The Optimal Design of Climate Agreements

Inequality, Trade, and Incentives for Climate Policy

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Energy Markets, Decarbonization, and Trade

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  - "Climate club", Nordhaus (2015): trade sanctions on non-participations to sustain larger "clubs"

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$\Rightarrow$ 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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▶ 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)
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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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Model

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

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

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2. Representative final good firm:

$$\max_{\ell_i, e^f_i, e^c_i, e^r_i} \; \mathrm{p}_i\, \mathcal{D}^y_i(\mathcal{E})\, z_i\, F(\ell_i, e^f_i, e^c_i, e^r_i) - w_i \ell_i - (q^f + \mathrm{t}^\varepsilon_i) e^f_i - (q^c_i + \mathrm{t}^\varepsilon_i) e^c_i - q^r_i e^r_i$$

– Climate externality: $\mathcal{D}^y_i(\mathcal{E})$, Income inequality z_i, Carbon tax: t^ε_i

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

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

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   ◦ Coal e^c_i produced at price $q^c_i = z^c_i \mathbb{P}_i$ ◦ Renewables e^r_i produced at price $q^r_i = z^r_i \mathbb{P}_i$

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Climate agreement design: “rules of the game”

- ***Definition:*** A climate agreement is a set $\{\mathbb{J}, \mathrm{t}^{\varepsilon}, \mathrm{t}^{b}\}$ 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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    - Assumption relaxed in an extension: oil-gas-specific tariffs

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  - All countries trade in oil-gas at price q^f
  - 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, $\mathrm{t}_{ki}^{b} = 0$ and $\mathrm{t}_k^{\varepsilon} = 0$.
    - 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, $\mathrm{t}_{ki}^{b} = 0$ and $\mathrm{t}_k^{\varepsilon} = 0$.
  - Indirect utility $\mathcal{U}_i(\mathbb{J}, \mathrm{t}^{\varepsilon}, \mathrm{t}^{b}) \equiv u\Big(\mathcal{D}_i^{y}\big(\mathcal{E}(\mathbb{J}, \mathrm{t}^{\varepsilon}, \mathrm{t}^{b})\big)\, c_i(\mathbb{J}, \mathrm{t}^{\varepsilon}, \mathrm{t}^{b})\Big)$

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  - Countries outside the club $k \notin \mathbb{J}$ have passive policies, $\mathrm{t}_{ki}^{b} = 0$ and $\mathrm{t}_k^{\varepsilon} = 0$.
  - Indirect utility $\mathcal{U}_i(\mathbb{J}, \mathrm{t}^{\varepsilon}, \mathrm{t}^{b}) \equiv u\Big(\mathcal{D}_i^y\big(\mathcal{E}_{(\mathbb{J},\mathrm{t}^{\varepsilon},\mathrm{t}^{b})}\big)\, c_{i(\mathbb{J},\mathrm{t}^{\varepsilon},\mathrm{t}^{b})}\Big)$
- Equilibrium concepts:
  - Unilateral participation decision of i, $\mathbb{J}\backslash\{i\}$, $\Rightarrow$ ***Nash equilibrium***

    Coalition $\mathbb{J}$ stable if $\quad \mathcal{U}_i(\mathbb{J}, \mathrm{t}^{\varepsilon}, \mathrm{t}^{b}) \geq \mathcal{U}_i(\mathbb{J}\backslash\{i\}, \mathrm{t}^{\varepsilon}, \mathrm{t}^{b}) \quad \forall i \in \mathbb{J}$
  - Sub-coalitional deviation $\Rightarrow$ ***Coalitional Nash equilibrium***

Optimal design with endogenous participation

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

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

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

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

  $\Rightarrow$ *Combinatorial Discrete Choice Problem* for $\mathbb{J} \in \mathcal{P}(\mathbb{I})$
  - Solution method: use a "squeezing procedure", as in Jia (2008), Arkolakis, Eckert, Shi (2023) extended to handle participation constraints, Approach, details, Deviations, Solution methods

Outline

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

Quantification

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

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- 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

