \eta_{n,d}}{\sum_{n=1}^{N} \alpha_{n,d} \eta_{n,d} - \sum_{n=1}^{N} \beta_n \zeta_n} \right) \tag{6}$$

Proof in Appendix B.

First, note that $\tau_{i,c}$ will always be (weakly) less than zero, indicating that the optimal policy is in fact a subsidy. The subsidy increases the price that clean producers receive, increasing clean output and lowering the market clearing price for the tradable good. The lower world price discourages dirty production but also encourages consumers to consumer more of good x and less of the numeraire good z. The economic rationale for subsidizing clean

[6] This case could separately be of interest if there were extra frictions (i.e. political economy reasons) that made implementing a tax more difficult than a subsidy.

production is to flood the market with clean production, crowding out dirty production and reducing the negative externality associated with doing so. The increase in consumption of x_i is an (inefficient) unintended consequence of subsidizing clean production. This trade-off is reflected in the expression for $\tau_{i,c}$ in Equation 6.

If world demand is perfectly inelastic ($\sum_n \beta_n \zeta_n = 0$), then an increase in clean production will entirely crowd out dirty production and the subsidy rate will be set at $\tau_{i,c} = -\gamma^*$. Here the clean subsidy is able to perfectly recreate the marginal incentives created by a pollution tax.[7] However, as demand becomes very elastic or dirty production becomes very inelastic, the subsidy for clean production mostly encourages an inefficient increase in consumption of x, rather than discouraging dirty production, and therefore has limited externality benefits. In the case where $|\sum_n \beta_n \zeta_n| >> \sum_n \alpha_{n,d} \eta_{n,d}$ the subsidy rate will go to zero.

2.3 Closed Economy

In a closed economy, domestic supply must meet domestic demand so country i price is set such that domestic markets clear

$$x_i(p_i) = x_{i,c}(p_i - \tau_{i,c}) + x_{i,d}(p_i - \tau_{i,d})$$

The policymaker in the closed economy sets tax and subsidy rates to maximize domestic welfare

$$\begin{aligned} \max_{\tau_{i,c}, \tau_{i,d}} \; & U_i(x_i, z_i) - \Gamma_i(X_d) \\ \text{s.t. } & x_i(p_i) = x_{i,c}(p_i - \tau_{i,c}) + x_{i,d}(p_i - \tau_{i,d}) \\ & T_i = \tau_{i,c} x_{i,c} + \tau_{i,d} x_{i,d} \end{aligned} \tag{7}$$

The domestically optimal tax and subsidy policy is given in Proposition 2.

Proposition 2. The closed economy policymaker setting tax and subsidy rates to maximize domestic welfare will tax dirty production equal to the domestic social cost of pollution and

[7] In this case, the only difference between a pollution tax and a clean subsidy is that the subsidy will feature a lower price for consumers and government revenue is negative by the amount of the subsidy. This results in a lump sum transfer from taxpayers to consumers, whereas the pollution tax is associated with a transfer from consumers to taxpayers. In a model with a representative consumer and lump sum taxes/subsidies, this has no effect on welfare, but if the social planner valued consumers and taxpayers separately this could be meaningful.

will not use clean subsidies.

$$\tau_{i,d} = \Gamma_i'(X_d) \equiv \gamma_i$$
$$\tau_{i,c} = 0$$

Proof in Appendix B.

Two things are worth noting about the privately optimal policy in the closed economy. First, the tax is proportional to only the marginal domestic damages from pollution (γ_i) rather than the marginal global damages from pollution ($\gamma^* = \sum_i \gamma_i$). This is the free riding problem in climate policy. If individual countries are only concerned with their domestic welfare, they will not consider the externality damages caused to other countries when pollution is emitted at home and will set insufficiently ambitious climate policy accordingly.

Second, moving to a closed economy and climate policy free riding does not affect the decision of which tax instrument to use. The policymaker in the closed economy only uses a tax on the dirty production process to correct for the externality, and the tax is set equal to the domestic social cost of pollution, like a Pigouvian tax calibrated only to domestic damages. There is no use for a subsidy on the clean production process and the tax rate on the dirty production process is not affected by the fact that other countries release pollutants as well. Although dirty production abroad impacts welfare at home, in a closed economy there are no economic interactions between countries meaning that there is no risk of leakage, but also no ability to crowd out foreign dirty production. Mathematically, foreign pollution affects the level of welfare but does not affect the marginal incentives. The closed economy simply takes foreign pollution as given and optimizes accordingly.

To further build intuition for how a subsidy on the clean production process could be useful, Corollary 2 shows the optimal subsidy rate when the closed economy policymaker cannot use a pollution tax.

Corollary 2. If the policymaker cannot implement a tax on the dirty production process, then the domestically optimal clean subsidy rate is

$$\tau_{i,c} = -\gamma_i \left(\frac{\alpha_{i,d}\eta_{i,d}}{\alpha_{i,d}\eta_{i,d} - \beta_i\zeta_{i,d}} \right)$$

Proof in Appendix B.

This expression for a closed economy clean subsidy is very similar to Corollary 1, except that it is calibrated only to the domestic economy. The optimal subsidy rate will be increasing as domestic dirty production becomes more elastic and decreasing as domestic demand becomes more elastic.

2.4 Open Economy

Finally, consider the domestically optimal policy for an individual open economy. In the open economy, the global market-clearing conditions hold, and the domestic policymaker sets policies to maximize domestic welfare, accounting for domestic damages from global pollution. For the domestic policymaker in country i that uses the set of taxes $\vec{\tau_i}$ and is considering a marginal increase in $\tau_{i,k} \in \vec{\tau_i}$, the first-order condition characterizing an optimal interior solution is

$$\lambda_i \cdot \underbrace{\vec{\tau_i} \cdot \frac{\partial \vec{x}}{\partial \tau_{i,k}}}_{\text{Fiscal Externality}} = \underbrace{\gamma_i \frac{\partial \sum_n x_{n,d}}{\partial \tau_{i,k}}}_{\text{Environmental Externality}} + \underbrace{\frac{\partial p}{\partial \tau_{i,k}} \left(x_{i,d} + x_{i,c} - x_i\right)}_{\text{Terms of Trade Manipulation}} + \underbrace{\left(\lambda_i - 1\right) x_{i,k}}_{\substack{\text{Value of Inframarginal} \\ \text{Transfer}}} \tag{8}$$

Derivation in Appendix B.

In order to focus on the role of correcting for the environmental externality, I ignore the last two terms, implicitly assuming that the domestic policymaker cannot use environmental policy to manipulate their terms of trade and ignores inframarginal transfers. Formally, these assumptions are:

Assumption 1. For the purpose of setting domestic policy, the policymaker acts *as if* $x_{i,d} + x_{i,c} - x_i = 0$.

Assumption 2. For each country $\lambda_i = 1$.

Ignoring terms of trade manipulation can be justified by strong international trade rules that allow domestic policy to correct for environmental policy but not to manipulate trade (as WTO rules aspire to do). Note that the terms of trade effect for country i is proportional to its net exports or imports of the tradeable good x. If country i produces as much of x_i as it consumes, as would happen if countries are identical, then the incentive to manipulate the terms of trade will not have first-order effects on the optimal tax or subsidy.

Ignoring inframarginal transfers, and therefore assuming $\lambda_i = 1$, is common in the literature on optimal externality correction (e.g. Griffith, O'Connell and Smith, 2019). This assumption is true in a representative consumer model if governments can use lump sum taxes and transfers to raise revenue.[8]

The primary difference between the policymaker's incentives in a closed economy and open economy relate to the potential for domestic policy to change the level of pollution

[8]Note that this assumption is also true in a model with heterogeneous consumers if the income tax system is set optimally Kaplow (2024). Crucially, if none of these explanations are true, the parameter will depend on how climate policy interacts with other policy goals such as redistribution and crucially depends on the progressivity of both the source and use of the revenue (as discussed in Goulder et al., 2019).

emitted abroad through an integrated market. This "pollution leakage" problem has been studied widely and will play a critical role in determining the optimal domestic policy. Following Fowlie and Reguant (2022), the marginal rate of pollution leakage for country i is defined as the increase in pollution abroad divided by the decrease in domestic pollution caused by a small increase in the pollution tax. Formally, this term is defined as

Definition 1.

$$L_i := \frac{-\sum_{n \neq i} \frac{\partial x_{n,d}}{\partial \tau_{i,d}}}{\frac{\partial x_{i,d}}{\partial \tau_{i,d}}} = \frac{\sum_{n \neq i} \alpha_{n,d} \eta_{n,d}}{\sum_{n \neq i} \alpha_{n,d} \eta_{n,d} + \sum_n \alpha_{n,c} \eta_{n,c} - \sum_n \beta_n \zeta_n}. \tag{9}$$

The second equality in the expression for the marginal rate of leakage is derived in Appendix B. Pollution leakage occurs because increasing the pollution tax for country i increases the world price p, which in turn sends a price signal for foreign dirty producers to increase their production. The leakage rate in the baseline model will be bounded between zero and one.[9]

2.4.1 Pollution Tax Only

I first consider the optimal policy for a country that only is able to use a pollution tax on the dirty production process. Here the policymaker must trade-off discouraging domestic dirty production against the possibility of pollution leakage. The optimal pollution-tax only rate is given in Proposition 3.

Proposition 3. If country i uses only a tax on dirty production to maximize welfare, the optimal pollution only tax is given as

$$\tau_{i,d} = \gamma_i (1 - L_i)$$

where L_i is the pollution leakage rate.

Proof in Appendix B.

Proposition 3 shows that in an open economy the optimal polluting tax is now smaller than the domestic social cost of pollution. Instead, the tax rate is adjusted to account for foreign leakage. When an open economy imposes a carbon tax, it puts a wedge between

[9] Section 4 explores the case where the emissions intensity of dirty production can vary between countries. In this case, the difference in emissions intensities will contribute to the leakage rate, with higher foreign emissions intensities leading to larger leakage. In the extreme case where the emissions intensity of foreign dirty production is much larger than the domestic emissions intensity, the leakage rate can be greater than one.

the price domestic producers receive and the world price, but also changes the world price. When the world price increases, foreign producers will increase production and consumers will decrease consumption. If foreign dirty producers increase production in response, then the net effect on worldwide pollution is smaller than the change in domestic dirty production. This is pollution leakage. Leakage makes the pollution tax less effective, and therefore the greater the leakage rate, the smaller the optimal pollution tax will be, when used alone.

2.4.2 Clean Subsidy Only

Instead, if the policymaker only uses a clean subsidy, they will set the subsidy rate in order to lower the worldwide price, reducing producer prices for dirty producers and decreasing production. When used alone, the domestically optimal clean subsidy rate is given by Proposition 4.

Proposition 4. If country i uses only a subsidy on clean production to maximize welfare, the optimal clean-subsidy rate is given as

$$\tau_{i,c} = -\gamma_i \left(\frac{\sum_n \alpha_{n,d}\eta_{n,d}}{\sum_n \alpha_{n,d}\eta_{n,d} + \sum_{n \neq i} \alpha_{n,c}\eta_{n,c} - \sum_n \beta_n \zeta_n} \right).$$

Proof in Appendix B.

The domestic clean subsidy now is influenced by the worldwide elasticity of dirty production, the worldwide elasticity of demand, and the elasticity of clean supply in the rest of the world. Equation 5 shows that the more elastic worldwide supply and demand is, the larger a subsidy rate is required to change the worldwide price. If it is worldwide dirty supply that is highly elastic, then it is worthwhile for an individual country to choose a large subsidy rate because even though it creates a large distortion domestically, a decrease in the worldwide price translates to a large reduction in global pollution. However, if instead world demand or clean supply in the rest of the world are very elastic, the domestic subsidy rate will be small. This is because very elastic foreign clean supply or world demand make it so that a large domestic subsidy is required to change the world price, creating large economic distortions domestically, but this change in the world price does not necessarily translate into reductions in global pollution. Therefore, if foreign clean supply or world demand are very elastic relative to world dirty supply, it will not be worthwhile for a domestic policymaker to use a large clean subsidy.

2.4.3 Combined Pollution Tax and Clean Subsidy

If the policymaker is able to use a pollution tax and a clean subsidy together, the policymaker now optimally uses both instruments as shown in Proposition 5.

