The Optimal Design of Climate Agreements

Inequality, Trade, and Incentives for Climate Policy

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Macro Lunch

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⇒ 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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  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)
  - ⇒ *Quantitative analysis of climate agreements and policy recommendation*

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

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

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2. Representative final good firm:

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

   – 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:

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

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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 $\{\mathbb{J}, t^{\varepsilon}, t^{b}\}$ 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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  – Avoid double tax (energy + carbon). Assumption relaxed in extension: oil-gas-specific tariffs

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

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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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- Indirect utility $\mathcal{U}_i(\mathbb{J}, t^{\varepsilon}, t^b) \equiv u\big(\mathcal{D}_i^y(\mathcal{E}(\mathbb{J}, t^{\varepsilon}, t^b)) \, c_i(\mathbb{J}, t^{\varepsilon}, t^b)\big)$

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▶ Equilibrium concepts:

- Unilateral participation decision of i, $\mathbb{J}\setminus\{i\}$, $\Rightarrow$ ***Nash equilibrium***

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

- Sub-coalitional deviation $\Rightarrow$ *Coalitional Nash equilibrium*

Optimal design with endogenous participation

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

$$\max_{\mathbb{J}, t^\varepsilon, t^b} \mathcal{W}(\mathbb{J}, t^\varepsilon, t^b) = \max_{t^\varepsilon, t^b} \max_{\mathbb{J}} \sum_{i \in \mathbb{I}} \omega_i \, \mathcal{U}_i(\mathbb{J}, t^\varepsilon, t^b)$$

$$s.t. \qquad \mathcal{U}_i(\mathbb{J}, t^\varepsilon, t^b) \geq \mathcal{U}_i(\mathbb{J} \backslash \{i\}, t^\varepsilon, t^b)$$

▶ Current design:

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

Outline

Quantification: Climate and parametrization

s

- ▶ 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: $\dot{\mathcal{S}}_t = \mathcal{E} - \delta_s \mathcal{S}_t, \quad T_{it} = \bar{T}_{i0} + \Delta_i \mathcal{S}_t$
  - Quadratic damage functions as in Nordhaus-DICE: $\mathcal{D}(T_{it} - T_i^\star) = e^{-\gamma(T_{it} - T_i^\star)^2}$
  - Feedback in Present discounted value: $\mathcal{D}_i^y(\mathcal{E}) = \bar{\rho} \int_0^\infty e^{-(\rho - n + (1-\eta)\bar{g})t} \mathcal{D}(T_{it} - T_i^\star) dt$

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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
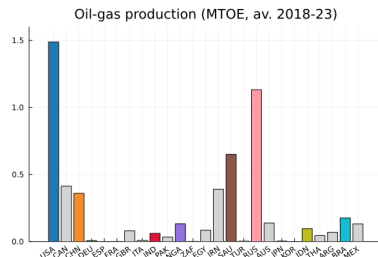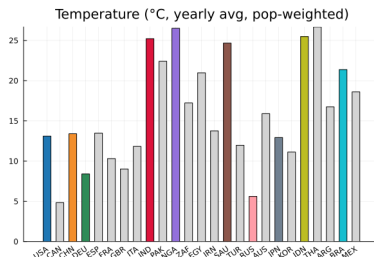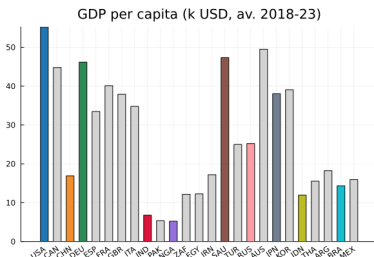
▶ Standard functional forms:

- 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 $\mathcal{P}_i$, Temperature T_{it_0}, Pattern scaling Δ_i
  • Mix: oil-gas e_i^f, Coal e_i^c, Low-carbon e_i^r, energy share, oil-gas prod° 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}

GDP per capita (k USD, av. 2018-23)   Temperature (°C, yearly avg, pop-weighted)   Oil-gas production (MTOE, av. 2018-23)

Details `Trade shares – details`

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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

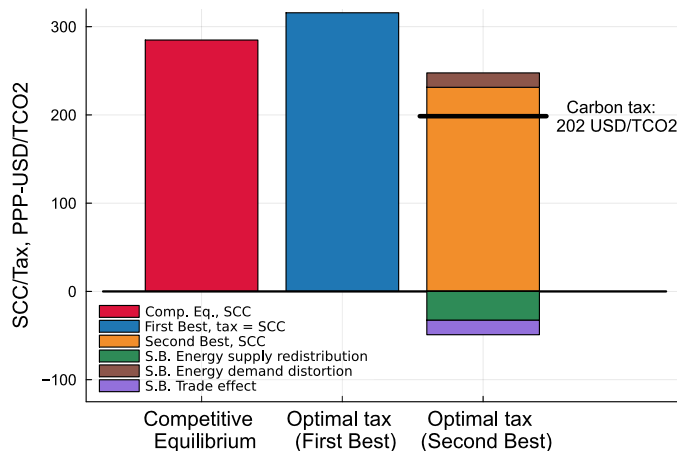## Optimal policy benchmarks

► 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

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  - 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 $\phi_i = \omega_i \mathcal{U}'(c_i) = \omega_j \mathcal{U}'(c_j)$