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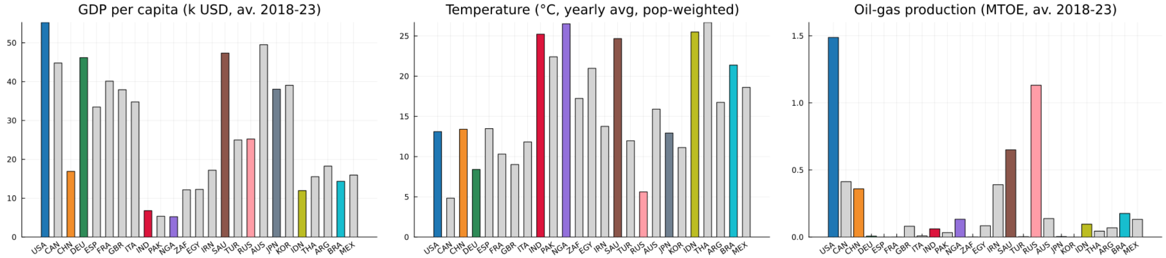
- Standard functional forms:
  - CRRA utility, Nested CES production, Iso-elastic fossil fuel extraction
- Parameters to match country-level variables Details calibration , Details country-level moments
  - TFP $z_i \Rightarrow$ GDP y_i, Population $\mathcal{P}_i$, Temperature T_{it_0}, Pattern scaling 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}

Quantitative application – Data and sample of countries

- Sample of 32 "countries": (i) **US**, (ii) Canada, (iii) **China**, (iv) **Germany**, France, Spain, Italy, Rest of EU, (v) UK, (vi) **India**, (vii) Pakistan, (viii) **Nigeria**, (ix) South-Africa, (x) Rest of Africa, (xi), Egypt, (xii) Iran, (xiii) **Saudi Arabia**, (xiv) Turkey, (xv) Rest of Middle-East+Maghreb (xvi) **Russia**, (xvii) Rest of CIS, (xviii) Australia, (xix) **Japan** (xx) Korea, (xxi) Indonesia, (xxii) Thailand, (xxiii) Rest of South-East Asia, (xxiv) Argentina, (xxv) **Brazil**, (xxvi) Mexico, (xxvi) Rest of Latin America, Data: Avg. 2018-2023.



Details [Trade shares – details]

Outline

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
    - Relies heavily on cross-country transfers to offset redistributive effects

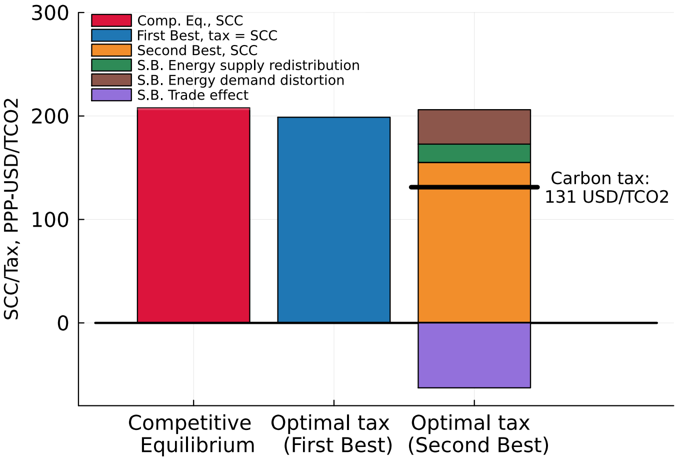
Optimal policy benchmarks

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

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

    - 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 (2024), Kortum, Weisbach (2022) Nash-Unilateral Policies

Second-Best climate policy

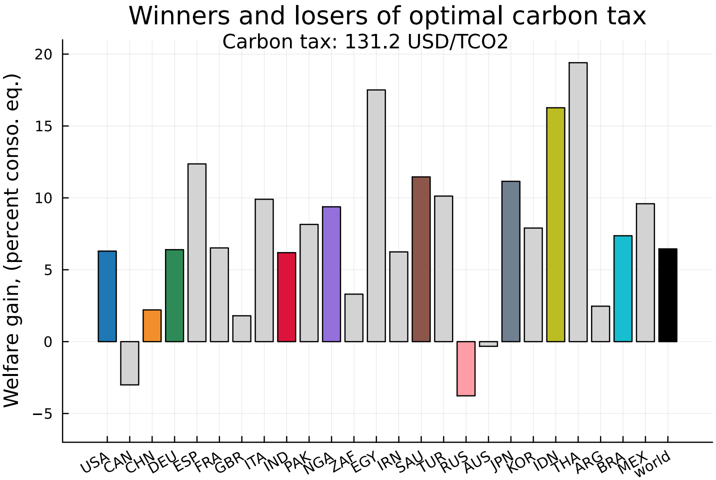


- Accounting for redistribution and lack of transfers

  $\Rightarrow$ implies a carbon tax lower than the Social Cost of Carbon (SCC), from \$155 to $\$131/tCO_2$.