Proposition 5. If country i uses both a production tax and clean subsidy, the optimal tax policy is given as

$$\tau_{i,d} = \gamma_i \left(1 - L_i \frac{1}{1-\omega_i}\right) \tag{10}$$

$$\tau_{i,c} = -\gamma_i \left(L_i \frac{1}{1-\omega_i}\right) \tag{11}$$

where L_i is the marginal rate of leakage and $\omega_i = \frac{\alpha_{i,c}\eta_{i,c}}{\sum_{n\neq i}\alpha_{n,d}\eta_{n,d}+\sum_n \alpha_{n,c}\eta_{n,c}-\sum_n \beta_n\zeta_n}$.

Proof in Appendix B.

Proposition 5 shows that in an open economy, it is optimal to use both a pollution tax and a clean subsidy. This is in contrast to the global policymaker and closed economy where a tax on the polluting production process was able to fully internalize the externality and there was no need for a clean subsidy. Openness to trade impacts the instrument choice of which tax and subsidy instruments the policymaker optimally chooses to use.

In Proposition 5, the pollution tax is still modified by an "adjusted" leakage term that is identical to the expression for the clean subsidy. This suggests that in the open economy, the pollution tax and clean subsidy are substitutes and market conditions that make a tax more/less effective make the clean subsidy less/more effective.[10]

Equation 9 shows that the leakage rate will be higher when foreign production is more elastic or has a greater market share relative to clean production and demand. These conditions make it so that an increase in the world price resulting from the pollution tax will result in a greater increase in foreign dirty production. At the same time, when foreign dirty production is very responsive to changes in the world price, a decrease in the world price resulting from a clean subsidy will lead to larger reductions in world pollution. The leakage effect from pollution taxes and the pollution abatement effect of clean subsidies work through the same mechanism, changing world pollution through changes in the world price. A stronger leakage effect reduces the effectiveness of the pollution tax but makes the clean subsidy more effective.

[10]The adjustment to the leakage term, $1/(1-\omega_i)$, captures the cross fiscal externality between the tax and subsidy rates. When both instruments are used, changing one instrument will impact the economic distortions created by the other instrument, an interaction accounted for by ω_i. As the country size gets smaller, ω_i will become small, and in the limit the adjustment to the leakage rate can be ignored.

At one extreme, when demand and clean supply are very inelastic, the leakage rate will approach one. This indicates that any reduction from domestic dirty production caused by the pollution tax will be almost entirely offset by an increase in foreign dirty production, and a pollution tax will not change world pollution. At the same time, any decrease in the world price from the clean subsidy will entirely crowd out dirty production, making the clean subsidy more effective.[11]

On the other hand, when foreign dirty production is very inelastic, or the foreign market is almost entirely clean, the leakage rate will be close to zero. Here the pollution tax can be set at the Pigouvian rate $\tau_{i,d} = \gamma_i$ without being undermined by pollution leakage. At the same time, setting a clean subsidy will be ineffective, as foreign pollution is very inelastic so any increase in domestic clean production will either crowd out foreign clean production or cause demand to increase. Even if domestic dirty production is elastic, this is most directly corrected for by the pollution tax rather than the clean subsidy.

More generally, the optimal policy rates in Proposition 5 are consistent with the targeting principle of optimal taxation if domestic dirty production and foreign dirty production are considered as separate externality producing goods. The generalized principle of targeting, as formulated by Kopczuk (2003), states that when externality producing goods are directly taxable, the optimal tax rates are expressed as the sum of the Pigouvian tax on the externality producing good and the optimal rates were there no externality. In the open economy context, only domestic dirty production is directly taxable, so the optimal policy rates should be the sum of the Pigouvian tax on domestic dirty production plus the optimal rates were there no externality from domestic dirty production.

Without an externality from domestic dirty production, the domestic policymaker would set rates on both clean and dirty production to reduce dirty production abroad. Here the optimal policy would be to subsidize both forms of domestic production equally as both instruments can be used to lower the world price and crowd out dirty production. The optimal policy expressions in Proposition 5 show this explicitly, both instruments are modified equally to reduce the world price, reducing foreign production. The only difference comes from an additive Pigouvian term to the domestic pollution tax used to correct for the externality from domestic dirty production.

[11] Although very inelastic clean supply makes it necessary to impose a larger subsidy to change the world price, the very limited behavioral response means that there is only a very limited economic distortion. The optimal subsidy rate ends up being independent from the elasticity of domestic clean production, just as the Pigouvian rate on a polluting good is independent of the supply elasticity.

2.5 Policy Ambition and Instrument Choice

The expressions for the optimal policy in Proposition 5 have important implications for policy ambition in the open economy. The optimal policy expressions lead directly to a separability result between policy ambition and instrument choice, as well as to the result that optimal policy ambition is invariant in the open economy, as stated in Proposition 6.

Proposition 6. The optimal policy ambition from the optimal combined pollution tax and clean subsidy, as measured as the sum of the tax rate and subsidy rate, is constant and always equal to the value of avoided pollution.

$$\tau_{i,d} + |\tau_{i,c}| = \gamma_i \tag{12}$$

Proposition 6 demonstrates that in the open economy, the total climate policy ambition is only a function of the value the domestic policymaker places on reductions in pollution, γ_i. This is true regardless of the values of the marginal leakage rate, market shares, or supply and demand elasticities domestically and abroad. Although all of these values will affect the optimal pollution tax rate and optimal clean subsidy rate individually, the total ambition of climate policy, as measured by the sum of the pollution tax and clean subsidy, will remain unchanged.

To investigate the choice of policy instruments, Equation 13 shows the expression for the optimal policy ratio, defined as the optimal pollution tax divided by the optimal clean subsidy.

$$\frac{\tau_{i,d}}{\tau_{i,c}} = -\frac{\sum_{n \neq i} \alpha_{n,c}\eta_{n,c} - \sum_n \beta_n \zeta_n}{\sum_{n \neq i} \alpha_{n,d}\eta_{n,d}}. \tag{13}$$

The optimal policy ratio provides a measure for how much country i should optimally rely on a pollution tax relative to a clean subsidy to reduce pollution.

Importantly, the optimal policy ratio does not depend on γ_i. Proposition 6 shows that γ_i is a sufficient statistic for policy ambition. The choice of policy instruments is therefore independent of the level of policy ambition, further demonstrating the separability between climate policy ambition and instrument choice. An open economy policymaker should therefore place the same relatively reliance on a tax vs a subsidy regardless of whether they only marginally value reductions in pollution or internalize all the global damages (all else equal).

A close examination of Equation 13 shows that the policy ratio changes in a way that is consistent with the effectiveness of pollution taxes and clean subsidies. If foreign dirty supply is much more responsive to price increases than foreign clean supply or world demand, a change in prices will have a large impact on foreign dirty production. This will make the leakage problem from a pollution tax worse but also make a clean subsidy more effective,

making country i favor a clean subsidy. On the other hand, if dirty supply is very inelastic, the leakage problem of a pollution tax is very minor while the clean subsidy is ineffective, making country i favor a clean subsidy.

Assuming constant elasticities, then the relative use of a tax/subsidy will be related to the market share in the rest of the world. If the foreign supply is mostly dirty, then it will be more attractive to use a clean subsidy as the marginal rate of leakage will be worse. However, if the foreign market is already dominated by clean supply, the clean subsidy will be relatively ineffective and there will be little leakage from the pollution tax, favoring the use of a pollution tax.

Equation 13 can also be written in terms of the marginal leakage rate of country i, as shown in Equation 14.

$$\frac{\tau_{i,d}}{\tau_{i,c}} = -\frac{1 - L_i - \omega_i}{L_i} \tag{14}$$

As country i becomes small, the leakage correction term, ω_i, will go to zero, and the optimal policy ratio will simply be equal to $-\frac{1-L_i}{L_i}$. The marginal rate of leakage is therefore a sufficient statistic for the optimal policy ratio in a small open economy. Economies with lower leakage rates should rely more heavily on pollution taxes while economies with higher leakage rates should instead rely on clean subsidies.

2.6 Numerical Example

This section presents a stylized example in a two country world for further intuition and concreteness. Consider policy in country i when the domestic (country i) and foreign (country j) supply and demand curves are linear and given as follows:[12]

$$\begin{aligned} x_{i,c} &= 2(p - \tau_{i,c}); & x_{j,c} &= p - \tau_{j,c} \\ x_{i,d} &= p - \tau_{i,d}; & x_{j,d} &= 2(p - \tau_{j,d}) \\ x_i &= 3 - \frac{\kappa}{2}p; & x_j &= 3 - \frac{\kappa}{2}p \end{aligned}$$

Country i is a lower cost and more elastic clean producer but a higher cost and less elastic dirty producer. In this stylized example with linear supply and demand, country i policy will not depend on the policy choices of country j.[13]

The rate of pollution leakage will be higher in country i, as country j has more elastic dirty production. As a result, country i will rely relatively more on the clean subsidy and relatively less on a pollution tax than country j. The parameter κ, controls the slope of the

[12] The case of linear supply given in this example comes from quadratic total cost curves.

[13] A more complete analysis of policy interaction effects is presented in Section 5

world demand curve and will affect the rate of pollution leakage, and therefore the optimal policy choices. Table 1 summarizes the leakage rate, optimal policies, and avoided global pollution from country i's policy under a high leakage ($\kappa = 0$) and low leakage ($\kappa = 1$) scenario when $\gamma_i = 1$.

Table 1: Country i Policy in a Two Country World ($\gamma_i = 1$)

	Case 1: High Leakage	Case 2: Low Leakage
Marginal Leakage Rate	0.4	0.33
Pollution Tax Rate	0.33	0.5
Clean Subsidy Rate	0.67	0.5
Avoided Global Pollution	28%	28%

Note: This table summarizes the leakage rates, optimal policies, and total avoided pollution for country i under a lower leakage (column 1) and higher leakage (column 2) scenario, where the difference in the leakage rate comes from making world demand more price sensitive. The marginal leakage rates are calculated according to Equation 9. The optimal pollution tax rate, $\tau_{i,d}$, and clean subsidy rate, $|\tau_{i,c}|$, are calculated according to Proposition 5 when $\gamma_i = 1$. Avoided global pollution is measured as the percent reduction in domestic and foreign dirty production from country i's optimal policy, relative to the case with no climate policy in either country.

The table shows the leakage rate, optimal policy, and avoided pollution for country i under each scenario when $\gamma_i = 1$. In the high leakage scenario, country i has a relatively high leakage rate (0.4) and relies much more on a clean subsidy than a pollution tax (the subsidy rate is twice the tax rate). In the low leakage scenario, the leakage rate decreases, making the pollution tax more effective and the clean subsidy less effective. As a result, the optimal tax rate increases and the optimal subsidy rate decreases, resulting in the two rates being equal. In both scenarios, the sum of the tax rate and subsidy rate is equal to γ_i, demonstrating that policy ambition is invariant to the rate of leakage (Proposition 6).

Finally, the last row shows how much country i policy reduces pollution from a baseline of no climate policy. In both the high and low leakage scenarios, the combined tax and subsidy policy reduces dirty production by 28%, indicating that higher leakage rates are not necessarily associated with less effective policy.[14] However, unlike the level of policy ambition that is always constant, the avoided pollution can change as the leakage rate changes. This change is not monotonic however, with avoided pollution increasing as leakage increases under some economic conditions and decreasing as leakage increases under other economic

[14]For country i, the absolute value of reduced pollution is actually higher under the high leakage rate. However, the baseline level of pollution is also higher under these parameter values so the percent reduction ends up being similar.

conditions.

3 Optimal Policy in Small Economies

This section discusses the role of climate policy in small open economies as the analysis in Section 2.4 does not explicitly discuss how country size affects the incentive to use a pollution tax or a clean subsidy. Given that small open economies have only very small effects on world prices, it is tempting to think that the open economy policymaker need not worry about pollution leakage from a pollution tax and that a clean subsidy would be ineffective, given that subsidies change foreign pollution through changing the world price. This reasoning, however, is incomplete as the following analysis shows.

