Pollution Taxes and Clean Subsidies in an Open Economy

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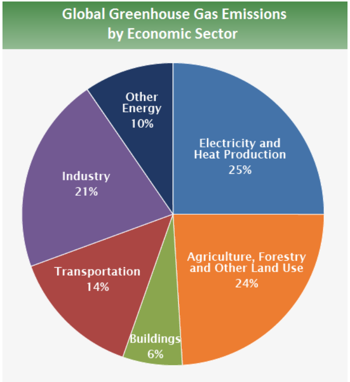
How to Address Climate Change?

- What tax policy instruments should be used to reduce greenhouse gas pollution?
- Economics 101/Targeting Principle suggests using a carbon tax
- In practice, countries and states have adopted both policies pricing pollution and subsidies for clean substitute goods
  - **Carbon Prices**: The European Union's Emissions Trading System, California's Cap and Trade, China's ETS, and British Columbia's Carbon Tax
  - **Clean Subsides**: US Clean Energy Manufacturing Tax Credit (from IRA), China's New Energy Vehicle Tax Exemption, and Canada's Clean Hydrogen Investment Tax Credit

Climate Change and Trade

- The majority of greenhouse gas emissions are associated with either the production or use of tradable goods
- Greenhouse gases are a classic example of a global pollutant. Damages occur regardless of where they are emitted
- Individual countries can only tax and subsidize activity that takes place domestically



Source: U.S. EPA and IPCC (2014)

Should an Open Economy Tax Pollution or Subsidize Clean Substitutes?

- **Research Question:** For a tradable good, should an open economy use a pollution tax or clean subsidy to correct for a global environmental externality?
  - How does openness to trade impact the incentives and policy choices of an individual jurisdiction?
  - What is the effect on the total climate policy ambition?

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  - How does openness to trade impact the incentives and policy choices of an individual jurisdiction?
  - What is the effect on the total climate policy ambition?
- **This paper:** Presents a multi-country optimal tax model with pollution taxes and clean subsidies on dirty and clean production

What is Different About an Individual Country?

- An individual country has different incentives than a global social planner
  - Individual countries taking unilateral action might only care about damages occurring domestically (domestic social cost of pollution)
  - **Free Riding:** With a global pollutant, damages to other countries from increased pollution are ignored
  - Issue regardless of the tradability of the externality producing industry
- An individual country has limited tax instruments
  - Domestic policymaker cannot (directly) tax dirty goods produced and consumed abroad
  - Restriction on tax instruments “breaks” targeting principle of optimal taxation

What is Different About an Open Economy?

- Trade creates economic linkages causing pollution leakage
- **Pollution Leakage:** Movement of polluting activity out of a high environmental tax jurisdiction as a result of the tax
  - With a global pollutant, leakage undermines the effectiveness of domestic pollution taxes
- Trade connects economic outcomes
  - Domestic tax policy might impact economic welfare abroad (i.e. tax exporting, changing terms of trade)
- Trade linkages could create policy interdependence
  - Domestic policy could affect policy abroad if it impacts foreign jurisdictions' marginal policy incentives

Results Preview

- Domestically optimal policy in an open economy
  - Openness to trade rationalizes the use of a clean subsidy in addition to a pollution tax
  - Reliance on tax vs. subsidy is determined by pollution leakage rate
  - Choice of instruments and level of policy ambition are separable. Pollution leakage impacts instrument choice but not policy ambition. Free-riding impacts policy ambition, but not instrument choice
- Calibrating to state-level electricity policy illustrates that cleaner markets will use pollution taxes more