- *Second-Best:* Social planner, single carbon tax without transfers
  - Optimal carbon tax t^{ε} correct climate externality, but also accounts for:
    (i) Redistribution motives, and G.E. effects on (ii) energy markets and (iii) trade leakage

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

  - 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,
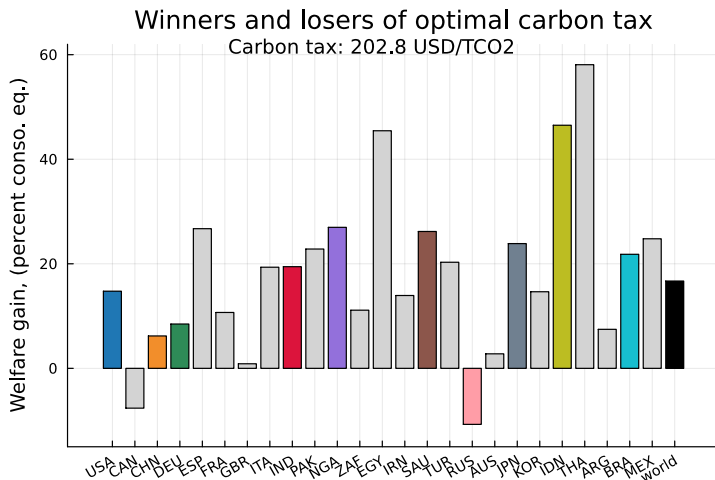 see Farrokhi, Lakshuripour (2025), Kortum, Weisbach (2022) Nash-Unilateral Policies

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

Winners and losers of optimal carbon tax
Carbon tax: 202.8 USD/TCO2

Outline

Main result and Intuition
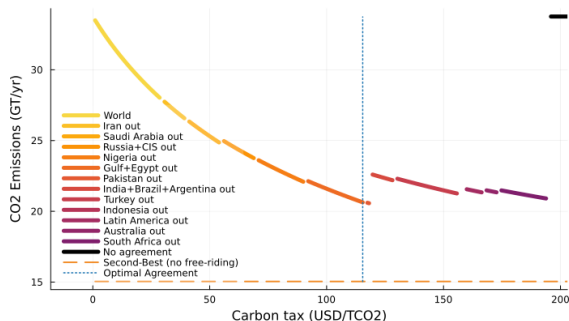
► The optimal climate agreement navigates the intensive and extensive margin tradeoff:

- *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/tCO_2

  • **Trade tariffs:** impose substantial tariff 90% on the goods from non-members

▶ Mechanism:

  – Countries participate depending on $\begin{cases} \text{(i) the cost of distortionary carbon taxation} \\ \text{(ii) the cost of tariffs (= the gains from trade)} \end{cases}$

  – 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

  $\Rightarrow$ Result, we need to decrease the carbon tax: *reduce ambition*
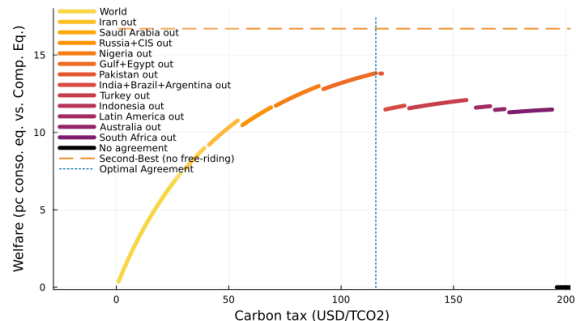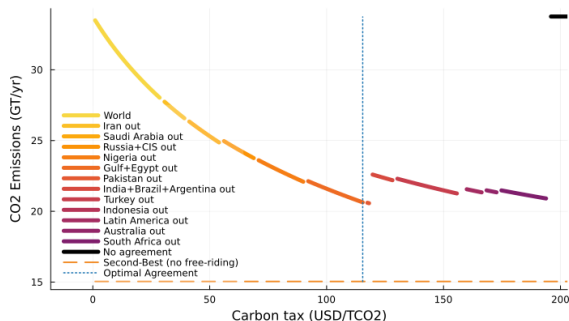
Laffer curve for carbon taxation

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

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 $t^{\varepsilon,\star} = \$200$