Consider the case with N identical countries where

$$x'_{i,d} = x'_d; \qquad x'_{i,c} = x'_c; \qquad x'_i = x' \quad \forall i.$$

In this case, the ratio of the pollution tax to the clean subsidy in any particular country is given as

$$\left|\frac{\tau_{i,d}}{\tau_{i,c}}\right| = \frac{(N-1)x'_c - Nx'_n}{(N-1)x'_{n,d}} = \frac{x'_c - x'}{x'_d} + \frac{-x'}{(N-1)x'_d}. \tag{15}$$

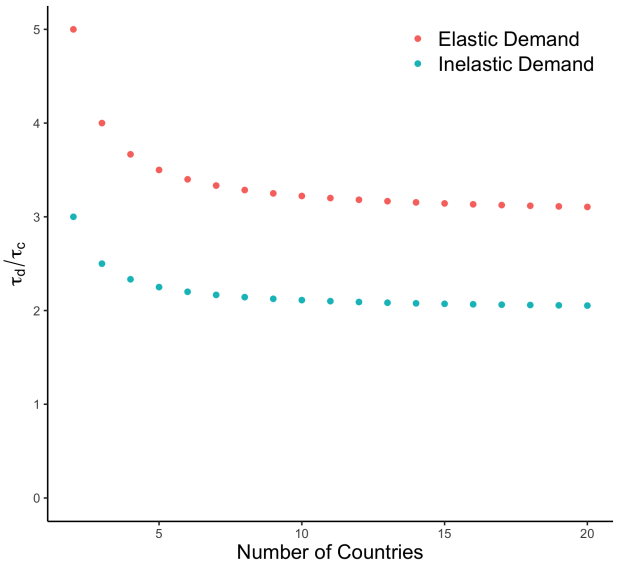
The number of countries impacts only the last term, $\frac{-x'}{(N-1)x'_d}$, which is positive. As the number of countries increases, this term becomes smaller, slightly decreasing the ratio of $|\frac{\tau_{i,d}}{\tau_{i,c}}|$. Therefore, as country size decreases, the open economy policymaker should still use both a pollution tax and clean subsidy. In fact, decreasing country size (by increasing the number of countries) will increase the leakage rate, giving the policymaker stronger incentives to use a clean subsidy rather than a tax.[15]

Figure 1 demonstrates this point, showing simulated values for Equation 15 as the number of countries increases for a relatively elastic demand example (red) and a relatively inelastic demand example (blue). As the number of countries increases, the policy ratio for both the elastic economy and inelastic economy asymptote, indicating that even for small open economies the optimal policy is to use both policy instruments. As country size decreases, $|\tau_{i,d}/\tau_{i,c}|$ decreases indicating that small economies rely more on clean subsidies, not less.

The policymaker setting taxes and subsidies trades off the environmental benefit of reducing worldwide pollution against the distortions caused in the domestic economy caused by the tax or subsidy. For a small open economy, a clean subsidy sends only a very small

[15]This is observation is true in general and not specific to identical countries. An examination of the leakage rate in Equation 9 reveals that decreasing domestic market share will decrease the denominator of L_i, resulting in a higher leakage rate.

Figure 1: Optimal Tax-to-Subsidy Ratio as Country Size Decreases



price signal but sends this price signal to many countries. In fact, with identical countries, the decrease in worldwide production from a marginal increase in the clean subsidy in one country is the same whether the economy is open or closed. Moving to an open economy, the effect on the world price is $\frac{1}{N}$ times smaller than in the closed economy, but it is reduces pollution in N countries instead of just 1, exactly offsetting the smaller change in price.

Large open economies rely less on a clean subsidy than a small economy due to the larger relative significance of demand distortions in the local market. When a clean subsidy increases the production of clean good domestically, some of this additional production crowds out foreign dirty production, but some crowds out foreign clean production or induces increased consumption. Inducing additional domestic consumption is an additional (inefficient) distortion caused by an increase in clean production. This distortion is less important in small open economies than large open economies, making the clean subsidy slightly more effective in a small economy.

4 Differing Emissions Intensities

In the base model of Section 2, one unit of dirty production is assumed to produce one unit of pollution. This section relaxes that assumption, allowing for the realistic case where the rate of pollution created by dirty production differs between countries.

The emissions intensity in country i is normalized to one. This normalization means that γ_i is still interpreted as the value to country i from the reduction in pollution associated with

a one unit decrease in country i dirty production. The relative emissions intensity in country $n \neq i$, e_n, can be interpreted as the amount of pollution produced for one unit of country n dirty production relative to the amount of pollution created by one unit of country i dirty production.

The rate of leakage in country i will still be defined as the increase in foreign emissions per each unit of avoided domestic emissions associated with the domestic pollution tax. Accounting for differing emissions intensities, the leakage rate is given by Equation 16.

$$L_i := \frac{-\sum_{n \neq i} e_n \frac{\partial x_{n,d}}{\partial \tau_{i,d}}}{\frac{\partial x_{i,d}}{\partial \tau_{i,d}}} = \frac{\sum_{n \neq i} e_n x'_{n,d}}{\left[\sum_{n \neq i} x'_{n,d} + \sum_n x'_{n,c} - \sum_n x'_n\right]} \tag{16}$$

The leakage rate is very similar to the base model, except that it now depends on the relative emissions intensity of dirty production abroad. If domestic dirty production is much dirtier than abroad ($e_n << 1$) then foreign dirty production has only a minor impact on global pollution and the leakage rate will be close to zero. On the other hand, as the emissions intensity of domestic dirty production decreases relative to the emissions intensity abroad, the leakage rate will increase and is no longer bounded above by one. When the domestic emissions intensity is very low relative to abroad, a tax on dirty domestic production could increase worldwide pollution by increasing much higher emitting dirty production abroad.

The variability in the emissions intensities will affect the domestic policymaker's optimal policy. The policymaker still values a marginal unit of avoided pollution at γ_i, which means that the environmental welfare impacts of domestic and foreign dirty production will differ. The domestically optimal policy is given in Proposition 7.

Proposition 7. The optimal tax and subsidy rates for the policymaker in country i are

$$\tau_{i,d} = \gamma_i \left(1 - L_i \frac{1}{1 - \omega_i}\right)$$
$$\tau_{i,c} = -\gamma_i L_i \frac{1}{1 - \omega_i}$$

Proposition 7 looks identical to Proposition 5. The fact that emissions intensities can vary between countries is entirely captured by the effect of e_n on the marginal leakage rate, L_i. A higher foreign emissions intensity will increase the leakage rate, resulting in a lower optimal tax rate and a higher optimal subsidy rate. When the adjusted leakage rate is less than one, the qualitative results from Section 2 remain unchanged: openness to trade creates an incentive for the domestic policymaker to both subsidize clean production and tax dirty production, and the overall level of climate ambition remains constant.

4.1 Optimal Policy with Leakage Rates Greater than One

Unlike in the uniform emissions intensity case of Section 2, where $L_i \in [0, 1]$, the fact that the leakage rate can be greater than one has important implications for policy. Specifically, when the adjusted leakage rate is greater than one, it is optimal for the domestic policymaker to subsidize, rather than tax domestic dirty production.[16] Even though dirty production still produces a negative externality, a leakage rate greater than one implies that encouraging additional domestic dirty production will crowd out enough of the even dirtier foreign production to reduce global emissions in aggregate.

In this case, the optimal policy will still set a constant wedge between domestic clean and dirty producers equal to γ_i.

$$\tau_{i,d} - \tau_{i,c} = \gamma_i \tag{17}$$

However, because both policies are subsidies, the total policy ambition will no longer be constant, when policy ambition is defined as $|\tau_{i,d}| + |\tau_{i,c}|$. As the leakage rate continue to increase above one, the policymaker will further subsidize domestic dirty and clean production. Intuitively, if domestic dirty production has a much smaller emissions intensity than abroad, dirty production at home is not very dirty and both instruments work in the same way—increasing domestic production to crowd out dirtier foreign production.

It will always remain the case that the policymaker wants to incentivize domestic clean production more than domestic dirty production by γ_i dollars per unit. The normalization of the domestic emissions intensity is important for interpreting this wedge as γ_i is interpreted as the value of reduced pollution associated with one unit of *domestic* dirty production.

This finding remains consistent with the generalized targeting principle as formulated by Kopczuk (2003). The targeting principle implies that a Pigouvian-like tax should be applied to domestic dirty production exactly equal to the externality it causes. The Pigouvian component should be additive to any other tax policy objectives, which in this case are crowding out foreign dirty production that cannot be directly taxed. When the adjusted leakage term is greater than one, the incentive to crowd out foreign production is large enough that the optimal tax on dirty production is negative (a subsidy). The constant wedge between domestic dirty and clean production follows directly from the additive correction prescribed by the targeting principle.

[16] Jaqua and Schaffa (2022) show that in geneal, it can be optimal to subsidize harmful activities when the policymaker is constrained from implementing the first best Pigouvian tax.

5 Multi-Country Equilibrium

Section 2 discusses unilaterally optimal policies used to correct for a global pollutant if the policies abroad are held fixed. However, climate policies in different countries may be interdependent if one country's policy impacts the marginal effectiveness or costs of foreign policy. With a global pollutant, interdependence is especially important as environmental damages are determined by worldwide pollution. Ultimately, it is the policy rates set by each country in a multi-country equilibrium that are welfare relevant.

If domestic policy induces foreign countries to increase their policy ambition, this will produce first-order benefits through reduced world pollution. On the other hand, if domestic policy weakens the incentives for foreign countries to enact climate policy, and foreign jurisdictions reduce policy ambition in response to an increase in domestic policy, this will have first-order costs to domestic welfare. If pollution taxes and clean subsidies have different interaction effects on foreign policies, and result in different multi-country equilibrium, this will directly affect welfare.

This section analyzes the role of policy interdependence in the open economy policymaker's choice between a pollution tax and clean subsidy. If policy interdependence varies based on which tax instruments are used, this could meaningfully impact the policymaker's choice of policy instrument in a manner that is not captured in Section 2. In order to investigate this possibility, this section studies the properties of the multi-country equilibrium in a non-cooperative Nash policy game when each country either only uses a pollution tax, only uses a clean subsidy, or uses both a tax and subsidy.

Policy interdependence in a non-cooperative game is captured by the strategic complementarity or substitutability between climate policy at home and policy abroad. Politicians and the media have increasingly discussed the US, EU, and China as competing in a "clean subsidy war" or a "green tech race" (e.g. Podesta, 2024; Wallace-Wells, 2024; Brower, 2023). Implicit in this language is the idea that clean subsidies are strategic complements—increasing subsidy rates at home lead to increases in subsidy rates abroad, creating a "race-to-the-top" in clean subsidies.

The following analysis shows that if countries compete in a Nash game, the nature of the strategic complementarity will be the same for pollution taxes and clean subsidies. If clean subsidies are strategic complements, then pollution taxes will also be strategic complements. This suggests that policy interdependence is not a reason to prefer one particular tax or subsidy instrument over the other. Although the nature of these complementarities may be important for considering overall climate policy ambition, it should not affect the decisions between which tax instrument to use.

5.1 Setup of the Multi-Country Equilibrium

I analyze the choice of each country's tax and subsidy rates as a Nash game. Consider the market environment described in Section 2 and denote the policy instruments of country i to be $\vec{\tau_i} \in \{\{\tau_{i,d}\}, \{\tau_{i,c}\}, \{\tau_{i,d}, \tau_{i,c}\}\}$. The set of policy instruments available to all countries is given as $\vec{\tau} = \sum_i \vec{\tau_i}$ and characterize the environmental policy-setting game. Each country sets its own tax and subsidy rates $\vec{\tau_i}$ to maximize domestic welfare, taking the tax rates set by other countries as given. Although tax rates do not impact other countries' marginal incentives directly, they might do so through their effect on equilibrium prices and quantities. In this setup, the world price p and equilibrium quantities of consumption and clean and dirty production are all implicitly defined by world tax and subsidy rates $\vec{\tau}$. Country i's best response functions are given by the optimal tax expressions in Propositions 3, 4, and 5, depending on which taxing instruments are available to the policymaker.

A Nash Equilibrium is characterized by a set of tax rates, τ, such that the price of the tradable good $p(\tau)$ is set so that markets clear and $\vec{\tau_i}$ is a best response given the instruments available and the set of tax rates in the rest of the world, $\vec{\tau}_{-i}$. In the remainder of this section, I discuss the equilibrium properties under different assumptions allowing countries to optimize with different policy instruments. Specifically, I consider comparative statics to changes in the domestic cost of pollution γ_i and how this increase can affect policy rates at home and abroad. An increase in γ_i can be interpreted as the policymaker in country i valuing emissions reductions more, and will lead country i to undertake more ambitious climate policy.

Although the strategic complementarities will depend on the convexity of the best-response functions, the complementarity will be the same for the pollution-tax-only and clean-subsidy-only games. This suggests that the choice between a pollution tax and clean subsidy will not impact the policy ambition of the multi-country equilibrium policy rates. The remainder of the section first analyzes the pollution-tax-only and clean-subsidy-only games where all countries are restricted to only using a single instrument, before discussing the combined tax and subsidy game.