Gains from cooperation – World Optimal policy

- Optimal carbon tax
  Second Best: $\sim \$131/tCO_2$
- Reduce fossil fuels / CO_2 emissions by 45% compared to the Competitive equilibrium (Business as Usual, BAU)
- Welfare difference between world optimal policy vs. comp. eq./BAU



Outline

Main result and Intuition

- The optimal climate agreement navigates the intensive and extensive margin tradeoff:
  - ***Participation:*** all the countries in the world with the exception of Russia, former Soviet countries, Saudi Arabia, Iran, Nigeria
  - ***Carbon tax:*** need to reduce tax level from \$131 to \$114/tCO_2
  - ***Trade tariffs:*** impose substantial tariff 50% on the goods from non-members

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  - ***Participation:*** all the countries in the world with the exception of Russia, former Soviet countries, Saudi Arabia, Iran, Nigeria
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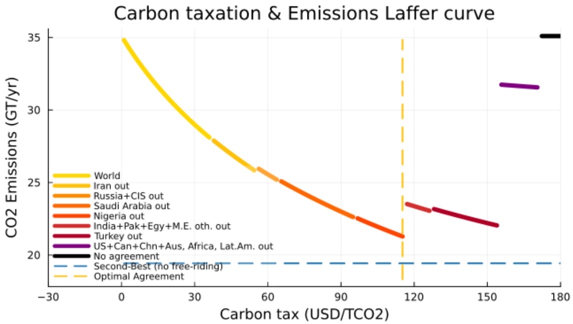
  - ***Trade tariffs:*** impose substantial tariff 50% on the goods from non-members

- 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*, because cost of taxing fossil-fuels $\gg$ cost of tariffs / autarky

$\Rightarrow$ As a result, we need to decrease the carbon tax

Laffer curve for carbon taxation

– Due to free-riding incentives, cannot reach globally optimal carbon tax $t^{\varepsilon,\star} = \$131$

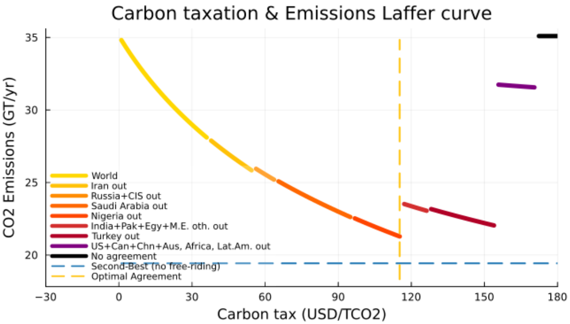


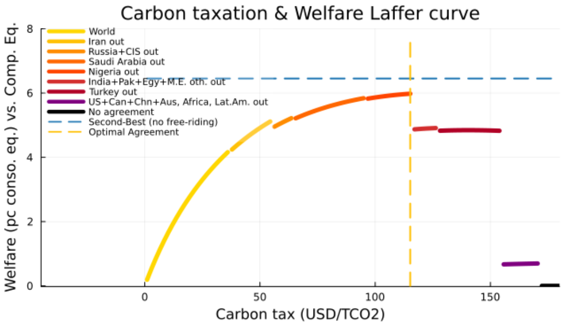
Emissions $\mathcal{E}$ (in $GtCO_2/yr$) and welfare $\mathcal{W}$ as function of the carbon tax t^{ε}, with tariff $t^{b} = 50\%$.

Laffer curve for carbon taxation

– Due to free-riding incentives, cannot reach globally optimal carbon tax $t^{\mathcal{E},\star} = \$131$

– Need to lower the carbon tax 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 $t^b = 50\%$.

