

# The Optimal Design of Climate Agreements

## Inequality, Trade, and Incentives for Climate Policy

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

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      - “**Climate club**”, Nordhaus (2015): trade sanctions on non-participations to sustain larger “clubs”
- ⇒ How can we design a climate agreement, to address **free-riding and endogenous participation** as well as **redistributive effects**, and effectively fight climate change?

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- The agreement boils down to a choice of countries, a carbon tax, a tariff rate
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  - vs. *Extensive margin*: a larger set of countries, at the cost of lowering the carbon tax

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vs. *Extensive margin*: a larger set of countries, at the cost of lowering the carbon tax

► 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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- ▶ IAM and macroeconomics of climate change and carbon taxation
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  - *HA model*: Bourany (2024), Krusell, Smith (2022), Kotlikoff, Kubler, Polbin, Scheidegger (2021)
  - *Spatial models*: Cruz, Rossi-Hansberg (2022, 2023) among others
- ⇒ ***Strategic and constrained policy with heterogeneous countries & trade***

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

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

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2. Representative final good firm:

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

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

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3. Energy markets

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

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

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

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## Climate agreement design: “rules of the game”

- **Definition:** A climate agreement is a set  $\{\mathbb{J}, \mathbf{t}^\varepsilon, \mathbf{t}^b\}$  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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  - All countries trade in oil-gas at price  $q^f$
  - Local, lump-sum rebate of taxes:  $t_i^{ls} = \mathbf{t}^e(e_i^f + e_i^c) + \sum_{j \notin \mathbb{J}} \mathbf{t}^b \tau_{ij} c_{ij} p_j$



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

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

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

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

## Optimal design with endogenous participation

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

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

- Current design:

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

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

⇒ *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

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



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- $\omega_i = \frac{1}{u'(\bar{c}_i)}$ , 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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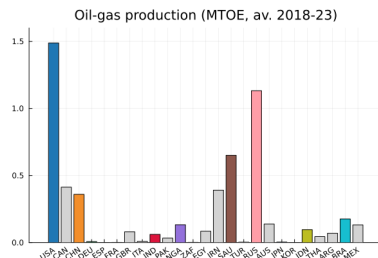
## ► Standard functional forms:

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## ► Parameters to match country-level variables Details calibration, Details country-level moments

- TFP  $z_i \Rightarrow$  GDP  $y_i$ , Population  $\mathcal{P}_i$ , Temperature  $T_{i0}$ , Pattern scaling  $\Delta_i$
- Mix: oil-gas  $e_i^f$ , Coal  $e_i^c$ , Low-carbon  $e_i^x$ , energy share, oil-gas prod<sup>o</sup>  $e_i^x$ , reserves  $\mathcal{R}_i$ , rents  $\pi_i^f$
- Trade: cost  $\tau_{ij}$  projected on distance, preferences  $a_{ij}$  to match import shares  $s_{ij}$

► 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.



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## Optimal policy benchmarks

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

## Optimal policy benchmarks

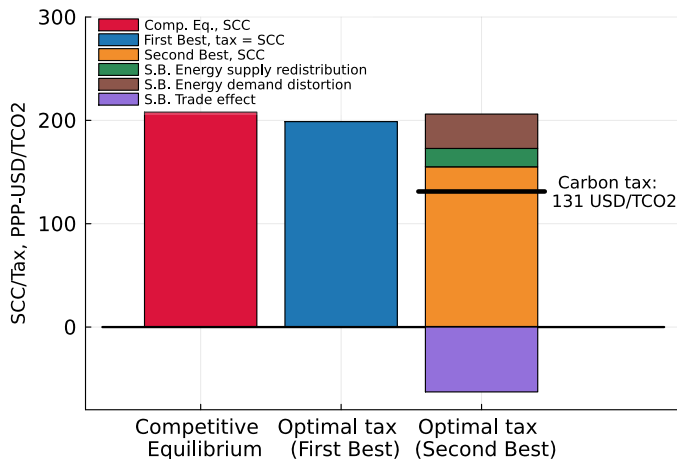
### ► Policy benchmarks, without free-riding incentives

- **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  $t^E$  correct climate externality, but also accounts for:
    - (i) Redistribution motives, and G.E. effects on (ii) energy markets and (iii) trade leakage