5.2 Single Policy Instrument Equilibrium

This subsection analyzes strategic complementarities in multi-country equilibrium where either all countries are restricted to only using a pollution tax or all countries are restricted to only using a clean subsidy. In the pollution-tax-only game, each country will set the domestic pollution tax according to Proposition 3 and will simply depend on the value of reduced emissions, γ_i, and the domestic leakage rate, L_i. In the clean-subsidy-only game,

each country will set subsidy rates according to Proposition 4. Equations 18 and 19 reproduce these equations written in terms of the slopes of the demand, clean supply, and dirty supply curves.

$$\tau_{i,d}^{\text{tax only}} = \gamma_i \left(1 - \frac{\sum_{n \neq i} x'_{n,d}}{\sum_{n \neq i} x'_{n,d} + \sum_n x'_{n,c} - \sum_n x'_n} \right) \tag{18}$$

$$\tau_{i,c}^{\text{subsidy only}} = -\gamma_i \left(\frac{\sum_n x'_{n,d}}{\sum_n x'_{n,d} + \sum_{n \neq i} x'_{n,c} - \sum_n x'_n} \right) \tag{19}$$

The slopes of the supply and demand curves are functions of the producer and consumer prices and $\gamma_i := \Gamma_i(\sum_n x_{n,d})$ is simply a function of total emissions. A domestic change to climate policy will therefore only affect the equilibrium climate policy abroad through a change in the world price or a change in the total quantity of global emissions.

The climate damage function, $\Gamma(\cdot)$, is often assumed to be either linear or convex. A linear climate damage function has a constant marginal damage parameter, γ_i, and therefore would imply that there are no policy interaction effects occurring through changing the total quantity of global emissions. Under this assumption, domestic policy will only affect policy abroad through a change in the global price.

However, if the damage function is convex, then a domestic increase in climate policy ambition will make the marginal damages less severe abroad, making equilibrium policy abroad less ambitious. This effect will be the same for both the pollution-tax-only game and the clean-subsidy-only game, pushing domestic and foreign policies towards strategic substitutes in either equilibrium set-up.

The policy interaction effects that occur through the world price could push domestic and foreign policy to either be strategic complements or strategic substitutes. To isolate this mechanism, the strategic complementarity can be calculated assuming the climate damage function is linear. These strategic complementarities between domestic and foreign policies are summarized in Table 2. The top row shows results for the pollution-tax-only game where each country optimizes using tax rates while the bottom row shows results from a clean-subsidy-only game where each country is restricted to only use a clean subsidy.

The three columns in table 2 show three cases with varying assumptions on the shapes of the demand and supply curves. For each case, the strategic complementarity is calculated for each game by considering the comparative statics for a small increase in the value of avoided pollution in country i, γ_i. An increase in γ_i will always increase the policy ambition in country i, but could either increase, decease, or not affect the policy ambition in country j. Derivations of the comparative statics are in Appendix B.

Table 2: Strategic Complementary Between Domestic and Foreign Climate Policy

	Case 1: Linear Supply and Demand	Case 2: Convex Demand	Case 3: Concave Demand
Pollution-tax-only game	No Interaction	Strategic Substitutes	Strategic Complements
Clean-subsidy-only game	No Interaction	Strategic Substitutes	Strategic Complements

Note: This table summarizes the strategic complementarities between domestic and foreign policy resulting from an exogenous increase in γ_i. The top row shows the case where each country only uses a pollution tax and the bottom row shows the case when each row only uses a clean subsidy. The increase in γ_i will always lead policy in country i to be more ambitious, but will have different effects on policy in country j. Policies are listed as strategic complements (substitutes) if policy j increases (decreases) in policy ambition when γ_i increases.

In Case 1, when supply and demand curves are linear, the slopes in Equations 18 and 19 will be constant and there will be no policy interaction effect. Increasing domestic policy ambition will not impact the marginal effectiveness or the marginal cost of environmental policy abroad, and the optimal policy rate abroad will remain unchanged. This is no longer true, when supply and demand curves are no longer linear, as changing policy in country i will impact the world price, which in turn will change the marginal leakage rate in country j. The nature of the policy interaction crucially depends on how the leakage rate abroad changes, which is determined by the convexity of the underlying supply and demand curves. Cases 2 and 3 show that allowing demand to be strictly convex or strictly concave will change the nature of the strategic complementarities.

Importantly, however, the sign of these policy interaction effects are the same within each column. Therefore, if pollution-taxes are strategic complements, it will also be the case that clean subsidies are strategic complements. This suggests that, although policy interaction effects are important for analyzing the level of policy ambition, they should not affect the choice of policy instruments.

5.3 Combined Tax and Subsidy Games

Finally, if all countries use both pollution taxes and clean subsidies, any policy interaction effects will simply shift whether the pollution tax or clean subsidy is emphasized rather than changing the overall level of policy ambition. This follow directly from Proposition 6 that

states that $\tau_{j,d} + |\tau_{j,c}| = \gamma_j$. Any policy spillover that increases the pollution tax rate abroad will necessarily reduce the clean subsidy rate abroad in order to hold γ_j constant.

The nature of this interaction will depend on the specific comparative statics examined. For example, considering an increase in γ_i, the effect on the world price and therefore the policy choices of countries abroad will depend on both on the comparative emphasis on taxes versus subsidies in country i, but also the supply slopes. The partial effect of an increase on γ_i on the equilibrium price is given as

$$\frac{\partial p}{\partial \gamma_i} = \frac{\partial p}{\partial \tau_{i,d}} \left(1 - \frac{\sum_{n \neq i} x'_{n,d}}{\sum_{n \neq i} x'_{n,d} + \sum_{n \neq i} x'_{n,c} - \sum_n x'_n} \right) - \frac{\partial p}{\partial \tau_{i,c}} \frac{\sum_{n \neq i} x'_{n,d}}{\sum_{n \neq i} x'_{n,d} + \sum_{n \neq i} x'_{n,c} - \sum_n x'_n}$$

It is therefore the case that increasing γ_i will increase p if and only if

$$\tau_{i,d} x'_{i,d} > \tau_{i,c} x'_{i,c}. \tag{20}$$

This effect on the price, p, is the mechanism through which there is policy interaction. In combination with the convexity of demand, the effect on p will determine if policy interactions make foreign jurisdictions shift towards tax rates or subsidy rates.

6 State-Level Electricity Policy Calibrations

This section illustrates important implications from the model by calibrating it to state-level electricity tax and subsidy policy in the United States. In the absence of federal policy, individual states setting uncoordinated climate policies face the same issues of pollution leakage and free-riding that individual countries do in a global market. Calibrating the state-level policy ratio under an assumption that there is no federal policy or coordination between states serves as an illuminating example for when an individual open-economy, be it a country or state, should rely more heavily on a pollution tax versus a clean subsidy.

Specifically, the geography of US electricity markets make state-level electricity policy a particularly useful example. The lower 48 states of the United States are composed of three different electricity grids (interconnections) that largely operate as independent markets, with almost no physical trade of electricity. These separate interconnections provide a natural side-by-side comparison to show how leakage rates and optimal policies for a particular state are determined primarily by the characteristics of the market rather than the characteristics of the state.

These calibrations are based on the model presented in Section 2, imposing strong assumptions on the nature of electricity markets. In addition to assuming that there is no interaction with federal policy and that previous state policies and regulations won't impact the policy ratio, these calibrations ignore justifications for taxes or subsidies based on political economy considerations, endogenous learning growth, or other market distortions. Nevertheless, the calibrations serve as an illustrative example as to how the market characteristics can influence the leakage rate and therefore the effectiveness of a pollution tax and clean subsidy through the mechanism discussed in this paper.

6.1 Brief Overview of Electricity Markets

The model is well suited for state electricity policy in many ways. Electricity can be produced from a number of different technologies with different pollution profiles associated with these technologies. Coal and natural gas production release greenhouse gas emissions (and local pollutants) while solar and wind power have close to zero direct emissions. However, once electricity is generated, it is impossible to tell which electrons were generated by clean versus dirty sources.

Furthermore, producers and consumers connected to the same grid interconnection largely operate as if in a single market where electricity generated in one location can easily be consumed elsewhere in the same interconnection.[17] In the United States, the lower 48 states are divided into three separate electric grid interconnections that largely operate as separate markets. Electricity generated in one part of an interconnection is a very close substitute for electricity generation elsewhere in the interconnection, but has only a minimal effect on incentives to generate electricity in the other interconnections. These features maps directly into the assumption of a homogeneous output where consumers do not distinguish output based on if it was produced domestically or abroad or by clean or dirty production processes.

Furthermore, states have been very active in passing both taxes on fossil fuel electricity generation and subsidies for renewable resources. Over thirty states have adopted renewable portfolio standards, mandating a share of their electricity come from renewable sources.[18] In addition, California, Washington, and several states in the Northeast (through the Regional Greenhouse Gas Initiative), have adopted fees on fossil fuel generated electricity (through cap and trade programs).[19] State level policies have been a significant share of the incentives

[17] Viewing an electric grid as a single market is, of course, a simplification that ignores electricity transmission constraints which can effectively fragment the grid into separate markets. However, for the long-run calibrations in this section, treating grid interconnections as a single homogeneous market is less problematic than a short-term analysis.

[18] https://www.ncsl.org/energy/state-renewable-portfolio-standards-and-goals

[19] https://www.c2es.org/document/us-state-carbon-pricing-policies/

faced by electric utilities and independent power producers (especially before the Inflation Reduction Act).

6.2 Instrument Choice in Electricity Markets

For each state, the optimal long run policy ratio can be calibrated from Equation 13. Doing so requires defining the geographic markets that electricity producers and consumers in each state belong to and calibrating the long-run price elasticities for the relevant market participants in the rest of the market. These calibrations define market geographies based on the major grid interconnections, and presents calibrations for states in the Eastern and Western Interconnection.[20]

With geographic markets defined, it is necessary to calibrate the relative slope of the long-run supply and demand curves.[21] Causally estimating long-run elasticities can be challenging in electricity markets as capital tends to be long lived, so relevant investment and production decisions are made based on expected prices and market conditions over 20-30 year time horizons rather than short-run price fluctuations. This is especially true for clean renewable energy sources that have high capital investment costs but near-zero marginal costs. Wind and solar supply is very inelastic to short-run changes in price but is much more responsive to longer run changes.

In order to overcome these obstacles, I estimate the relative slope of state-level clean and dirty supply curves, $x'_{i,c}/x'_{i,d}$, using the Renewable Energy Deployment System Model (ReEDS) published by the National Renewable Energy Laboratory.[22] ReEDS models the investment and production decisions of electricity generators in the United States, estimating the least-cost way of supplying sufficient electricity in each region, while accounting for a number of factors such as resource potential, transmission constraints, environmental regulations, and reliability concerns.

I estimate $x'_{i,c}/x'_{i,d}$ from ReEDS by considering changes in clean and dirty production under different scenarios for electricity demand. Intuitively, these estimates are based on whether a projected demand shock is met by increasing electricity from clean or dirty sources

[20] Figure D.1 shows a map of the three major interconnections in the lower 48 states. The Eastern Interconnection is made up of states east of the Rocky Mountains, excluding Texas, while the Western Interconnection is comprised of the Rocky Mountain and western states. Texas is largely its own interconnection and is ignored in this analysis as it is essentially a closed economy.

[21] Rather than calibrate elasticities and market shares, I calibrate relative slopes of the supply and demand curves directly. The equivalent version of Equation 13 is $\tau_{i,d}/\tau_{i,c} = -(\sum_{n\neq i} x'_{n,c} - \sum_n x'_n)/\sum_{n\neq i} x'_{n,d}$.

[22] ReEDS is a publicly available tool used by policymakers, grid planners, and market participants to estimate how changing market conditions will impact the total investment and production of electricity by different technologies through 2050. Although its predictions are forecasts, rather than observed data, it is a reasonable approximation of the information set energy developers and utilities use to make investment decisions.

of production. Additional details on the ReEDS model and the estimation of $x'_{i,c}/x'_{i,d}$ are discussed in Appendix C.

The ratio of the tax rate to subsidy rate also depends on ratio of the demand elasticity to the dirty supply elasticity. I calibrate this ratio to be zero, assuming that demand is perfectly inelastic. Although short run demand for electricity is often assumed to be perfectly inelastic, this is clearly not true for long run demand. This calibration may be reasonable if (dirty) supply remains much more elastic than demand, even in the long-run. However, the calibrated optimal policy ratio is best viewed as a lower bound on the relative use of the pollution tax, as increasing the demand elasticity will decrease the leakage rate, making a pollution tax more effective and a clean subsidy less effective.

