The Optimal Design of Climate Agreements
Inequality, Trade, and Incentives for Carbon Policy

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Motivation

- Fighting climate change requires implementing ambitious carbon reduction policies
  - The "free-riding problem" causes climate inaction
    individual countries have no incentives to implement globally optimal policies
  - Climate policy has redistributive effects across countries: (i) differences in incomes, (ii) change in climate, (iii) energy markets, (iv) reallocation through trade (leakage)
- Proposals to fight climate inaction and the free-riding problem:
  - International cooperation through climate agreements, e.g. UN's COP
  - Trade sanctions needed to give incentives to countries to reduce emissions meaningfully
    - "Climate club", Nordhaus (2015): trade sanctions on non-participations to sustain larger "clubs"
    - Carbon Border Adjustment mechanisms (CBAM), EU policy: carbon tariffs

Introduction

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

- Climate club setting:
  The agreement boils down to a carbon tax, a tariff rate and a choice of countries
- Trade-off:
  Intensive margin: a "climate club" with few countries and large emission reductions
  vs. *Extensive margin:* a larger set of countries, at the cost of lowering the carbon tax
- Build a Climate-Macro model (IAM) with heterogeneous countries and international trade to study the strategic implications of climate agreements and the optimal club design

Preview of the results:

- An optimally chosen agreement can undermine free-riding and lower emissions by 30%
  - Recover most welfare and climate gains of the policy benchmark absent free-riding
- Optimal climate agreement:
  - Need to lower carbon tax from \$150 to \$100/tCO_2
    to accommodate participation of South-Asia and Middle-East
  - Beneficial to leave fossil fuels producing countries, like Russia, outside of the climate agreement
- Mechanism:
  - Participation relies on a trade-off between $\begin{cases} \text{(i) the cost of distortionary carbon taxation} \\ \text{(ii) the cost of tariffs (= the gains from trade)} \end{cases}$
  - 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 $\Rightarrow$ need to decrease the carbon tax

Literature

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

  ⇒ ***Quantitative analysis of climate agreements and policy recommendation***
- Trade policy and environment policies:
  - *Trade and carbon policies:* Farrokhi, Lashkaripour (2024)Farrokhi, Lashkaripour (2024), Kortum, Weisbach (2023), Böhringer, Carbone, Rutherford (2012, 2016), Hsiao (2022), Shapiro (2021), Caliendo et al. (2024)
  - *Tariff policy:* Ossa (2014), Costinot et al. (2015), Adao, Costinot (2022), Antràs et al. (2022)

  ⇒ ***Optimal design of climate agreements with free-riding incentives***
- IAM and macroeconomics of climate change and carbon taxation
  - *RA model:* Nordhaus DICE (1996-), Weitzman (2014), Golosov et al. (2014)Golosov et al. (2014), Hassler et al (2019)
  - *HA model:* Krusell Smith (2022), Kotlikoff, Kubler, Polbin, Scheidegger (2021)
  - *Spatial models:* Cruz, Rossi-Hansberg (2022, 2023) among others

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 endogenous participation
6. Main result:
   The Optimal Climate Agreement
7. Extensions
8. Conclusion

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Model – Household & Firms

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

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

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

$$\mathbb{P}_i = \left(\sum_j a_{ij}(\tau_{ij}(1+\mathrm{t}_{ij}^b)\mathrm{p}_j)^{1-\theta}\right)^{\frac{1}{1-\theta}}$$

2. Competitive final good firm:

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

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

Model – Energy markets & Emissions

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

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

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

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

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

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

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

Model – Equilibrium

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

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

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

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Climate agreements and endogenous participation

- ***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.:
  - Countries $i \in \mathbb{J}$ pay carbon tax $\mathrm{t}_i^{\varepsilon} = \mathrm{t}^{\varepsilon}$
  - If j exits agreement, club members $i \in \mathbb{J}$ impose uniform tariffs $\mathrm{t}_{ij}^{b} = \mathrm{t}^{b}$ on goods from j
    They still trade with club members in oil-gas at price q^f
  - Local, lump-sum rebate of taxes $\mathrm{t}_i^{ls} = \mathrm{t}^{\varepsilon}(e_i^f + e_i^c) + \sum_{j \notin \mathbb{J}} \mathrm{t}^{b} \tau_{ij} c_{ij} \mathrm{p}_j$
  - Indirect utility $\mathcal{U}_i(\mathbb{J}, \mathrm{t}^{\varepsilon}, \mathrm{t}^{b}) \equiv u(c_{i(\mathbb{J}, \mathrm{t}^{\varepsilon}, \mathrm{t}^{b})})$