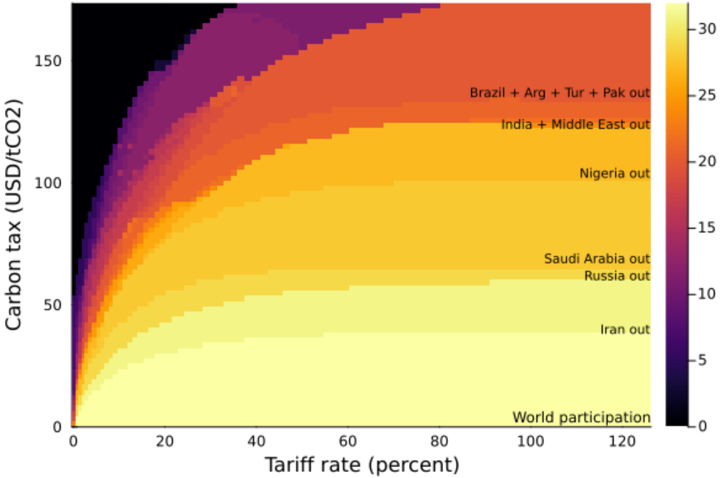
Climate Agreements: Intensive vs. Extensive Margin

- **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 $\mathcal{E}\uparrow$



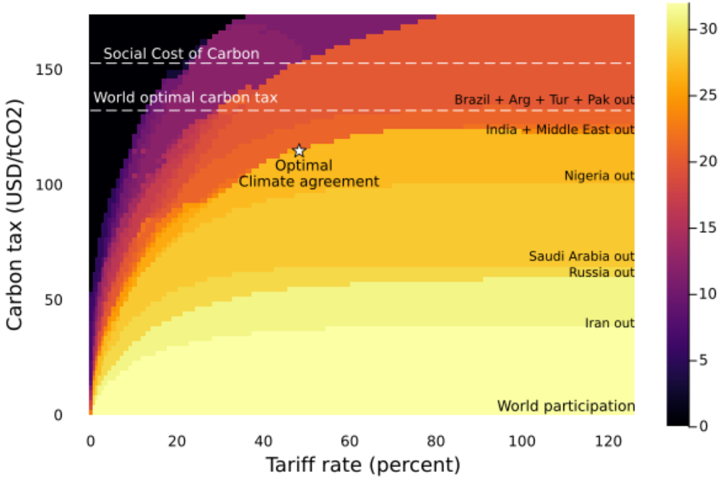
Optimal Climate Agreement

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

$\Rightarrow$ need to reduce carbon tax from \$131 to \$114

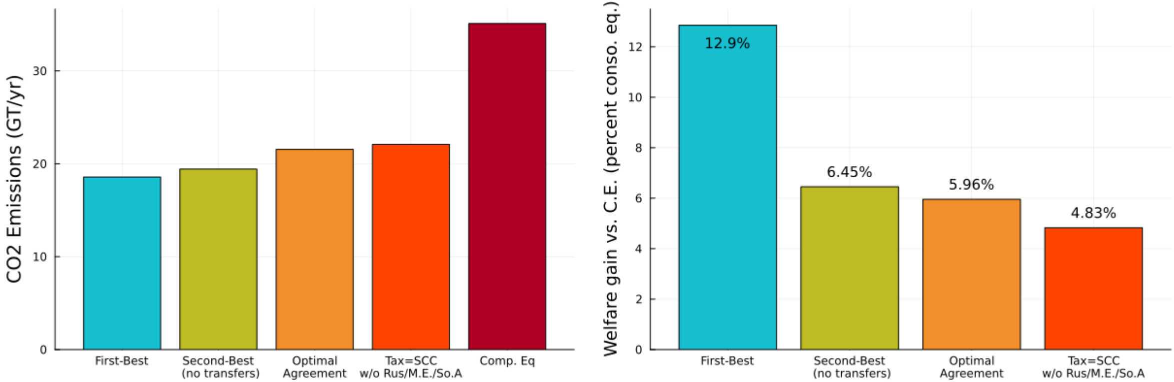
$\Rightarrow$ Beneficial to leave several fossil-fuel producers outside the agreement
e.g. no incentive for Russia to join: cold, closed to trade, large fossil-fuel producer

Graph welfare



Emission reduction vs. Welfare: Different metrics!

