

The Optimal Design of Climate Agreements

Inequality, Trade, and Incentives for Carbon Policy

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Motivation

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 - International cooperation through climate agreements

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- ▶ Proposals to fight climate inaction and the free-riding problem:
 - International cooperation through climate agreements
 - Trade sanctions needed to give incentives to countries to reduce emissions meaningfully
 - “Climate club”, Nordhaus (2015): trade sanctions on non-participations to sustain larger “clubs”
 - Carbon Border Adjustment mechanisms (CBAM), EU policy: carbon tariffs

Introduction

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The agreement boils down to a carbon tax, a tariff rate and a choice of countries
 - Social “designer” maximizing world welfare
- Trade-off:
Intensive margin: a “climate club” with few countries and large emission reductions
vs. *Extensive margin*: a larger set of countries, at the cost of lowering the carbon tax

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Intensive margin: a “climate club” with few countries and large emission reductions
vs. *Extensive margin*: a larger set of countries, at the cost of lowering the carbon tax
- Build a Climate-Macro model (IAM) with heterogeneous countries and trade to study the strategic implications of climate agreements and the optimal club design
 - Analyze the redistributive effects of climate policy and trade policy

Main results:

- Despite complete freedom of policy instruments, **impossible** to achieve the world's optimal policy with complete participation
 - Need to lower **carbon tax** from **\$150 to \$100** to accommodate participation of South-Asia and Middle-East
 - Beneficial to **leave fossil fuels producing countries**, like Russia, outside of the climate agreement

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- **Mechanism:**
 - Participation relies on a trade-off between $\left\{ \begin{array}{l} \text{(i) the cost of distortionary carbon taxation} \\ \text{(ii) the cost of tariffs (= the gains from trade)} \end{array} \right.$
 - For countries like Russia/Middle-East/South-Asia: cost of taxing fossil-fuels \gg cost of tariffs
they do not join the club with high carbon tax – *for any tariffs*
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- **Additional instruments:**
 - Welfare improvement with transfers, c.f. UN COP27's "loss and damage" fund
 - Fossil-fuel specific (input) tariffs can replicate the optimal policy

Literature

- ▶ Theoretical model of climate agreements: cooperation
 - *Climate clubs and cooperation*: Nordhaus (2015), Barrett (1994), Harstad (2012), Maggi (2016), Barrett (2003, 2013, 2022), Iverson (2024), Hagen and Schneider (2021), Chari, Nicolini, Teles (2023)
 - *Dynamics of coalition building*: Ray and Vohra (2015), Okada (2023), Nordhaus (2021), Harstad (2023), Maggi and Staiger (2022)
- ⇒ *Quantitative analysis of climate agreements and policy recommendation*

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3. Climate Agreements Design
4. Quantification
5. Policy Benchmarks:
Optimal Policy without endogenous participation
6. Main result:
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7. Extensions
8. Conclusion

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Model – Household & Firms

► Deterministic Neoclassical economy

- countries $i \in \mathbb{I}$, heterogeneous in many dimensions: income, temperature, energy production, etc.
- In each country, five agents:

1. Representative household $\mathcal{U}_i = \max_{c_{ij}} u(c_i)$, Trade, à la Armington

$$c_i = \left(\sum_j a_{ij}^{\frac{1}{\theta}} c_{ij}^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}}$$

$$\mathbb{P}_i = \left(\sum_j a_{ij} (\tau_{ij} (1 + t_{ij}^b) p_j)^{1-\theta} \right)^{\frac{1}{1-\theta}}$$

$$\sum_{j \in \mathbb{I}} c_{ij} \underbrace{(1 + t_{ij}^b)}_{\text{tariff}} \underbrace{\tau_{ij}}_{\text{iceberg cost}} p_j = \underbrace{w_i \ell_i}_{\text{labor income}} + \underbrace{\pi_i^f}_{\text{fossil firm profit}} + \underbrace{t_i^{ls}}_{\text{lump-sum transfers}}$$

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$$\mathbb{P}_i = \left(\sum_j a_{ij} (\tau_{ij} (1+t_{ij}^b) p_j)^{1-\theta} \right)^{\frac{1}{1-\theta}}$$

2. Competitive final good firm:

$$\max_{\ell_i, e_i^f, e_i^c, e_i^r} p_i \mathcal{D}_i(\mathcal{E}) z_i F(\ell_i, e_i^f, e_i^c, e_i^r) - w_i \ell_i - (q^f + t_i^\varepsilon) e_i^f - (q_i^c + t_i^\varepsilon) e_i^c - q_i^r e_i^r$$

- Externality: Damage function $\mathcal{D}_i(\mathcal{E})$, Income inequality from z_i , Carbon tax: t_i^ε

Model – Energy markets & Emissions

3. Competitive fossil fuels (oil-gas) producer, extracting e_i^x

$$\pi_i^f = \max_{e_i^x} q^f e_i^x - \mathcal{C}_i^f(e_i^x) \mathbb{P}_i$$

- Energy traded in international markets, at price q^f

$$E^f = \sum_{i \in \mathbb{I}} e_i^f = \sum_{i \in \mathbb{I}} e_i^x$$

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4. Coal energy firm, CRS: $e_i^c = \frac{1}{z_i^c} x_i^c \quad \Rightarrow \text{price } q_i^c = z_i^c \mathbb{P}_i$

5. Renewable energy firm, CRS: $e_i^r = \frac{1}{z_i^r} x_i^r \quad \Rightarrow \text{price } q_i^r = z_i^r \mathbb{P}_i$

with $x_i^f = \mathcal{C}_i^f(e_i^x)$, x_i^c, x_i^r same CES aggregator as c_i .

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- Climate system: mapping from emission $\mathcal{E} = \sum_{\mathbb{I}} e_i^f + e_i^c$ to damage $\mathcal{D}_i(\mathcal{E})$

Model – Equilibrium

- Given policies $\{t_i^\varepsilon, t_{ij}^b, t_i^{ls}\}_i$, a **competitive equilibrium** is a set of decisions $\{c_{ij}, e_i^f, e_i^c, e_i^r, e_i^x\}_{ij}$, emission $\{\mathcal{E}\}_i$ changing climate and prices $\{p_i, w_i, q_i^c, q_i^r\}_i, q^f$ such that:
 - Households choose $\{c_{ij}\}_{ij}$ to max. utility s.t. budget constraint
 - Firm choose inputs $\{e_i^f, e_i^c, e_i^r\}_i$ to max. profit
 - Oil-gas firms extract/produce $\{e_i^x\}_i$ to max. profit. + Elastic renewable, coal supplies $\{e_i^c, e_i^r\}$
 - Emissions \mathcal{E} affects climate and damages $\mathcal{D}_i(\mathcal{E})$
 - Government budget clear $\sum_i t_i^{ls} = \sum_i t_i^\varepsilon (e_i^f + e_i^c) + \sum_{i,j} t_{ij}^b c_{ij} \tau_{ij} p_j$
 - Prices $\{p_i, w_i, q^f\}$ adjust to clear the markets for energy $\sum_{\mathbb{I}} e_{it}^x = \sum_{\mathbb{I}} e_{it}^f$ and for each good

$$y_i := \mathcal{D}_i(\mathcal{E}) z_i F(\ell_i, e_i^f, e_i^r, e_i^r) = \sum_{k \in \mathbb{I}} \tau_{ki} c_{ki} + \sum_{k \in \mathbb{I}} \tau_{ki} (x_{ki}^f + x_{ki}^c + x_{ki}^r)$$

with x_{ki}^ℓ export of good i as input in ℓ -energy production in k

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Ramsey Problem with endogenous participation

- **Definition:** A climate agreement is a set $\{\mathbb{J}, \mathbf{t}^\varepsilon, \mathbf{t}^b\}$ of $\mathbb{J} \subseteq \mathbb{I}$ countries and a C.E. s.t.:
- Countries $i \in \mathbb{J}$ pay carbon tax $\mathbf{t}_i^\varepsilon = \mathbf{t}^\varepsilon$
 - If j exits agreement, club members $i \in \mathbb{J}$ impose uniform tariffs $\mathbf{t}_{ij}^b = \mathbf{t}^b$ on goods from j
They still trade with club members in oil-gas at price q^f
 - Local, lump-sum rebate of taxes $\mathbf{t}^{ls} = \mathbf{t}^\varepsilon(e_i^f + e_i^c) + \sum_{j \notin \mathbb{J}} \mathbf{t}^b \tau_{ij} c_{ij} p_j$
 - Indirect utility $\mathcal{U}_i(\mathbb{J}, \mathbf{t}^\varepsilon, \mathbf{t}^b) \equiv u(c_i(\mathbb{J}, \mathbf{t}^\varepsilon, \mathbf{t}^b))$