- Equilibrium concepts:
  - Exit from the agreement: unilateral deviation 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

- 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
    - 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 the marginal values for global welfare and individual welfare is

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

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

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

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

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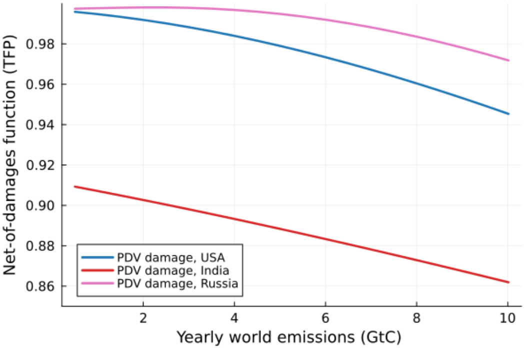
Quantification – Climate system and damage

- Static economic model:
  decisions $e_i^f + e_i^c$ taken "once and for all", $\mathcal{E} = \sum_i e_i^f + e_i^c$
  - Climate system:
  $$\dot{\mathcal{S}}_t = \mathcal{E} - \delta_s \mathcal{S}_t$$
  $$T_{it} = \bar{T}_{i0} + \Delta_i \mathcal{S}_t$$
  - Path damages heterogeneous across countries
    Quadratic, c.f. Nordhaus-DICE / IAM
  $$\mathcal{D}(T_{it} - T_i^\star) = e^{-\gamma (T_{it} - T_i^\star)^2}$$
  - Economic feedback in Present discounted value
  $$\mathcal{D}_i(\mathcal{E}) = \bar{\rho}_i \int_0^\infty e^{-\overbrace{(\rho - n_i + \eta \bar{g}_i)}^{\equiv \bar{\rho}_i} t} \mathcal{D}\big(T_{it} - T_i^\star\big) dt$$
  - Similarly for $LCC_i, SCC_i \ldots$



Quantification

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

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

Details Pareto weights

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

More details

Calibration

- Parameters calibrated from the literature
  - Macro parameter: Household utility, Production function, Trade elasticities
  - Damage parameter: γ from Krusell, Smith (2022) & Barrage, Nordhaus (2023)

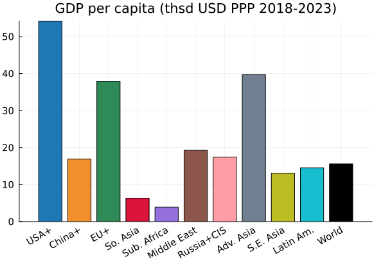
    Target temperature: $T_i^\star = \alpha T^\star + (1-\alpha) T_{it_0}$ with $T^\star = 14.5$, $\alpha = 0.5$.

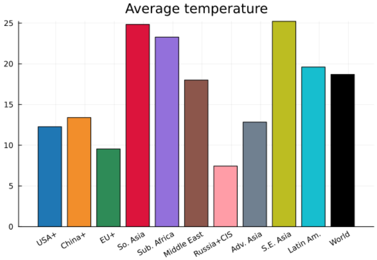
- Parameters to match "world" moments from the data Details calibration
  - Climate parameters: match IAM's Pulse experiment
  - CES shares in capital/labor/energy to match aggregate shares

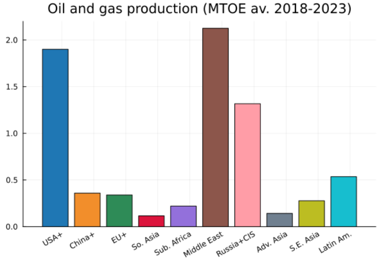
- Parameters to match (exactly) country-level variables Details country-level moments
  - TFP $z_i \Rightarrow$ GDP y_i, Population $\mathcal{P}_i$, Temperature T_{it_0}, Pattern scaling Δ_i
  - Energy mix (Oil-gas e_i^f, Coal e_i^c, Non-carbon e_i^r), energy share, oil-gas prod°, reserves, rents
  - Trade: cost τ_{ij} projected on distance, preferences a_{ij} to match import shares