– 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:
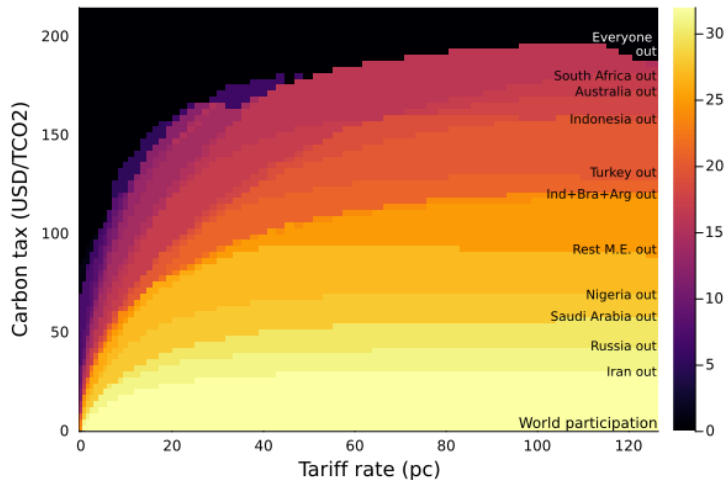
  given a coalition:
  higher tax t^ε, emissions $\mathcal{E}$ ↓,
  improve welfare $\mathcal{W}$ ↑

▶ Extensive margin:

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

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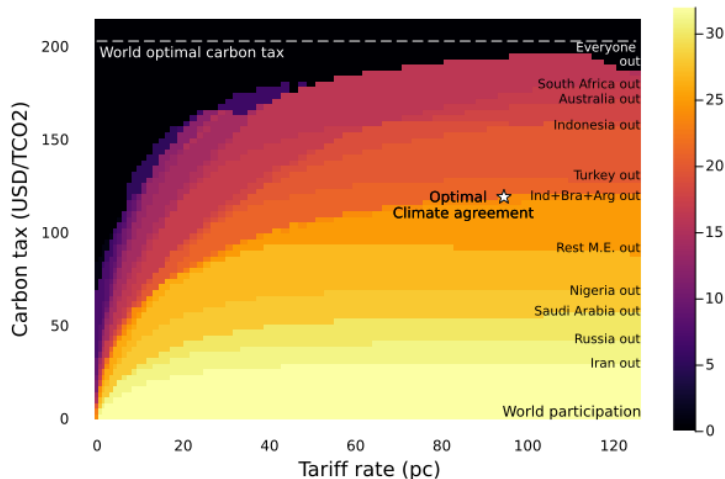
► Despite full discretion of instruments (t^ε, t^b), we cannot sustain an agreement with Russia, Middle East, South-Asia & South America

⇒ 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%
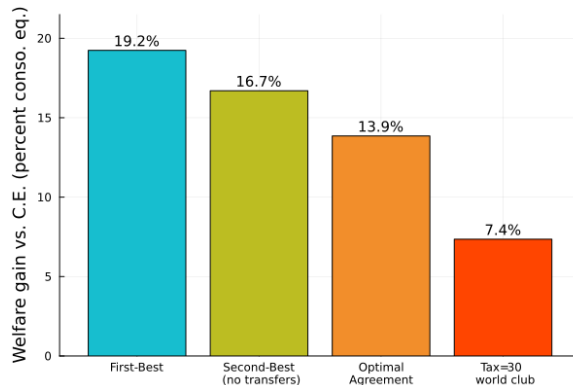
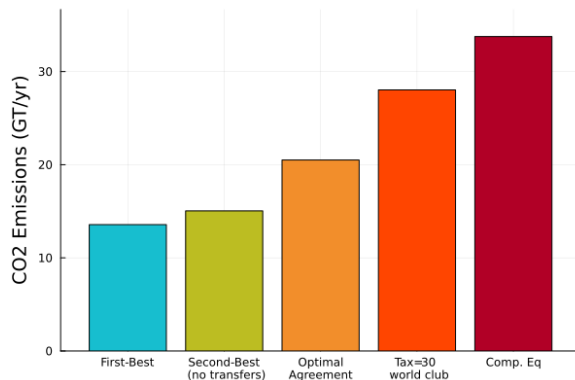# Emission reduction vs. Welfare: Different metrics!

- 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 $t^\varepsilon = SCC = \$230$: *participation collapses, no aggreement*

  – Carbon tax with full participation, (e.g. FL 2025), $t^\varepsilon = \$30$, intensive margin ↓

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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^ε

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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  - Such costs increase exponentially in the number of countries I

▶ Optimal – country specific – carbon taxes:
- Without free-riding / exogenous participation

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

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

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

back

Optimal design with endogenous participation

▶ Equilibrium concepts and participation constraints:

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

$$\mathcal{U}_i(\mathbb{J}, \mathfrak{t}^{\varepsilon}, \mathfrak{t}^b) \geq \mathcal{U}_i(\mathbb{J}\backslash\{i\}, \mathfrak{t}^{\varepsilon}, \mathfrak{t}^b) \qquad \forall i \in \mathbb{J}$$