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 - Indirect utility $\mathcal{U}_i(\mathbb{J}, t^\varepsilon, t^b) \equiv u(c_i(\mathbb{J}, t^\varepsilon, t^b))$
- Two equilibrium concepts:
- Exit: unilateral deviation of i , $\mathbb{J} \setminus \{i\}$, \Rightarrow **Nash equilibrium**

Coalition \mathbb{J} stable if $\mathcal{U}_i(\mathbb{J}, t^\varepsilon, t^b) \geq \mathcal{U}_i(\mathbb{J} \setminus \{i\}, t^\varepsilon, t^b) \quad \forall i \in \mathbb{J}$

- Sub-coalitional deviation \Rightarrow **Coalitional Nash equilibrium**
 - No country i and subcoalition $\hat{\mathbb{J}}$ would be better off in $\mathbb{J} \setminus \hat{\mathbb{J}}$ than in the current agreement \mathbb{J}
 - Under such equilibrium, the optimal agreement results are identical
 \Rightarrow *more in the paper* and details here

Optimal design with endogenous participation

- Objective: search for the optimal *and stable* climate agreement

$$\begin{aligned} \max_{\mathbb{J}, t^{\varepsilon}, t^b} \mathcal{W}(\mathbb{J}, t^{\varepsilon}, t^b) &= \max_{t^{\varepsilon}, t^b} \max_{\mathbb{J}} \sum_{i \in \mathbb{I}} \omega_i \mathcal{U}_i(\mathbb{J}, t^{\varepsilon}, t^b) \\ \text{s.t.} \quad &\mathcal{U}_i(\mathbb{J}, t^{\varepsilon}, t^b) \geq \mathcal{U}_i(\mathbb{J} \setminus \{i\}, t^{\varepsilon}, t^b) \end{aligned}$$

- Current design:

(i) choose taxes $\{t^{\varepsilon}, t^b\}$ [outer problem]

(ii) choose the coalition \mathbb{J} s.t. participation constraints hold [inner problem]

\Rightarrow *Combinatorial Discrete Choice Problem* for $\mathbb{J} \in \mathcal{P}(\mathbb{I})$

Solution method

- ▶ Current design: $\max_{\mathbf{t}} \max_{\mathbb{J}} \mathcal{W}(\mathbb{J}, \mathbf{t})$ s.t. $\mathcal{U}_j(\mathcal{J}, \mathbf{t}) \geq \mathcal{U}_j(\mathcal{J} \setminus \{i\}, \mathbf{t})$
- ▶ Inner problem: CDCP Solution method
 - Use a “squeezing procedure”, as in Jia (2008), Arkolakis, Eckert, Shi (2023) extended to handle participation constraints

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 - Squeezing step:

$$\Phi(\mathcal{J}) \equiv \{j \in \mathbb{I} \mid \Delta_j \mathcal{W}(\mathcal{J}) > 0 \text{ \& } \Delta_j \mathcal{U}_j(\mathcal{J}, \mathbf{t}) > 0, \forall j \in \mathcal{J}\}$$

where the marginal values for global welfare and individual welfare is

$$\Delta_j \mathcal{W}(\mathcal{J}, \mathbf{t}) \equiv \mathcal{W}(\mathcal{J} \cup \{j\}, \mathbf{t}) - \mathcal{W}(\mathcal{J} \setminus \{j\}, \mathbf{t}) = \sum_{i \in \mathbb{I}} p_i \omega_i (\mathcal{U}_i(\mathcal{J} \cup \{j\}, \mathbf{t}) - \mathcal{U}_i(\mathcal{J} \setminus \{j\}, \mathbf{t}))$$

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- Iterative procedure build lower bound $\underline{\mathcal{J}}$ and upper bound $\overline{\mathcal{J}}$ by successive squeezing steps

$$\underline{\mathcal{J}}^{(k+1)} = \Phi(\underline{\mathcal{J}}^{(k)}) \qquad \overline{\mathcal{J}}^{(k+1)} = \Phi(\overline{\mathcal{J}}^{(k)})$$

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Quantification – Climate system and damage

► Static economic model:

decisions $e_i^f + e_i^c$ taken “once and for all”, $\mathcal{E} = \sum_i e_i^f + e_i^c$

- Climate system:

$$\dot{S}_t = \mathcal{E} - \delta_s S_t$$

$$T_{it} = \bar{T}_{i0} + \Delta_i S_t$$

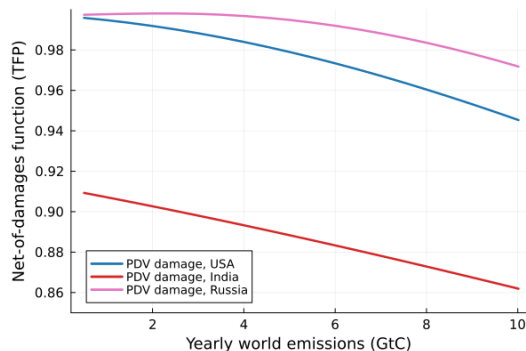
- Path damages heterogeneous across countries
Quadratic, c.f. Nordhaus-DICE / IAM

$$\mathcal{D}(T_{it} - T_i^*) = e^{-\gamma(T_{it} - T_i^*)^2}$$

- Economic feedback in Present discounted value

$$\mathcal{D}_i(\mathcal{E}) = \bar{\rho}_i \int_0^\infty e^{-\overbrace{(\rho - n_i + \eta \bar{g}_i)}^{\equiv \bar{\rho}_i} t} \mathcal{D}(T_{it} - T_i^*) dt$$

- Similarly for $LCC_i, SCC_i \dots$



Quantification

- Pareto weights ω_i : Imply no redistribution motive
 \bar{c}_i conso in initial equilibrium $t = 2020$ w/o climate change

$$\omega_i = \frac{1}{u'(\bar{c}_i)} \quad \Leftrightarrow \quad C.E.(\bar{c}_i) \in \operatorname{argmax}_{\bar{c}_i} \sum_i \omega_i u(\bar{c}_i)$$

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- Functional forms:
 - Utility: CRRA η
 - Production function $\bar{y} = zF(\ell_i, k_i, e_i^f, e_i^c, e_i^r)$
 - Nested CES energy e_i vs. labor-capital Cobb-Douglas bundle $k_i^\alpha \ell_i^{1-\alpha}$, elasticity $\sigma_y < 1$
 - Energy: fossil/coal/renewable $\sigma_e > 1$, $CES(e_i^f, e_i^c, e_i^r)$, elasticity σ^e
 - Energy extraction of oil-gas: isoelastic $\mathcal{C}^f(e^x) = \bar{\nu}_i (e_i^x / \mathcal{R}_i)^{1+\nu_i} \mathcal{R}_i$

More details

Calibration

- ▶ Parameters calibrated from the literature
- ▶ Parameters to match “world” moments from the data [Details calibration](#)
- ▶ Parameters to match (exactly) country level variables:

Calibration

► Parameters calibrated from the literature

- Macro parameter: discount rate $\rho = 1.5\%$, CRRA $\eta = 1.5$
- Damage parameter: γ from Krusell, Smith (2022) & Barrage, Nordhaus (2023)
Target temperature: $T_i^* = \alpha T^* + (1 - \alpha) T_{it_0}$ with $T^* = 14.5$, $\alpha = 0.5$.
- Energy: Elasticity of energy vs. capital labor $\sigma^y = 0.3$, from Bourany (2022), Elasticity between energy sources $\sigma^e = 2.2$, from Stern Review
- Long-term Growth: $\bar{g} = 1\%$, world population growth $n = 0.35\%$, UN
- Trade elasticity $\theta = 5.63$, align with gravity regression & trade literature ACR

► Parameters to match “world” moments from the data

[Details calibration](#)

► Parameters to match (exactly) country level variables:

Calibration

- ▶ Parameters calibrated from the literature
- ▶ Parameters to match “world” moments from the data Details calibration
 - Climate parameters: climate sensitivity χ , carbon decay δ_s
match IAM’s Pulse experiment, c.f. Dietz et al. (2021)
 - CES shares in capital/labor/energy to match aggregate shares
Oil-gas: $\omega^f = 56\%$, coal $\omega^c = 27\%$, Non-carbon $\omega^r = 17\%$, Capital $\alpha = 35\%$
- ▶ Parameters to match (exactly) country level variables:

Calibration

- ▶ Parameters calibrated from the literature
- ▶ Parameters to match “world” moments from the data Details calibration
- ▶ Parameters to match (exactly) country level variables:
 - GDP, Population, UN, WDI
 - Energy mix (oil, gas, coal, non-carbon), energy consumption, energy share energy production, proved reserves, energy rent
Data from Statistical Energy Review (2024), from Energy Institute
 - Temperature, Pattern scaling
data from Burke, Hsiang, Miguel (2015)
 - Trade: cost τ_{ij} projected on distance, preferences a_{ij} to match import shares
Data from CEPII, Conte, et al (2022)

Matching country-level moments

Table: Heterogeneity across countries

Dimension of heterogeneity	Model parameter	Matched variable from the data	Source
Population	Country size \mathcal{P}_i	Population	UN
TFP/technology/institutions	Firm productivity z_i	GDP per capita (2019-PPP)	WDI
Productivity in energy	Energy-augmenting productivity z_i^e	Energy cost share	SRE
Cost of coal energy	Cost of coal production \mathcal{C}_i^c	Energy mix/coal share e_i^c/e_i	SRE
Cost of non-carbon energy	Cost of non-carbon production \mathcal{C}_i^r	Energy mix/coal share e_i^r/e_i	SRE
Local temperature	Initial temperature T_{i0}	Pop-weighted yearly temperature	Burke et al
Pattern scaling	Pattern scaling Δ_i	Sensitivity of T_{it} to world \mathcal{T}_t	Burke et al
Oil-gas reserves	Reserves \mathcal{R}_i	Proved Oil-gas reserves	SRE
Cost of oil-gas extraction	Slope of extraction cost $\bar{\nu}_i$	Oil-gas extracted/produced e_i^x	SRE
Cost of oil-gas extraction	Curvature of extraction cost ν_i	Profit π_i^f / energy rent	WDI
Trade costs	Distance iceberg costs τ_{ij}	Geographical distance $\tau_{ij} = d_{ij}^\beta$	CEPII
Armington preferences	CES preferences a_{ij}	Trade flows	CEPII

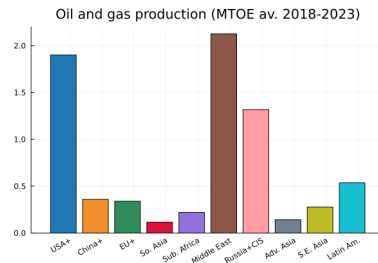
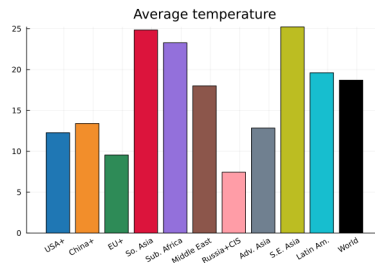
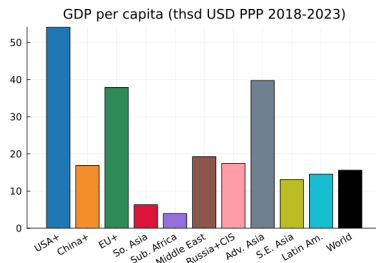
Matching country-level moments

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Quantitative application – Sample of 10 “regions”

- ▶ Sample of 10 “regions”: (i) US+Canada, (ii) China+HK, (iii) EU+UK+Schengen, (iv) South Asia, (v) Sub-saharian Africa, (vi) Middle-East+North Africa, (vii) Russia+CIS, (viii) Japan+Korea+Australia+Taiwan+Singap., (ix) South-East Asia (Asean), (x) Latin America **WIP: 25 countries + 7 regions**
- ▶ Data (Avg. 2018-2023)



Details [Trade shares – details](#)

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5. **Policy Benchmarks:**
Optimal Policy without endogenous participation
6. Main result:
The Optimal Climate Agreement
7. Extensions
8. Conclusion

Optimal policy : benchmarks

- ▶ Policy benchmarks, without endogenous participation
 - ***First-Best***, Social planner maximizing global welfare with unlimited instruments
 - Pigouvian result: Carbon tax = Social Cost of Carbon
 - Relies heavily on cross-country transfers to offset redistributive effects

Optimal policy : benchmarks

► Policy benchmarks, without endogenous participation

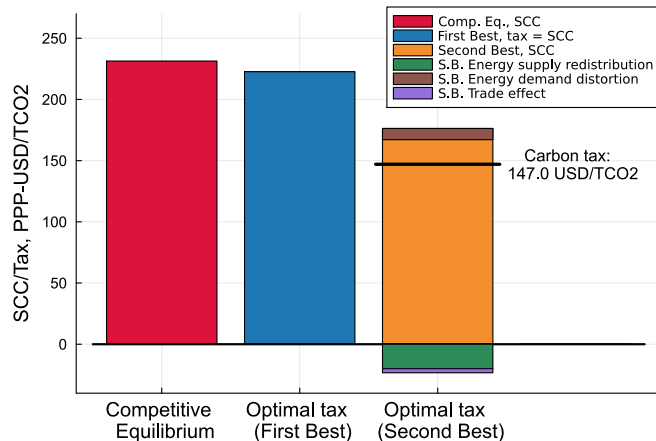
- **First-Best**, Social planner maximizing global welfare with unlimited instruments
 - Pigouvian result: Carbon tax = Social Cost of Carbon
 - Relies heavily on cross-country transfers to offset redistributive effects
- **Second-Best**: Social planner, single carbon tax without transfers
 - Optimal carbon tax t^E correct climate externality, but also accounts for:
 - (i) Redistribution motives, G.E. effects on (ii) energy markets and (iii) trade leakage

$$t^E = \underbrace{\sum_i \phi_i LCC_i}_{=SCC} + \sum_i \phi_i \text{Supply Redistrib}_i^o + \sum_i \phi_i \text{Demand Distort}_i^o - \sum_i \text{Trade Redistrib}_i^o \quad \phi_i \propto \omega_i u'(c_i)$$

- Details: *Competitive equilibrium* [Details eq 0](#), *First-Best*, with unlimited instruments [Details eq 1](#), *Second-best*, Ramsey policy with limited instruments [Details eq 2](#)

- More details in companion paper: Bourany (2024)

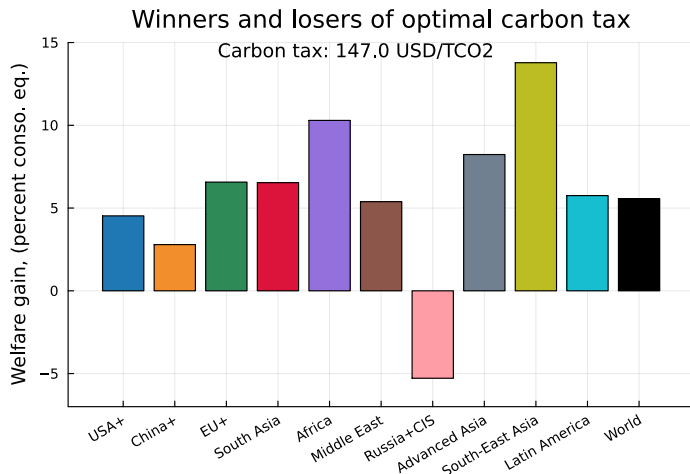
Second-Best climate policy



- Accounting for redistribution and lack of transfers
⇒ implies a carbon tax lower than the Social Cost of Carbon

Gains from cooperation – World Optimal policy

- ▶ Optimal carbon tax
Second Best: $\sim \$147/tCO_2$
- ▶ Reduce fossil fuels / CO_2 emissions by 42% compared to Competitive equilibrium (Business as Usual, BAU)
- ▶ Welfare difference between world optimal policy vs. Comp. Eq./BAU

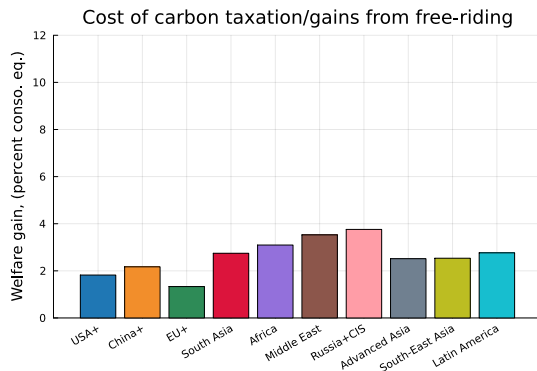


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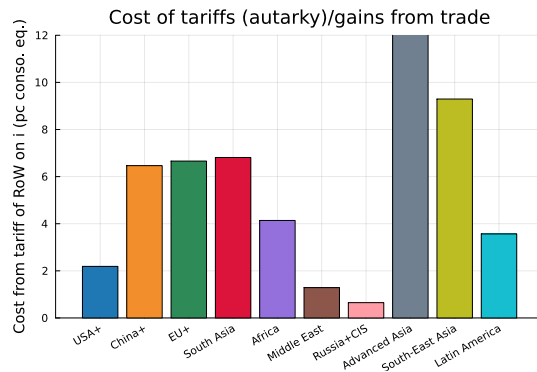
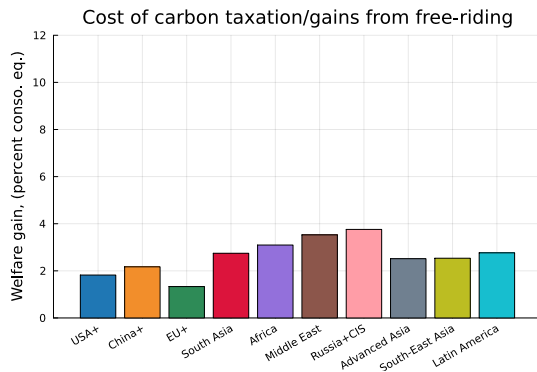
Trade-off – Cost of Carbon Taxation vs. Gains from trade