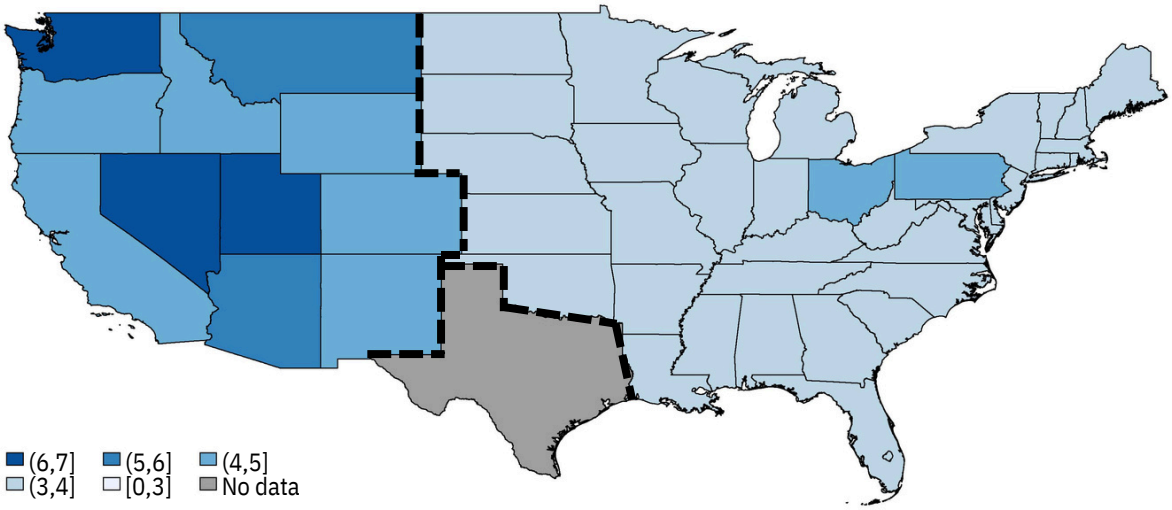
Figure 2 shows the optimal policy ratio for states in the eastern and western interconnections. The dotted black line indicates the approximate border of the interconnections used to assign states to separate markets.[23] States shaded in darker blue indicate that the optimal choice of instruments in those states relies more heavily on the pollution tax, while states shaded in lighter blue should rely less heavily on the pollution tax.[24] Note that the optimal mix of tax instruments is heavily favored to a pollution tax in all states. Even in the eastern states where the clean subsidy is relatively more effective, the optimal clean subsidy rate is only one third the tax rate on polluting production. On the other extreme, the calibrations suggest that the clean subsidy rate should be less than one sixth the pollution tax rate in Washington, Utah and Nevada.

The reliance on the pollution tax (even with inelastic demand) can be understood by considering the long run forecasts for electricity supply. Long-run forecasts suggest that the electric grid will be predominately supplied by clean sources in 2050 under current policy and technology assumptions, as shown in Figure D.2 in Appendix D. If the slope of the supply curve is proportional to market share, as is the case with constant-elasticity production, this suggests that clean production is relatively more responsive than dirty production to changes in price. This in turn implies the long-run leakage problem within an interconnection from imposing state-level pollution taxes should be minimal. Additional pollution taxes in a particular state will increase electricity prices, but if the grid is already expected to be predominately clean, this increase in price will likely simply induce more clean production rather than dirty production. Conversely, a clean subsidy that encourages in-state production

[23] As shown in Figure D.1, the interconnection boundaries do not perfectly coincide to state boundaries so I assign states to interconnections based on the market the majority of the state is in.

[24] The gray shading of Texas indicates there is no calibration available, since Texas has its own interconnection and is treated as a closed economy for this exercise. Without other states in the interconnection, there is no leakage associated with Texas state policy and the optimal state-level policy would be to only use a pollution tax, as discussed in Proposition 2.

Figure 2: Optimal State Level Electricity Tax to Subsidy Ratio ($\tau_{i,d}/\tau_{i,c}$)



of clean energy is likely to simply crowd-out out-of-state clean electricity production on a grid that is dominated by clean production.

The second takeaway from Figure 2 is that there are striking differences in the optimal instrument mix based on market. States in the Eastern Interconnection are all shaded much lighter blue than states in the Western Interconnection, with only one state in the East (Ohio) more reliant on a pollution tax than the least reliant state in the West (California). Intuitively, the policy ratio of a given state is dependent on the characteristics of the rest of the market (leaving out the "home" state). When there are many jurisdictions, leaving out one particular jurisdiction will only slightly modify the relative supply elasticities, and therefore the optimal policy ratios for jurisdictions in a large market should be relatively similar.

In addition, the fact that the west is more dependent on pollution taxes for future policy is consistent with differences in the current and predicted future profile of generation in each interconnection. Figure D.2 in Appendix D illustrates that clean electricity generators have a higher market share in the Western Interconnection than in the East, and this is expected to remain the case through 2050. On a cleaner grid, price changes are more likely to induce changes in clean rather than dirty production. This suggests that in the relatively cleaner Western Interconnection, leakage is likely less of an issue for pollution taxes and clean subsidies are likely to crowd out other clean production rather than dirty production.

7 Conclusion

National and subnational governments setting climate policies have used both clean subsidies and pollution taxes to correct for greenhouse gas emissions, despite the widespread advocacy for pollution taxes from economists. Although the use of clean subsidies can be rationalized if other market imperfections are present, the classic "targeting principle" of optimal taxation suggests that a policymaker in a closed economy should correct for an environmental externality with a direct tax on pollution and that a clean subsidy is of no use. However, an open economy limits the taxing jurisdiction of an individual policymaker, making the targeting principle no longer directly applicable.

This paper demonstrates that openness to trade creates an economic rationale for clean subsidies to supplement pollution taxes, even when markets are perfectly competitive and no other externalities or frictions are present. The optimal environmental policy of an open economy uses both a pollution tax and a clean subsidy, with the relative importance of each policy determined by the marginal rate of pollution leakage. Furthermore, this paper shows that the policy ambition is invariant to the degree of leakage. This implies that a higher pollution leakage rate should not discourage climate policy generally, but instead shift some of the reliance from a pollution tax to a clean subsidy.

Finally, it has been suggested the subsidies may induce "clean subsidy races," potentially serving as a mechanism to overcome free-riding in climate policy. The analysis of multi-country Nash games suggest that, under perfect competition, the policy interaction effects for clean subsidies and pollution taxes should be similar. Conditions that would lead to a clean subsidy race to the top would also lead to a carbon tax race to the top, suggesting that while policy interactions are important for analyzing the level of policy ambition, these effects do not influence the efficient choice of policy instruments.

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A Model Extensions

A.1 Border Carbon Adjustments

I allow the social planner to additionally impose a tax on consumption of the tradable good. Taxing both consumption and production can be used to recreate the incentives of a border tax (as pointed out by Böhringer, Rosendahl and Storrøsten (2017) and Weisbach et al. (2023) in the context of pollution leakage). I add a consumption tax, t_i, to the baseline model and allow the policymaker to jointly optimize production taxes on clean and dirty production and consumption of the tradable good. Doing so is akin to extending the analysis of Weisbach et al. (2023) to allow a clean substitute good with a subsidy.

The consumer problem is only slightly altered to include a tax t_i on the tradable good x_i. The consumer's problem is now

$$\begin{aligned} &\max_{x_i, z_i} U_i(x_i, z_i) \\ &\qquad \text{s.t. } y_i + \pi_i = (p + t_i)x_i + z_i \end{aligned}$$

The firms' problems are unchanged and market clearing condition is unchanged as well. The domestic policymaker jointly optimizes $\tau_{i,d}$, $\tau_{i,c}$, and t_i. The optimal tax and subsidy rates are given by Proposition 8.

Proposition 8. A domestic policymaker using a pollution tax, clean subsidy, and consumer tax will set tax and subsidy rates as follows:

$$\begin{aligned} \tau_{i,d} &= \gamma_i \left(1 - L_i \frac{1}{1 - \omega_i^{bca}}\right) \\ \tau_{i,c} &= -\gamma_i L_i \frac{1}{1 - \omega_i^{bca}} \\ t_i &= \gamma_i L_i \frac{1}{1 - \omega_i^{bca}} \end{aligned}$$

where $\omega_i^{bca} = \frac{\alpha_{i,c}\eta_{i,c} - \beta_i \zeta_i}{\sum_{n \neq i} \alpha_{n,d}\eta_{n,d} + \sum_n \alpha_{n,c}\eta_{n,c} - \sum_n \beta_n \zeta_n}$.

A few notes are worth making. First, even with the tax on consumption serving as a way to control for leakage (and a way to compare to a BCA), there is still a role for the clean subsidy to discourage foreign production. In fact, the expression for the clean subsidy is largely unchanged from the baseline model (with the only difference being the baseline model included a term for x_i' in the denominator).

Second, instead of only taxing dirty production at γ_i, the tax is divided between $\tau_{i,d}$ and

t_i, but it remains true that $\tau_{i,d} + t_i = \gamma_i$. This is the insight from Weisbach et al. (2023), that it is optimal to divide the Pigouvian tax between upstream production and downstream consumption. This is clearly seen if clean production is perfectly inelastic ($\eta_{n,c} = 0$), in which case these results mirror the results of Weisbach et al. (2023). This insight does not negate the use of a clean subsidy, nor does it depend on a subsidy not being present.

B Proofs

B.1 Proof of Proposition 1

The social planner sets tax rates and subsidy rates in each country to maximize the sum of world welfare.

$$\max_{\{\tau_{i,c},\tau_{i,d}\,\forall i\}} \sum_{n=1}^{N} \Bigg(\max_{x_n,z_n} \left[u_n(x_n,z_n) + \mu_n\left(y_n + T_n - px_n - z_n\right)\right] + \mu_n \left(\max_{x_{n,c},x_{n,d}} \left[(p-\tau_{n,c})x_{n,c} - C_{n,c}(x_{n,c}) + (p-\tau_{n,d})x_{n,d} - C_{n,d}(x_{n,d})\right] \right) + \lambda_n(x_{i,c}\tau_{i,c} + x_{i,d}\tau_{i,d}) - \Gamma_n(\sum_{m=1}^{N} x_{m,d}) \Bigg)$$

Differentiating with respect to $\tau_{i,c}$ and $\tau_{i,d}$, the social planner's first order conditions are

$$\begin{aligned}
\frac{\partial W}{\partial \tau_{i,c}} =& \frac{\partial p}{\partial \tau_{i,c}} \sum_{n=1}^{N} \left[\mu_n\left(x_{n,c} + x_{n,d} - x_n\right)\right] + \sum_{n=1}^{N} \left[\lambda_n \left(\tau_{n,c}\frac{\partial x_{n,c}}{\partial \tau_{i,c}} + \tau_{n,d}\frac{\partial x_{n,d}}{\partial \tau_{i,c}}\right)\right] + \\
& (\lambda_i - \mu_i)x_{i,c} - \sum_{n=1}^{N} \Gamma'_n(\sum_{m=1}^{N} x_{m,d}) \sum_{m=1}^{N} \frac{\partial x_{m,d}}{\partial \tau_{i,c}} = 0 \\
\frac{\partial W}{\partial \tau_{i,d}} =& \frac{\partial p}{\partial \tau_{i,d}} \sum_{n=1}^{N} \left[\mu_n\left(x_{n,c} + x_{n,d} - x_n\right)\right] + \sum_{n=1}^{N} \left[\lambda_n \left(\tau_{n,c}\frac{\partial x_{n,c}}{\partial \tau_{i,d}} + \tau_{n,d}\frac{\partial x_{n,d}}{\partial \tau_{i,d}}\right)\right] + \\
& (\lambda_i - \mu_i)x_{i,d} - \sum_{n=1}^{N} \Gamma'_n(\sum_{m=1}^{N} x_{m,d}) \sum_{m=1}^{N} \frac{\partial x_{m,d}}{\partial \tau_{i,d}} = 0
\end{aligned}$$

If the social planner can provide lump sum transfers between countries or values welfare equally between countries $\mu_n = \mu_m$ and $\sum_{n=1}^{N} \left[\mu_n\left(x_{n,c} + x_{n,d} - x_n\right)\right] = 0$. Similarly, if the social planner ignores within country distribution consequences (or has separate instruments available to correct these distortions), $\lambda_i = \mu_i = 1$. Under these conditions, the social planner sets optimal tax and subsidy rates to trade-off the marginal *global* benefits of reduced environmental pollution against the marginal *global* inefficiency caused by each tax/subsidy rate (captured by marginal fiscal externalitites).

