

Virtual Seminar on Climate Economics



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The Optimal Design of Climate Agreements

Inequality, Trade, and Incentives for Climate Policy

Thomas Bourany

COLUMBIA / EIEF

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 - **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”

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 - **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”
- ⇒ How can we design a climate agreement, to address **free-riding and endogenous participation** as well as **redistributive effects**, and effectively fight climate change?

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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

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► In this paper:

- I build a rich Integrated-Assessment Model (IAM) with heterogeneous countries, energy markets, international trade, and countries’ **strategic behaviors**

► Preview of the results:

- **Impossibility result**: Because of free-riding, we cannot achieve **both** a **high carbon tax** and **complete participation**, despite **arbitrary** trade tariffs
- **Optimal club design**: (i) need to **lower the carbon tax** below the Pigouvian benchmark, (ii) impose large trade tariffs and (iii) leave several fossil-fuel producers outside the agreement

Literature

- ▶ Theoretical model of climate agreements: cooperation
 - *Climate clubs and cooperation*: Nordhaus (2015), Barrett (1994, 2003, 2013, 2022), Carraro, Siniscalco (1993), Chander, Tulkens (1995, 1997), Dutta, Radner (2004, 2006), Harstad (2012), Maggi (2016), Hagen, Schneider (2021), Iverson (2024)
 - *Coalition building*: Ray, Vohra (2015), Nordhaus (2021), Harstad (2023), Maggi, Staiger (2022)
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- ▶ IAM and macroeconomics of climate change and carbon taxation
 - *RA model*: Nordhaus DICE (1996-), Weitzman (2014), Golosov et al. (2014), Hassler et al (2019)
 - *HA model*: Bourany (2024), Krusell, Smith (2022), Kotlikoff, Kubler, Polbin, Scheidegger (2021)
 - *Spatial models*: Cruz, Rossi-Hansberg (2022, 2023) among others
- ⇒ ***Strategic and constrained policy with heterogeneous countries & trade***

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 - ⇒ ***Strategic and constrained policy with heterogeneous countries & trade***
- ▶ Trade policy and environment policies:
 - *Trade and carbon policies*: Farrokhi, Lashkaripour (2024), Kortum, Weisbach (2023), Böhringer, Carbone, Rutherford (2012, 2016), Hsiao (2022), Shapiro (2021), Caliendo et al. (2024), Copeland, Taylor, (2004), Bourany, Rosenthal-Kay (2025)
 - *Tariff policy*: Ossa (2014), Costinot et al. (2015), Adao, Costinot (2022), Antràs et al. (2022)
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1. Introduction
2. Model:
An Integrated Assessment Model with Heterogenous Countries and Trade
3. Climate Agreements Design
4. Quantification
5. Policy Benchmarks:
Optimal Policy without Free-riding Incentives
6. Main result:
The Optimal Climate Agreement
7. Extensions
8. Conclusion

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Model

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

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

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2. Representative final good firm:

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

- Climate externality: $\mathcal{D}_i^y(\mathcal{E})$, Income inequality z_i , Carbon tax: t_i^ε

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3. Energy markets

- Fossil-fuels (oil-gas) producer, extracting e_i^x , selling on international market, at price q^f :

$$\pi_i^f = \max_{e_i^x} q^f e_i^x - \mathcal{C}_i^f(e_i^x) \mathbb{P}_i \quad E^f = \sum_{i \in \mathbb{I}} e_i^f = \sum_{i \in \mathbb{I}} e_i^x$$

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- Coal e_i^c produced at price $q_i^c = z_i^c \mathbb{P}_i$ ◦ Renewables e_i^r produced at price $q_i^r = z_i^r \mathbb{P}_i$

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Climate agreement design: “rules of the game”

- **Definition:** A climate agreement is a set $\{\mathbb{J}, t^e, t^b, t^f\}$ of $\mathbb{J} \subseteq \mathbb{I}$ countries and a C.E. s.t.:
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 - Single **uniform carbon tax**. Corresponds to the Pigouvian (First-Best) benchmark

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 - Single uniform tariff on goods. **Extension** considering carbon-tariffs ($\sim$ CBAM)

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 - Provides “issue linkage” between the trade and climate policies

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 - Two cases: with / without oil-gas-specific tariffs. Baseline: **without**, avoid double tax (energy+carbon)

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 - Local, lump-sum rebate of taxes: $t_i^{ls} = \mathbf{t}^\varepsilon(e_i^f + e_i^c) + \sum_{j \notin \mathbb{J}} \mathbf{t}^b \tau_{ij} c_{ij} p_j$

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 - No cross-countries transfers allowed. Assumption relaxed in an extension: “climate fund”

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 - Countries outside the club $k \notin \mathbb{J}$ have passive policies, $t_{ki}^b = 0$ and $t_k^\varepsilon = 0$.
 - No retaliation. Assumption relaxed in an extension: coordination to retaliate and trade wars

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 - Countries outside the club $k \notin \mathbb{J}$ have passive policies, $t_{ki}^b = 0$ and $t_k^\varepsilon = 0$.
 - Indirect utility $\mathcal{U}_i(\mathbb{J}, \mathbf{t}^\varepsilon, \mathbf{t}^b, \mathbf{t}^f) \equiv u(\mathcal{D}_i^y(\mathcal{E}(\mathbb{J}, \mathbf{t}^\varepsilon, \mathbf{t}^b, \mathbf{t}^f)) c_i(\mathbb{J}, \mathbf{t}^\varepsilon, \mathbf{t}^b, \mathbf{t}^f))$

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 - If j **exits the agreement**, club members $i \in \mathbb{J}$ impose uniform tariffs $t_{ij}^b = t^b$ on goods from j
 - Countries in the club benefit from free-trade $t_{ij}^b = 0$ (or “status-quo” policy).
 - Countries in the club trade oil-gas at price q^f . Countries outside: $q^f(1-t^f)$
 - Local, lump-sum rebate of taxes: $t_i^{ls} = t^e(e_i^f + e_i^c) + \sum_{j \notin \mathbb{J}} t^b \tau_{ij} c_{ij} p_j$
 - Countries outside the club $k \notin \mathbb{J}$ have **passive policies**, $t_{ki}^b = 0$ and $t_k^e = 0$.
 - Indirect utility $\mathcal{U}_i(\mathbb{J}, t^e, t^b, t^f) \equiv u(\mathcal{D}_i^y(\mathcal{E}(\mathbb{J}, t^e, t^b, t^f)) c_i(\mathbb{J}, t^e, t^b, t^f))$
- **Equilibrium concepts:**
- Unilateral participation decision of i , $\mathbb{J} \setminus \{i\}$, $\Rightarrow$ **Nash equilibrium**
- Coalition $\mathbb{J}$ stable if
$$\mathcal{U}_i(\mathbb{J}, t^e, t^b, t^f) \geq \mathcal{U}_i(\mathbb{J} \setminus \{i\}, t^e, t^b, t^f) \quad \forall i \in \mathbb{J}$$
- Sub-coalitional deviation $\Rightarrow$ **Coalitional Nash equilibrium**

Optimal design with endogenous participation

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

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

- Current design:

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

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

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

- Solution method: “squeezing procedure”, as Jia (2008), AFT (2017), Arkolakis Eckert Shi (2023) extended to handle participation constraints, Approach, details, Deviations, Solution methods

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Quantification: Climate and parametrization