Relation to Existing Literature

- Targeting, Climate Instrument Choice, and Clean Subsidies
  - Clausing and Wolfram (2023); Borenstein and Kellogg (2023); Anderson, Marinescu and Shor (2023); Acemoglu et al. (2012, 2016); Xiang (2023); Sandmo (1975); Dixit (1985); Kopczuk (2003); Kotchen and Maggi (2024)
  - **This paper:** Shows open economies provide an efficiency rationale for clean subsidy
- Pollution Leakage
  - Markusen (1975); Fischer and Fox (2012); Böhringer, Rosendahl and Storrøsten (2017); Fowlie and Reguant (2022); Grubb et al. (2022); Fowlie, Reguant and Ryan (2016); Domınguez-Iino (2023); Hsiao (2024); Kotchen and Maggi (2024)
  - **This paper:** Shows conditions that create leakage make clean subsidies more effective
- Climate Policy in International Context
  - Copeland and Taylor (1995, 2004); Ogawa and Wildasin (2009); Kotchen (2018); Eichner and Pethig (2019); Kortum and Weisbach (2022); Weisbach et al. (2023); Clausing and Wolfram (2023); Nordhaus (2015); Farrokhi and Lashkaripour (2025)
  - **This paper:** Shows climate ambition and tax/subsidy instrument choice are separable

The Model

Model Setup - Demand

- There are N countries, indexed by i
- Consumers demand energy intensive good x_i and a numeraire good z_i
- Good x is traded globally at worldwide consumer price p
- The representative consumer has exogenous income y_i, government transfers T_i, and owns the domestic firm with associated profits π_i, and solves a standard consumer problem

$$\max_{x_i, z_i} U_i(x_i, z_i) \qquad \text{s.t. } y_i + \pi_i + T_i = px_i + z_i$$

  - x can be produced by a clean or dirty production, but final goods are perfect substitutes
  - Utility is assumed to be quasi-linear
- Demand for x by country i is given as a function of p, $x_i(p)$

Model Setup - Supply

- Good x is produced with a dirty ($x_{i,d}$) or clean ($x_{i,c}$) production process
  - Production in country i has costs $C_{i,c}(x_{i,c})$ and $C_{i,d}(x_{i,d})$
- Governments can impose an output tax/subsidy on dirty ($\tau_{i,d} > 0$) or clean ($\tau_{i,c} < 0$) domestic production, creating a wedge between producer prices and the world price
  - Positive values of $\tau_{i,c}$ and $\tau_{i,d}$ correspond to taxes and negative values are subsidies
- The firm produces $x_{i,c}$ and $x_{i,d}$ to maximize profits

$$\max_{x_{i,c},x_{i,d}} \pi_i = \max_{x_{i,c},x_{i,d}} (p - \tau_{i,c})x_{i,c} - C_{i,c}(x_{i,c}) + (p - \tau_{i,d})x_{i,d} - C_{i,d}(x_{i,d})$$

- Country i supply of x using the clean and dirty production process are given as functions of the producer prices $x_{i,c}(p - \tau_{i,c})$ and $x_{i,d}(p - \tau_{i,d})$

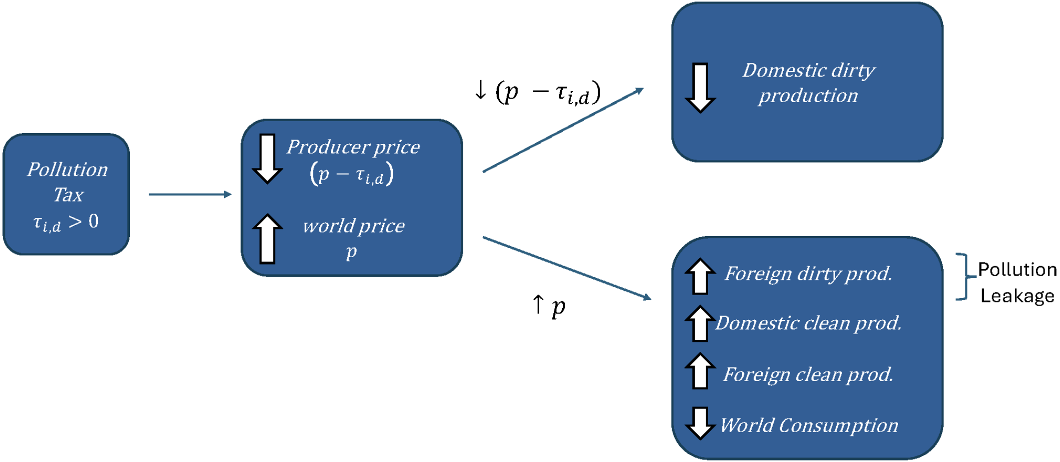
Model Setup - Policymaker's Problem

- Dirty production releases a global pollutant. Damages are a function of world dirty production, $X_d = \sum_n x_{n,d}$
- Domestic welfare is impacted by damage function $\Gamma_i(X_d)$