Gains from **unilateral exit** from agreement vs. **Gains from trade**, i.e. loss from tariffs/autarky



Trade-off – Cost of Carbon Taxation vs. Gains from trade

Gains from **unilateral exit** from agreement vs. **Gains from trade**, i.e. loss from tariffs/autarky



Theoretical investigation: decomposing the welfare effects

► Experiment:

- Start from the equilibrium where carbon tax $t_j^e = 0, t_{jk}^b = 0, \forall j$,
- Change in welfare: Linear approximation around that point \Rightarrow small changes in carbon tax $dt_j^e, \forall j$ and tariffs $dt_{j,k}^b, \forall j, k$ for a club J

$$\frac{dV_i}{u'(c_i)} = \eta_i^c d \ln p_i + \left[-\eta_i^c \bar{\gamma}_i \frac{1}{\bar{\nu}} - \eta_i^c s_i^e s_i^f + \eta_i^\pi (1 + \frac{1}{\bar{\nu}}) \right] d \ln q^f - \left[\eta_i^c s_i^e (s_i^c + s_i^r) + \eta_i^\pi \frac{1}{\bar{\nu}} + 1 \right] d \ln \mathbb{P}_i$$

- GE effect on energy markets $d \ln q^f \approx \bar{\nu} d \ln E^f + \dots$, due to taxation

$$d \ln q^f = - \frac{\bar{\nu}}{1 + \bar{\gamma} + \text{Cov}_i(\tilde{\lambda}_i^f, \bar{\gamma}_i) + \bar{\nu} \bar{\lambda}^{\sigma f}} \sum_i \tilde{\lambda}_i^f J_i dt^e + \sum_i \beta_i d \ln p_i$$

- Climate damage $\bar{\gamma}_i = \gamma(T_i - T_i^*) T_i s^{E/S}$
- Trade and leakage effect: GE impact of t_j^e and $t_{j,k}^b$ on y_i and p_i

◦ Params: σ energy demand elast^y, s^e energy cost share, $\bar{\nu}$ energy supply inverse elas^y

Decomposing the welfare effects: gains from trade

- Start from the equilibrium where carbon tax $t_j^f = 0, t_{jk}^b = 0, \forall j$,
- Change in welfare: Linear approximation around that point \Rightarrow small changes in carbon tax $dt_j^f, \forall j$ and tariffs $dt_{j,k}^b, \forall j, k$

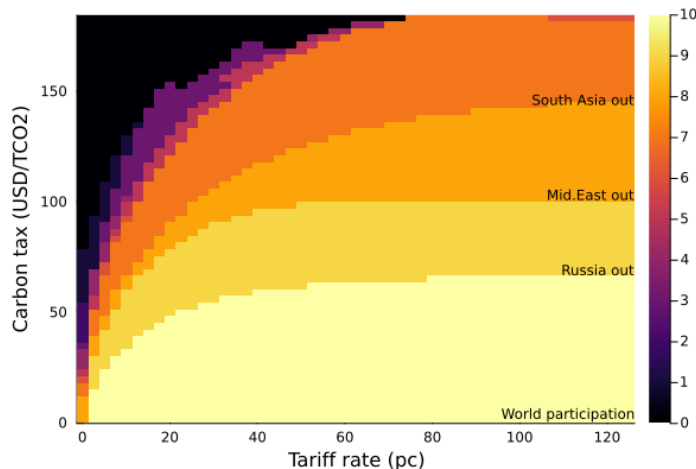
$$d \ln p = \mathbf{A}^{-1} \left[-(\mathbf{I} - \mathbf{T} \odot \mathbf{v}^y) \alpha^{y,qf} + \mathbf{T} (v^{ex} \odot \frac{1}{v} + v^{ef} \frac{\sigma^y}{1-s^e} + v^{ne}) - \left((\mathbf{I} - \mathbf{T} \odot \mathbf{v}^y) \alpha^{y,z} - \frac{\sigma^y}{1-s^e} \right) \bar{\gamma} \frac{1}{v} \right] d \ln q^f \\ + \left[-(\mathbf{I} - \mathbf{T} \odot \mathbf{v}^y) \alpha^{y,qf} + \mathbf{T} (v^{ef} \odot \frac{\sigma^y}{1-s^e}) \right] \odot \mathbf{J} d \ln t^e + \theta (\mathbf{T} \mathbf{S} \odot \mathbf{J} \odot d \ln t^b - \mathbf{T} (\mathbf{1} + \mathbf{S}') \odot (\mathbf{J} \odot d \ln t^b)')$$

- Params: \mathbf{S} Trade share matrix, \mathbf{T} income flow matrix, θ , Armington CES
- General equilibrium (and leakage) effects summarized in a complicated matrix \mathbf{A} : price affect energy demand, oil-gas extraction, energy trade balance, output, etc.

Details Market Clearing for good

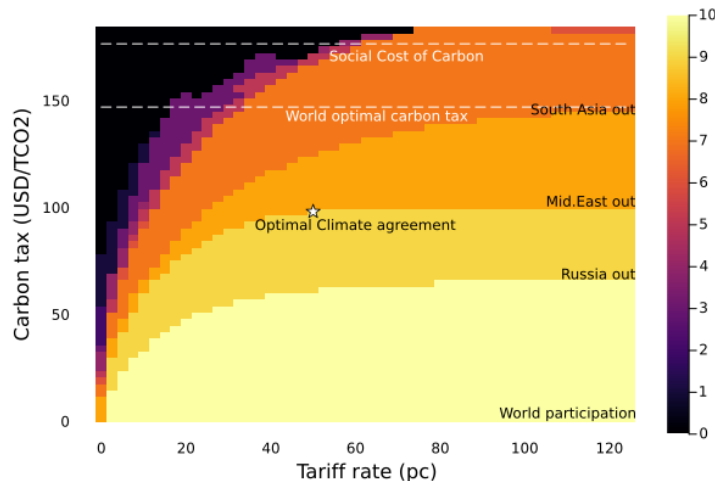
Climate Agreements: Intensive vs. Extensive Margin

- **Intensive margin:**
higher tax, emissions ↓, welfare ↑
- **Extensive margin:**
higher tax, participation ↓,
free-riding and emissions ↑



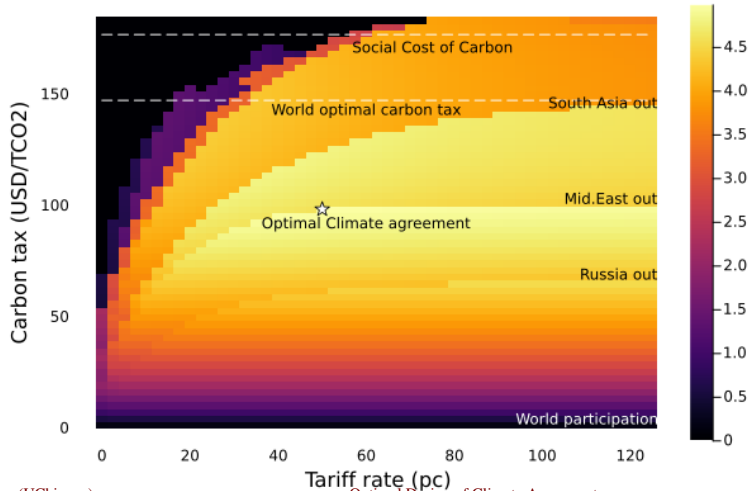
Optimal Climate Agreement

- ▶ Despite full freedom of instruments (t^e, t^b)
 ⇒ can not sustain an agreement with Russia & Middle East
 ⇒ need to reduce carbon tax from \$147 to \$98
- ▶ Intuition:
 relatively cold and closed economy, and fossil-fuel producers



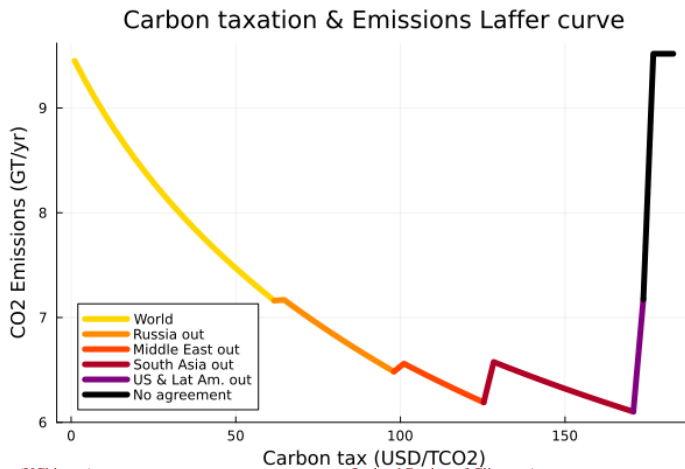
Climate agreement and welfare

Recover 90% of welfare gains, i.e. 5% out of 5.5% conso equivalent.