► Climate block: Climate System

- Static economic model: decisions taken “once and for all”, e.g. $\mathcal{E} = \sum_i e_i^f + e_i^c$.
- “Dynamic” climate system: $\dot{S}_t = \mathcal{E} - \delta_s S_t, \quad T_{it} = \bar{T}_{i0} + \Delta_i S_t$
- Quadratic damage functions as in Nordhaus-DICE: $\mathcal{D}(T_{it} - T_i^*) = e^{-\gamma(T_{it} - T_i^*)^2}$
- Feedback in Present discounted value: $\mathcal{D}_i^y(\mathcal{E}) = \bar{\rho} \int_0^\infty e^{-(\rho - n + (1 - \eta)\bar{g})t} \mathcal{D}(T_{it} - T_i^*) dt$

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- **Estimate** γ from trade data (as Rudik, Lyn, Tan, and Ortiz-Bobea (2021)) Damage, Gravity

$$\log \mathbb{E}[X_{ij}/X_{ii}] = \beta_0(T_{jt} - T_{it}) + \beta_1(T_{jt}^2 - T_{it}^2) + \varsigma_{ij} + \varsigma_t + \Gamma' W_{it} + \Omega' W_{jt}$$

$$\Rightarrow \gamma = 0.012 \approx 3 \times \gamma_{DICE}$$

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$$\Rightarrow \gamma = 0.012 \approx 3 \times \gamma_{DICE}$$

► Pareto weights ω_i , Negishi, to imply no redistribution motive

- $\omega_i = \frac{1}{u'(\bar{c}_i)}$, for $\bar{c}_i$ conso in initial equilibrium $t = 2020$ w/o climate change Details Pareto weights

► Standard functional forms:

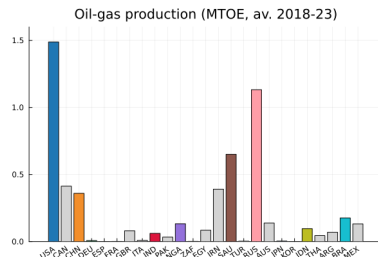
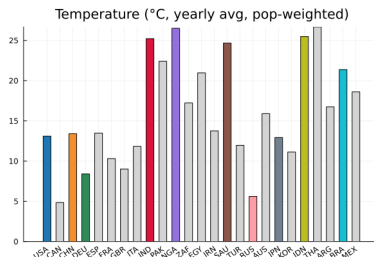
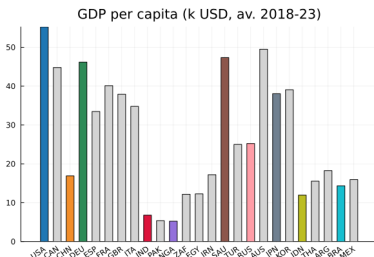
- CRRA utility, Nested CES production, Iso-elastic fossil fuel extraction Details Functional forms

Quantification: Matching countries level data

► Sample of 32 “countries”: incl. US, China, India, Nigeria, Saudi Arabia, Russia, Japan, Brazil, etc..

► Parameters matching country-level data (avg. 2018-2023) Details calibration Details country-level moments

- TFP $z_i \Rightarrow$ GDP y_i , Population p_i , Temperature T_{i0} , Pattern scaling Δ_i
- Mix: oil-gas e_i^f , Coal e_i^c , Low-carbon e_i^r , energy share, oil-gas prod^o e_i^x , reserves $\mathcal{R}_i$, rents π_i^f
- Trade: cost τ_{ij} projected on distance, preferences a_{ij} to match import shares s_{ij}



Details Trade shares – details

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Optimal policy benchmarks

- ▶ Policy benchmarks, without free-riding incentives
 - **First-Best**, Social planner maximizing global welfare with unlimited instruments
 - Pigouvian result: Carbon tax = Social Cost of Carbon (SCC) = $\partial \mathcal{W} / \partial \mathcal{E} / u'(c_i)$
 - Relies heavily on cross-country transfers to offset redistributive effects $\phi_i = \omega_i \mathcal{U}'(c_i) = \omega_j \mathcal{U}'(c_j)$

Optimal policy benchmarks

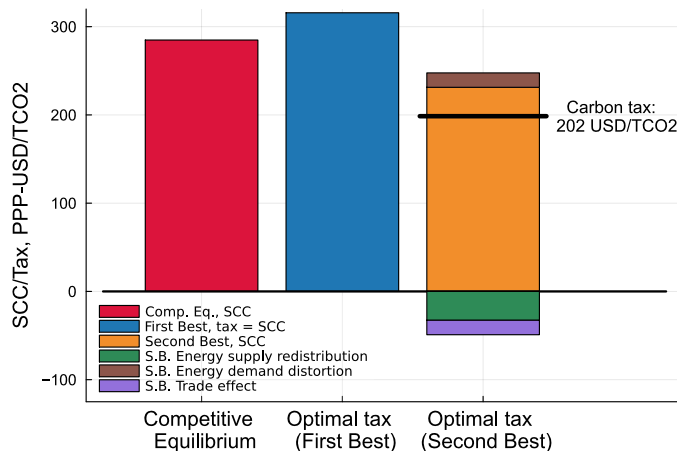
► Policy benchmarks, without free-riding incentives

- **First-Best**, Social planner maximizing global welfare with unlimited instruments
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 - Relies heavily on cross-country transfers to offset redistributive effects $\phi_i = \omega_i \mathcal{U}'(c_i) = \omega_j \mathcal{U}'(c_j)$
- **Second-Best**: Social planner, single carbon tax without transfers
 - Optimal carbon tax t^e correct climate externality, but also accounts for:
 - (i) Redistribution motives, and G.E. effects on (ii) energy markets and (iii) trade leakage

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

- Details: **CE**, **First-Best**, **Second-Best**, **Club policy**
- Companion paper: Bourany (2024), *Climate Change, Inequality, and Optimal Climate Policy*
- **Unilateral policy**: local planners choose their own optimal climate-trade policy, see Farrokhi, Laksharipour (2025), Kortum, Weisbach (2022) **Nash-Unilateral Policies**

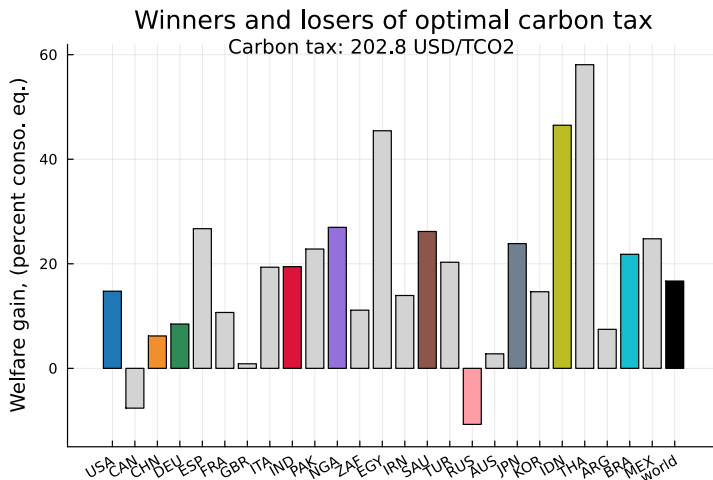
Second-Best climate policy



- Accounting for redistribution and lack of transfers
 ⇒ implies a carbon tax lower than the Social Cost of Carbon (SCC), from \$230 to \$200/ tCO_2 .