Quantitative application – Sample of 10 “regions”

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







Details Trade shares – details

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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

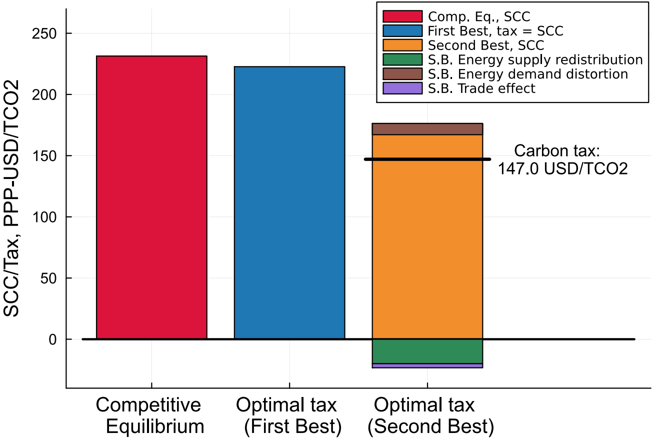
  - ***Second-Best:*** Social planner, single carbon tax without transfers
    - Optimal carbon tax t^{ε} correct climate externality, but also accounts for:
      (i) Redistribution motives, G.E. effects on (ii) energy markets and (iii) trade leakage

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

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

  - More details in companion paper: Bourany (2024)

Second-Best climate policy

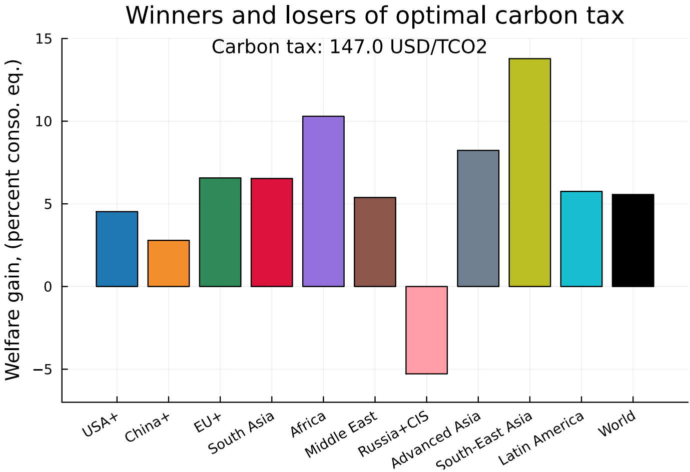


- Accounting for redistribution and lack of transfers

  ⇒ implies a carbon tax lower than the Social Cost of Carbon

Gains from cooperation – World Optimal policy

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



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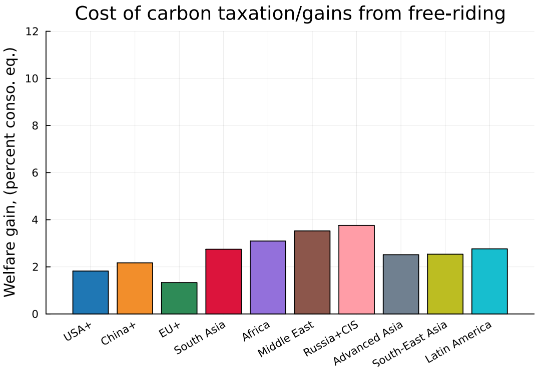
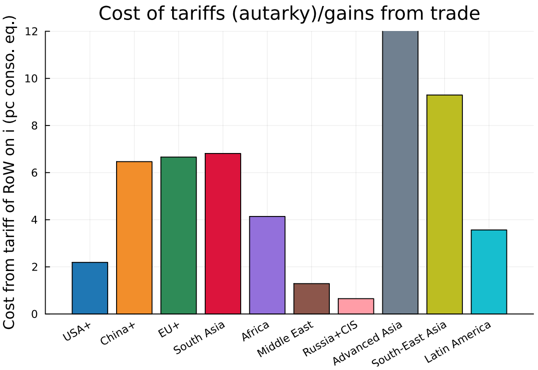
Trade-off – Cost of Carbon Taxation vs. Gains from trade