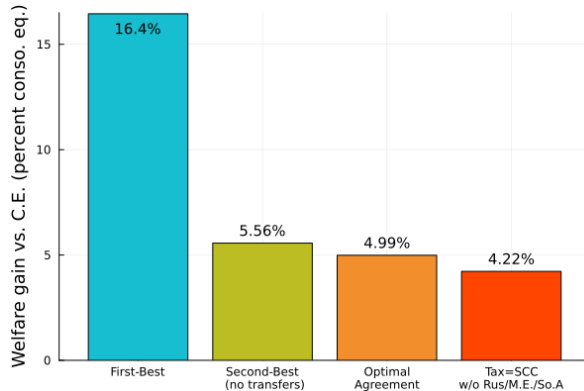
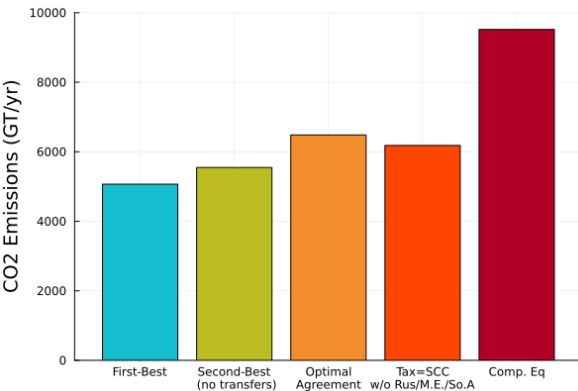
Carbon taxation, Participation and the Laffer Curve

Extensive margin: Higher tax may reduce participation, concentrates the cost of mitigation on the **remaining members** of the agreement \Rightarrow dampen welfare



Welfare and emission reduction: Different metrics!

- Agreements with tariffs recover 91% of welfare gains from the Second-Best – optimal carbon tax without transfers – at a cost of increasing emissions by 13%
- First-best allocation relies heavily on transfers to be able to impose a higher carbon tax



Coalition building

- ▶ Sequence of countries joining the climate agreement?
 - Country with the most interest in joining the club? Can the club be constructed?

Coalition building

► Sequence of "rounds" of the static equilibrium

- At each round (n) , countries decide to enter or not depending on the gain

$$\Delta_i \mathcal{U}_i(\mathbb{J}^{(n)}) = \mathcal{U}_i(\mathbb{J}^{(n)} \cup \{i\}, t^\varepsilon, t^b) - \mathcal{U}_i(\mathbb{J}^{(n)} \setminus \{i\}, t^\varepsilon, t^b)$$

- Construction evaluated at the optimal carbon tax $t^\varepsilon = 98\%$, and tariff $t^b = 50\%$.
- Sequential procedure – coming for free from our CDCP algorithm / squeezing procedure
- Idea analogous to Farrokhi, Lashkaripour (2024)

Coalition building

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► Result: sequence up to the optimal climate agreement

- Round 1: European Union
- Round 2: China, South East Asia (Asean)
- Round 3: North America, South Asia, Africa, Advanced East Asia, Latin America
- Round 4: Middle-East
- ✱ Stay out of the agreement: Russia+CIS

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Retaliation

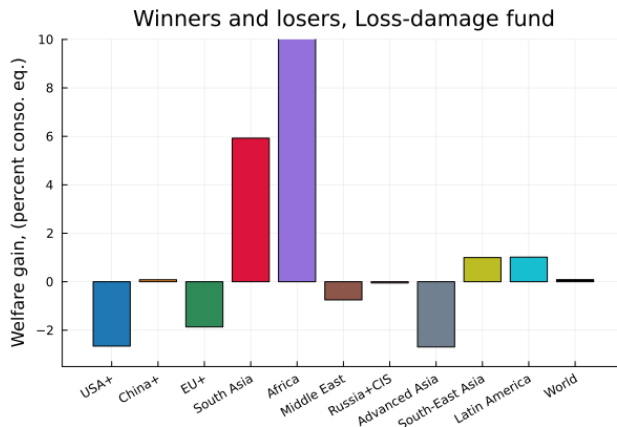
- ▶ Retaliation: Suppose the regions outside the agreement impose retaliatory tariffs to the club members
- ▶ Would that undermine the existence and the construction of the club?
- ▶ Exercise:
 - Countries outside the club $j \notin \mathbb{J}$ impose a tariffs $t_{ji} = \beta t_{ij}$ on club members i
 - Reaction function $\beta \in [0, 1]$.

Transfers – Loss and damage funds

- ▶ COP28 Major policy proposal:
Loss and damage funds for countries vulnerable to the effects of climate change
- ▶ Simple implementation in our context: lump-sum receipts of carbon tax revenues:

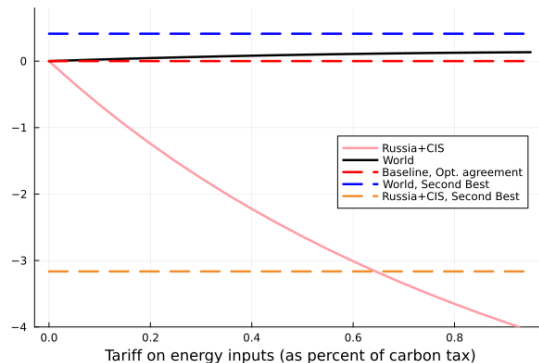
$$t_i^{ls} = (1 - \alpha)t^\varepsilon \varepsilon_i + \alpha \frac{1}{P} \sum_j t^\varepsilon \varepsilon_j$$

- ▶ In practice: transfers from large emitters to low emitters



Taxation of fossil fuels energy inputs

- ▶ Current climate club:
only imposes penalty tariffs on final goods, not on energy imports
 - Empirically relevant, c.f. Shapiro (2021):
inputs are more emission-intensives but trade policy is biased against final goods output
- ▶ Alternative: tax energy import from non-participants $t_{ij}^{bf} = \beta t^b \mathbb{1}\{i \in \mathbb{J}, j \notin \mathbb{J}\}$



Dynamic coalition formation

- Current “equilibrium”: $t_i^\varepsilon = 0, t_{ij}^b = 0$
- Optimal club equilibrium $t_i^\varepsilon = t^{\varepsilon*}, t_{ij}^b = t^{b*} \mathbb{1}\{i \in \mathbb{J}, j \notin \mathbb{J}\}$
- Optimal agreement follows the planner taxes and participation decision:

$$\mathbb{J}^* = \mathbb{J}(t^{\varepsilon*}, t^{b*})$$

► What is driving the coordination failure?

- Possible explanation: coalition building and *bargaining* may never reach such equilibrium:

$$\bar{\mathbb{J}}_{t_0}(0, 0) = \mathbb{I} \quad \xrightarrow[t \rightarrow T]{?} \quad \bar{\mathbb{J}}_T(t^{\varepsilon*}, t^{b*}) = \mathbb{J}^*$$

- Can we find a sequence $\mathbb{J}_t, t_t^f, t_t^b$ such that

$$\{\mathbb{J}_{t_0}, t_{t_0}^f, t_{t_0}^b\} = \{\bar{\mathbb{J}}_{t_0}, 0, 0\} \qquad \{\mathbb{J}_T, t_T^\varepsilon, t_T^b\} = \{\bar{\mathbb{J}}_T, t^{f*}, t^{b*}\}$$

- Instruments used by leader countries (e.g. E.U., U.S. or China?) to reach such agreement?