Gains from cooperation – World Optimal policy

- ▶ Optimal carbon tax
Second Best: $\sim \$200/tCO_2$
- ▶ Reduce fossil fuels / CO_2 emissions by 55% compared to the Competitive equilibrium (Business as Usual, BAU)
- ▶ Welfare difference between world optimal policy vs. comp. eq./BAU



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Main result and Intuition

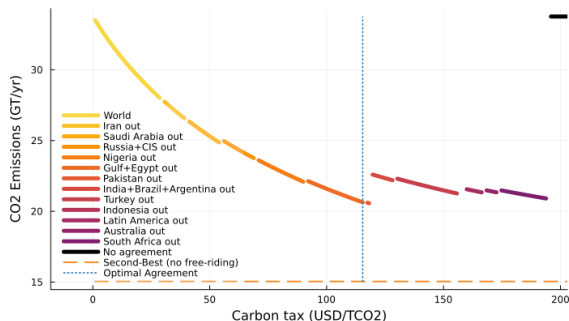
- ▶ The optimal climate agreement navigates the **intensive** and **extensive** margin tradeoff:
 - **Participation:** most countries in the world with the exception of: *Russia, former Soviet countries, Saudi Arabia, Gulf countries, Egypt, Iran, Nigeria*
 - **Carbon tax:** reduce carbon tax from \$200 to \$120/ tCO_2
 - **Trade tariffs:** impose substantial tariff 90% on the goods from non-members

Main result and Intuition

- ▶ The optimal climate agreement navigates the **intensive** and **extensive** margin tradeoff:
 - **Participation:** most countries in the world with the exception of: *Russia, former Soviet countries, Saudi Arabia, Gulf countries, Egypt, Iran, Nigeria*
 - **Carbon tax:** reduce carbon tax from \$200 to \$120/tCO₂
 - **Trade tariffs:** impose substantial tariff 90% on the goods from non-members
 - ▶ **Mechanism:**
 - Countries participate depending on $\left\{ \begin{array}{l} \text{(i) the cost of distortionary carbon taxation} \\ \text{(ii) the cost of tariffs (= the gains from trade)} \end{array} \right.$
 - Russia/Middle East/South Asia do not join the club for high carbon tax *for any tariffs* when cost of taxing fossil-fuels $\gg$ cost of tariffs / autarky
- ⇒ Result, we need to decrease the carbon tax: *reduce ambition*

Laffer curve for carbon taxation

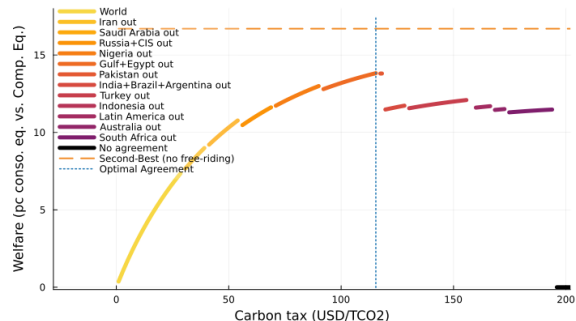
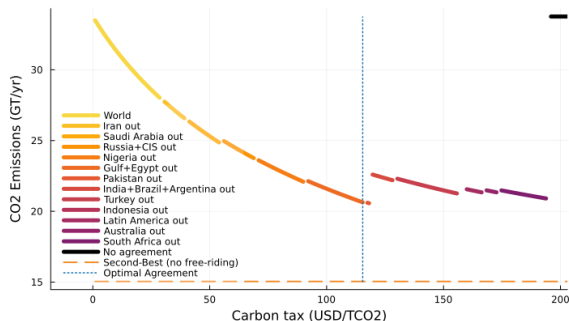
- Due to free-riding incentives, **cannot reach** globally optimal carbon tax $t^{\varepsilon,*} = \$200$



Emissions $\mathcal{E}$ (in $GtCO_2/yr$) and welfare $\mathcal{W}$ as function of the carbon tax t^{ε} , with tariff $t^b = 90\%$.

Laffer curve for carbon taxation

- Due to free-riding incentives, **cannot reach** globally optimal carbon tax $t^{\varepsilon,*} = \$200$
- Need to lower the carbon tax to \$120 to **increase participation**:
Improve welfare by sharing the costs of carbon mitigation with *more countries*



Emissions $\mathcal{E}$ (in $GtCO_2/yr$) and welfare $\mathcal{W}$ as function of the carbon tax t^{ε} , with tariff $t^b = 90\%$.

Climate Agreements: Intensive vs. Extensive Margin

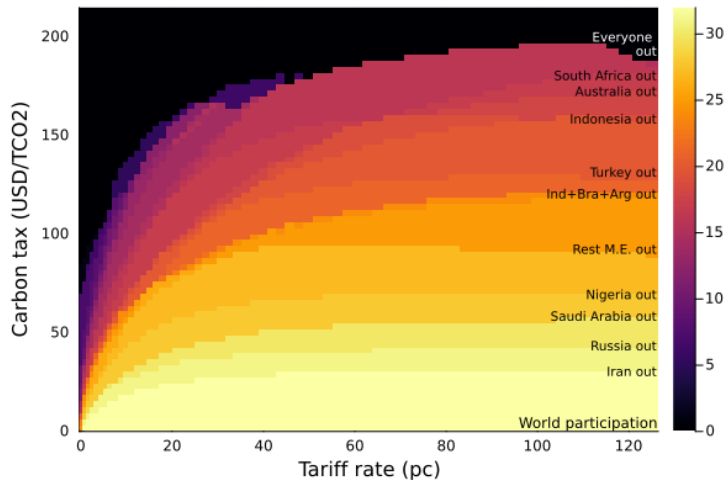
► Intensive margin:

given a coalition:

higher tax $t^{\mathcal{E}}$, emissions $\mathcal{E} \downarrow$,
improve welfare $\mathcal{W} \uparrow$

► Extensive margin:

carbon tax also deters
participation
individual countries free-ride
increasing emissions $\mathcal{E} \uparrow$



Optimal Climate Agreement

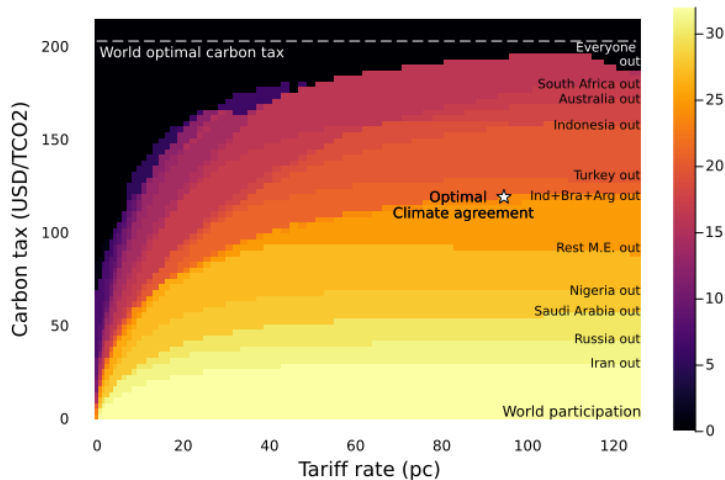
► Despite full discretion of instruments (t^e, t^b), we cannot sustain an agreement with Russia, Middle East, South-Asia & South America

⇒ need to **reduce carbon tax** from \$200 to \$120

⇒ Beneficial to **leave several fossil-fuel producers outside the agreement**
e.g. no incentive for Russia to join: cold, closed to trade, large fossil-fuel producer