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





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 $d\ln q^f \approx \bar{\nu} d\ln E^f + \ldots$, due to taxation

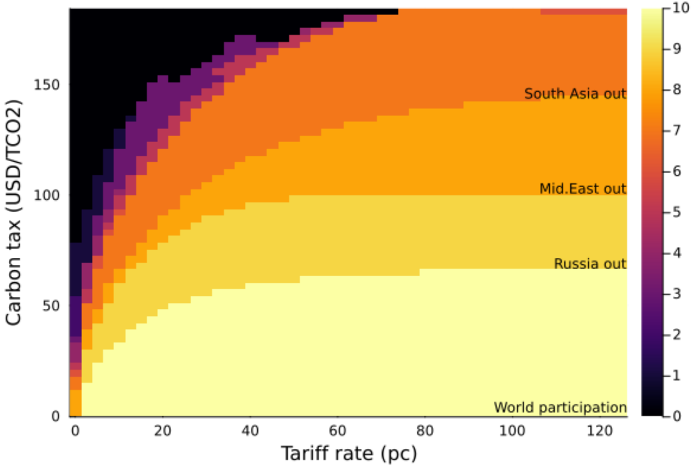
$$d\ln q^f = -\frac{\bar{\nu}}{1+\bar{\gamma}+\mathbb{C}\mathrm{ov}_i(\widetilde{\lambda}_i^f, \bar{\gamma}_i) + \bar{\nu}\overline{\lambda}^{\sigma,f}} \sum_i \widetilde{\lambda}_i^f \mathrm{J}_i d\mathrm{t}^{\varepsilon} + \sum_i \beta_i d\ln \mathrm{p}_i$$

    - 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

Climate Agreements: Intensive vs. Extensive Margin

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

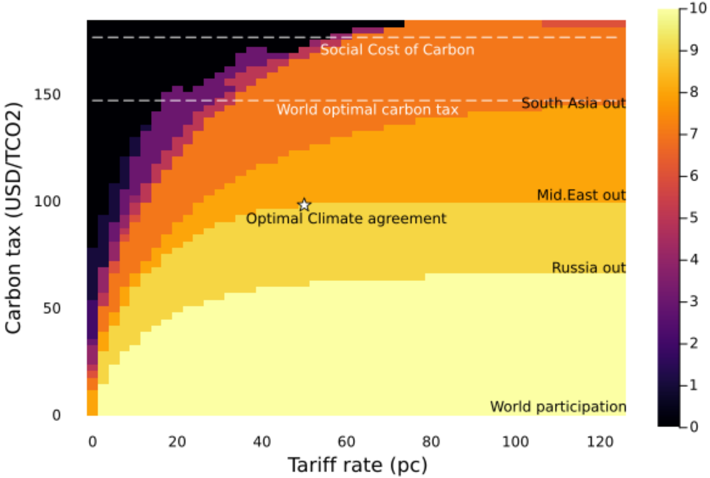


Optimal Climate Agreement

- Despite full freedom of instruments (t^{ε}, t^{b})

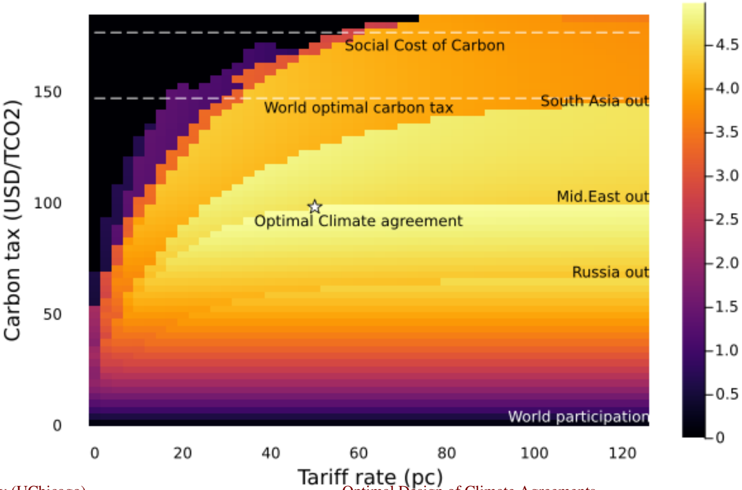
  $\Rightarrow$ can not sustain an agreement with Russia & Middle East