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

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

    – Stability requires to check all potential coalitions $\mathbb{J} \in \mathcal{P}(\mathbb{I})$ as all sub-coalitions $\mathbb{J}\backslash\hat{\mathbb{J}}$ are
       considered as deviations in the equilibrium
    – Requires to solve all the combination $\mathbb{J}, \mathfrak{t}^f, \mathfrak{t}^b$, 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

$$\max_{\mathbb{J}, t^\varepsilon, t^b} \mathcal{W}(\mathbb{J}, t^\varepsilon, t^b) = \max_{t^\varepsilon, t^b} \max_{\mathbb{J}} \sum_{i \in \mathbb{I}} \omega_i \, \mathcal{U}_i(\mathbb{J}, t^\varepsilon, t^b) = \max_{\mathbb{J}} \max_{t^\varepsilon, t^b} \sum_{i \in \mathbb{I}} \omega_i \, \mathcal{U}_i(\mathbb{J}, t^\varepsilon, t^b)$$

$$s.t. \qquad \mathcal{U}_i(\mathbb{J}, t^\varepsilon, t^b) \geq \mathcal{U}_i(\mathbb{J} \backslash \{i\}, t^\varepsilon, t^b)$$

- Current design:
  - (i) choose taxes $\{t^\varepsilon, t^b\}$ [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 $\{t^\varepsilon, t^b\}$ [inner problem]
  - (iii) check participation constraints for $(\mathbb{J}, t^\varepsilon, t^b)$
    - ▶ Computation: 2^N choices of coalition, M policies (grid search?), N unilateral deviations

  back

Country deviation and policy

▶ Consider coalition $\mathbb{J}$. Suppose we search for optimal policy $\mathsf{t}^\varepsilon(\mathbb{J}), \mathsf{t}^b(\mathbb{J})$

  - Requires to compute allocation $\mathcal{U}_i\big(\mathbb{J}, \mathsf{t}^\varepsilon(\mathbb{J}), \mathsf{t}^b(\mathbb{J})\big)$

  - Participation constraints $\mathcal{U}_i\big(\mathbb{J}, \mathsf{t}^\varepsilon(\mathbb{J}), \mathsf{t}^b(\mathbb{J})\big) \geq \mathcal{U}_i\big(\mathbb{J}\backslash\{i\}, \mathsf{t}^\varepsilon(\mathbb{J}\backslash\{i\}), \mathsf{t}^b(\mathbb{J}\backslash\{i\})\big)$ with multiplier $\nu_{\mathbb{J},i}$

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    with multiplier $\nu_{\mathbb{J}\backslash\{i\},j}$
  - Etc etc.

▶ Implies that we would need to solve *jointly* for $2^{\mathbb{I}}$ 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: $\max_{\mathbf{t}} \max_{\mathbb{J}} \mathcal{W}(\mathbb{J}, \mathbf{t})$ *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:

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

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

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

- Squeezing procedure converges to the optimal set under *Complementarity* $\boxed{\text{Assumption, Details}}$

$\boxed{\text{Back, solution method}}$

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 $\mathcal{J}' \supseteq \mathcal{J}$.

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

$$\text{(SCD-C, PC)}$$

back

Quantification – Trade and Damage fct estimation

- Armington Trade model:

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

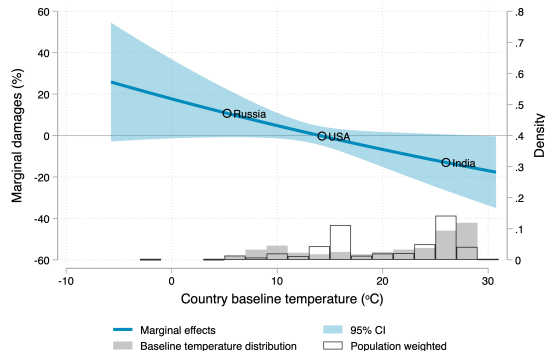with

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

- Estimating gravity equation regression (PPML):

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

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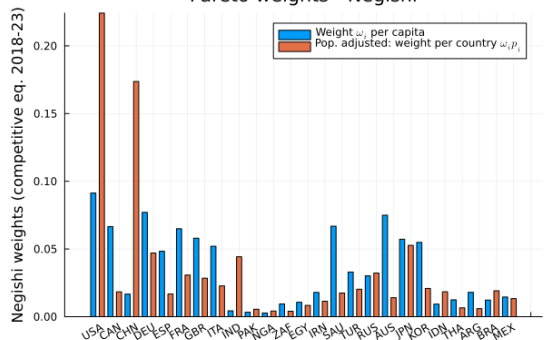
$$\omega_i = \frac{1}{u'(\bar{c}_i)}$$

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

- Imply no redistribution motive in $t = 2020$

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

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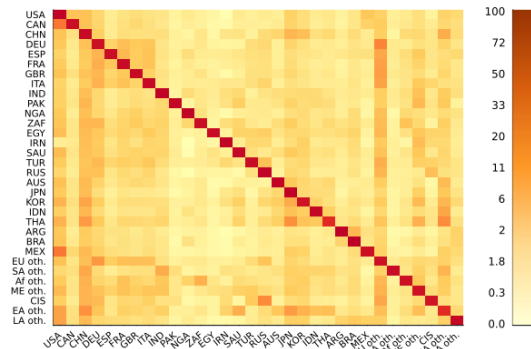