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

- 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

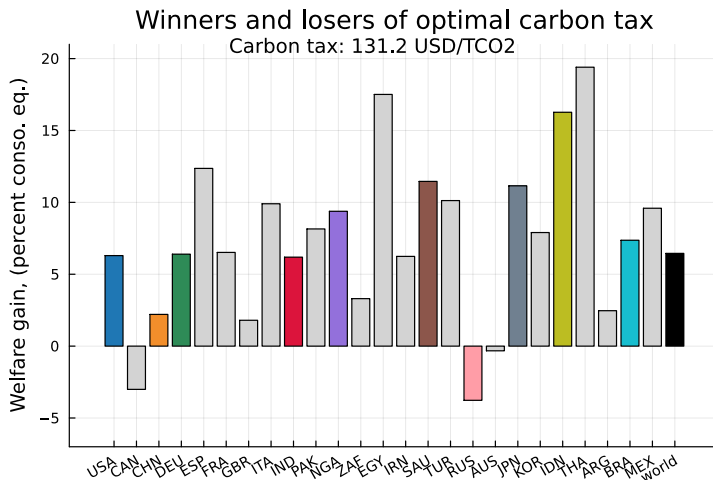


- Accounting for redistribution and lack of transfers  
 $\Rightarrow$  implies a carbon tax lower than the Social Cost of Carbon (SCC), from \$155 to \$131/ $tCO_2$ .



## 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



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## Main result and Intuition

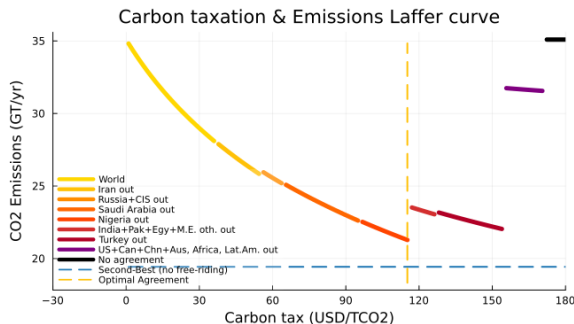
- ▶ The optimal climate agreement navigates the **intensive** and **extensive** margin tradeoff:
  - **Participation:** all the countries in the world with the exception of Russia, former Soviet countries, Saudi Arabia, Iran, Nigeria
  - **Carbon tax:** need to reduce tax level from \$131 to \$114/ $tCO_2$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

## Main result and Intuition

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    - **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
  - ▶ **Mechanism:**
    - Countries participate depending on  $\left\{ \begin{array}{l} \text{(i) the cost of distortionary carbon taxation} \\ \text{(ii) the cost of tariffs (= the gains from trade)} \end{array} \right.$
    - Russia/Middle East/South Asia do not join the club for high carbon tax *for any tariffs*, because cost of taxing fossil-fuels  $\gg$  cost of tariffs / autarky
- ⇒ As a result, we need to decrease the carbon tax

## Laffer curve for carbon taxation

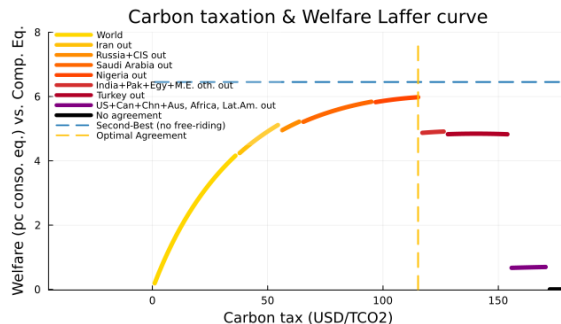
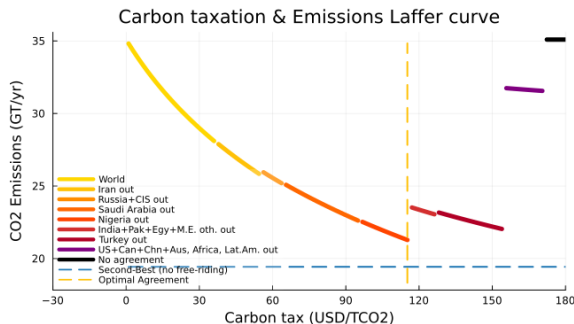
- Due to free-riding incentives, **cannot reach** globally optimal carbon tax  $t^{\epsilon,*} = \$131$



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

## Laffer curve for carbon taxation

- Due to free-riding incentives, **cannot reach** globally optimal carbon tax  $t^{\varepsilon,*} = \$131$
- 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  $t^{\varepsilon}$ , with tariff  $t^b = 50\%$ .