The optimal tax and subsidy rates are characterized by

$$\sum_{n=1}^{N}\left[\lambda_n\tau_{n,c}\frac{\partial x_{n,c}}{\partial\tau_{i,d}}+(\lambda_n\tau_{n,d}-\gamma^*)\frac{\partial x_{n,d}}{\partial\tau_{i,d}}\right]=0$$
$$\sum_{n=1}^{N}\left[\lambda_n\tau_{n,c}\frac{\partial x_{n,c}}{\partial\tau_{i,c}}+(\lambda_n\tau_{n,d}-\gamma^*)\frac{\partial x_{n,d}}{\partial\tau_{i,c}}\right]=0$$

for all countries i. These first order conditions are satisfied for all i if $\tau_{i,d}=\frac{\gamma^*}{\lambda_i}$ and $\tau_{i,c}=0$, a direct application of the targeting principle.

B.2 Proof of Corollary 1

Proof. Following the Proof of Proposition 1, when $\tau_{i,d}=0$ for all countries i, the optimal subsidy rates are characterized by

$$\frac{\partial W}{\partial\tau_{i,c}}=\sum_{n=1}^{N}\left(\lambda_n\tau_{n,c}\frac{\partial x_{n,c}}{\partial\tau_{i,c}}\right)-\sum_{n=1}^{N}\Gamma'_n(\sum_{m=1}^{N}x_{m,d})\sum_{m=1}^{N}\frac{\partial x_{m,d}}{\partial\tau_{i,c}}=0.$$

The optimal subsidy rates are therefore defined by

$$\underbrace{\begin{pmatrix}\frac{\partial x_{1,c}}{\partial\tau_{1,c}} & \dots & \frac{\partial x_{N,c}}{\partial\tau_{1,c}}\\ \dots & \dots & \dots\\ \frac{\partial x_{1,c}}{\partial\tau_{N,c}} & \dots & \frac{\partial x_{N,c}}{\partial\tau_{N,c}}\end{pmatrix}}_{\text{Behavioral Response (B)}}\begin{pmatrix}\tau_{1,c}\\ \dots\\ \tau_{N,c}\end{pmatrix}=\gamma^*\begin{pmatrix}\sum_n\frac{\partial x_{n,d}}{\partial\tau_{1,c}}\\ \dots\\ \sum_n\frac{\partial x_{n,d}}{\partial\tau_{N,c}}\end{pmatrix}\tag{21}$$

Inverting matrix B therefore solves for the optimal subsidy rates. To invert B, note that $\frac{\partial x_{i,c}}{\partial\tau_{j,c}}=x'_{i,c}\cdot\left(\frac{\partial p}{\partial\tau_{j,c}}-\mathbb{1}_{i=j}\right)$ and B can therefore be written as

$$B=\underbrace{\begin{pmatrix}-x'_{1,c} & 0 & \dots & 0\\ 0 & -x'_{2,c} & \dots & 0\\ \dots & \dots & \dots & \dots\\ 0 & 0 & \dots & -x'_{N,c}\end{pmatrix}}_{\text{A}}+\underbrace{\begin{pmatrix}\frac{\partial p}{\partial\tau_{1,c}}\\ \dots\\ \frac{\partial p}{\partial\tau_{N,c}}\end{pmatrix}}_{u}\underbrace{\begin{pmatrix}x'_{1,c}\\ \dots\\ x'_{N,c}\end{pmatrix}^T}_{v}$$

From the Sherman-Morrison formula,

$$B^{-1} = A^{-1} - \frac{A^{-1}uv^TA^{-1}}{1 + v^TA^{-1}u}$$

Note that

$$A^{-1}uv^TA^{-1} = \frac{1}{\sum_n \left(x'_{n,d} + x'_{n,c} - x'_n\right)} J_N$$
$$1 + v^TA^{-1}u = 1 - \sum_n \frac{\partial p}{\partial \tau_{n,c}}$$

where J_N is the N x N matrix of ones.

Therefore solving for the τ vector and evaluating B^{-1} in Equation 21, the optimal subsidy rate for country i, $\tau_{i,c}$ is given by

$$\begin{aligned}
\tau_{i,c} &= -\gamma^* \left(\frac{\sum_n \frac{\partial x_{n,d}}{\partial \tau_{i,c}}}{x'_{i,c}} + \frac{1}{1 - \sum_n \frac{\partial p}{\partial \tau_{n,c}}} \frac{\sum_j \sum_n \frac{\partial x_{n,d}}{\partial \tau_{j,c}}}{\sum_n \left(x'_{n,d} + x'_{n,c} - x'_n\right)} \right) \\
&= -\gamma^* \left(\frac{\sum_n x'_{n,d} \frac{\partial p}{\partial \tau_{i,c}}}{x'_{i,c}} + \frac{1}{1 - \sum_n \frac{\partial p}{\partial \tau_{n,c}}} \frac{\sum_j \left[\sum_n x'_{n,d} \frac{\partial p}{\partial \tau_{j,c}}\right]}{\sum_n \left(x'_{n,d} + x'_{n,c} - x'_n\right)} \right) \\
&= -\gamma^* \left(\frac{\sum_n x'_{n,d}}{\sum_n \left(x'_{n,d} + x'_{n,c} - x'_n\right)} \left(1 + \frac{\sum_j \frac{\partial p}{\partial \tau_{j,c}}}{1 - \sum_n \frac{\partial p}{\partial \tau_{n,c}}}\right) \right) \\
&= -\gamma^* \left(\frac{\sum_n x'_{n,d}}{\sum_n \left(x'_{n,d} + x'_{n,c} - x'_n\right)} \left(\frac{1}{1 - \sum_n \frac{\partial p}{\partial \tau_{n,c}}}\right) \right) \\
&= -\gamma^* \left(\frac{\sum_n x'_{n,d}}{\sum_n \left(x'_{n,d} + x'_{n,c} - x'_n\right) - \sum_n x'_{n,c}} \right) \\
&= -\gamma^* \left(\frac{\sum_n x'_{n,d}}{\sum_n \left(x'_{n,d} - x'_n\right)} \right)
\end{aligned}$$

□

B.3 Proof of Proposition 2

In a closed economy, when $\lambda_i = 1$, the policymakers' first order conditions for the combined tax and subsidy rates are given by

$$\underbrace{\begin{pmatrix} \frac{\partial x_{i,d}}{\partial \tau_{i,d}} & \frac{\partial x_{i,c}}{\partial \tau_{i,d}} \\ \frac{\partial x_{i,d}}{\partial \tau_{i,c}} & \frac{\partial x_{i,c}}{\partial \tau_{i,c}} \end{pmatrix}}_{\text{Behavioral Response (B)}} \begin{pmatrix} \tau_{i,d} \\ \tau_{i,c} \end{pmatrix} = \gamma_i \begin{pmatrix} \sum_{n=1}^{N} \frac{\partial x_{n,d}}{\partial \tau_{i,d}} \\ \sum_{n=1}^{N} \frac{\partial x_{n,d}}{\partial \tau_{i,c}} \end{pmatrix}$$

As there is no trade, the domestic market will not affect prices abroad, and changes in $\tau_{i,d}$ and $\tau_{i,c}$ will only impact $x_{i,d}$ and $x_{i,c}$. Dirty production abroad is therefore taken as given and $\sum_{n=1}^{N} \frac{\partial x_{n,d}}{\partial \tau_{i,d}} = \frac{\partial x_{i,d}}{\partial \tau_{i,d}}$. The first order equations are therefore given as

$$\underbrace{\begin{pmatrix} \frac{\partial x_{i,d}}{\partial \tau_{i,d}} & \frac{\partial x_{i,c}}{\partial \tau_{i,d}} \\ \frac{\partial x_{i,d}}{\partial \tau_{i,c}} & \frac{\partial x_{i,c}}{\partial \tau_{i,c}} \end{pmatrix}}_{\text{Behavioral Response (B)}} \begin{pmatrix} \tau_{i,d} \\ \tau_{i,c} \end{pmatrix} = \gamma_i \begin{pmatrix} \frac{\partial x_{i,d}}{\partial \tau_{i,d}} \\ \frac{\partial x_{i,d}}{\partial \tau_{i,c}} \end{pmatrix}$$

By inspection, this condition is satisfied if $\tau_{i,d} = \gamma_i$ and $\tau_{i,c} = 0$.

B.4 Proof of Corollary 2

When the pollution tax is constrained to be zero, the first order condition for the subsidy is given by

$$\tau_{i,c} \frac{\partial x_{i,c}}{\partial \tau_{i,c}} = \gamma_i \frac{\partial x_{i,d}}{\partial \tau_{i,c}}.$$

In the closed economy, markets clear domestically so $\frac{\partial p}{\partial \tau_{i,c}} = \frac{x'_{i,c}}{x'_{i,c} + x'_{i,d} - x'_i}$. Substituting in $\frac{\partial x_{i,c}}{\partial \tau_{i,c}} = x'_{i,c} \cdot \left(\frac{\partial p}{\partial \tau_{i,c}} - 1 \right)$, $\frac{\partial x_{i,d}}{\partial \tau_{i,c}} = x'_{i,d} \cdot \frac{\partial p}{\partial \tau_{i,c}}$ and the expression for $\frac{\partial p}{\partial \tau_{i,c}}$ proves the Corollary.

B.5 Derivation of Equation 8

In order to derive the open economy policymakers' first order condition for tax instrument $\tau_{i,k}$ on quantity $x_{i,k}$ consider the policymaker's objective function. If the policymaker uses

the set of tax instruments $\vec{\tau}_i$, their maximization problem is

$$\max_{\vec{\tau}} \Bigg\{ \max_{x_i, z_i} \left[U_i(x_i, z_i) + \mu_i(y_i + \pi_i - p x_i - z_i) \right] - \Gamma_i \left(\sum_{n=1}^{N} x_{n,d} \right) + \nu_i \Bigg(\pi_i - \max_{x_{i,c}} \left[(p - \tau_{i,c}) x_{i,c} - C_{i,c}(x_{i,c}) \right] - \max_{x_{i,d}} \left[(p - \tau_{i,d}) x_{i,d} - C_{i,d}(x_{i,d}) \right] \Bigg) + \lambda_i \left(\vec{x} \cdot \vec{\tau} \right) \Bigg\}$$

Differentiating with respect to $\tau_{i,k}$ and making use of the envelope theorem, leads to $\nu_i = -\mu_i$ and therefore to

$$\lambda_i \vec{\tau_i} \cdot \frac{\partial \vec{x}}{\partial \tau_{i,k}} = \gamma_i \frac{\partial \sum_n x_{n,d}}{\partial \tau_{i,k}} + \frac{\partial p}{\partial \tau_{i,k}} \left(x_{i,d} + x_{i,c} - x_i \right) + \left(\lambda_i - 1 \right) x_{i,k}$$

B.6 Derivation of Equation 9

By definition, the marginal leakage rate is given as

$$L_i := \frac{-\sum_{n \neq i} \frac{\partial x_{n,d}}{\partial \tau_{i,d}}}{\frac{\partial x_{i,d}}{\partial \tau_{i,d}}}$$

Noting that $\tau_{i,d}$ only affects pollution abroad through its effect on the output price, this equation can be rewritten as

$$L_i = \frac{-\sum_{n \neq i} x'_{n,d} \frac{\partial p}{\partial \tau_{i,d}}}{x'_{i,d} \left(\frac{\partial p}{\partial \tau_{i,d}} - 1 \right)} = \frac{-\sum_{n \neq i} x'_{n,d} \cdot \frac{x'_{i,d}}{\sum_n \left(x'_{n,d} + x'_{n,c} - x'_n \right)}}{x'_{i,d} \frac{-\left(\sum_{n \neq i} x'_{n,d} + \sum_n x'_{n,c} - \sum_n x'_n \right)}{\sum_n \left(x'_{n,d} + x'_{n,c} - x'_n \right)}} = \frac{\sum_{n \neq i} x'_{n,d}}{\sum_{n \neq i} x'_{n,d} + \sum_n x'_{n,c} - \sum_n x'_n}.$$

Rewriting the slopes of the supply and demand curves in terms or elasticities yields equation 9.