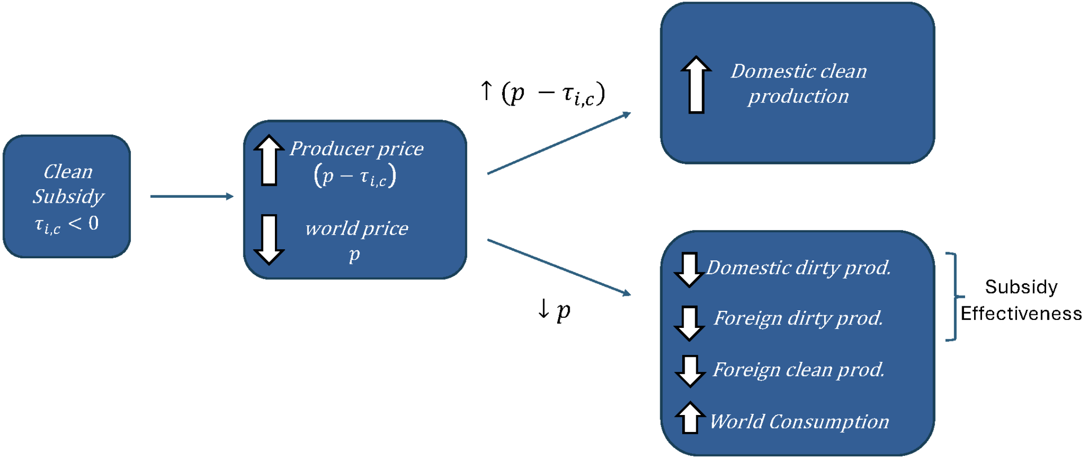
$$W_i = U_i(x_i, z_i) - \Gamma_i(X_d)$$

- Damage function captures how much policymaker i cares about climate change
- The policymaker sets taxes and subsidies $\tau_{i,c}$ and $\tau_{i,d}$ to maximize country i welfare subject to the consumer and firm's maximizing behavior, world market clearing, and government budget constraint

Pollution Tax Intuition



Clean Subsidy Intuition



Benchmark Comparisons

Benchmark 1 - Global Policymaker

- Consider a social planner maximizing global welfare
- Set $\tau_{i,c}$, $\tau_{i,d}$ for all countries subject to optimizing behavior and market clearing conditions
- Optimal policy is classic Pigouvian tax on dirty production, subsidy plays no role

$$\tau_{i,d} = \gamma^* = \Gamma^{*\prime}\left(\sum_i c_{i,d}\right)$$
$$\tau_{i,c} = 0$$

where γ^* is the marginal *global* cost of pollution

- If individual country policymakers do not fully internalize global damages, $\gamma^* > \gamma_i$

Clean Subsidy Only

Benchmark 2 - Closed Economy

- Now consider a policymaker in a closed economy who only cares about domestic welfare
- Optimal policy is a pollution tax calibrated to domestic social cost of carbon

$$\tau_{i,d} = \gamma_i$$
$$\tau_{i,c} = 0$$

- Subsidy still plays no role
- Individual country free-riding. Domestic policymaker may only value domestic benefits of avoided emissions, $\gamma_i \leq \gamma^*$. Individual countries may set insufficiently ambitious climate policy

Clean Subsidy Only

Open Economy

Open Economy Policy Tradeoffs

- In an open economy, the policymaker's first order condition for tax instrument $\tau_{i,k}$ is

$$\vec{\tau} \cdot \frac{\partial \vec{x}}{\partial \tau_{i,k}} = \frac{\gamma_i}{\lambda_i}\frac{\partial x_{i,d}}{\partial \tau_{i,k}} + \frac{\gamma_i}{\lambda_i}\frac{\partial X_{-i,d}}{\partial \tau_{i,k}} + \frac{\mu_i}{\lambda_i}\frac{\partial p}{\partial \tau_{i,k}}\left(x_{i,c} + x_{i,d} - x_i\right) + \frac{(\lambda_i - \mu_i)}{\lambda_i} x_{i,k}$$