- Agreements with tariffs recover 92% of welfare gains from the Second-Best – optimal carbon tax without transfers – at a cost of increasing emissions by 11%
- Setting the policy "wrongly" at $t^{\varepsilon} = SCC = \$155$ lowers the participation:
  India, Pakistan, Egypt, Turkey, Argentina, Brazil, Rest of Middle-East, all exit the agreement



Outline

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: zero! 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

  $\Rightarrow$ Need a large coalition at a cost of lowering the carbon tax from the world optimum \$130 to \$110
- 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

Optimal design with endogenous participation

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  - 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 $\{\mathrm{t}^{\varepsilon}_i, \mathrm{t}^{b}_{ij}\}_{ij}$
    - Such costs increase exponentially in the number of countries I
- Optimal – country specific – carbon taxes:
  - Without free-riding / exogeneous participation

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

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

$$\mathrm{t}^{\varepsilon}_i \propto \frac{1}{\big(\omega_i + \nu_i(\mathbb{J})\big)u'(c_i)}\Big[SCC + SCF - SCT\Big]$$

back

Optimal design with endogenous participation

- Equilibrium concepts and participation constraints:
  - ***Nash equilibrium*** $\Rightarrow$ unilateral deviation $\mathbb{J}\backslash\{j\}$, $\quad \mathbb{J} \in \mathbb{S}(\mathrm{t}^f, \mathrm{t}^b)$ if:

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

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

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

    - 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 $\mathbb{J}, \mathrm{t}^f, \mathrm{t}^b$, 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

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

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

- Current design:
  - (i) choose taxes $\{\mathrm{t}^{\varepsilon},\mathrm{t}^{b}\}$ [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 $\{\mathrm{t}^{\varepsilon},\mathrm{t}^{b}\}$ [inner problem]
  - (iii) check participation constraints for $(\mathbb{J},\mathrm{t}^{\varepsilon},\mathrm{t}^{b})$
  - ▶ 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 $\mathrm{t}^{\varepsilon}(\mathbb{J}), \mathrm{t}^{b}(\mathbb{J})$
  - Requires to compute allocation $\mathcal{U}_i\big(\mathbb{J}, \mathrm{t}^{\varepsilon}(\mathbb{J}), \mathrm{t}^{b}(\mathbb{J})\big)$
  - Participation constraints $\mathcal{U}_i\big(\mathbb{J}, \mathrm{t}^{\varepsilon}(\mathbb{J}), \mathrm{t}^{b}(\mathbb{J})\big) \geq \mathcal{U}_i\big(\mathbb{J}\backslash\{i\}, \mathrm{t}^{\varepsilon}(\mathbb{J}\backslash\{i\}), \mathrm{t}^{b}(\mathbb{J}\backslash\{i\})\big)$ with multiplier $\nu_{\mathbb{J},i}$
  - Requires to compute allocation $\mathcal{U}_i\big(\mathbb{J}\backslash\{i\}, \mathrm{t}^{\varepsilon}(\mathbb{J}\backslash\{i\}), \mathrm{t}^{b}(\mathbb{J}\backslash\{i\})\big)$
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  - 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

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

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

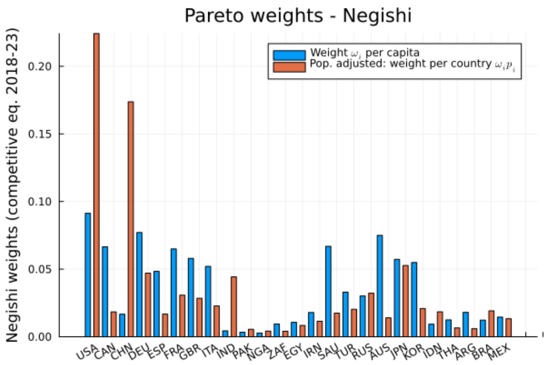
$$\left\{\begin{array}{l} \Delta_i \mathcal{U}_i(\mathcal{J} \cup \{j\}) \geq 0 \\ \& \left[\begin{array}{l} \left(\Delta_j \mathcal{W}(\mathcal{J} \cup \{j\}) \geq 0 \ \& \ \Delta_i \mathcal{U}_i(\mathcal{J}) \geq 0\right) \\ \text{or } \Delta_i \mathcal{U}_i(\mathcal{J}) < 0 \end{array}\right. \end{array}\right.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

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

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



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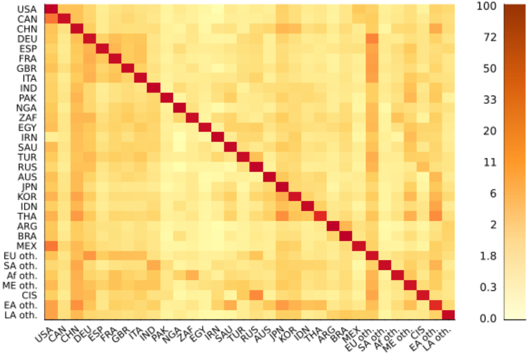
Quantification – Trade model