  $\Rightarrow$ need to reduce carbon tax from \$147 to \$98
- Intuition:
  relatively cold and closed economy, and fossil-fuel producers



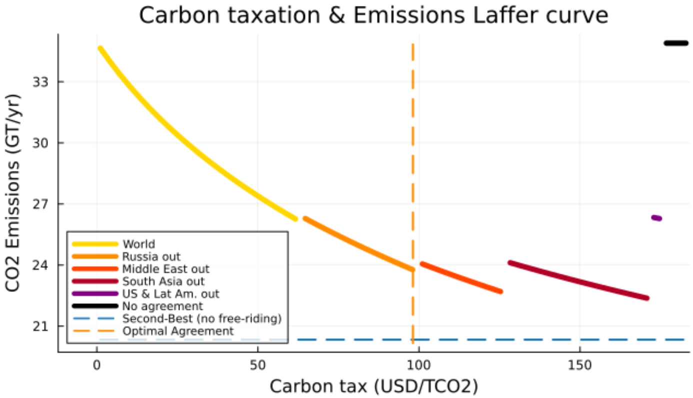
Climate agreement and welfare

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



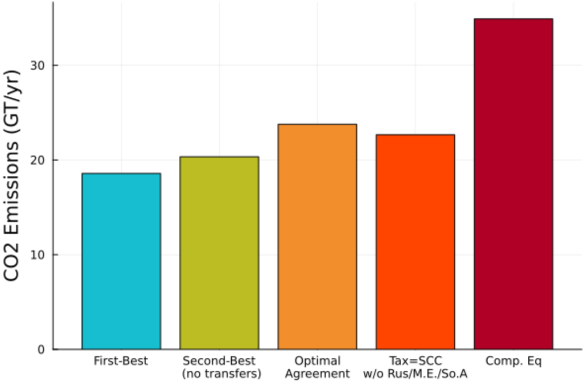
Carbon taxation, Participation and the Laffer Curve

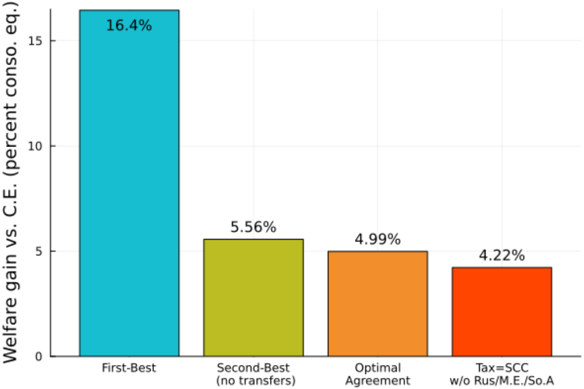
Extensive margin: Higher tax may reduces participation, concentrates the cost of mitigation on the remaining members of the agreement $\Rightarrow$ dampen welfare



Welfare and emission reduction: Different metrics!

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





Coalition building

- How to build sequentially the climate coalition?
  - Which countries have the most interest in joining the club?
- 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 $\mathrm{t}^{\varepsilon} = 98\$$, and tariff $\mathrm{t}^{b} = 50\%$.
  - Sequential procedure – coming for free from our CDCP algorithm / squeezing procedure
  - Idea analogous to Farrokhi, Lashkaripour (2024)
- Result: sequence up to the optimal climate agreement
  - Round 1: European Union
  - Round 2: China, South East Asia (Asean)
  - Round 3: North America, South Asia, Africa, Advanced East Asia, Latin America
  - Round 4: Middle-East
  - $\notin$ Stay out of the agreement: Russia+CIS