Pareto weights - Negishi

back

Quantification – Trade model

- Armington Trade model:

$$s_{ij} \equiv \frac{c_{ij}p_{ij}}{c_i \mathbb{P}_i} = a_{ij}\frac{((1+\mathsf{t}_{ij})\tau_{ij}\mathsf{p}_j)^{1-\theta}}{\sum_k a_{ik}((1+\mathsf{t}_{ik})\tau_{ik}\mathsf{p}_k)^{1-\theta}}$$

- 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. $a_{ij} \propto (1+\bar{\mathsf{t}}_{ij})\bar{\tau}_{ij}\bar{a}_{ij}$
$\Rightarrow$ 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:

$$s_{ij} = \frac{c_{ij}p_{ij}}{c_i \mathbb{P}_i} = a_{ij} \frac{(\tau_{ij}(1+t_{ij}^b)p_j)^{1-\theta}}{\sum_k a_{ik}(\tau_{ik}(1+t_{ik}^b)p_k)^{1-\theta}} \qquad \& \qquad \mathbb{P}_i = \Big(\sum_j a_{ij}(\tau_{ij}p_j)^{1-\theta} \Big)^{\frac{1}{1-\theta}}$$

- Energy consumption doesn't internalize climate damage:

$$p_i MP e_i = q^e$$

- Inequality, as measured in local welfare units:

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

- "Local Social Cost of Carbon", for region i

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

back

Step 1: World First-best policy

▶ Maximizing welfare of the world Social Planner:

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

- Full array of instruments: cross-countries lump-sum transfers t_i^{ls}, unrestricted individual carbon taxes t_i^{ε} on energy e_i^f, e_i^c, unrestricted bilateral tariffs t_{ij}^b
- Budget constraint: $\sum_i t_i^{ls} = \sum_i t_i^f e_i^f + \sum_{i,j} t_{ij}^b c_{ij} \tau_{ij} p_j$

▶ 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:

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

- Energy use:

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

- Social cost of carbon:

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

- Decentralization:

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

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

back

Step 2: World optimal Ramsey policy

▶ Maximizing welfare of the world Social Planner:

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

- One single instrument: uniform carbon tax t^f on energy e_i^f
- Rebate tax lump-sum to HHs $t_i^{ls} = t^\varepsilon e_i^f + t^\varepsilon e_i^c$

▶ 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 $[\upsilon_i]$ & 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}:

$$\text{w/ free trade} \qquad u'(c_i) = \lambda_i$$

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

▶ Relative welfare weights, representing inequality

$$\widehat{\lambda}_i = \frac{\omega_i \lambda_i}{\bar{\lambda}} = \frac{\omega_i u'(c_i)}{\frac{1}{I} \sum_{\mathbb{I}} \omega_j u'(c_j)} \lessgtr 1 \qquad \Rightarrow \qquad \begin{array}{l} \text{ceteris paribus, poorer} \\ \text{countries have higher } \widehat{\lambda}_i \end{array}$$

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:

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

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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:

$$SCC = \sum_{\mathbb{I}} \widehat{\lambda}_i \, LCC_i = \sum_{\mathbb{I}} \omega_i \, LCC_i + \mathbb{C}\text{ov}_i(\widehat{\lambda}_i, LCC_i)$$

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

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

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

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  ○ Params: $\mathcal{C}^f_{EE}$ agg. fossil inv. elasticity, s^e_i energy cost share and σ_i energy demand elasticity

▶ *Proposition 2:* Optimal fossil energy tax:

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

  – Reexpressing demand terms:

$$\mathfrak{t}^\varepsilon = \left(1 + \mathbb{C}\text{ov}_i\left(\widehat{\lambda}^w_i, \widehat{\frac{\sigma_i e_i}{1-s^e_i}}\right)\right)^{-1}\left[\sum_{\mathbb{I}} \omega_i \, LCC_i + \mathbb{C}\text{ov}_i\left(\widehat{\lambda}^w_i, LCC_i\right) + \mathcal{C}^f_{EE}\,\mathbb{C}\text{ov}_i\left(\widehat{\lambda}^w_i, e^f_i - e^x_i\right) - q^f\,\mathbb{E}_j[\widehat{\mu}_j]\right]$$

back

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 t^f
  • Countries $i \in \mathbb{J}$ can unilaterally leave, subject to retaliation tariff $t^{b,r}$ on goods and get consumption $\tilde{c}_i$
  • 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

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► Participation constraints:
$$u(c_i) \geq u(\tilde{c}_i) \qquad [\nu_i]$$

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

Step 3: Ramsey Problem with participation constraints

▶ Participation constraints

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

▶ Second-Best social valuation with participation constraints

• Participation incentives change our "social welfare weights" $\widehat{\widehat{\lambda}}_i \propto \omega_i(1+\nu_i)u'(c_i)$

w/ Armington trade $\qquad (1+\nu_i)u'(c_i) = \lambda_i \Big(\sum_{j \in \mathbb{I}} a_{ij}(\tau_{ij}\mathrm{p}_j)^{1-\theta} \Big[1 + \frac{\omega_j}{\omega_i}\frac{\mu_j}{\lambda_i} - \frac{\eta_{ij}}{\theta\lambda_i}(1-s_{ij}) \Big]^{1-\theta} \Big)^{\frac{1}{1-\theta}} = \lambda_i \mathbb{P}_i$