Conclusion

- ▶ In this project, I solve for the optimal design of climate agreements
 - Correcting for inequality, redistribution effects through energy markets and trade leakage, as well as free-riding incentives
- ▶ Climate agreement design jointly solves for:
 - The optimal choice of countries participating
 - The carbon tax and tariff levels, accounting for both the climate externality, redistributive effects and the participation constraints
- ▶ Optimal coalition depends on the trade-off between
 - the gain from cooperation and free riding incentives
 - the gain from trade, i.e. the cost of retaliatory tariffs

⇒ Need a large coalition and a carbon at 70% of the world optimum
- ▶ Extensions:
 - Extend this to dynamic settings: coalition building
 - Explore additional policy proposal to improve the optimal agreement

Conclusion

Thank you!

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Appendices

Optimal design with endogenous participation

► Equilibrium concepts and participation constraints:

- **Nash equilibrium** \Rightarrow unilateral deviation $\mathbb{J} \setminus \{j\}$, $\mathbb{J} \in \mathbb{S}(t^f, t^b)$ if:

$$\mathcal{U}_i(\mathbb{J}, t^e, t^b) \geq \mathcal{U}_i(\mathbb{J} \setminus \{i\}, t^e, t^b) \quad \forall i \in \mathbb{J}$$

- **Coalitional Nash-equilibrium** $\mathbb{C}(t^f, t^b)$: robust of sub-coalitions deviations:

$$\mathcal{U}_i(\mathbb{J}, t^f, t^b) \geq \mathcal{U}_i(\mathbb{J} \setminus \hat{\mathbb{J}}, t^f, t^b) \quad \forall i \in \hat{\mathbb{J}} \text{ \& \& } \forall \hat{\mathbb{J}} \subseteq \mathbb{J} \cup \{i\}$$

- Stability requires to check all potential coalitions $\mathbb{J} \in \mathcal{P}(\mathbb{I})$ as all sub-coalitions $\mathbb{J} \setminus \hat{\mathbb{J}}$ are considered as deviations in the equilibrium
- Requires to solve all the combination \mathbb{J}, t^f, t^b , by exhaustive enumeration.
 \Rightarrow becomes very computationally costly for $I = \#(\mathbb{I}) > 10$

back

Welfare and Pareto weights

- Welfare:

$$\mathcal{W}(\mathbb{J}) = \sum_{i \in \mathbb{I}} \omega_i u(c_i)$$

- Pareto weights ω_i :

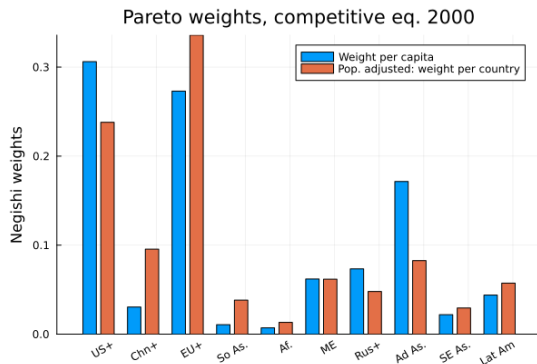
$$\omega_i = \frac{1}{u'(\bar{c}_i)}$$

for \bar{c}_i consumption in initial equilibrium
“without climate change“, i.e. year = 2020

- Imply no redistribution motive in $t = 2020$

$$\omega_i u'(\bar{c}_i) = \omega_j u'(\bar{c}_j) \quad \forall i, j \in \mathbb{I}$$

- Climate change, taxation, and climate agreement (tax + tariffs) have redistributive effects
 \Rightarrow change distribution of c_i



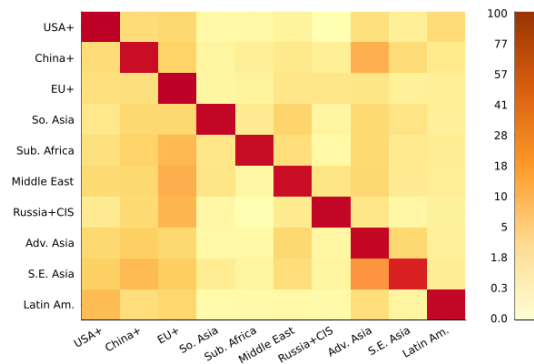
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Quantification – Trade model

- Armington Trade model:

$$s_{ij} \equiv \frac{c_{ij}p_{ij}}{c_i p_i} = a_{ij} \frac{((1+t_{ij})\tau_{ij}p_j)^{1-\theta}}{\sum_k a_{ik}((1+t_{ik})\tau_{ik}p_k)^{1-\theta}}$$

- CES $\theta = 5.63$ estimated from a gravity regression
- Iceberg cost τ_{ij} as projection of distance
 $\log \tau_{ij} = \beta \log d_{ij}$
- Preference parameters a_{ij} identified as remaining variation in the trade share s_{ij}
 \Rightarrow policy invariant


[back](#)

Step 0: Competitive equilibrium & Trade

- ▶ Each household in country i maximize utility and firms maximize profit
- ▶ Standard trade model results:
 - Consumption and trade:

$$s_{ij} = \frac{c_{ij}p_{ij}}{c_i p_i} = a_{ij} \frac{(\tau_{ij}(1+t_{ij}^b)p_j)^{1-\theta}}{\sum_k a_{ik}(\tau_{ik}(1+t_{ik}^b)p_k)^{1-\theta}} \quad \& \quad p_i = \left(\sum_j a_{ij}(\tau_{ij}p_j)^{1-\theta} \right)^{\frac{1}{1-\theta}}$$

- Energy consumption doesn't internalize climate damage:

$$p_i M P e_i = q^e$$

- Inequality, as measured in local welfare units:

$$\lambda_i = u'(c_i)$$

- “Local Social Cost of Carbon”, for region i

$$LCC_i = \frac{\partial \mathcal{W}_i / \partial \mathcal{E}}{\partial \mathcal{W}_i / \partial c_i} = \frac{\psi_i^{\mathcal{E}}}{\lambda_i} = \Delta_i \gamma (T_i - T_i^*) p_i y_i \quad (> 0 \text{ for warm countries})$$

Step 1: World First-best policy

- Maximizing welfare of the world Social Planner:

$$\mathcal{W} = \max_{\{\mathbf{t}, \mathbf{e}, \mathbf{q}\}_i} \sum_{i \in \mathbb{I}} \omega_i u(c_i) = \sum_{\mathbb{I}} \mathcal{W}_i$$

- Full array of instruments: cross-countries lump-sum transfers \mathbf{t}_i^{ls} , individual carbon taxes \mathbf{t}_i^f on energy e_i^f , unrestricted bilateral tariffs \mathbf{t}_{ij}^b
 - Budget constraint: $\sum_i \mathbf{t}_i^{ls} = \sum_i \mathbf{t}_i^f e_i^f + \sum_{i,j} \mathbf{t}_{ij}^b c_{ij} \tau_{ij} p_j$
- Maximize welfare subject to
- Market clearing for good $[\mu_i]$, market clearing for energy μ^e

back

Step 1: World First-best policy

► Social planner results:

- Consumption:

$$\omega_i u'(c_i) = \left[\sum_j a_{ij} (\tau_{ij} \omega_j \mu_j)^{1-\theta} \right]^{\frac{1}{1-\theta}} = \mathbb{P}_i \qquad \omega_i \frac{u'(c_i)}{\mathbb{P}_i} = \bar{\lambda}$$

- Energy use:

$$\omega_i \mu_i MPe_i = \mu^e + SCC$$

- Social cost of carbon:

$$SCC = \sum_j \omega_j \Delta_j \gamma (T_i - T_i^*) y_j \mu_j$$

- Decentralization:

large transfers to equalize marg. utility + carbon tax = SCC

$$t^e = SCC \qquad t_i^{lb} = c_i^* \mathbb{P}_i - w_i \ell_i + \pi_i^f \qquad s.t. \quad u'(c_i^*) = \bar{\lambda} \mathbb{P}_i / \omega_i$$

Step 2: World optimal Ramsey policy

- Maximizing welfare of the world Social Planner:

$$\mathcal{W} = \max_{\{\mathbf{t}, \mathbf{e}, \mathbf{q}\}_i} \sum_{i \in \mathbb{I}} \omega_i u(c_i) = \sum_{\mathbb{I}} \mathcal{W}_i$$

- One single instrument: uniform carbon tax \mathbf{t}^f on energy e_i^f
- Rebate tax lump-sum to HHs $\mathbf{t}_i^L = \mathbf{t}^e e_i^f + \mathbf{t}^e e_i^c$
- Ramsey policy: Primal approach, maximize welfare subject to
 - Budget constraint $[\lambda_i]$, Market clearing for good $[\mu_i]$, market clearing for energy
 - Optimality (FOC) conditions for good demands $[\eta_{ij}]$, energy demand $[v_i]$ & supply $[\theta_i]$, etc.
 - Trade-off faced by the planner:
 - (i) Correcting climate externality, (ii) Redistributive effects, (iii) Distort energy demand and supply (iv) Distort good demand