Outline

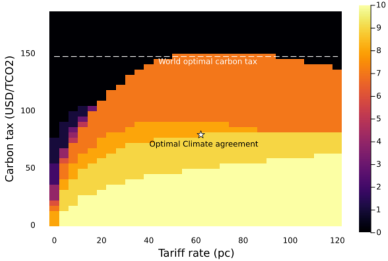
1. Introduction
2. Model:
   An Integrated Assessment Model with Heterogenous Countries and Trade
3. Climate Agreements Design
4. Quantification
5. Policy Benchmarks:
   Optimal Policy without endogenous participation
6. Main result:
   The Optimal Climate Agreement
7. **Extensions**
8. Conclusion

Retaliation

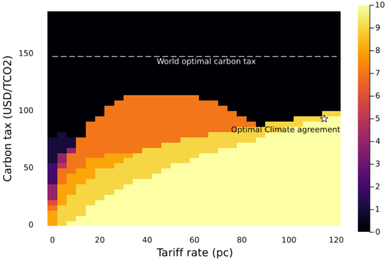
- Trade policy retaliation:
  Suppose the regions outside the agreement impose retaliatory tariffs to club members

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

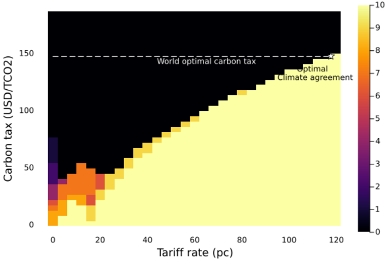
$\beta = 0.25$



$\beta = 0.5$



$\beta = 1.0$

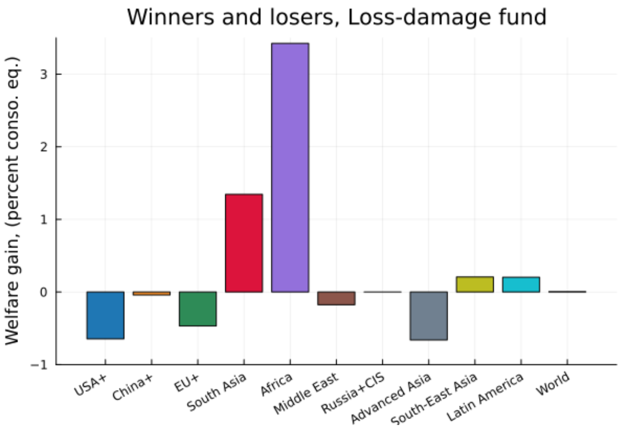


Transfers – Loss and damage funds

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

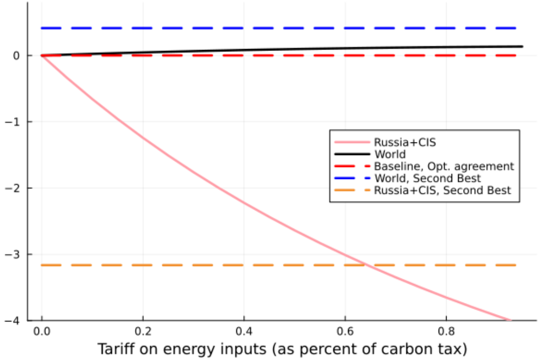
$$\mathrm{t}_i^{ls} = (1-\alpha)\,\mathrm{t}^{\varepsilon}\varepsilon_i + \alpha\frac{1}{\mathcal{P}}\sum_j \mathrm{t}^{\varepsilon}\varepsilon_j$$

- In practice: transfers from large emitters to low emitters



Taxation of fossil fuels energy inputs

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



Conclusion

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

  $\Rightarrow$ Need a large coalition and a carbon tax at 65% of the world optimum
- Extensions:
  - Extend this to dynamic settings: coalition building and bargaining

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

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

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

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

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:

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

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

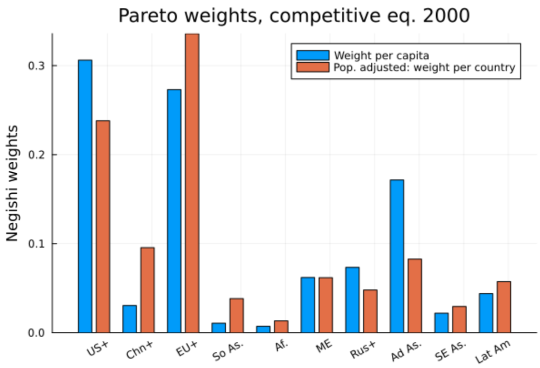
$$\mathcal{U}_i(\mathbb{J}, \mathrm{t}^f, \mathrm{t}^b) \geq \mathcal{U}_i(\mathbb{J}\backslash\hat{\mathbb{J}}, \mathrm{t}^f, \mathrm{t}^b) \ \forall i \in \hat{\mathbb{J}} \ \& \ \forall \ \hat{\mathbb{J}} \subseteq \mathbb{J} \cup \{i\}$$