B.7 Proof of Proposition 3

Under Assumptions 1 and 2 the optimal tax rate is given by

$$\tau_{i,d} \frac{\partial x_{i,d}}{\partial \tau_{i,d}} = \gamma_i \frac{\partial \sum_n x_{n,d}}{\partial \tau_{i,d}}$$

Noting that $\frac{\partial x_{i,d}}{\partial \tau_{i,d}} = x'_{i,d} \cdot (\frac{\partial p}{\partial \tau_{i,d}} - 1)$ and $\frac{\partial x_{n,d}}{\partial \tau_{i,d}} = x'_{n,d} \cdot \frac{\partial p}{\partial \tau_{i,d}}$ for $n \neq i$, the optimal tax rate is given by

$$\tau_{i,d} = \gamma_i \left(1 - \frac{\frac{\partial p}{\partial \tau_{i,d}}}{1 - \frac{\partial p}{\partial \tau_{i,d}}} \frac{\sum_{n \neq i} x'_{n,d}}{x'_{i,d}} \right).$$

Substituting in the expression for $\frac{\partial p}{\partial \tau_{i,d}}$ from Equation 5 proves the Proposition.

B.8 Proof of Proposition 4

Under Assumptions 1 and 2 the optimal tax/subsidy rate on the clean good is given by

$$\tau_{i,c} \frac{\partial x_{i,c}}{\partial \tau_{i,c}} = \gamma_i \frac{\partial \sum_n x_{n,d}}{\partial \tau_{i,c}}.$$

Noting that $\frac{\partial x_{i,c}}{\partial \tau_{i,c}} = x'_{i,c} \cdot (\frac{\partial p}{\partial \tau_{i,c}} - 1)$ and $\frac{\partial x_{n,d}}{\partial \tau_{i,c}} = x'_{n,d} \cdot \frac{\partial p}{\partial \tau_{i,c}}$, the optimal (subsidy) rate is given by

$$\tau_{i,c} = -\gamma_i \left(\frac{\frac{\partial p}{\partial \tau_{i,c}}}{1 - \frac{\partial p}{\partial \tau_{i,c}}} \frac{\sum_n x'_{n,d}}{x'_{i,c}} \right).$$

Substituting in the expression for $\frac{\partial p}{\partial \tau_{i,d}}$ from Equation 5 proves the Proposition.

B.9 Proof of Proposition 5

When $\vec{\tau_i} = \{\tau_{i,d}, \tau_{i,c}\}$, and Assumptions 1 and 2 hold, the first order conditions from Equation 8 imply an interior solution satisfies

$$\underbrace{\begin{pmatrix} \frac{\partial x_{i,d}}{\partial \tau_{i,d}} & \frac{\partial x_{i,c}}{\partial \tau_{i,d}} \\ \frac{\partial x_{i,d}}{\partial \tau_{i,c}} & \frac{\partial x_{i,c}}{\partial \tau_{i,c}} \end{pmatrix}}_{\text{Behavioral Response (B)}} \begin{pmatrix} \tau_{i,d} \\ \tau_{i,c} \end{pmatrix} = \gamma_i \begin{pmatrix} \sum_{n=1}^{N} \frac{\partial x_{n,d}}{\partial \tau_{i,d}} \\ \sum_{n=1}^{N} \frac{\partial x_{n,d}}{\partial \tau_{i,c}} \end{pmatrix} \tag{22}$$

The optimal tax and subsidy rates are therefore

$$\begin{pmatrix} \tau_{i,d} \\ \\ \tau_{i,c} \end{pmatrix} = \gamma_i B^{-1} \begin{pmatrix} \sum_{n=1}^{N} \frac{\partial x_{n,d}}{\partial \tau_{i,d}} \\ \\ \sum_{n=1}^{N} \frac{\partial x_{n,d}}{\partial \tau_{i,c}} \end{pmatrix} \tag{23}$$

To analytically invert matrix B, note that each element in B can be decomposed into the wedge between the producer price and world price and changes to the world price. B can be written as

$$B = \begin{pmatrix} x'_{i,d}\left(\frac{\partial p}{\partial \tau_{i,d}} - 1\right) & x'_{i,c}\frac{\partial p}{\partial \tau_{i,d}} \\ x'_{i,d}\frac{\partial p}{\partial \tau_{i,c}} & x'_{i,c}\left(\frac{\partial p}{\partial \tau_{i,c}} - 1\right) \end{pmatrix} = \begin{pmatrix} -x'_{i,d} & 0 \\ 0 & -x'_{i,c} \end{pmatrix} + \begin{pmatrix} \frac{\partial p}{\partial \tau_{i,d}} \\ \frac{\partial p}{\partial \tau_{i,c}} \end{pmatrix} \begin{pmatrix} x'_{i,d} \\ x'_{i,c} \end{pmatrix}^T$$

With this decomposition of B, B^{-1} can be calculated with the Sherman-Morrison formula as

$$B^{-1} = A^{-1} - \frac{A^{-1}uv^T A^{-1}}{1 + v^T A^{-1} u}$$

where

$$A = \begin{pmatrix} -x'_{i,d} & 0 \\ \\ 0 & -x'_{i,c} \end{pmatrix}; \qquad u = \begin{pmatrix} \frac{\partial p}{\partial \tau_{i,d}} \\ \\ \frac{\partial p}{\partial \tau_{i,c}} \end{pmatrix}; \qquad v = \begin{pmatrix} x'_{i,d} \\ \\ x'_{i,c} \end{pmatrix}.$$

The optimal tax rates are therefore

$$\begin{aligned} \begin{pmatrix} \tau_{i,d} \\ \\ \tau_{i,c} \end{pmatrix} = \gamma_i & \begin{pmatrix} -\frac{1}{x'_{i,d}} & 0 \\ 0 & -\frac{1}{x'_{i,c}} \end{pmatrix} \begin{pmatrix} -x'_{i,d} + \sum_{n=1}^{N} x'_{n,d}\frac{\partial p}{\partial \tau_{i,d}} \\ \\ \sum_{n=1}^{N} x'_{n,d}\frac{\partial p}{\partial \tau_{i,c}} \end{pmatrix} \\ & - \gamma_i \left(\frac{1}{\sum_{n \neq i} x'_{n,d} + \sum_{n \neq i} x'_{n,c} - \sum_n x'_n} \right) \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} -x'_{i,d} + \sum_n (x'_{n,d}\frac{\partial p}{\partial \tau_{i,d}}) \\ \sum_n (x'_{n,d}\frac{\partial p}{\partial \tau_{i,c}}). \end{pmatrix} \end{aligned}$$

Substituting in the expression for the change in the price level given by Equation 5 and simplifying proves Proposition 5.

B.10 Proof of Multi-Country Comparative Statics

Consider a pollution tax game where countries use pollution taxes to correct for the externality. The Nash Equilibrium is a set of tax rates $\vec{\tau}$ such that market clearing holds and each country's tax rate represents their optimal tax rate, given the tax rates (and therefore subsequent equilibrium prices and quantities and elasticities) set by foreign countries. Nash Equilibirum is therefore characterize by the following set of $f_1, f_2, ...f_n$ where

$$f_i: \ \gamma_i \left(1 - \frac{\sum_{j \neq i} x'_{j,d}(p(\vec{\tau}) - \tau_{j,d}))}{\sum_{j \neq i} x'_{j,d}(p(\vec{\tau}) - \tau_{j,d})) + \sum_j x'_{j,c}(p(\vec{\tau}) - \tau_{j,c})) - \sum_j x'_j(p(\vec{\tau}))}\right) - \tau_{i,d}$$

Consider the comparative statics for if country i ups their ambition of their climate policy γ_i, perhaps because new science reveals that the global pollutant will impose larger damages. The comparative statics are given by the implicit function theorem

$$\frac{\partial \vec{\tau}}{\partial \gamma_i} = -[J_{f,\tau}]^{-1} J_{f,\gamma_i}$$

where $J_{f,\tau}$ is an n x n matrix where element i, j is $\frac{\partial f_i}{\partial \tau_{j,d}}$ and J_{f,γ_i} is an n x 1 vector. Under linear supply and convex demand,

$$\frac{\partial f_i}{\partial \tau_{j,d}} = -\gamma_i \frac{\sum_{j \neq i} x'_{j,d}}{(\sum_{j \neq i} x'_{j,d} + \sum_j x'_{j,c} - \sum_j x'_j)^2} \left(\sum_j x''_j\right) \frac{\partial p}{\partial \tau_{j,d}} - \mathbb{1}_{i=j} \tag{24}$$

Therefore

$$J_{f,\tau} = u \ v^T - I_N \tag{25}$$

where I_n is the n x n identity matrix and u and v are N dimensional vectors with elements n given by

$$u_n = \gamma_n \frac{-\sum_{j \neq n} x'_{j,d} \sum_j x''_j}{(\sum_{j \neq n} x'_{j,d} + \sum_j x'_{j,c} - \sum_j x'_j)^2} \tag{26}$$

$$v_n = \frac{\partial p}{\partial \tau_{n,d}} \tag{27}$$

The inverse of $J_{f,\tau}$ can therefore be computed using the Sherman-Morrison formula

$$[J_{f,\tau}]^{-1} = (-I_N)^{-1} - \frac{(-I_N)^{-1}uv^t(-I_N)^{-1}}{1+v^t(-I_N)^{-1}u} = (-I_N) - \frac{uv^t}{1+v^t(-I_N)u} \tag{28}$$

Looking first at the denominator, $1+v^t(-I_N)u$. We know that $-I_N u$ is an N x 1 vector with n^{th} element given by

$$\gamma_n \frac{\sum_{j\neq n} x'_{j,d} \sum_j x''_j}{(\sum_{j\neq n} x'_{j,d} + \sum_j x'_{j,c} - \sum_j x'_j)^2}$$

so

$$\begin{aligned} D :=& 1 + v^t(-I_N)u \\ =& 1 + \sum_{n=1}^{N} \left(\frac{\gamma_n \sum_{j\neq n}(x'_{j,d})x'_{n,d}}{(\sum_{j\neq n} x'_{j,d} + \sum_j x'_{j,c} - \sum_j x'_j)^2} \right) \frac{\sum_j x''_j}{\sum_j (x_{j,d} + x'_{j,c} - x'_j)} \end{aligned} \tag{29}$$

The (i,j) element of $[J_{f,\tau}]^{-1}$ is therefore

$$\frac{\gamma_n}{D} \frac{x'_{j,d} \sum_{n\neq i} x'_{n,d} \sum_n x''_n}{(\sum_{n\neq i} x'_{n,d} + \sum_n x'_{n,c} - \sum_n x'_n)^2 (\sum_n x'_{n,d} + \sum_n x'_{n,c} - \sum_n x'_n)} - \mathbb{1}_{i=j}$$

Now consider the comparative statics for an increase in γ_i. $[J_{f,\gamma_i}]$ is an n dimension where the i^{th} element is given by $\frac{\partial f_i}{\partial \gamma_i}$.

This increase will impact the Nash equilibrium tax rates as follows:

$$\begin{aligned} \frac{\partial \tau_{j,d}}{\partial \gamma_i} = & \left(\mathbb{1}_{i=j} - \frac{\gamma_n}{D} \frac{x'_{j,d} \sum_{n\neq i} x'_{n,d} \sum_n x''_n}{(\sum_{n\neq i} x'_{n,d} + \sum_n x'_{n,c} - \sum_n x'_n)^2 (\sum_n x'_{n,d} + \sum_n x'_{n,c} - \sum_n x'_n)} \right) \\ & \left(1 - \frac{\sum_{j\neq i} x'_{j,d}}{\sum_{j\neq i x'_{j,d}} + \sum_j x'_{j,c} - \sum_j x'_j} \right) \end{aligned}$$

Therefore for $\sum_n x''_n > 0$, then $\frac{\partial \tau_{j,d}}{\partial \gamma_i} \leq 0$ for $j \neq i$.

C US State Electricity Calibrations

C.1 Background of ReEDS

The National Renewable Energy Lab's Regional Energy Deployment System Model (ReEDS) is an electricity production and capacity expansion model designed to model electricity production and investment in generation capacity across different technology types and locations. Supply and demand are modeled for 134 different geographic balancing authorities and at 17 different time slices per year meant to capture geographic, diurnal and seasonal variations in demand and supply patterns (Ho et al., 2021). Supply is modeled as a detailed cost-minimization problem where regional investments in generating capacity and transmission networks are made along with production decisions, such that there is sufficient supply to meet demand in all time periods and all geographies. In addition, a number of additional technical system constraints are imposed to better match the model with constraints faced by grid planners, such as planning reserve constraints, maximum/minimum operating constraints, and transmission constraints, to name a few (Ho et al., 2021).