- Armington Trade model:

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

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

$$s_{ij} = \frac{c_{ij}p_{ij}}{c_i\mathbb{P}_i} = a_{ij}\frac{(\tau_{ij}(1+\mathrm{t}^b_{ij})\mathrm{p}_j)^{1-\theta}}{\sum_k a_{ik}(\tau_{ik}(1+\mathrm{t}^b_{ik})\mathrm{p}_k)^{1-\theta}} \qquad \& \qquad \mathbb{P}_i = \left(\sum_j a_{ij}(\tau_{ij}\mathrm{p}_j)^{1-\theta}\right)^{\frac{1}{1-\theta}}$$

  - Energy consumption doesn't internalize climate damage:

$$\mathrm{p}_i MPe_i = q^e$$

  - Inequality, as measured in local welfare units:

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

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

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

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 $\mathrm{t}_i^{\varepsilon}$ on energy e_i^f, e_i^c, unrestricted bilateral tariffs t_{ij}^b
  - Budget constraint: $\sum_i \mathrm{t}_i^{ls} = \sum_i \mathrm{t}_i^f e_i^f + \sum_{i,j} \mathrm{t}_{ij}^b c_{ij} \tau_{ij} \mathrm{p}_j$

- 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

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

back

Step 2: World optimal Ramsey policy

- Maximizing welfare of the world Social Planner:

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

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

- 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}:

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

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

- Relative welfare weights, representing inequality

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

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:

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

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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:

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

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

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

∘ Params: $\mathcal{C}^f_{EE}$ agg. fossil inv. elasticity, s^e_i 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:

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

  – Reexpressing demand terms:

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

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 $\mathrm{t}^{b,r}$ 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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  - 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:

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

- 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" $\widehat{\widetilde{\lambda}}_i \propto \omega_i(1+\nu_i)u'(c_i)$

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

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

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

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

$$= \frac{1}{1-\vartheta_{\mathbb{J}^c}} \sum_{i \in \mathbb{I}} \widetilde{\lambda}_i LCC_i + \frac{1}{1-\vartheta_{\mathbb{J}^c}} \mathcal{C}^f_{EE} \sum_{i \in \mathbb{I}} \widetilde{\lambda}_i (e^f_i - e^x_i) - \sum_{i \in \mathbb{J}} \widetilde{\upsilon}_i \frac{q^f(1-s^f_i)}{\sigma e^f_i}$$

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

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Step 4: Unilateral optimal policy

- Unilateral Social Planner maximizing local welfare

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

  - Instruments: local carbon taxes $\mathrm{t}_i^{\varepsilon}$ 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:

$$\mathrm{t}_{ij}^b = \omega_j^{(i)} \frac{\mu_j^{(i)}}{\lambda_i}$$

  - 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:

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

  - 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 $q^e e_i / \mathrm{p}_i y_i$

- 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^x_{it} 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^x_i, $\mathcal{R}_{it}$ calibrated to *proven reserves* data from BP. ν_i extraction cost curvature to match profit $\pi^f_i = \frac{\bar{\nu}_i \nu_i}{1+\nu_i}(\frac{e^x_i}{\mathcal{R}_i})^{\nu_i}\mathcal{R}_i\mathbb{P}_i$
  - Future: Choose $(\bar{\nu}_i, \nu_i, \mathcal{R}_i)$ to match marginal cost $\mathcal{C}_e$ & extraction data e^x_i (BP, IEA)
- Coal and Renewable: Production $\bar{e}^r_i, \bar{e}^x_i$ and price q^c_i, q^r_i
  - Calibrate $q^c_i = z^c\mathbb{P}_i$, $q^r_{it} = z^r\mathbb{P}_i$
    Choose z^c_i, z^r_i to match the energy mix (e^f_i, e^c_i, e^r_i)
- Population dynamics
  - Match UN forecast for growth rate / fertility

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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 $\mathrm{t}_j^{\varepsilon} = 0, \mathrm{t}_{jk}^{b} = 0, \forall j$,
  - Change in welfare: Linear approximation around that point $\Rightarrow$ small changes in carbon tax $d\mathrm{t}_j^{\varepsilon}, \forall j$ and tariffs $d\mathrm{t}_{j,k}^{b}, \forall j, k$ for a club J_i