    - 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

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



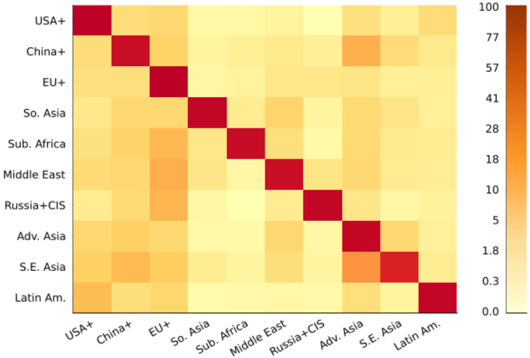
back

Quantification – Trade model

- Armington Trade model:

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

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



back

Step 0: Competitive equilibrium & Trade

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

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

  - 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

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

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}, individual carbon taxes t_i^f on energy e_i^f, 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 $[\mu_i]$, market clearing for energy μ^e

back

Step 1: World First-best policy

- Social planner results:
  - Consumption:

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

  - Energy use:

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

  - Social cost of carbon:

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

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

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

back

Step 2: World optimal Ramsey policy

- Maximizing welfare of the world Social Planner:

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

  - 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 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

$$\widehat{\lambda}_i = \frac{\omega_i \lambda_i}{\bar{\lambda}} = \frac{\omega_i u'(c_i)}{\frac{1}{I} \sum_{\mathbb{I}} \omega_j u'(c_j)} \lessgtr 1 \qquad \Rightarrow$$

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:

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

  - 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:

$$SCC = \sum_{\mathbb{I}} \widehat{\lambda}_i \, LCC_i = \textstyle\sum_{\mathbb{I}} LCC_i + \mathbb{C}\mathrm{ov}_i\left(\widehat{\lambda}_i, LCC_i\right)$$

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

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

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

- *Proposition 2:* Optimal fossil energy tax:

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

  – Reexpressing demand terms:

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

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
- 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

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

- *Proposition 3.1:* Second-Best social valuation with participation constraints
  - Participation incentives change our measure of inequality

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

$$\Rightarrow \qquad \widehat{\widetilde{\lambda}}_i = \frac{\omega_i(\widetilde{\lambda}_i+\widetilde{\mu}_i)}{\frac{1}{J}\sum_{\mathbb{J}}\omega_i(\widetilde{\lambda}_i+\widetilde{\mu}_i)} \neq \widehat{\lambda}_i$$

$$\text{vs. w/o trade} \qquad \widehat{\widetilde{\lambda}}_i = \frac{\omega_i(1+\nu_i)u'(c_i)}{\frac{1}{J}\sum_{\mathbb{J}}\omega_j(1+\nu_j)u'(c_j)} \neq \widehat{\lambda}_i$$

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

Step 3: Participation constraints & Optimal policy

- *Proposition 3.2:* Second-Best taxes:
  - Taxation with imperfect instruments:
    - Climate change & general equilibrium effects on fossil market affects all countries $i \in \mathbb{I}$
    - Need to adjust for the "outside" countries $i \notin \mathbb{J}$ not subject to the tax, which weight on the energy market as $\vartheta_{\mathbb{J}^c} \approx \frac{E_{\mathbb{J}^c}}{E_{\mathbb{I}}} \frac{\nu\sigma}{q^f(1-s^f)}$
      with ν fossil supply elasticity, σ energy demand elasticity and s^f energy cost share.
  - Optimal fossil energy tax $t^f(\mathbb{J})$:

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

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

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

back

Welfare decomposition

- Armington model of trade with energy:
  - Linearized market clearing

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

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

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

back

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

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

back

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