- Country i trades off the fiscal externality from the tax against:
  - The change in domestically sourced pollution
  - The change in foreign sourced pollution (leakage)
  - Manipulating the terms of trade
  - Relative utility of transfers from the government

Assumptions

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  - The change in domestically sourced pollution
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  - Manipulating the terms of trade
  - Relative utility of transfers from the government
- **Assumptions:** Policymaker acts as if $x_{i,c} + x_{i,d} - x_i = 0$ and $\lambda_i = \mu_i$
  - This puts aside terms-of-trade and redistribution/revenue raising considerations
  - These considerations are additively separable

Assumptions

Pollution Leakage

- In the open economy, taxes and subsidies change the *world* price which affects production and consumption abroad
- Country i's marginal rate of pollution leakage is defined as the increases in foreign emissions for each unit of avoided domestic emissions from a pollution tax (Fowlie and Reguant, 2022)

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

where $\alpha_{n,k}, \beta_n$ is the production/consumption market share and $\eta_{n,d}$ and ζ_n are the price elasticities of supply and demand

- Leakage rate is higher when *foreign* dirty supply is more elastic and lower when clean supply or demand are more elastic

Open Economy - Pollution Tax Only

- Pollution leakage impacts the effectiveness of a pollution tax is an open economy
- Optimal design of a pollution tax must be modified to account for leakage (Fowlie and Reguant, 2022; Böhringer et al., 2022)
- When a pollution tax is used alone, the optimal tax rate is

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

- The optimal tax rate is even smaller than the rate set by the closed economy
- Optimal tax rate is affected by free riding and pollution leakage

Open Economy Optimal Policy

- In an open economy, the optimal policy uses both carbon taxes and clean subsidies

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

  where L_i is the marginal rate of leakage and ω_i is a small correction term
- Carbon tax is reduced by a "pollution leakage adjustment" and magnitude of clean subsidy is proportional to leakage term
  - Pollution leakage makes a pollution tax less effective but a clean subsidy more effective

Border Carbon Adjustment

When to Use a Tax vs Subsidy

- Relative importance of carbon tax determined by the marginal pollution leakage rate

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

- High leakage rate makes the policymaker optimally use a clean subsidy more and a pollution tax less
  - The marginal leakage rate is a sufficient statistic for the policy ratio for a small open economy $(\omega_i \to 0)$
- Optimal policy ratio does not directly depend on the domestic social cost of carbon emissions

Elasticity Version

Open Economy Policy Ambition

- Define climate policy ambition as the sum of the tax rate and subsidy rate
- Optimal policy ambition is constant. Only depends on the domestic marginal social cost of carbon.

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

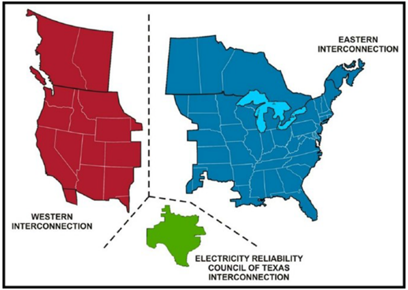
- Pollution leakage rate does not impact policy ambition. Simply changes what tax instruments to use

Avoided Pollution

US Electricity Calibrations

Electricity Markets and Policies

- Illustrates model implications by looking at electricity markets
- Three major grids in US. Side by side comparison for how markets influence leakage and optimal policy
- Model is well suited for electricity
    - Renewable and fossil generated electricity are close substitutes
    - Generation anywhere within the same market (grid interconnection) is highly substitutable
- Significant history of state pollution taxes and clean subsidies



Source: Federal Energy Regulatory Commission.