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

• 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 $t^f(\mathbb{J})$:

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

  $$= \frac{1}{1 - \vartheta_{\mathbb{J}^c}} \sum_{i \in \mathbb{I}} \widetilde{\lambda}_i LCC_i + \frac{1}{1 - \vartheta_{\mathbb{J}^c}} \mathcal{C}_{EE}^f \sum_{i \in \mathbb{I}} \widetilde{\lambda}_i (e_i^f - e_i^x) - \sum_{i \in \mathbb{J}} \widetilde{\upsilon}_i \frac{q^f (1 - s_i^f)}{\sigma e_i^f}$$

  - 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)

  back

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: $\omega_j^{(i)} := 0$

back

Step 4: Unilateral optimal policy

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

• Local Cost of Carbon:

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

• 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:

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

• 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

back

Quantification – Firms

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

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

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

- Calibrate TFP z_i to match $y_i = GDP_i$ per capita in 2019-23 (avg. PPP).
- Technology: $\omega^f = 56\%, \omega^c = 27\%, \omega^f = 17\%, \epsilon = 12\%$ 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:

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

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

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 $q_i^c = z^c \mathbb{P}_i$, $q_{it}^r = z^r \mathbb{P}_i$
    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

  back

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:

$$\dot{\mathcal{S}}_t = \mathcal{E} - \delta_s \mathcal{S}_t$$
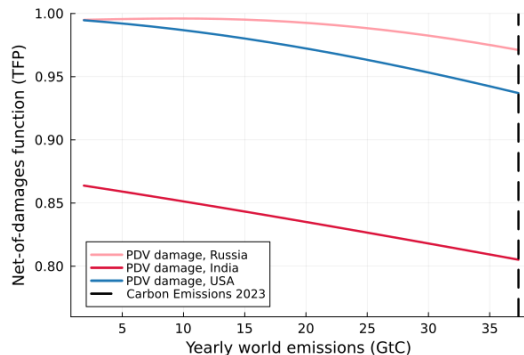$$T_{it} = \bar{T}_{i0} + \Delta_i \mathcal{S}_t$$

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

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

- Economic feedback in Present discounted value

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

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

Net-of-damages function (TFP) vs Yearly world emissions (GtC)

PDV damage, Russia
PDV damage, India
PDV damage, USA
Carbon Emissions 2023

Calibration   Table: Baseline calibration ($\star$ = 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$\star$	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.
$T^\star$	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 $\mathcal{C}_i^c$	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_{it_0}	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

back

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 $dt_j^\varepsilon, \forall j$ and tariffs $dt_{j,k}^b, \forall j, k$ for a club J_i

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

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

$$d\ln q^f = -\frac{\bar{\nu}}{1+\bar{\gamma}+\mathbb{C}\mathrm{ov}_i(\widetilde{\lambda}_i^f, \bar{\gamma}_i) + \bar{\nu}\overline{\lambda}^{\sigma,f}} \sum_i \widetilde{\lambda}_i^f J_i dt^\varepsilon + \sum_i \beta_i d\ln p_i$$

  – Climate damage $\bar{\gamma}_i = \gamma(T_i - T_i^\star) T_i \, s^{E/S}$
  – Trade and leakage effect: GE impact of t_j^ε and $t_{j.}^b$ 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

$$\left(\frac{d\mathrm{p}_i}{d\mathrm{p}_i} + \frac{dy_i}{y_i}\right) = \sum_k \boldsymbol{t}_{ik}\Big[\Big(\frac{\mathrm{p}_k y_k}{v_k}\Big)(d\ln \mathrm{p}_k + d\ln y_k) + \frac{q^f e_k^x}{v_k}d\ln e_k^x - \frac{q^f e_k^f}{v_k}d\ln e_k^f + \frac{q^f(e_k^x - e_k^f)}{v_k}d\ln q^f$$
$$+ \theta \sum_h \big(s_{kh}d\ln \mathrm{t}_{kh} - (1+s_{ki})d\ln \mathrm{t}_{ki}\big) + (\theta-1)\sum_h \big(s_{kh}d\ln \mathrm{p}_h - d\ln \mathrm{p}_i\big)\Big]$$