## Climate Agreements: Intensive vs. Extensive Margin

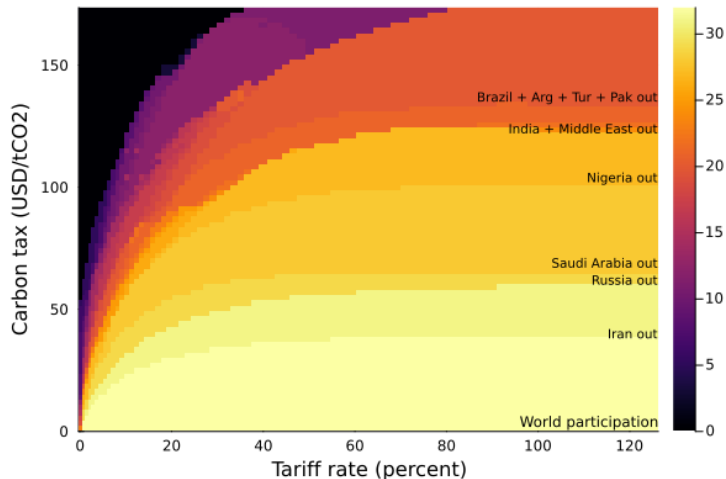
### ► Intensive margin:

given a coalition:

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

### ► Extensive margin:

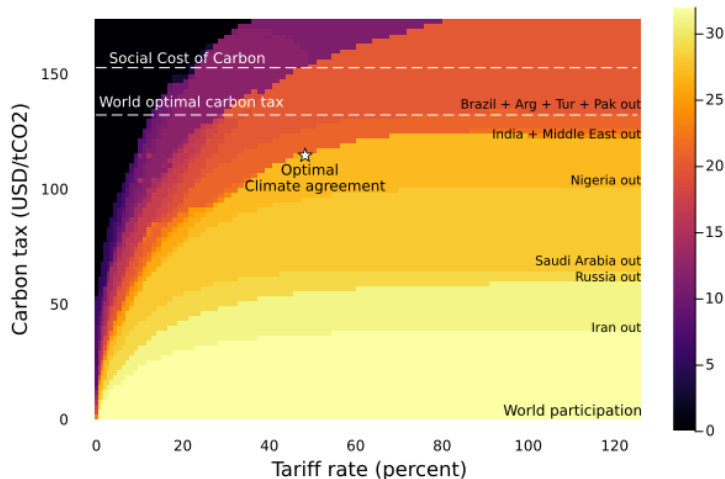
carbon tax also deters  
participation  
individual countries free-ride  
increasing emissions  $\mathcal{E} \uparrow$



## Optimal Climate Agreement

- ▶ Despite full discretion of instruments ( $t^E, t^b$ ), we cannot sustain an agreement with Russia, Middle East, South-Asia & South America
- ⇒ need to **reduce carbon tax** from \$131 to \$114
- ⇒ 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

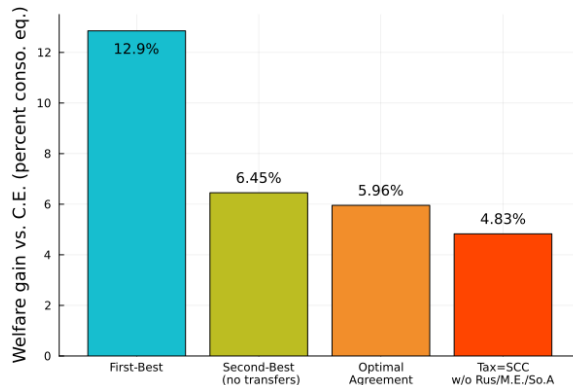
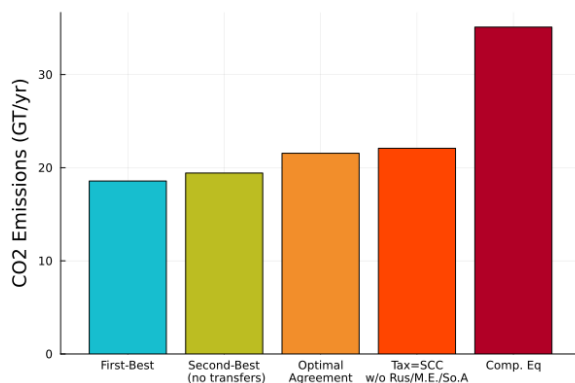
Graph welfare