Electricity Clean and Dirty Supply

- Optimal policy ratio depends on the relative slopes of the clean vs dirty supply curves
- Calibrate demand to be inelastic ($x'_n = 0$). Lower bound on policy ratio (understates role of pollution tax)

$$\frac{\tau_{i,d}}{\tau_{i,c}} \geq -\frac{\sum_{n \neq i} X'_{n,c}}{\sum_{n \neq i} X'_{n,d}}$$

- Electricity generation responds along entry and investment margins (especially for renewables). Long-run elasticities are important
- Ideal variation would be to see how clean and dirty supply respond to shocks to (expected) prices over 20-30 year horizons
    - Not many natural experiments of exogenous price variation over this long a time horizon

Estimation Using ReEDS

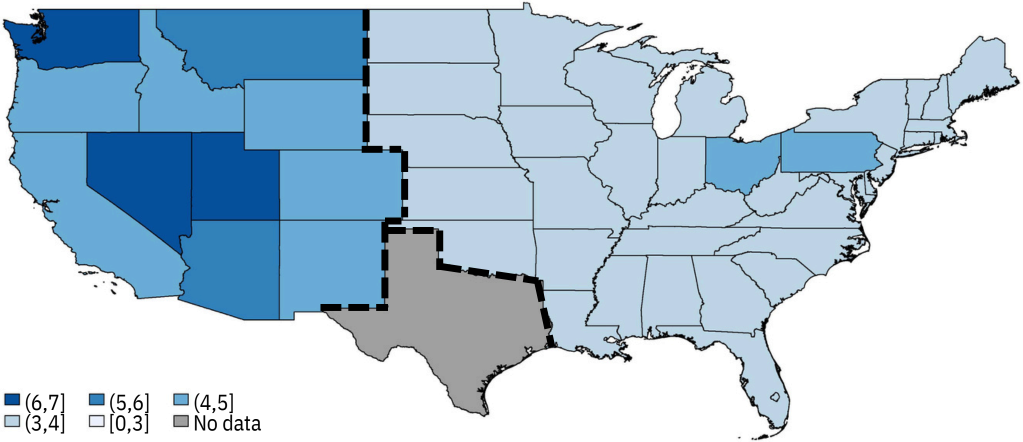
- Estimate relative long-run supply curve elasticities in 2050 using model of electric grid investment and production (NREL ReEDS Capacity Expansion Model)
- Model calculates least cost way of supplying electricity subject to grid-constraints
- Use model simulated demand shocks. Does clean or dirty supply respond more when demand is higher

Table: Interconnection Characteristics in 2050

	Eastern IC	Western IC
Dirty Share	17%	7%
$\hat{x}'_{i,c}/\hat{x}'_{i,d}$	3.5	5.2

Estimation Details | Technology Classifications | Market Shares

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



Conclusion

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1. Openness to trade provides an efficiency rationale to subsidizing clean production in addition to taxing pollution
2. The reliance of a tax vs subsidy depends on the marginal rate of leakage
   - The greater the marginal pollution leakage rate, the more an open economy should optimally use a clean subsidy relative to a carbon tax
3. Overall policy ambition is constant and equal to how much the domestic policymaker values reduced emissions
   - Ambition is independent of the rate of leakage
4. Calibrations illustrate that leakage rates depend on the rest of the market
   - Long-run trajectory for electricity is clean so (additional) long-run policies should use pollution taxes

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- Comments and questions are appreciated. Thank you! *okay@umich.edu*

Appendix

References

Acemoglu, Daron, Philippe Aghion, Leonardo Bursztyn, and David Hemous. 2012. "The Environment and Directed Technical Change." *American Economic Review*, 102(1): 131–166.

Acemoglu, Daron, Ufuk Akcigit, Douglas Hanley, and William Kerr. 2016. "Transition to Clean Technology." *Journal of Political Economy*, 124(1): 52–104.

Anderson, Soren, Ioana Marinescu, and Boris Shor. 2023. "Can Pigou at the Polls Stop Us Melting the Poles?" *Journal of the Association of Environmental and Resource Economists*, 10(4).

Borenstein, Severin, and Ryan Kellogg. 2023. "Carbon Pricing, Clean Electricity Standards, and Clean Electricity Subsidies on the Path to Zero Emissions." *Environmental and Energy Policy and the Economy*, 4: 125–176.