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

$$\Big[(\mathbf{I}-\mathbf{T}\odot v^y)[\mathbf{I}-\alpha^{y,p}\odot\mathbf{I}] + \mathbf{T}(v^{e^x}\odot\tfrac{1}{\nu}) + \mathbf{T}v^{e^f}\tfrac{\sigma^y}{1-s^e} - (\theta-1)(\mathbf{TS}-\mathbf{T}') - \Big((\mathbf{I}-\mathbf{T}\odot v^y)\alpha^{y,z}-\tfrac{\sigma^y}{1-s^e}\Big)\odot\bar{\gamma}\mathbf{I}\odot(\tfrac{\lambda^x}{\nu})'\Big]d\ln \mathrm{p} =$$
$$\Big[-(\mathbf{I}-\mathbf{T}\odot v^y)\alpha^{y,qf} + \mathbf{T}(v^{e^x}\odot\tfrac{1}{\nu}+v^{e^f}\tfrac{\sigma^y}{1-s^e}+v^{ne}) - \Big((\mathbf{I}-\mathbf{T}\odot v^y)\alpha^{y,z}-\tfrac{\sigma^y}{1-s^e}\Big)\bar{\gamma}\tfrac{1}{\nu}\Big]d\ln q^f$$
$$+ \Big[-(\mathbf{I}-\mathbf{T}\odot v^y)\alpha^{y,qf} + \mathbf{T}(v^{e^f}\odot\tfrac{\sigma^y}{1-s^e})\Big]\odot\mathbf{J}d\ln \mathrm{t}^\varepsilon + \theta\big(\mathbf{TS}\odot\mathbf{J}\odot d\ln \mathrm{t}^b - \mathbf{T}(\mathbb{1}+\mathbf{S}')\odot(\mathbf{J}\odot d\ln \mathrm{t}^b)'\big)$$

back

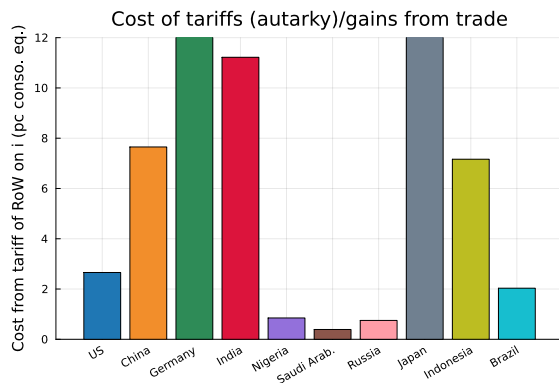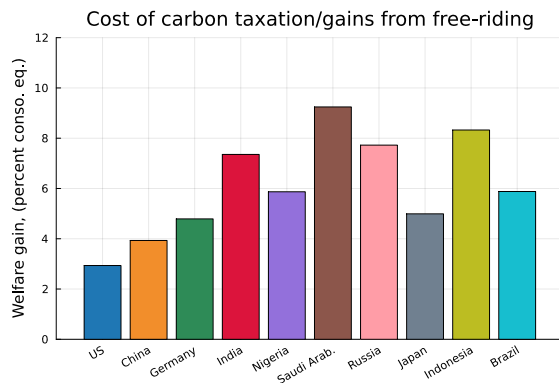# Trade-off – Cost of Carbon Taxation vs. Gains from trade

Gains from unilateral exit from agreement vs. Gains from trade, i.e. loss from tariffs/autarky
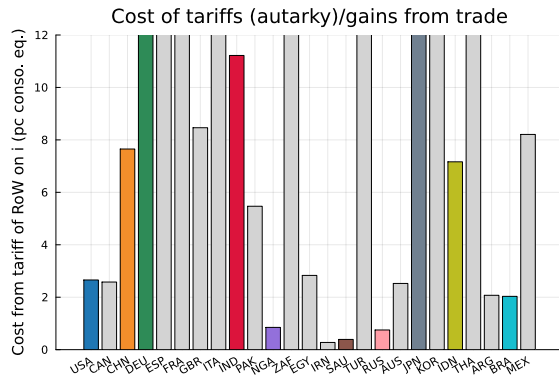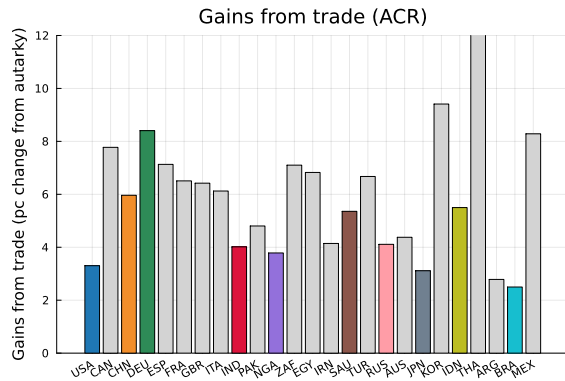
Trade-off – Cost of Carbon Taxation vs. Gains from trade