Graph welfare

Mechanisms

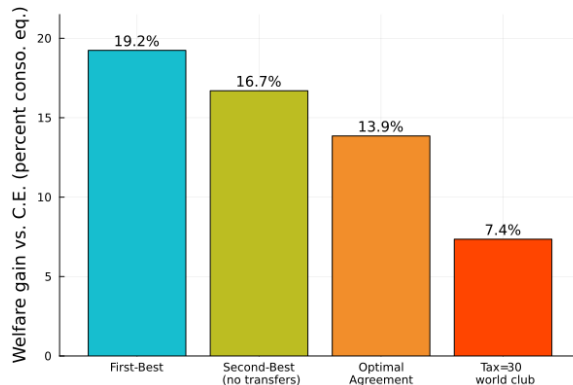
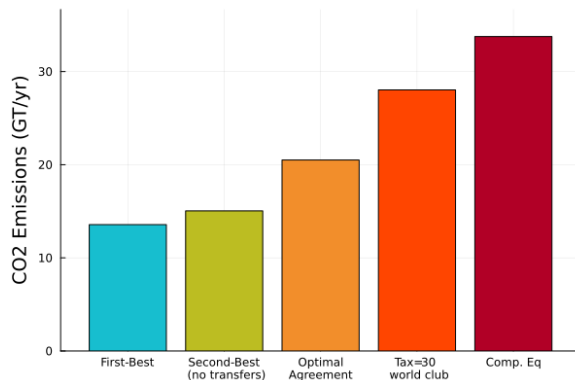


Emission reduction vs. Welfare: Different metrics!

- Agreements with tariffs recover 83% of welfare gains from the Second-Best – optimal carbon tax without transfers – at a cost of increasing emissions by 36%

Emission reduction vs. Welfare: Different metrics!

- Agreements with tariffs recover 83% of welfare gains from the Second-Best – optimal carbon tax without transfers – at a cost of increasing emissions by 36%
 - Setting policy “wrongly” at $t^E = SCC = \$230$: *participation collapses, no agreement*
 - Carbon tax with full participation, (e.g. FL 2025), $t^E = \$30$, *intensive margin* ↓



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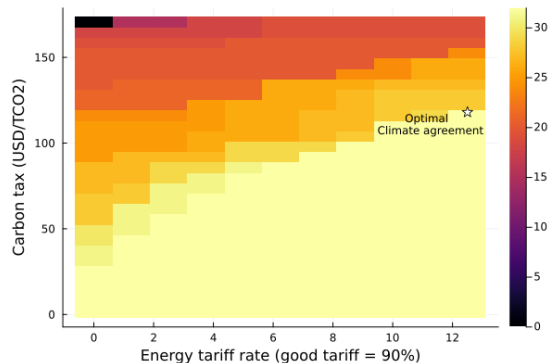
Taxation of fossil fuels energy inputs

- ▶ Current climate club:
Tariffs only on final goods, not energy imports
- ▶ Alternative: Fossil-fuels specific tariffs t^f on non-members $\sim$ price cap on oil-gas exports

$$q_{\mathbb{J}}^f = (1 + t^f) q_{\mathbb{I} \setminus \mathbb{J}}^f$$

if non-members export fossil fuels to the club

- ▶ Optimal tariffs $t^{bf} / q_{\mathbb{J}}^f = 15\%$
 - Compares to the \$60 price-cap from EU (out of $\sim$ \$100 /barrel) on Russian oil (!)
- ⇒ Include fossil fuels exporters
- ⇒ However, can't include marginal countries (e.g. India, Brazil) with higher carbon tax



Extensions

1. Coalition building [details](#)
 - Sequential procedure: Europe as first mover, then US & Asia, then developing countries
2. Transfers – Climate fund, c.f. COP29's proposal, [details](#)
 - Optimal size: small! Advanced economies lose from lump-sum transfers to developing countries
3. Carbon Border Adjustment Mechanism (CBAM), c.f. EU policy [details](#)
 - Still need a very high carbon tariff to incentivize participation
4. Fossil-fuels specific tariffs $\sim$ price cap on oil-gas exports, [details](#)
 - Target energy rent of fossil-fuel producers:
can induce their participation but can not increase the optimal carbon tax t^E
5. Retaliation – Trade war between club and non-club members, [details](#)
 - Moderate retaliation induce a lower carbon tax, Large “trade war” induces “mutual destruction” and can promote cooperation

Conclusion

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

⇒ Need a large coalition at a cost of lowering the carbon tax from the world optimum \$200 to \$120
- ▶ Future research:
 - Dynamic policy games, bargaining, and coalition building

Conclusion

Thank you!

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Appendices

Optimal design with endogenous participation

- ▶ Why uniform policy instruments t^ε and t^b for all club members:
 - Our social planner/designer solution represents the outcome of a “bargaining process” between countries (with bargaining weights ω_i).
 - Deviation from Coase theorem:
 - With transaction/bargaining cost: impossible to reach a consensual decision on $I + I \times I$ instruments $\{t_i^\varepsilon, t_{ij}^b\}_{ij}$
 - Such costs increase exponentially in the number of countries I

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 - Deviation from Coase theorem:
 - With transaction/bargaining cost: impossible to reach a consensual decision on $I + I \times I$ instruments $\{t_i^\varepsilon, t_{ij}^b\}_{ij}$
 - Such costs increase exponentially in the number of countries I
- ▶ Optimal – country specific – carbon taxes:
 - Without free-riding / exogeneous participation

$$t_i^\varepsilon = \frac{1}{\phi_i} t^\varepsilon \propto \frac{1}{\omega_i u'(c_i)} [SCC + SCF - SCT]$$

- With participation constraints: multiplier $\nu_i(\mathbb{J})$

$$t_i^\varepsilon \propto \frac{1}{(\omega_i + \nu_i(\mathbb{J})) u'(c_i)} [SCC + SCF - SCT]$$

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

Climate club design:

- Separation of the joint problem into inner and outer problems, s.t. participation constraints

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

- Current design:

- (i) choose taxes $\{t^e, t^b\}$ [outer problem]
- (ii) choose the coalition $\mathbb{J}$ s.t. participation constraints hold [inner problem]

► Computation:

M policies (grid search), 2^N choices of coalition (include both unilateral and subcoalition dev.)

- Alternative

- (i) choose the coalition $\mathbb{J}$ [outer problem]
- (ii) choose taxes $\{t^e, t^b\}$ [inner problem]
- (iii) check participation constraints for $(\mathbb{J}, t^e, t^b)$

► Computation: 2^N choices of coalition, M policies (grid search?), N unilateral deviations