## 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  $t^E = SCC = \$155$  lowers the participation: India, Pakistan, Egypt, Turkey, Argentina, Brazil, Rest of Middle-East, **all exit the agreement**



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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: 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  $t^E$
5. Retaliation – Trade war between club and non-club members, [details](#)
  - Moderate retaliation induce a lower carbon tax, Large “trade war” induces “mutual destruction” and can promote cooperation

# Conclusion

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

⇒ Need a large coalition at a cost of lowering the carbon tax from the world optimum \$130 to \$110
- ▶ Future research:
  - Dynamic policy games, bargaining, and coalition building

# Conclusion

**Thank you!**

**[thomasbourany@uchicago.edu](mailto:thomasbourany@uchicago.edu)**

# Appendices

## Optimal design with endogenous participation

- ▶ Why uniform policy instruments  $t^\varepsilon$  and  $t^b$  for all club members:
  - Our social planner/designer solution represents the outcome of a “bargaining process” between countries (with bargaining weights  $\omega_i$ ).
  - 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 / exogeneous participation

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

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

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



## Optimal design with endogenous participation

### ► Equilibrium concepts and participation constraints:

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

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

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

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

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

back

## Climate club design:

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

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

- Current design:

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

► Computation:

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

- Alternative

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

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

back

## Country deviation and policy

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

back

## Solution method

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

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    - Squeezing step:

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

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

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

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  - Use a “squeezing procedure”, as in Jia (2008), Arkolakis, Eckert, Shi (2023) extended to handle participation constraints
    - Squeezing step:

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

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

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

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

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

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

Back, solution method

## Complementarity

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

IF the coalition  $\mathcal{J}$  makes (i) allocation outcomes better for welfare with  $\{j\}$ , if both  $\mathcal{J}$  and  $\mathcal{J} \cup \{j\}$  are stable, or (ii) the coalition  $\mathcal{J} \cup \{j\}$  is stable if  $\mathcal{J}$  is unstable  
THEN one of these conditions should also be respected for larger coalitions  $\mathcal{J}' \supseteq \mathcal{J}$ .

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

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

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# Welfare and Pareto weights

- Welfare:

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

- Pareto weights  $\omega_i$ :

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

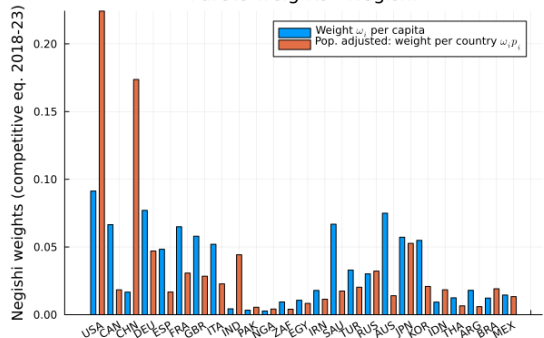
for  $\bar{c}_i$  consumption in initial equilibrium  
“without climate change“, i.e. year = 2020

- Imply no redistribution motive in  $t = 2020$

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

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

Pareto weights - Negishi



back



## Quantification – Trade model

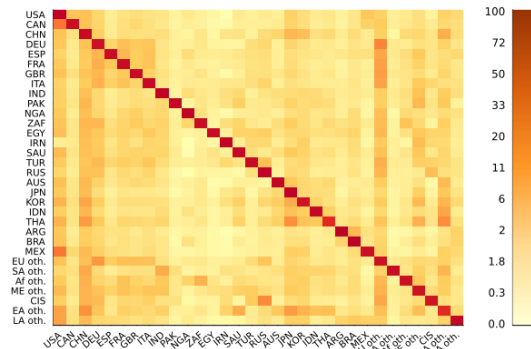
- Armington Trade model:

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

- Estimated gravity equation regression:

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

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


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## Step 0: Competitive equilibrium & Trade

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

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

- Energy consumption doesn't internalize climate damage:

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

- Inequality, as measured in local welfare units:

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

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

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

## Step 1: World First-best policy

- Maximizing welfare of the world Social Planner:

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

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

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## Step 1: World First-best policy

### ► Social planner allocation and decentralization:

- Consumption:

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

- Energy use:

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

- Social cost of carbon:

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

- Decentralization:

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

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

## Step 2: World optimal Ramsey policy

- Maximizing welfare of the world Social Planner:

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

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

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## Step 2: World optimal Ramsey policy

► The planner takes into account

- (i) the **marginal value of wealth**  $\lambda_i$
- (ii) the **shadow value of good  $i$** , from market clearing,  $\mu_i$ :
- (iii) the **shadow value of bilateral trade  $ij$** , from household FOC,  $\eta_{ij}$ :

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

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

► Relative welfare weights, representing inequality

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

## Step 2: Optimal policy – Social Cost of Carbon

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

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

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

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- Social Cost of Carbon for the planner:

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

- Social Cost of Carbon integrates these inequalities:

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



## Step 2: Optimal policy – Other motives

► Taxing fossil energy has additional redistributive effects:

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

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

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

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◦ Params:  $C_{EE}^f$  agg. fossil inv. elasticity,  $s_i^e$  energy cost share and  $\sigma_i$  energy demand elasticity

### ► Proposition 2: Optimal fossil energy tax:

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

– Reexpressing demand terms:

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

## Step 3: Ramsey Problem with participation constraints

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

## 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  $q^f$
- ▶ Participation constraints:

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

- ▶ Welfare:

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

## Step 3: Ramsey Problem with participation constraints

### ► Participation constraints

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

### ► Second-Best social valuation with participation constraints

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

w/ Armington trade

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

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

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

## Step 3: Participation constraints & Optimal policy

### ► Proposition 3.2: Second-Best taxes:

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

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

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

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

## Step 4: Unilateral optimal policy

- Unilateral Social Planner maximizing local welfare

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

- Instruments: local carbon taxes  $\mathbf{t}_i^\varepsilon$  on energy  $e_i^f, e_i^c$ , unrestricted bilateral tariffs  $\mathbf{t}_{ij}^b$ , 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:

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

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

## Step 4: Unilateral optimal policy

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

- Local Cost of Carbon:

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

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

### ► Optimal local carbon tax:

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

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



## Quantification – Firms

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

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

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

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

- Damage functions in production function  $y$ :

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

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

# Quantification – Energy markets

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

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# Calibration

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

<i>Technology &amp; Energy markets</i>			
$\alpha$	0.35	Capital share in $F(\cdot)$	Capital/Output ratio
$\epsilon$	0.12	Energy share in $F(\cdot)$	Energy cost share (8.5%)
$\sigma$	0.3	Elasticity capital-labor vs. energy	Complementarity in production (c.f. Bourany 2022)
$\omega^f$	0.56	Fossil energy share in $e(\cdot)$	Oil-gas/Energy ratio
$\omega^c$	0.27	Coal energy share in $e(\cdot)$	Coal/Energy ratio
$\omega^r$	0.17	Non-carbon energy share in $e(\cdot)$	Non-carbon/Energy ratio
$\sigma_e$	2.0	Elasticity fossil-renewable	Slight substitutability & Study by Stern
$\delta$	0.06	Depreciation rate	Investment/Output ratio
$\bar{g}$	0.01*	Long run TFP growth	Conservative estimate for growth
<i>Preferences &amp; Time horizon</i>			
$\rho$	0.015	HH Discount factor	Long term interest rate & usual calib. in IAMs
$\eta$	1.5	Risk aversion	Standard Calibration
$n$	0.0035	Long run population growth	Average world population growth
<i>Climate parameters</i>			
$\xi^f, \xi^c$	2.761 & 3.961	Emission factor – Oil+nat. gas vs. Coal	Conversion 1 MTOE $\Rightarrow$ 1 MT CO <sub>2</sub>
$\chi$	2.3/1e6	Climate sensitivity	Pulse experiment: 100 GtC $\equiv$ 0.23° C medium-term warming
$\delta_s$	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)
$\alpha^T$	0.5	Weight historical climate for optimal temp.	Marginal damage correlated with initial temp.
$T^*$	14.5	Optimal yearly temperature	Average yearly temperature/Developed economies