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Step 2: World optimal Ramsey policy

- The planner takes into account

- (i) the **marginal value of wealth** λ_i
- (ii) the **shadow value of good i** , from market clearing, μ_i :
- (iii) the **shadow value of bilateral trade ij** , from household FOC, η_{ij} :

w/ free trade $u'(c_i) = \lambda_i$

vs. w/ Armington trade $u'(c_i) = \lambda_i \left(\sum_{j \in \mathbb{I}} a_{ij} (\tau_{ij} p_j)^{1-\theta} \left[1 + \frac{\omega_j}{\omega_i} \frac{\mu_j}{\lambda_i} - \frac{\eta_{ij}}{\theta \lambda_i} (1-s_{ij}) \right]^{1-\theta} \right)^{\frac{1}{1-\theta}}$

- Relative welfare weights, representing inequality

$$\hat{\lambda}_i = \frac{\omega_i \lambda_i}{\bar{\lambda}} = \frac{\omega_i u'(c_i)}{\frac{1}{I} \sum_{j \in \mathbb{I}} \omega_j u'(c_j)} \leq 1 \quad \Rightarrow \quad \text{ceteris paribus, poorer countries have higher } \hat{\lambda}_i$$

Step 2: Optimal policy – Social Cost of Carbon

► Key objects: Local vs. Global Social Cost of Carbon:

- Marginal cost of carbon $\psi_i^\mathcal{E}$ for country i
- “Local social cost of carbon” (LCC) for region i :

$$LCC_i := \frac{\partial \mathcal{W}_i / \partial \mathcal{E}}{\partial \mathcal{W}_i / \partial w_i} = \frac{\psi_i^\mathcal{E}}{\lambda_i} = \Delta_i \gamma (T_i - T_i^*) y_i p_i$$

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- Social Cost of Carbon for the planner:

$$SCC := \frac{\partial \mathcal{W} / \partial \mathcal{E}}{\partial \mathcal{W} / \partial w} = \frac{\sum_{\mathbb{I}} \omega_i \psi_i^\mathcal{E}}{\frac{1}{I} \sum_{\mathbb{I}} \omega_i \lambda_i}$$

- Social Cost of Carbon integrates these inequalities:

$$SCC = \sum_{\mathbb{I}} \hat{\lambda}_i LCC_i = \sum_{\mathbb{I}} LCC_i + \mathbb{Cov}_i(\hat{\lambda}_i, LCC_i)$$

Step 2: Optimal policy – Other motives

► Taxing fossil energy has additional redistributive effects:

1. Through energy markets: distort supply, lowers eq. fossil price, benefit net importers
2. Distort energy demand, of countries that need more or less energy
3. Reallocate goods production, which is then supplied internationally

$$\text{Supply Redistrib}^{\circ sb} + \text{Demand Distort}^{\circ sb} - \text{Trade effect}^{sb} = \underbrace{C_{EE}^f}_{\text{agg. supply inv. elast}^y} \underbrace{\text{Cov}_i(\hat{\lambda}_i, e_i^f - e_i^x)}_{\text{energy T-o-T redistrib}^{\circ}} - \underbrace{\text{Cov}_i\left(\hat{v}_i, \frac{q^f(1-s_i^e)}{\sigma_i e_i}\right)}_{\text{demand distortion}} - q^f \underbrace{\mathbb{E}_j[\hat{\mu}_j]}_{\text{good T-o-T redistrib}^{\circ}}$$

○ Params: C_{EE}^f agg. fossil inv. elasticity, s_i^e energy cost share and σ_i energy demand elasticity

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◦ Params: \mathcal{C}_{EE}^f agg. fossil inv. elasticity, s_i^e energy cost share and σ_i energy demand elasticity

► Proposition 2: Optimal fossil energy tax:

$$\Rightarrow \quad \mathfrak{t}^f = \text{SCC}^{sb} + \text{Supply Redistribution}^{sb} + \text{Demand Distortion}^{sb} - \text{Trade effect}^{sb}$$

– Reexpressing demand terms:

$$\mathfrak{t}^e = \left(1 + \text{Cov}_i\left(\widehat{\lambda}_i^w, \frac{\widehat{\sigma}_i e_i}{1-s_i^e}\right)\right)^{-1} \left[\sum_{\mathbb{I}} \text{LCC}_i + \text{Cov}_i(\widehat{\lambda}_i^w, \text{LCC}_i) + \mathcal{C}_{EE}^f \text{Cov}_i(\widehat{\lambda}_i^w, e_i^f - e_i^x) - q^f \mathbb{E}_j[\widehat{\mu}_j] \right]$$

Step 3: Ramsey Problem with participation constraints

- ▶ Consider that countries can “exit” climate agreement.
- ▶ For a climate “club” of $\mathbb{J} \subset \mathbb{I}$ countries:
 - Countries $i \in \mathbb{J}$ are subject to a carbon tax τ^f
 - Countries $i \in \mathbb{J}$ can unilaterally leave, subject to retaliation tariff $\tau^{b,r}$ on goods and get consumption \tilde{c}_i
 - Countries $i \notin \mathbb{J}$ trade in goods subject to tariff τ^b with club members and countries outside the club. They still trade with the club members in energy at price q^f

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- ▶ Participation constraints:

$$u(c_i) \geq u(\tilde{c}_i) \quad [\nu_i]$$

- ▶ Welfare:

$$\mathcal{W} = \max_{\{t, e, q\}_i} \sum_{\mathbb{J}} \omega_i u(c_i) + \sum_{\mathbb{J}^c} \alpha \omega_i u(c_i)$$

Step 3: Ramsey Problem with participation constraints

► Participation constraints

$$u(c_i) \geq u(\tilde{c}_i) \quad [\nu_i]$$

► Proposition 3.1: Second-Best social valuation with participation constraints

- Participation incentives change our measure of inequality

$$\text{w/ trade:} \quad \omega_i(1+\nu_i)u'(c_i) = \left(\sum_{j \in \mathbb{I}} a_{ij}(\tau_{ij}p_j)^{1-\theta} \left[\omega_i \tilde{\lambda}_i + \omega_j \tilde{\mu}_j + \tilde{\eta}_{ij}(1-s_{ij}) \right]^{1-\theta} \right)^{\frac{1}{1-\theta}}$$

$$\Rightarrow \quad \hat{\tilde{\lambda}}_i = \frac{\omega_i(\tilde{\lambda}_i + \tilde{\mu}_i)}{\frac{1}{J} \sum_{j \in \mathbb{J}} \omega_i(\tilde{\lambda}_i + \tilde{\mu}_i)} \neq \hat{\lambda}_i$$

$$\text{vs. w/o trade} \quad \hat{\tilde{\lambda}}_i = \frac{\omega_i(1+\nu_i)u'(c_i)}{\frac{1}{J} \sum_{j \in \mathbb{J}} \omega_j(1+\nu_j)u'(c_j)} \neq \hat{\lambda}_i$$

- Similarly, the “effective Pareto weights” are $\alpha\omega_i$ for countries outside the club $i \notin \mathbb{J}$ and $\omega_i(\alpha - \nu_i)$ for retaliation policy on $i \in \mathbb{J}$

Step 3: Participation constraints & Optimal policy

► Proposition 3.2: Second-Best taxes:

- Taxation with imperfect instruments:
 - Climate change & general equilibrium effects on fossil market affects all countries $i \in \mathbb{I}$
 - Need to adjust for the "outside" countries $i \notin \mathbb{J}$ not subject to the tax, which weight on the energy market as $\vartheta_{\mathbb{J}^c} \approx \frac{E_{\mathbb{J}^c}}{E_{\mathbb{I}}} \frac{\nu \sigma}{q^f (1-s^f)}$
with ν fossil supply elasticity, σ energy demand elasticity and s^f energy cost share.
- Optimal fossil energy tax $t^f(\mathbb{J})$:

$$\Rightarrow t^f(\mathbb{J}) = \text{SCC} + \text{SVF}$$

$$= \frac{1}{1 - \vartheta_{\mathbb{J}^c}} \sum_{i \in \mathbb{I}} \tilde{\lambda}_i \text{LCC}_i + \frac{1}{1 - \vartheta_{\mathbb{J}^c}} C_{EE}^f \sum_{i \in \mathbb{I}} \tilde{\lambda}_i (e_i^f - e_i^x) - \sum_{i \in \mathbb{J}} \tilde{\lambda}_i \frac{q^f (1-s_i^f)}{\sigma}$$