Country deviation and policy

- ▶ Consider coalition $\mathbb{J}$. Suppose we search for optimal policy $\mathbf{t}^{\varepsilon}(\mathbb{J}), \mathbf{t}^b(\mathbb{J})$
 - Requires to compute allocation $\mathcal{U}_i(\mathbb{J}, \mathbf{t}^{\varepsilon}(\mathbb{J}), \mathbf{t}^b(\mathbb{J}))$
 - Participation constraints $\mathcal{U}_i(\mathbb{J}, \mathbf{t}^{\varepsilon}(\mathbb{J}), \mathbf{t}^b(\mathbb{J})) \geq \mathcal{U}_i(\mathbb{J} \setminus \{i\}, \mathbf{t}^{\varepsilon}(\mathbb{J} \setminus \{i\}), \mathbf{t}^b(\mathbb{J} \setminus \{i\}))$ with multiplier $\nu_{\mathbb{J},i}$
 - Requires to compute allocation $\mathcal{U}_i(\mathbb{J} \setminus \{i\}, \mathbf{t}^{\varepsilon}(\mathbb{J} \setminus \{i\}), \mathbf{t}^b(\mathbb{J} \setminus \{i\}))$
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 - Etc etc.
- ▶ Implies that we would need to solve *jointly* for $2^{\mathbb{J}}$ allocations and policy for coalitions $\mathbb{J}$, and each of them with $2^{\mathbb{J}}$ constraints and multipliers $\Rightarrow$ untractable

back

Solution method

- ▶ Current design: $\max_{\mathbf{t}} \max_{\mathbb{J}} \mathcal{W}(\mathbb{J}, \mathbf{t}) \text{ s.t. } \mathcal{U}_j(\mathcal{J}, \mathbf{t}) \geq \mathcal{U}_j(\mathcal{J} \setminus \{i\}, \mathbf{t})$
- ▶ 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 marginal values of $j \in \mathcal{J}$ for global $\Delta_j \mathcal{W}(\mathcal{J}, \mathbf{t})$ and individual welfare $\Delta_j \mathcal{U}_j(\mathcal{J}, \mathbf{t})$ are:

$$\Delta_j \mathcal{W}(\mathcal{J}, \mathbf{t}) \equiv \mathcal{W}(\mathcal{J} \cup \{j\}, \mathbf{t}) - \mathcal{W}(\mathcal{J} \setminus \{j\}, \mathbf{t}) \qquad \Delta_j \mathcal{U}_j(\mathcal{J}, \mathbf{t}) \equiv \mathcal{U}_j(\mathcal{J} \cup \{j\}, \mathbf{t}) - \mathcal{U}_j(\mathcal{J} \setminus \{j\}, \mathbf{t})$$

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

where marginal values of $j \in \mathcal{J}$ for global $\Delta_j \mathcal{W}(\mathcal{J}, \mathbf{t})$ and individual welfare $\Delta_j \mathcal{U}_j(\mathcal{J}, \mathbf{t})$ are:

$$\Delta_j \mathcal{W}(\mathcal{J}, \mathbf{t}) \equiv \mathcal{W}(\mathcal{J} \cup \{j\}, \mathbf{t}) - \mathcal{W}(\mathcal{J} \setminus \{j\}, \mathbf{t}) \quad \Delta_j \mathcal{U}_j(\mathcal{J}, \mathbf{t}) \equiv \mathcal{U}_j(\mathcal{J} \cup \{j\}, \mathbf{t}) - \mathcal{U}_j(\mathcal{J} \setminus \{j\}, \mathbf{t})$$

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

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

- Squeezing procedure converges to the optimal set under *Complementarity* Assumption, Details

Back, solution method

Complementarity

- Application of *Squeezing procedure* as in Arkolakis, Eckert, Shi (2023)
- Condition: Single Crossing Differences in choice (SCD-C),
that I extend to account for participation constraints (SCD-C,PC)
- In our setting, condition as follows:

IF the coalition $\mathcal{J}$ makes (i) allocation outcomes better for welfare with $\{j\}$, if both $\mathcal{J}$ and $\mathcal{J} \cup \{j\}$ are stable, or (ii) the coalition $\mathcal{J} \cup \{j\}$ is stable if $\mathcal{J}$ is unstable

THEN one of these conditions should also be respected for larger coalitions $\mathcal{J}' \supseteq \mathcal{J}$.

$$\left\{ \begin{array}{l} \Delta_i \mathcal{U}_i(\mathcal{J} \cup \{j\}) \geq 0 \\ \& \left[\begin{array}{l} \left(\Delta_j \mathcal{W}(\mathcal{J} \cup \{j\}) \geq 0 \& \Delta_i \mathcal{U}_i(\mathcal{J}) \geq 0 \right) \\ \text{or } \Delta_i \mathcal{U}_i(\mathcal{J}) < 0 \end{array} \right] \end{array} \right. \Rightarrow \left\{ \begin{array}{l} \Delta_i \mathcal{U}_i(\mathcal{J}' \cup \{j\}) \geq 0 \\ \& \left[\begin{array}{l} \left(\Delta_j \mathcal{W}(\mathcal{J}' \cup \{j\}) \geq 0 \& \Delta_i \mathcal{U}_i(\mathcal{J}') \geq 0 \right) \\ \text{or } \Delta_i \mathcal{U}_i(\mathcal{J}') < 0 \end{array} \right] \end{array} \right.$$

$\forall \mathcal{J} \subseteq \mathcal{J}' \quad \forall j \in \mathbb{I} \quad (\text{SCD-C, PC})$

Quantification – Trade and Damage fct estimation

- Armington Trade model:

$$\frac{X_{ijt}}{X_{iit}} = \left(p_{jt} / p_{it} \right)^{1-\theta} \varsigma_{ij} \varsigma_t \tilde{a}_{ijt} \tilde{\tau}_{ijt}$$

with

$$p_{it} = \mathcal{D}_i(T_{it}) \varsigma_i h(q_{it})$$

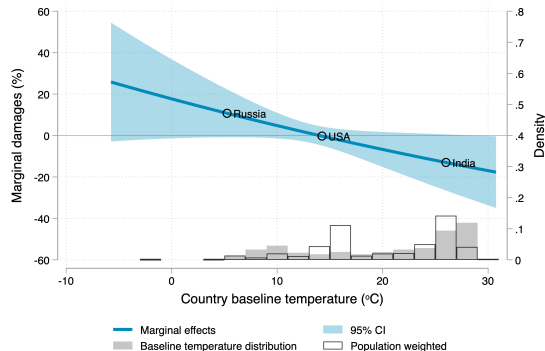
- Estimating gravity equation regression (PPML):

$$\begin{aligned} \log \mathbb{E}[X_{ij}/X_{ii}] = & \beta_0(T_{jt} - T_{it}) + \beta_1(T_{jt}^2 - T_{it}^2) \\ & + \varsigma_{ij} + \varsigma_t + \Gamma' W_{it} + \Omega' W_{jt}. \end{aligned}$$

- Result:

$$\Rightarrow \gamma = 3 \times \gamma_{DICE} = 0.012$$

- Implies Social Cost of Carbon = \$300



back

Welfare and Pareto weights

- Welfare:

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

- Pareto weights ω_i :

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

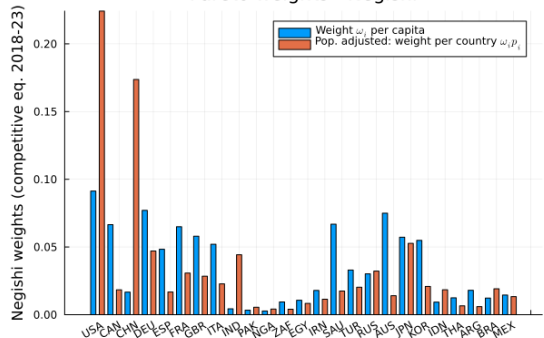
for $\bar{c}_i$ consumption in initial equilibrium
“without climate change“, i.e. year = 2020

- 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

Pareto weights - Negishi



back

Quantification – Trade model

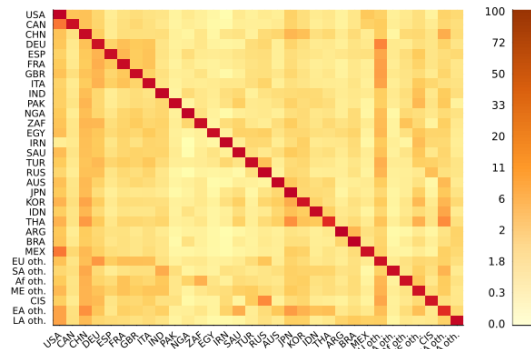
- Armington Trade model:

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

- Estimated gravity equation regression:

$$\log(s_{ij}) = f_i + f_j + \underbrace{\beta(1-\theta)}_{=\kappa} \log d_{ij}$$

- Get $\kappa = -1.43$, CES $\theta = 5$ minimizing variance of a_{ij}
- Iceberg cost τ_{ij} as projection of distance
 $\log \tau_{ij} = \beta \log d_{ij}$
- Preferences a_{ij} captures the remaining variation in trade shares s_{ij} , i.e. $a_{ij} \propto (1+t_{ij})\bar{\tau}_{ij}\bar{a}_{ij}$
 $\Rightarrow$ invariant to the club policies



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:

$$p_i MPe_i = q^e$$

- Inequality, as measured in local welfare units:

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

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

$$LCC_i = -\frac{\partial \mathcal{W}_i / \partial \mathcal{E}}{\partial \mathcal{W}_i / \partial c_i} = \frac{\psi_i^{\mathcal{E}}}{\lambda_i} \rightarrow \frac{\Delta_i \chi}{\rho - n + (1 - \eta) \bar{g}} (T_i - T_i^*) [\gamma^y p_i y_i + \gamma^u c_i p_i] \quad (> 0 \text{ for warm regions})$$

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 $\mathbf{t}_i^{ls}$, unrestricted individual carbon taxes $\mathbf{t}_i^e$ on energy e_i^f, e_i^c , 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 i , $[\mu_i]$, market clearing for energy μ^e

back

Step 1: World First-best policy

► Social planner allocation and decentralization:

- Consumption:

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

- Energy use:

$$\omega_i \mu_i M P e_i = \mu^e + SCC$$

- Social cost of carbon:

$$SCC \rightarrow \sum_j \omega_j \frac{\Delta_j \chi}{\rho - n + (1 - \eta) \bar{g}} (T_j - T_j^*) [\gamma^y \mu_j y_j + \gamma^u c_j \mathbb{P}_j]$$

- Decentralization:

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

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

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 $[\nu_i]$ & 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/reallocate final good demand

back

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 :

$$LCC_i := \frac{\partial \mathcal{W}_i / \partial \mathcal{E}}{\partial \mathcal{W}_i / \partial w_i} = \frac{\psi_i^{\mathcal{E}}}{\lambda_i} \rightarrow \frac{\Delta_i \chi}{\rho - n + (1 - \eta) \bar{g}} (T_i - T_i^*) [\gamma^y p_i y_i + \gamma^u c_i \mathbb{P}_i]$$

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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:

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

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: 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:

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

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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 - Countries $i \notin \mathbb{J}$ trade in goods subject to tariff t^b with club members and countries outside the club. They still trade with the club members in energy at price q^f
- ▶ 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

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

► Second-Best social valuation with participation constraints

- Participation incentives change our “social welfare weights” $\hat{\lambda}_i \propto \omega_i(1+\nu_i)u'(c_i)$

w/ Armington trade

$$(1+\nu_i)u'(c_i) = \lambda_i \left(\sum_{j \in \mathbb{I}} a_{ij}(\tau_{ij} p_j)^{1-\theta} \left[1 + \frac{\omega_j}{\omega_i} \frac{\mu_j}{\lambda_i} - \frac{\eta_{ij}}{\theta \lambda_i} (1-s_{ij}) \right]^{1-\theta} \right)^{\frac{1}{1-\theta}} = \lambda_i \mathbb{P}_i$$

$$\Rightarrow \quad \hat{\lambda}_i = \frac{\omega_i(1+\nu_i)u'(c_i)}{\frac{1}{J} \sum_{j \in \mathbb{J}} \omega_j(1+\nu_j)u'(c_j)} \neq \hat{\lambda}_i$$

- Similarly, the “effective Pareto weights” are $\alpha \omega_i$ for countries outside the club $i \notin \mathbb{J}$

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 $t^f(\mathbb{J})$:

$$\Rightarrow t^f(\mathbb{J}) = \text{SCC} + \text{Supply Redistrib}^{\text{osb}} + \text{Demand Distort}^{\text{osb}} - \text{Trade effect}^{\text{sb}}$$

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

- Optimal tariffs/export taxes $t_{ij}^b(\mathbb{J})$ for $j \notin \mathbb{J}$
As of now, only opaque system of equations (fixed point w/ demand/multipliers)

Step 4: Unilateral optimal policy

- Unilateral Social Planner maximizing local welfare

$$\mathcal{W}_i = \max_{\mathbf{t}_i, \mathbf{c}_i} u(c_i)$$

- Instruments: local carbon taxes t_i^ε on energy e_i^f, e_i^c , unrestricted bilateral tariffs t_{ij}^b , and lump-sum rebate to the household.
- Maximize welfare subject to the market clearing for good j , $[\mu_j^{(i)}]$, market clearing for fossil energy $\mu^{f(i)}$ and local optimality conditions

- Unilateral tariffs:

$$t_{ij}^b = \omega_j^{(i)} \frac{\mu_j^{(i)}}{\lambda_i}$$

- Terms of trade manipulation weighted by $\omega_j^{(i)}$: the more planner i internalizes the good j 's market clearing, the higher the tariffs. Small Open Econ: $\omega_j^{(i)} := 0$

Step 4: Unilateral optimal policy

► Social planner i allocation and local social cost of carbon:

- Local Cost of Carbon:

$$LCC_i = -\frac{\partial \mathcal{W}_i / \partial \mathcal{E}}{\partial \mathcal{W}_i / \partial c_i} \rightarrow \frac{\chi}{\rho - n + (1 - \eta)\bar{g}} \left(\Delta_i(T_i - T_i^*) [\gamma^y p_i y_i + \gamma^u c_i \mathbb{P}_i] + \sum_j \omega_j^{(i)} \frac{\mu_j^{(i)}}{\lambda_i} \Delta_j(T_j - T_j^*) \gamma^y p_j y_j \right)$$

- International trade makes the LCC_i correlated across regions due to goods-trade linkages ($\approx$ spatial diffusion of climate shocks from region j)

► Optimal local carbon tax:

$$t_i^\varepsilon = -q^f \frac{\mu_i^{(i)}}{\lambda_i} + q^f \nu_i \frac{e_i^f - e_i^x}{e_i^x} + LCC_i$$

- Internalizes (i) good production distortion $\mu_i^{(i)}$, (ii) energy supply redistribution (w/ ν_i inverse supply elasticity), and (iii) Pigouvian motives LCC_i .
- The tax becomes a carbon *subsidy* if oil-gas exports are large $e_i^x > e_i^f$, and if the local cost of carbon LCC_i is small

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 $\gamma^y = \gamma^{+, y} \mathbb{1}_{\{T > T_i^*\}} + \gamma^{-, y} \mathbb{1}_{\{T < T_i^*\}}$
- Symmetric damage: $\gamma_i^{\pm, y} = \bar{\gamma}^{\pm, y}$ & $T_i^* = \bar{\alpha} T_{it_0} + (1 - \bar{\alpha}) T^*$

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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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:

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

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

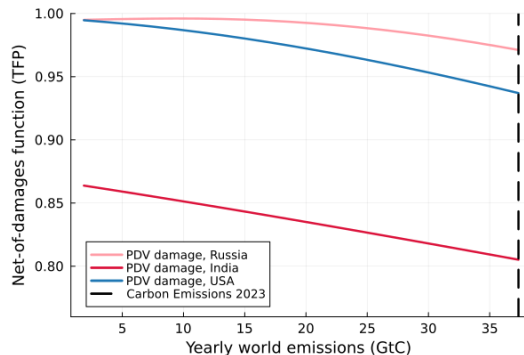
- Path damages heterogeneous across countries
Quadratic, c.f. Nordhaus-DICE / IAM

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

- Economic feedback in Present discounted value

$$\mathcal{D}_i^y(\mathcal{E}) = \bar{\rho} \int_0^\infty e^{-\overbrace{(\rho - n + (1-\eta)\bar{g})}^{\equiv \bar{\rho}} t} \mathcal{D}(T_{it} - T_i^*) dt$$

- Similarly for $\mathcal{D}_i^u(\mathcal{E})$, SCC and $LCC_i \dots$

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Calibration

Table: Baseline calibration (* = subject to future changes) [back](#)

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, ξ^c	2.761 & 3.961	Emission factor – Oil+nat. gas vs. Coal	Conversion 1 MTOE $\Rightarrow$ 1 MT CO ₂
χ	2.3/1e6	Climate sensitivity	Pulse experiment: 100 GtC $\equiv$ 0.23° C medium-term warming
δ_s	0.0004	Carbon exit from atmosphere	Pulse experiment: 100 GtC $\equiv$ 0.15° C long-term warming
$\gamma^\oplus$	0.003406	Damage sensitivity	Nordhaus, Barrage (2023)
α^T	0.5	Weight historical climate for optimal temp.	Marginal damage correlated with initial temp.
T^*	14.5	Optimal yearly temperature	Average yearly temperature/Developed economies

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 C_i^c	Energy mix/coal share e_i^c/e_i	SRE
Cost of non-carbon energy	Cost of non-carbon production C_i^r	Energy mix/coal share e_i^r/e_i	SRE
Local temperature	Initial temperature T_{it_0}	Pop-weighted yearly temperature	Burke et al
Pattern scaling	Pattern scaling Δ_i	Sensitivity of T_{it} to world $\bar{T}_t$	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

Theoretical investigation: decomposing the welfare effects

► Experiment:

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

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

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

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

- Climate damage $\tilde{\gamma}_i = \gamma(T_i - T_i^*) T_i s^{E/S}$
- Trade and leakage effect: GE impact of t_j^ε and t_{jk}^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

back

Welfare decomposition

► Armington model of trade with energy:

- Linearized market clearing

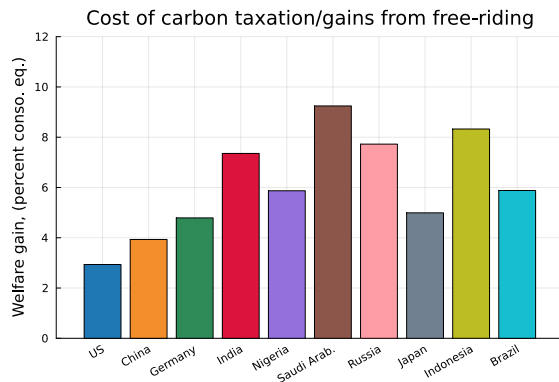
$$\begin{aligned} \left(\frac{dp_i}{dp_i} + \frac{dy_i}{y_i} \right) = \sum_k t_{ik} \left[\left(\frac{p_k y_k}{v_k} \right) (d \ln p_k + d \ln y_k) + \frac{q^f e_k^x}{v_k} d \ln e_k^x - \frac{q^f e_k^f}{v_k} d \ln e_k^f + \frac{q^f (e_k^x - e_k^f)}{v_k} d \ln q^f \right. \\ \left. + \theta \sum_h (s_{kh}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

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

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

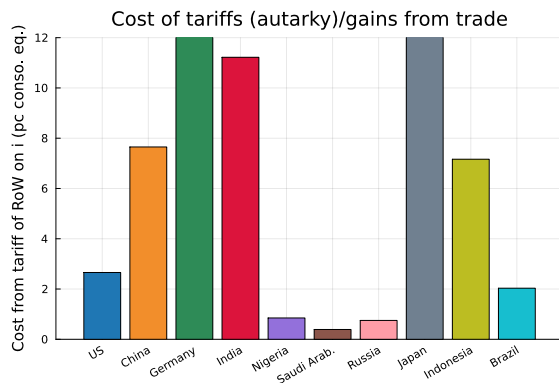
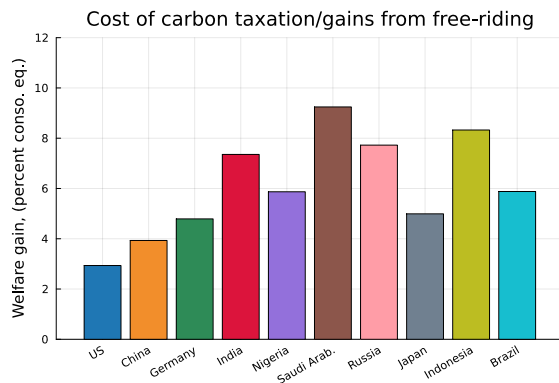
Trade-off – Cost of Carbon Taxation vs. Gains from trade

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

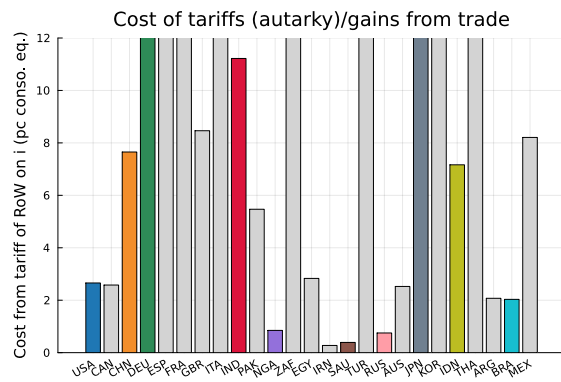
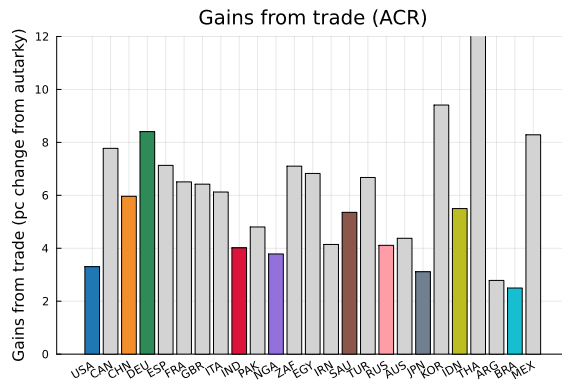
Gains from **unilateral exit** from agreement vs. **Gains from trade**, i.e. loss from tariffs/autarky



Welfare decomposition [Linear decomposition](#), *Comparison ACR* [ACR](#) [back](#)

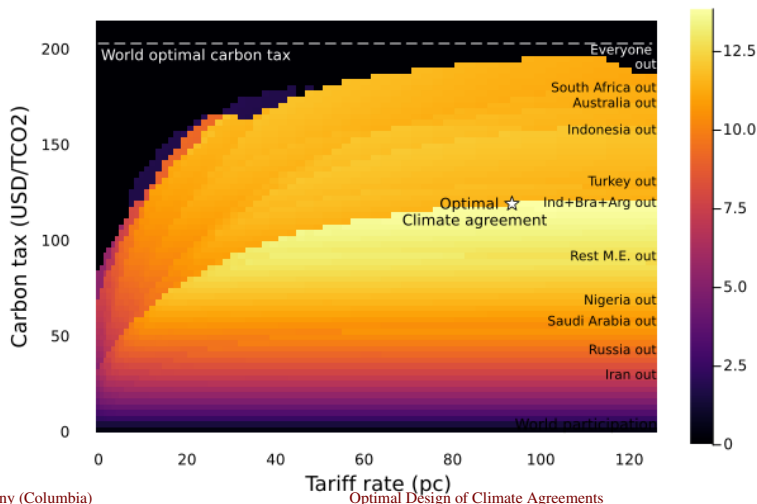
Trade-off – Gains from trade

Gains from trade (ACR) vs. loss from tariffs/autarky in this model [back](#)



Climate agreement and welfare

Recover 83% of welfare gains, i.e. 14% out of 17% conso equivalent. [back](#)



Coalition building

- ▶ How to build sequentially the climate coalition?
 - Which countries have the most interest in joining the club?