# Matching country-level moments

**Table:** Heterogeneity across countries

Dimension of heterogeneity	Model parameter	Matched variable from the data	Source
Population	Country size $\mathcal{P}_i$	Population	UN
TFP/technology/institutions	Firm productivity $z_i$	<b>GDP per capita (2019-PPP)</b>	WDI
Productivity in energy	Energy-augmenting productivity $z_i^e$	Energy cost share	SRE
Cost of coal energy	Cost of coal production $C_i^c$	Energy mix/coal share $e_i^c/e_i$	SRE
Cost of non-carbon energy	Cost of non-carbon production $C_i^r$	Energy mix/coal share $e_i^r/e_i$	SRE
Local temperature	Initial temperature $T_{it_0}$	<b>Pop-weighted yearly temperature</b>	Burke et al
Pattern scaling	Pattern scaling $\Delta_i$	Sensitivity of $T_{it}$ to world $\bar{T}_t$	Burke et al
Oil-gas reserves	Reserves $\mathcal{R}_i$	Proved Oil-gas reserves	SRE
Cost of oil-gas extraction	Slope of extraction cost $\bar{\nu}_i$	<b>Oil-gas extracted/produced <math>e_i^x</math></b>	SRE
Cost of oil-gas extraction	Curvature of extraction cost $\nu_i$	Profit $\pi_i^f$ / energy rent	WDI
Trade costs	Distance iceberg costs $\tau_{ij}$	Geographical distance $\tau_{ij} = d_{ij}^\beta$	CEPII
Armington preferences	CES preferences $a_{ij}$	Trade flows	CEPII

# Theoretical investigation: decomposing the welfare effects

## ► Experiment:

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

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

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

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

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

◦ Params:  $\sigma$  energy demand elast<sup>y</sup>,  $s^e$  energy cost share,  $\bar{\nu}$  energy supply inverse elas<sup>y</sup>

back

## Welfare decomposition

### ► Armington model of trade with energy:

- Linearized market clearing

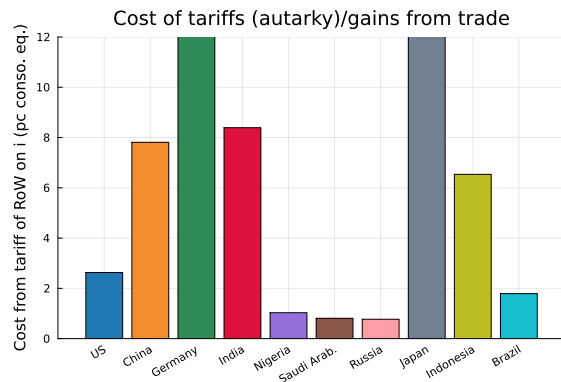
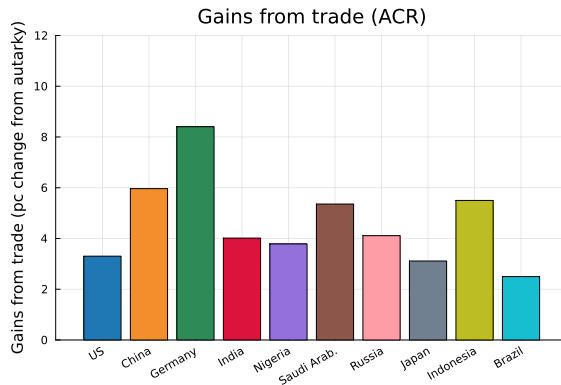
$$\begin{aligned} \left( \frac{dp_i}{dp_i} + \frac{dy_i}{y_i} \right) = \sum_k t_{ik} \left[ \left( \frac{p_k y_k}{v_k} \right) (d \ln p_k + d \ln y_k) + \frac{q^f e_k^x}{v_k} d \ln e_k^x - \frac{q^f e_k^f}{v_k} d \ln e_k^f + \frac{q^f (e_k^x - e_k^f)}{v_k} d \ln q^f \right. \\ \left. + \theta \sum_h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