- Optimal tariffs/export taxes $t^{b,r}(\mathbb{J})$ and $t^b(\mathbb{J})$: In search for a closed-form expression
As of now, only opaque system of equations (fixed point w/ demand/multipliers)

Welfare decomposition

► Armington model of trade with energy:

- Linearized market clearing

$$\left(\frac{dp_i}{dp_i} + \frac{dy_i}{y_i}\right) = \sum_k t_{ik} \left[\left(\frac{p_k y_k}{v_k}\right) (d \ln p_k + d \ln y_k) + \frac{q^f e_k^x}{v_k} d \ln e_k^x - \frac{q^f e_k^f}{v_k} d \ln e_k^f + \frac{q^f (e_k^x - e_k^f)}{v_k} d \ln q^f \right. \\ \left. + \theta \sum_h (s_{kh} d \ln t_{kh} - (1 + s_{ki}) d \ln t_{ki}) + (\theta - 1) \sum_h (s_{kh} d \ln p_h - d \ln p_i) \right]$$

- Fixed point for price level $d \ln p_i$

$$\left[(\mathbf{I} - \mathbf{T} \odot \mathbf{v}^y) [\mathbf{I} - \alpha^{y,p} \odot \mathbf{I}] + \mathbf{T} (v^{e^x} \odot \frac{1}{v}) + \mathbf{T} v^{e^f} \frac{\sigma^y}{1 - s^e} - (\theta - 1) (\mathbf{TS} - \mathbf{T}') - \left((\mathbf{I} - \mathbf{T} \odot \mathbf{v}^y) \alpha^{y,z} - \frac{\sigma^y}{1 - s^e} \right) \odot \bar{\gamma} \mathbf{I} \odot \left(\frac{\lambda^x}{v} \right)' \right] d \ln \mathbf{p} = \\ \left[- (\mathbf{I} - \mathbf{T} \odot \mathbf{v}^y) \alpha^{y,q^f} + \mathbf{T} (v^{e^x} \odot \frac{1}{v} + v^{e^f} \frac{\sigma^y}{1 - s^e} + v^{ne}) - \left((\mathbf{I} - \mathbf{T} \odot \mathbf{v}^y) \alpha^{y,z} - \frac{\sigma^y}{1 - s^e} \right) \bar{\gamma} \frac{1}{v} \right] d \ln q^f \\ + \left[- (\mathbf{I} - \mathbf{T} \odot \mathbf{v}^y) \alpha^{y,q^f} + \mathbf{T} (v^{e^f} \odot \frac{\sigma^y}{1 - s^e}) \right] \odot \mathbf{J} d \ln \mathbf{t}^e + \theta (\mathbf{TS} \odot \mathbf{J} \odot d \ln \mathbf{t}^b - \mathbf{T} (\mathbf{1} + \mathbf{S}') \odot (\mathbf{J} \odot d \ln \mathbf{t}^b)')$$

Quantification – Firms

- Production function $y_i = \mathcal{D}_i^y(T_i) z_i F(k, \varepsilon(e^f, e^r))$

$$F_i(\varepsilon(e^f, e^c, e^r), \ell) = \left[(1 - \epsilon)^{\frac{1}{\sigma_y}} (\bar{k}^\alpha \ell^{1-\alpha})^{\frac{\sigma_y-1}{\sigma_y}} + \epsilon^{\frac{1}{\sigma_y}} \left(z_i^e \varepsilon_i(e^f, e^c, e^r) \right)^{\frac{\sigma_y-1}{\sigma_y}} \right]^{\frac{\sigma_y}{\sigma_y-1}}$$

$$\varepsilon_i(e^f, e^c, e^r) = \left[(\omega^f)^{\frac{1}{\sigma_e}} (e^f)^{\frac{\sigma_e-1}{\sigma_e}} + (\omega^c)^{\frac{1}{\sigma_e}} (e^c)^{\frac{\sigma_e-1}{\sigma_e}} + (\omega^r)^{\frac{1}{\sigma_e}} (e^r)^{\frac{\sigma_e-1}{\sigma_e}} \right]^{\frac{\sigma_e}{\sigma_e-1}}$$

- Calibrate TFP z_i to match $y_i = GDP_i$ per capita in 2019-23 (avg. PPP).
- Technology: $\omega^f = 56\%$, $\omega^c = 27\%$, $\omega^r = 17\%$, $\epsilon = 12\%$ for all i
- Calibrate (z_i^e) to match Energy/GDP $q^e e_i / p_i y_i$

- Damage functions in production function y :

$$\mathcal{D}_i^y(T) = e^{-\gamma_i^{\pm, y} (T - T_i^*)^2}$$

- Asymmetry in damage to match empirics with $\gamma^y = \gamma^{+, y} \mathbb{1}_{\{T > T_i^*\}} + \gamma^{-, y} \mathbb{1}_{\{T < T_i^*\}}$
- Today $\gamma_i^{\pm, y} = \bar{\gamma}^{\pm, y}$ & $T_i^* = \bar{\alpha} T_{it_0} + (1 - \bar{\alpha}) T^*$

Quantification – Energy markets

- ▶ Fossil production e_{it}^x and reserve \mathcal{R}_{it}
 - Cost $\mathcal{C}_i(e^x, \mathcal{R}) = \frac{\bar{\nu}_i}{1+\nu_i} \left(\frac{e^x}{\mathcal{R}} \right)^{1+\nu_i} \mathcal{R}$
 - Now: $\bar{\nu}_i$ to match extraction data e_i^x , \mathcal{R}_{it} calibrated to *proven reserves* data from BP. ν_i extraction cost curvature to match profit $\pi_i^f = \frac{\bar{\nu}_i \nu_i}{1+\nu_i} \left(\frac{e_i^x}{\mathcal{R}_i} \right)^{\nu_i} \mathcal{R}_i \mathbb{P}_i$
 - Future: Choose $(\bar{\nu}_i, \nu_i, \mathcal{R}_i)$ to match marginal cost \mathcal{C}_e & extraction data e_i^x (BP, IEA)
- ▶ Coal and Renewable: Production \bar{e}_i^r, \bar{e}_i^x and price q_i^c, q_i^r
 - Calibrate $q_i^c = z^c \mathbb{P}_i, q_i^r = z^r \mathbb{P}_i$
Choose z_i^c, z_i^r to match the energy mix (e_i^f, e_i^c, e_i^r)
- ▶ Population dynamics
 - Match UN forecast for growth rate / fertility

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Calibration

Table: Baseline calibration (★ = subject to future changes)

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Technology & Energy markets

α	0.35	Capital share in $F(\cdot)$	Capital/Output ratio
ϵ	0.12	Energy share in $F(\cdot)$	Energy cost share (8.5%)
σ	0.3	Elasticity capital-labor vs. energy	Complementarity in production (c.f. Bourany 2022)
ω^f	0.56	Fossil energy share in $e(\cdot)$	Oil-gas/Energy ratio
ω^c	0.27	Coal energy share in $e(\cdot)$	Coal/Energy ratio
ω^r	0.17	Non-carbon energy share in $e(\cdot)$	Non-carbon/Energy ratio
σ_e	2.0	Elasticity fossil-renewable	Slight substitutability & Study by Stern
δ	0.06	Depreciation rate	Investment/Output ratio
\bar{g}	0.01★	Long run TFP growth	Conservative estimate for growth

Preferences & Time horizon

ρ	0.015	HH Discount factor	Long term interest rate & usual calib. in IAMs
η	1.5	Risk aversion	Standard Calibration
n	0.0035	Long run population growth	Average world population growth

Climate parameters

ξ^f	2.761	Emission factor – Oil & natural gas	Conversion 1 $MTOE \Rightarrow 1 MT CO_2$
ξ^c	3.961	Emission factor – Oil & natural gas	Conversion 1 $MTOE \Rightarrow 1 MT CO_2$
χ	2.3/1e6	Climate sensitivity	Pulse experiment: 100 $GtC \equiv 0.23^\circ C$ medium-term warming
δ_s	0.0004	Carbon exit from atmosphere	Pulse experiment: 100 $GtC \equiv 0.15^\circ C$ long-term warming
γ^\oplus	0.003406	Damage sensitivity	Nordhaus, Barrage (2023)
γ^\ominus	$0.25 \times \gamma^\oplus$	Damage sensitivity	Nordhaus' DICE & Rudik et al (2022)
α^T	0.5	Weight historical climate for optimal temp.	Marginal damage correlated with initial temp.
T^\star	14.5	Optimal yearly temperature	Average yearly temperature/Developed economies