Böhringer, Christoph, Carolyn Fischer, Knut Einar Rosendahl, and Thomas Fox Rutherford. 2022. "Potential impacts and challenges of border carbon adjustments." *Nature Climate Change*, 12(1): 22–29.

Böhringer, Christoph, Knut Einar Rosendahl, and Halvor Briseid Storrøsten. 2017. "Robust policies to mitigate carbon leakage." *Journal of Public Economics*, 149: 35–46.

Clausing, Kimberly A., and Catherine Wolfram. 2023. "Carbon Border Adjustments, Climate Clubs, and Subsidy Races When Climate Policies Vary." *Journal of Economic Perspectives*, 37(3): 137–162.

Copeland, Brian R, and M. Scott Taylor. 1995. "Trade and Transboundary Pollution." *American Economic Review*, 85(4): 716–737.

Copeland, Brian R, and M Scott Taylor. 2004. "Trade, Growth, and the Environment." *Journal of Economic Literature*.

Dixit, Avinash. 1985. "Tax policy in open economies." In *Handbook of Public Economics*. Vol. 1, 313–374. Elsevier.

Domınguez-Iino, Tomas. 2023. "Efficiency and Redistribution in Environmental Policy: An Equilibrium Analysis of Agricultural Supply Chains."

Eichner, Thomas, and Rüdiger Pethig. 2019. "Strategic pollution control and capital tax competition." *Journal of Environmental Economics and Management*, 94: 27–53.

Farrokhi, Farid, and Ahmad Lashkaripour. 2025. "Can Trade Policy Mitigate Climate Change?" *Econometrica*, , (Forthcoming).

Fischer, Carolyn, and Alan K. Fox. 2012. "Comparing policies to combat emissions leakage: Border carbon adjustments versus rebates." *Journal of Environmental Economics and Management*, 64(2): 199–216.

Fowlie, Meredith L., and Mar Reguant. 2022. "Mitigating Emissions Leakage in Incomplete Carbon Markets." *Journal of the Association of Environmental and Resource Economists*, 9(2): 307–343.

Fowlie, Meredith, Mar Reguant, and Stephen P Ryan. 2016. "Market-Based Emissions Regulation and Industry Dynamics." *Journal of Political Economy*, 124(1).

Grubb, Michael, Nino David Jordan, Edgar Hertwich, Karsten Neuhoff, Kasturi Das, Kaushik Ranjan Bandyopadhyay, Harro Van Asselt, Misato Sato, Ranran Wang, William A. Pizer, and Hyungna Oh. 2022. "Carbon Leakage, Consumption, and Trade." *Annual Review of Environment and Resources*, 47(1): 753–795.

Hsiao, Allan. 2024. "Coordination and Commitment in International Climate Action."

Kopczuk, Wojciech. 2003. "A Note on Optimal Taxation in the Presence of Externalities." *Economics Letters*, 80(1): 81–86.

Kortum, Samuel, and David A. Weisbach. 2022. "Optimal Unilateral Carbon Policy."

Assumptions

- Production using one technology doesn't affect the marginal cost of other technology
- Optimal policy ignores incentive to manipulate terms of trade
  - Justified if countries are (1) small, (2) identical, or (3) constrained by international agreements
- Optimal policy ignores "marginal cost of public funds" considerations
  - Justified if there are lump sum taxes or tax systems set optimally
  - If not, MCPF considerations are separable

Back

Global Policymaker Clean Subsidy Only

- Global policymaker will use subsidy if it is restricted from using pollution tax
- Optimal subsidy rate in each country is given by

$$\tau_{i,c} = -\gamma^* \left(\frac{\sum_{n=1}^N x'_{n,d}}{\sum_{n=1}^N x'_{n,d} - \sum_{n=1}^N x'_n} \right)$$

- When demand is perfectly inelastic, $x'_n = 0$, $\tau_{i,c} = \gamma$ and subsidy recreates marginal incentives of the tax