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

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

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

    - Climate damage $\bar{\gamma}_i = \gamma(T_i - T_i^\star) T_i\, s^{E/S}$
    - Trade and leakage effect: GE impact of $\mathrm{t}_j^{\varepsilon}$ and $\mathrm{t}_{j,}^{b}$ 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

$$
\begin{aligned}
\Big(\frac{d\mathrm{p}_i}{d\mathrm{p}_i} + \frac{dy_i}{y_i}\Big) = \sum_k \boldsymbol{t}_{ik}\Big[\Big(\frac{\mathrm{p}_k y_k}{v_k}\Big)(d\ln \mathrm{p}_k + d\ln y_k) + \frac{q^f e^x_k}{v_k} d\ln e^x_k - \frac{q^f e^f_k}{v_k} d\ln e^f_k + \frac{q^f (e^x_k - e^f_k)}{v_k} d\ln q^f \\
+ \theta \sum_h \big(s_{kh} d\ln \mathrm{t}_{kh} - (1+s_{ki}) d\ln \mathrm{t}_{ki}\big) + (\theta-1) \sum_h \big(s_{kh} d\ln \mathrm{p}_h - d\ln \mathrm{p}_i\big)\Big]
\end{aligned}
$$

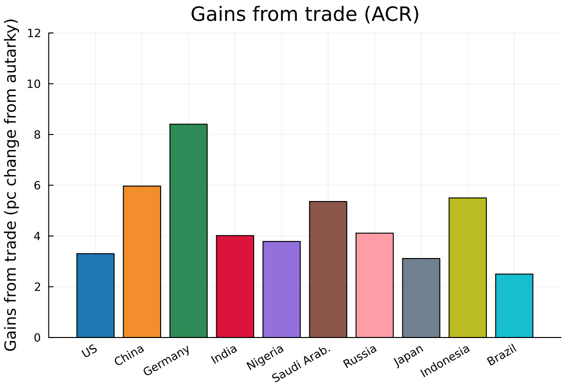
  - Fixed point for price level $d\ln p_i$

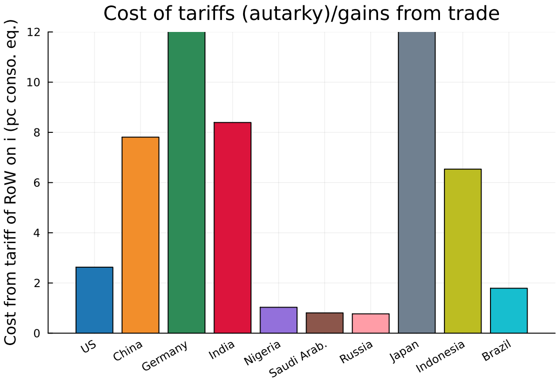
$$
\begin{aligned}
&\Big[(\mathbf{I}-\mathbf{T}\odot v^y)[\mathbf{I}-\alpha^{y,p}\odot\mathbf{I}] + \mathbf{T}(v^{e^x}\odot\tfrac{1}{\nu}) + \mathbf{T}v^{e^f}\tfrac{\sigma^y}{1-s^e} - (\theta-1)(\mathbf{TS}-\mathbf{T}') - \Big((\mathbf{I}-\mathbf{T}\odot v^y)\alpha^{y,z} - \tfrac{\sigma^y}{1-s^e}\Big)\odot\bar{\gamma}\mathbf{I}\odot\big(\tfrac{\lambda^x}{\nu}\bi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

back

Trade-off – Gains from trade

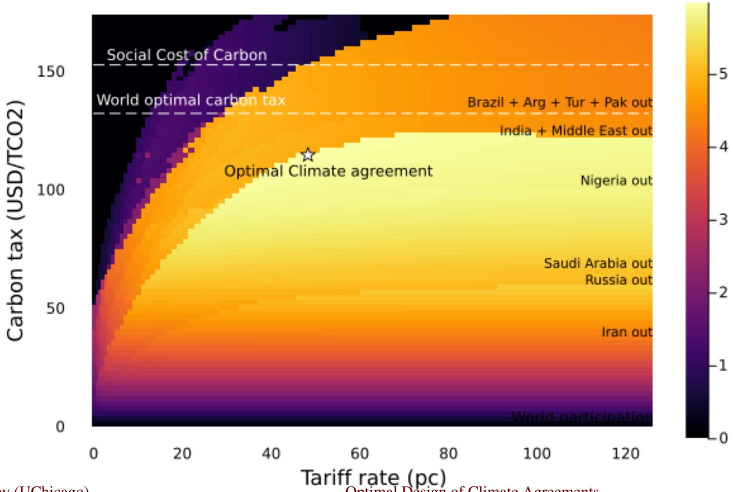
Gains from trade (ACR) vs. loss from tariffs/autarky in this model back