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 $t^\varepsilon = 100\$$, and tariff $t^b = 50\%$.
- Sequential procedure – coming *for free* from our CDCP algorithm / squeezing procedure
- Idea analogous to Farrokhi, Lashkaripour (2024)

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► Result: sequence up to the optimal climate agreement [back](#)

- Round 1: European Union, China
- Round 2: US, UK, Turkey, Japan, Korea, Thailand, Rest of Asia, Africa, Lat. Am
- Round 3: India, Pakistan, South Africa, Brazil, Mexico, Indonesia, Canada
- Round 4: Argentina

⊄ Stay out of the agreement: Russia, CIS, Saudi Arabia, Iran, Nigeria, Egypt, Gulf countries

► For high tariffs (above $t^b > 60\%$), we get a coordination failure:

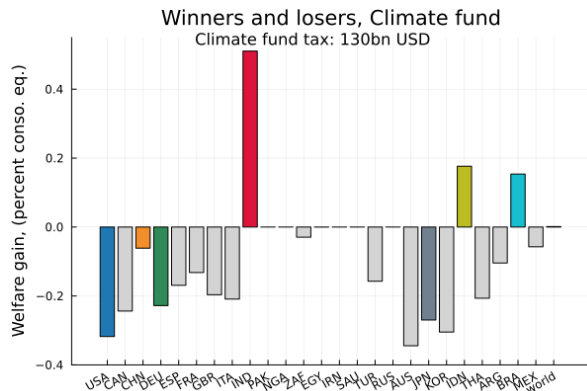
- When the club is empty, no one enter by itself
- When the club is optimal, no one wants to leave

Transfers – Climate fund

- ▶ COP29 Major policy proposal:
New Collective Quantified Goal (NCQG) on Climate Finance for developing countries
- ▶ In our context: lump-sum rebate of carbon tax revenues (transfers from large to low emitters)

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

- ▶ Optimal transfers: [back](#)
 - $\alpha^* = 0.5\%$: Optimal for rich countries to do limited lump-sum transfers.
 $\Rightarrow \alpha \sum_j t^\varepsilon \varepsilon_j \approx \130 bn
 - Compare it to COP discussions:
 $\$300 \text{ bn}$ in COP29, $\$120 \text{ bn}$ in COP30



Carbon tariffs - EU's CBAM

- Carbon Border Adjustment Mechanism: European Union's "Carbon tariff"

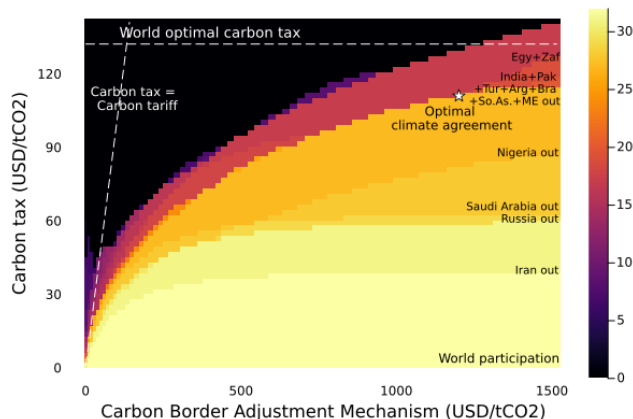
- Tariff t_{ij}^b scaling w/ carbon content ξ_j^y

$$t_{ij}^b = \xi_j^y t^{b,\varepsilon} = \frac{\varepsilon_j}{y_j p_j} t^{b,\varepsilon} \quad \text{if } i \in \mathbb{J}, j \notin \mathbb{J},$$

- Objective: fight carbon/trade leakage.
But also has strategic effects
(foster participation to the club)

- Optimal Carbon tariff:

- Border price of carbon $t^{b,\varepsilon} > \$1000$
- Additional constraint $t^{\varepsilon} = t^{b,\varepsilon}$
⇒ prevents any large stable club



Taxation of fossil fuels energy inputs

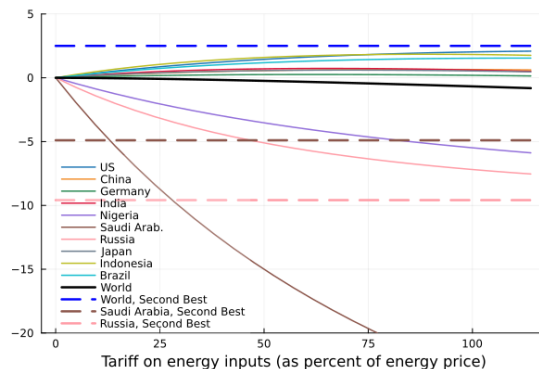
- Current climate club: [back](#)
Tariffs only on final goods, not energy imports
 - Empirically relevant, c.f. Shapiro (2021): inputs are more emission-intensives but trade policy is biased against final goods output

- Alternative: tax energy import t_{ij}^{bf} of non-members

$$q_{\mathbb{J}}^f = (1 + t_{ij}^{bf}) q_{\mathbb{I} \setminus \mathbb{J}}^f$$

if non-members export fossil fuels to the club

- Optimal tariffs $t^{bf} / q_{\mathbb{J}}^f = 30\%$
 - Compares to the \$60 price-cap from EU (out of $\sim \$100$ /barrel) on Russian oil (!)

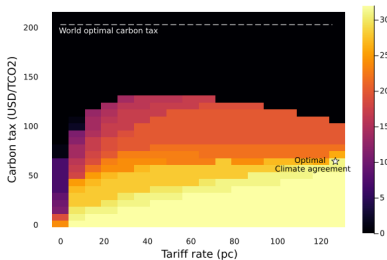


Trade retaliation

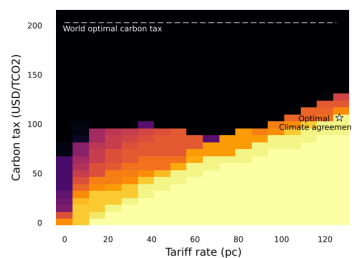
- ▶ Trade war and policy retaliation:
Suppose the regions outside the agreement impose retaliatory tariffs to club members
- ▶ Exercise, retaliation rule
 - Countries outside the club $j \notin \mathbb{J}$ impose tariffs $t_{ji} = \beta t_{ij}$ on club members $i \in \mathbb{J}$

[back](#)

$\beta = 0.25$



$\beta = 0.5$



$\beta = 1.0$