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

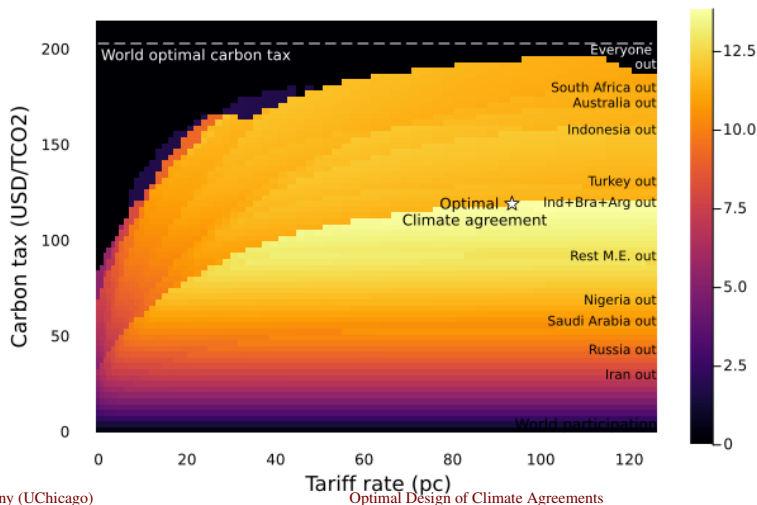*Welfare decomposition* (Linear decomposition), *Comparison ACR* (ACR) (back)

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)

Coalition building

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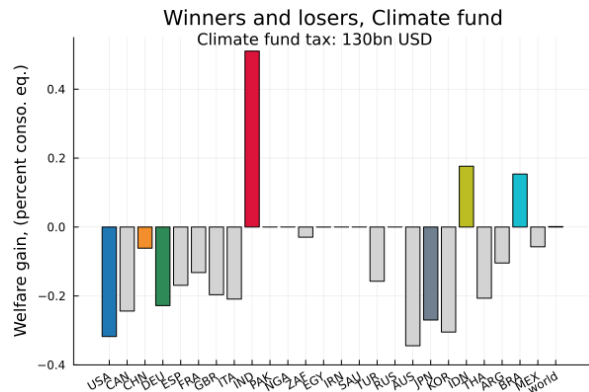
- When the club is empty, no one enter by itself
- When the club is optimal, no one wants to leave

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)

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

▶ Optimal transfers: back

- $\alpha^\star = 0.5\%$: 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:
  $\$300\,bn$ in COP29, $\$120\,bn$ in COP30

Winners and losers, Climate fund
Climate fund tax: 130bn USD

Carbon tariffs - EU's CBAM

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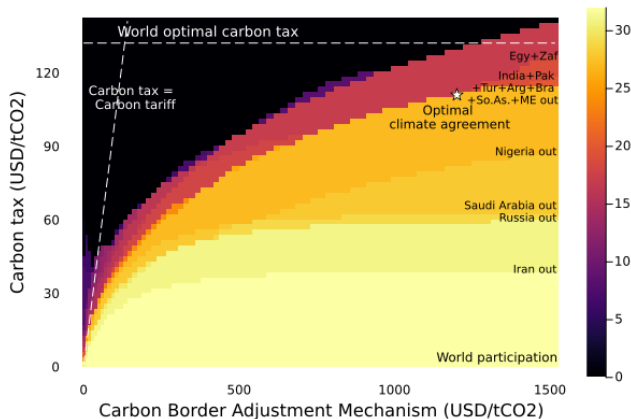European Union's "Carbon tariff"

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

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

▶ 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 $t^\varepsilon = t^{b,\varepsilon}$
    $\Rightarrow$ prevents any large stable club

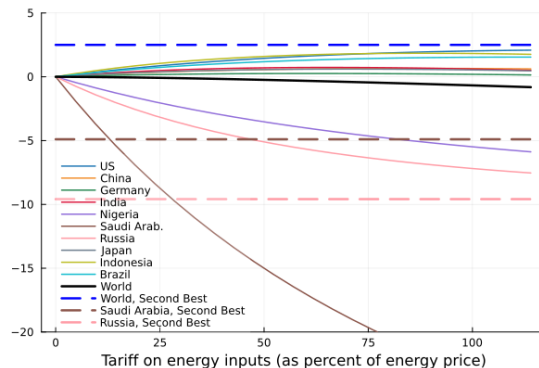

back

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

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

   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 (!)

Tariff on energy inputs (as percent of energy price)

(Legend: US, China, Germany, India, Nigeria, Saudi Arab., Russia, Japan, Indonesia, Brazil, World, World Second Best, Saudi Arabia Second Best, Russia Second Best)

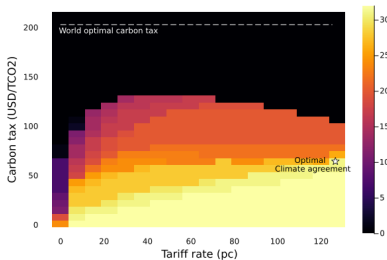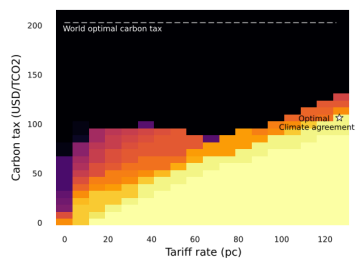## Trade retaliation

▶ 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 $\mathrm{t}_{ji} = \beta\, \mathrm{t}_{ij}$ on club members $i \in \mathbb{J}$ back

$\beta = 0.25$ $\beta = 0.5$ $\beta = 1.0$