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

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

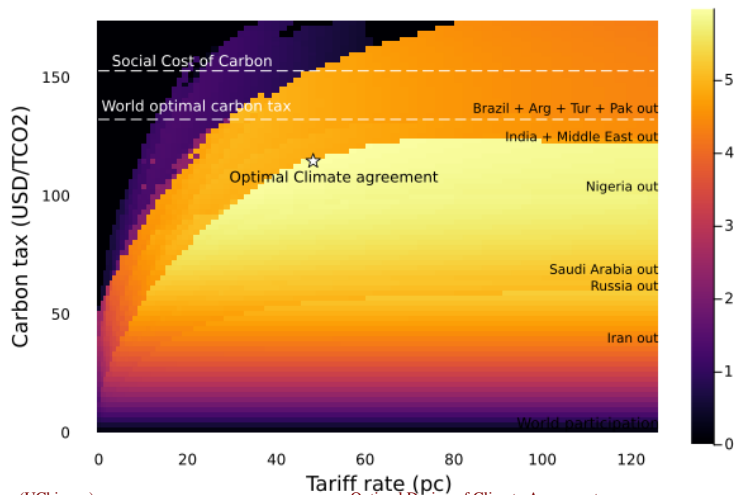
## Trade-off – Gains from trade

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

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

- Construction evaluated at the optimal carbon tax  $t^\varepsilon = 114\$$ , and tariff  $t^b = 50\%$ .
- Sequential procedure – coming *for free* from our CDCP algorithm / squeezing procedure
- Idea analogous to Farrokhi, Lashkaripour (2024)

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

- Round 1: European Union, 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

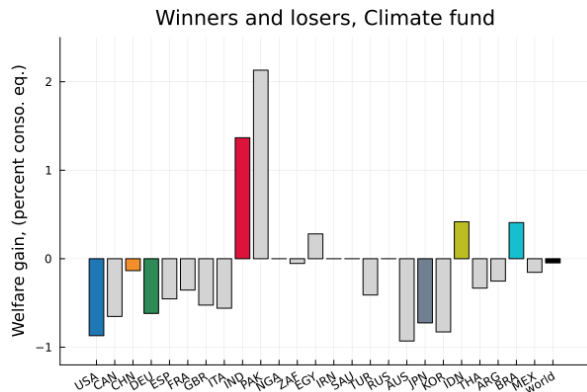
⊄ Stay out of the agreement: Russia, CIS, Saudi Arabia, Iran, Nigeria

## 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)

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

- ▶ Optimal transfers: [back](#)
  - $\alpha^* = 0\%$ : Not optimal for rich countries to do lump-sum transfers.
  - I compare to the \$300 bn agreed in COP29: most countries loses, 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"

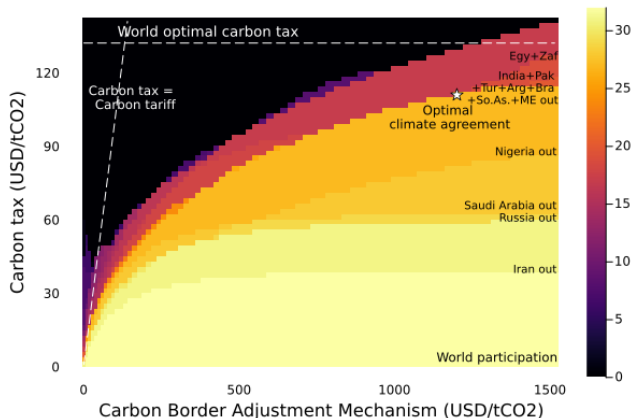
- Tariff  $t_{ij}^b$  scaling w/ carbon content  $\xi_j^y$

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

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

- ▶ Optimal Carbon tariff:

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



# Taxation of fossil fuels energy inputs

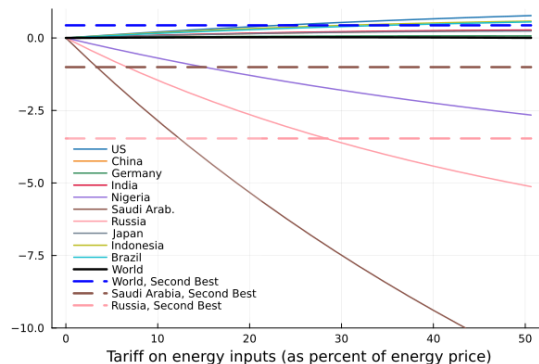
- Current climate club: [back](#)  
Tariffs only on final goods, not energy imports
  - Empirically relevant, c.f. Shapiro (2021): inputs are more emission-intensives but trade policy is biased against final goods output

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

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

if non-members export fossil fuels to the club

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



## Trade retaliation

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