Back

Closed Economy Clean Subsidy Only

- In a closed economy, with only a clean subsidy, the optimal subsidy rate it

$$\tau_{i,c} = -\gamma_i \left(\frac{x'_{i,d}}{x'_{i,d} - x'_i} \right)$$

- Expression is similar to global social planner
- There is still free riding (proportional to γ_i not γ^*
- Depends on domestic (rather than world) characteristics

Back

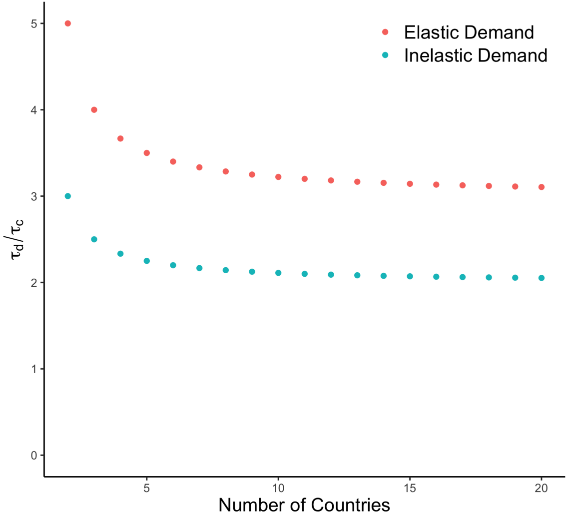
Small Open Economy

- Even a small open economy wants to use a subsidy even though subsidy works by changing the world price
- A small economy subsidy has a small price effect but it impacts many countries. Environmental benefit remains proportional to distortions in domestic market
- For N identical countries, the optimal tax to subsidy ratio for any individual country is given by

$$\left|\frac{\tau_{i,d}}{\tau_{i,c}}\right| = \frac{x_c' - x'}{x_d'} + \frac{-x'}{(N-1)x_d'}.$$

- As country size decreases, subsidy is used relatively more

Small Open Economy Simulations



Avoided Pollution

- Consider change in world pollution to a marginal increase in policy ambition

$$\sum_n \frac{\partial x_{n,d}}{\partial \gamma_i} = -x'_{i,d}\left(1 - \frac{L_i}{1-\omega_i}\right)\left(1 - \frac{\sum_n x'_{n,d}}{\sum_n \left(x'_{n,d} + x'_{n,c} - x'_n\right)}\right) - \sum_n x'_{n,d}\frac{L_i}{1-\omega_i}\frac{x'_{i,c}}{\sum_n \left(x'_{n,d} + x'_{n,c} - x'_n\right)}$$

- Effect of leakage rate on avoided pollution is ambiguous
  - If $x_{i,d}$ is very large, increase in L_i makes policy less effective (reduces magnitude)
  - If $x_{i,d}$ is very small, increase in L_i makes policy more effective (larger magnitude)

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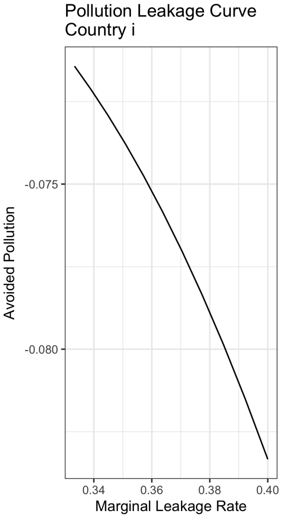
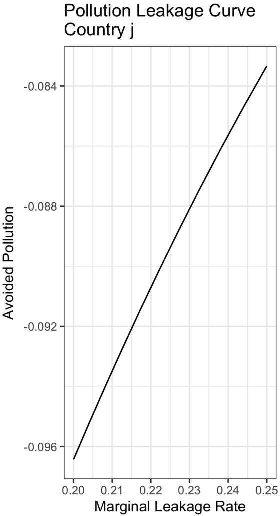
Avoided Pollution Simulations





Border Carbon Adjustment

- Role of subsidy is robust to the inclusion of a border adjustment
- Industry Border Carbon Adjustment can be written as including a consumption tax
- When consumption of x_i can be taxed at rate t, the optimal tax rates are