Climate agreement and welfare

Recover 92% of welfare gains, i.e. 6% out of 6.5% 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

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

  - Construction evaluated at the optimal carbon tax $\mathrm{t}^{\varepsilon} = 114\$$, and tariff $\mathrm{t}^{b} = 50\%$.
  - 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, i.e. Germany, France, Spain, Italy, Rest of EU
  - Round 2: China, UK, Turkey, Rest of South and South-East Asia
  - Round 3: USA, Japan, Korea, Australia, Thailand, Indonesia, Pakistan, Rest of Africa & Latin America
  - Round 4: Canada, South-Africa, Mexico
  - Round 5: India, Brazil, Egypt, Argentina, Rest of Middle-East

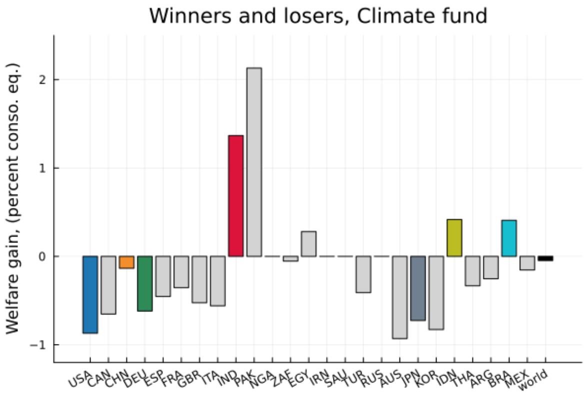
  $\notin$ Stay out of the agreement: Russia, CIS, Saudi Arabia, Iran, Nigeria

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
  - $\alpha^{\star} = 0\%$: Not optimal for rich countries to do lump-sum transfers.
  - I compare to the \$300 *bn* agreed in COP29: most countries looses, biggest winners (not shown) "Rest of Africa" and "Rest of South Asia"

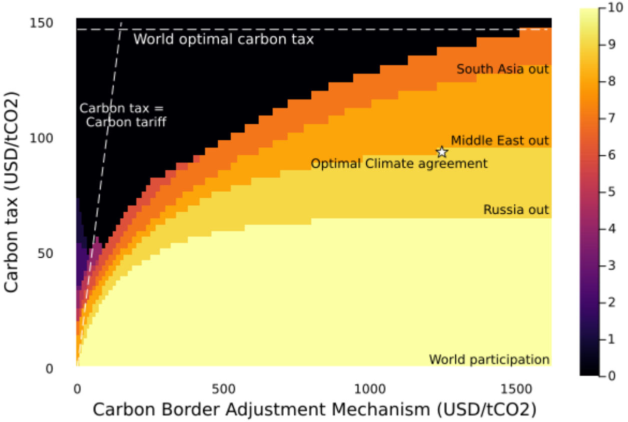


Carbon tariffs - EU's CBAM

- Carbon Border Adjustment Mechanism: European Union's "Carbon tariff"
  - Tariff t^b_{ij} scaling w/ carbon content ξ^y_j

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

- 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



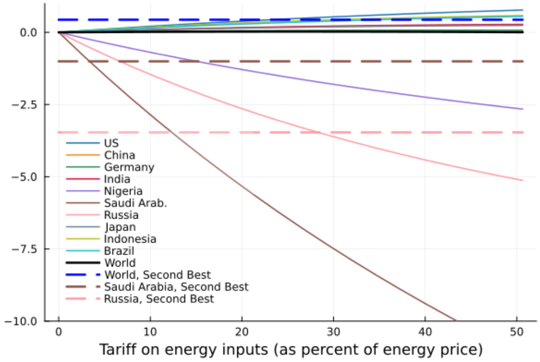
back

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

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

  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: back
  - Countries outside the club $j \notin \mathbb{J}$ impose tariffs $t_{ji} = \beta\, t_{ij}$ on club members $i \in \mathbb{J}$

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