The ReEDS model solves for minimum cost investment and production decisions based, in part, on a number of exogenous variables. These exogenous variables include technological improvements, residential PV, electricity policy, and end use residential electricity demand (Gagnon et al., 2024). In addition, a separate demand module can optionally be turned on or off allowing demand to either be fully exogenous or endogenously respond. In the 2023 scenario analysis, the model is solved under a variety of assumed values for the exogenous variables. For the policy calibrations, I use the mid-case scenario along with the High Demand Growth scenario, which maintains the same assumptions expect for assuming a higher growth rate for electricity demand.

C.2 Estimation of Relative Supply Responses

The ReEDS model publishes the model predicted total quantity of electricity generated by each technology type in each state through 2050. However, it does not publish electricity prices or explicitly state a price elasticity. In order to get around this, I will take advantage of the fact that ReEDS publishes output under a range of different model assumptions and the fact that the optimal tax and subsidy rates really depend on the ratio of the clean/dirty supply elasticities rather than the level of the elasticity itself.

Consider the following equations relating clean and dirty production in state i for firm f

to expected discounted future output prices:

$$x_{i,c,f} = \beta_{i,c}\mathbb{E}\left[\sum_{t=0}^{25}\frac{p_{i,t,f}}{(1+r)^t}\right] + \varepsilon_{i,c,f}$$
$$x_{i,d,f} = \beta_{i,d}\mathbb{E}\left[\sum_{t=0}^{25}\frac{p_{i,t,f}}{(1+r)^t}\right] + \varepsilon_{i,d,f}$$

The parameters of interest are $\beta_{i,c}$ and $\beta_{i,d}$ but $p_{t,f}$ is currently unobserved. In addition, prices and quantities are endogenous, so even if expected future prices were observed an instrument would be necessary to estimate $\beta_{i,c}$ and $\beta_{i,d}$. Suppose there exists an instrument z_f for $P_f = \mathbb{E}\left[\sum_{t=0}^{25}\frac{p_{t,f}}{(1+r)^t}\right]$ such that $\mathbb{E}[z_f\varepsilon_{i,c}] = \mathbb{E}[z_f\varepsilon_{i,c}] = 0$. Consider z_f to be a binary demand shock such that $z_f = 1$ in the "High-Demand Growth" scenario and $z_f = 0$ in the "Mid-Case" scenario. The identifying assumption is that demand only affects supply of clean and dirty production through changes to the expected future price P_f.

If we observed P_f, $\beta_{i,c}$ and $\beta_{i,d}$ could be estimated using z_f as an instrument.

$$\hat{\beta}^{iv}_{i,c} = \frac{\overline{x}_{i,c,f|z_i=1} - \overline{x}_{i,c,f|z_i=0}}{\overline{P}_{i,f|z_i=1} - \overline{P}_{i,f|z_i=0}} \tag{30}$$
$$\hat{\beta}^{iv}_{i,d} = \frac{\overline{x}_{i,d,f|z_i=1} - \overline{x}_{i,d,f|z_i=0}}{\overline{P}_{i,f|z_i=1} - \overline{P}_{i,f|z_i=0}} \tag{31}$$

Here $\overline{x}_{i,c,f|z_i=1}$ is the sample average for clean generator in state i under the "High Demand Growth" scenario and $\overline{x}_{i,c,f|z_i=0}$ is the sample average in the "Mid-Case" scenario. Given that P_f is not directly observed, $\hat{\beta}^{iv}_{i,c}$ cannot be estimated directly. However, the optimal policy ratio depends on the ratio of the slope estimates, rather than the slope estimate itself. Under the assumption that expected output prices are the same for clean and dirty production, the denominators will be the same in Equations 30 and 31. The ratio of slope estimated can therefore be estimated as

$$\frac{\hat{\beta}^{iv}_{i,c}}{\hat{\beta}^{iv}_{i,d}} = \frac{\overline{x}_{i,c,f|z_i=1} - \overline{x}_{i,c,f|z_i=0}}{\overline{x}_{i,d,f|z_i=1} - \overline{x}_{i,d,f|z_i=0}}.$$

If demand is perfectly inelastic, the optimal tax to subsidy ratio for state i can therefore be

estimated as

$$\left|\frac{\tau_{i,d}}{\tau_{i,c}}\right| = \frac{\sum_{n\neq i} x'_{n,c}}{\sum_{n\neq i} x'_{n,d}} = \frac{\sum_{n\neq i}\left(\overline{x}_{n,c,f|z_i=1} - \overline{x}_{n,c,f|z_i=0}\right)}{\sum_{n\neq i}\left(\overline{x}_{n,d,f|z_i=1} - \overline{x}_{n,d,f|z_i=0}\right)}. \tag{32}$$

C.3 Data Details

The model output from the ReEDS 2023 Standard Scenarios includes state level modeled electric generating capacity (in MW) and production (in MWh) by generating technology in even years from 2024 through 2050. I classify technologies as either clean, dirty, or other generating technologies according to Table C.1. Clean technologies include solar, wind, and nuclear while dirty technologies are predominately coal and natural gas (without carbon capture). A variety of technologies are classified as "other" that are not easily classified as clean or dirty. For example, storage technologies emissions depend on the marginal source of electricity when they are charged and life-cycle emissions from biopower depend on how they are grown. Finally, carbon capture technologies can dramatically reduce, but not fully eliminate emissions from coal or natural gas fueled power-plants.

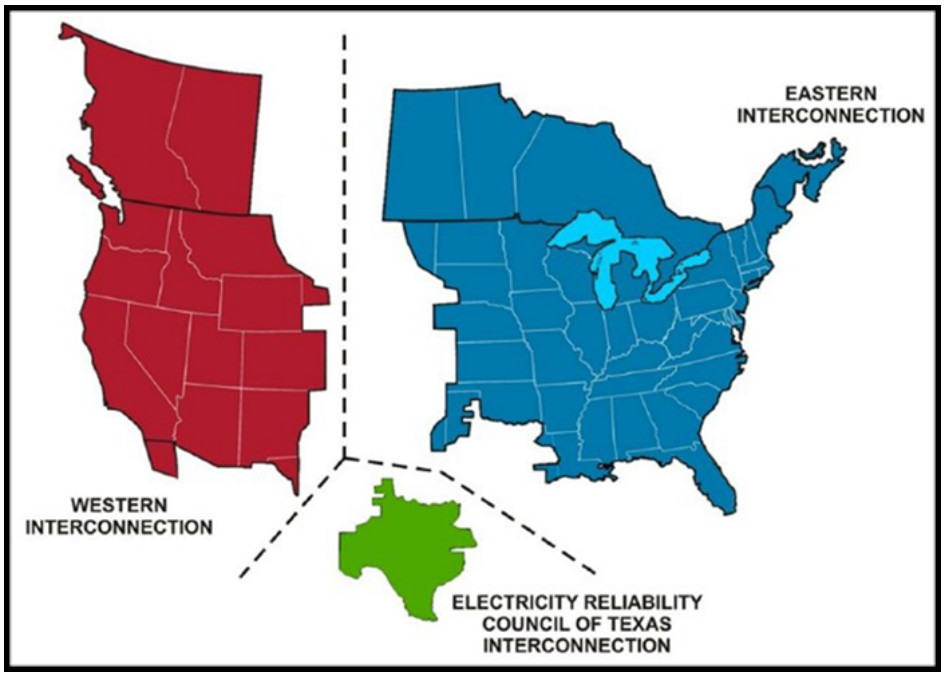
Table C.1: Electricity Generating Technology Classification

Clean Technologies	Dirty Technologies	Other Technologies
Solar Photovoltaic (Utility scale + distributed)	Coal	Electric Battery Storage (4 & 8 Hour)
Wind (Onshore + Offshore)	Natural Gas (Combined Cycle)	Pumped Hydro Storage
Nuclear (Traditional + SMR)	Natural Gas (Comubstion Turbine)	Canadian Imports
Geothermal	Oil-gas-steam	Biopower
Hydropower		Hydrogen Combustion Turbine
Concentrating Solar Power		Coal and Natural Gas with CCS

Data are aggregated across technology types and within each interconnections. Figure D.2 shows the evolution of production shares by each fuel type in the three interconnections. Prod

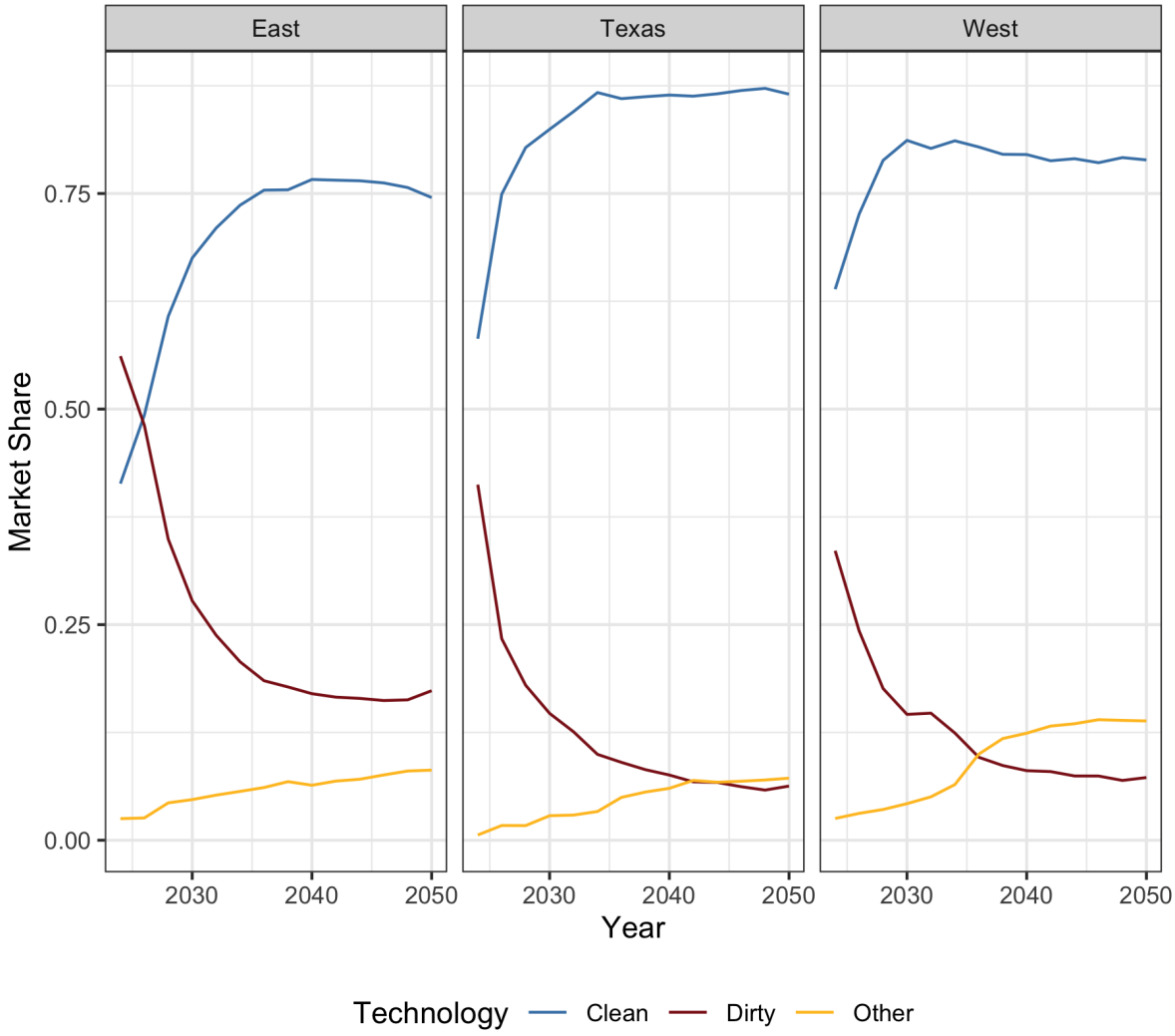
D Appendix Figures

Figure D.1: The Three Major Electricity Interconnections



Source: Federal Energy Regulatory Commission. https://www.ferc.gov/OPP/western-markets-explainer

Figure D.2: Projected Market Shares in Major Electricity Interconnections Under Current Policy



Source: Data from the National Renewable Energy Laboratory's ReEDS Model Mid-Case 2023 Scenario and author's calculations.