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

$$\tau_{i,c} = -\gamma_i L_i \, \frac{1}{1 - \omega_i^{bca}}$$

$$t_i = \gamma_i L_i \, \frac{1}{1 - \omega_i^{bca}}$$

where $\omega_i^{bca} = \frac{x'_{i,c} - x'_i}{\sum_{j \neq i} x'_{j,d} + \sum_j x'_{j,c} - \sum_j x'_j}$

Back

Optimal Policy Ratio as a Function of Leakage Rate

- Optimal policy ratio can be written in terms of marginal leakage rate

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

- Marginal leakage rate L_i is defined as $L_i = \frac{\sum_{n \neq i} x'_{n,d}}{\sum_{n \neq i} x'_{n,d} + \sum_n x'_{n,c} - \sum_n x'_n}$
- ω_i is a correction term $\omega_i = \frac{x'_{i,c}}{\sum_{n \neq i} x'_{n,d} + \sum_n x'_{i,c} - \sum_n x'_i}$
    - Correction accounts for welfare effects from cross fiscal externalities
    - As country size decreases, ω_i goes to zero

Back

Optimal Policy Ratio - Elasticity Version

- Optimal policy ratio can be written in terms of elasticities and market shares

$$\frac{\tau_{i,d}}{\tau_{i,c}} = -\frac{\sum_{n\neq i} \alpha_{n,c}\eta_{n,c} - \sum_n \alpha_n \eta_n}{\sum_{n\neq i} \alpha_{n,d}\eta_{n,d}}$$

- $\alpha_{i,d} = \frac{x_{i,d}}{\sum_n x_n}$, $\alpha_{i,c} = \frac{x_{i,d}}{\sum_n x_n}$, and $\alpha_i = \frac{x_i}{\sum_n x_n}$ are the market shares of country i dirty production, clean production, and consumption
- $\eta_{i,d} = \frac{x'_{i,d}}{x_{i,d}/p}$, $\eta_{i,c} = \frac{x'_{i,c}}{x_{i,c}/p}$, and $\eta_i = \frac{x'_i}{x_n/p}$ are the country i price elasticities of dirty supply, clean supply, and demand

Back

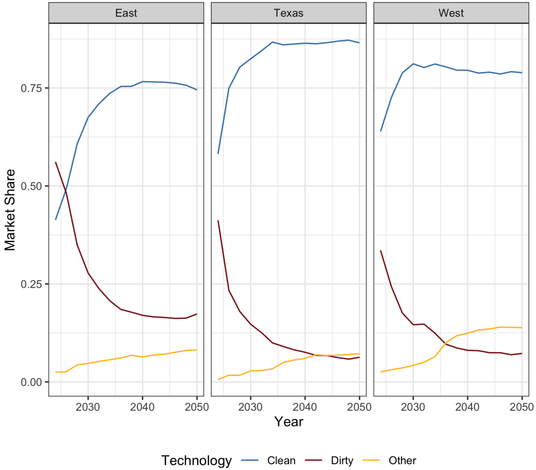
ReEDS Electricity Generating Capacities

Table: 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 (Combustion Turbine)	Canadian Imports
Geothermal	Oil-gas-steam	Biopower
Hydropower		Hydrogen Combustion Turbine
Concentrating Solar Power		Coal and Natural Gas with CCS

Back

ReEDS Mid-Case Market Shares



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ReEDS Estimation

- ReEDS publishes generation by technology type by state out through 2050
- Consider quantity today which is a function of future expected prices

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

- $\beta_{i,c}/\beta_{i,d}$ is the parameter of interest
  - Prices and quantities are equilibrium outcomes in model
  - $P = \mathbb{E}\left[\sum_{t=0}^{25} \frac{p_{i,t,f}}{(1+r)^t}\right]$ is not observed
  - Use (model simulated) demand shocks as instrument

Back

ReEDS Estimation

- Demand shock z_i where $z_i = 1$ under "High Demand Growth" scenario and $z_i = 0$ under "Mid-Case Scenario"
- If P was observed, we could estimate $\beta_{i,c}$ and $\beta_{i,d}$ as

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

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

- However, we only care about $\beta_{i,c}/\beta_{i,d}$ which can be estimated from observed data as

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

Back