The Optimal Design of Climate Agreements

Inequality, Trade, and Incentives for Carbon Policy

WORK IN PROGRESS

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Introduction

- Fighting climate change requires implementing ambitious carbon reduction policies
  - The “free-riding problem” causes climate inaction:
    the tax costs are local and the climate benefits are global
  - Moreover, such climate policy redistributes across countries through
    (i) energy markets (ii) change in climate, and (iii) reallocation of activity through trade

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  - Trade sanctions need to be imposed on non-participants to sustain a “club” and reduce emissions meaningfully

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Introduction

⇒ How can we design an optimal climate agreement that implements the optimal energy taxation in the presence of inequality and policy constraints?

- Climate agreement boils down to a carbon price, a tariff rate and a choice of countries
- Build a Climate-Macro model with heterogeneous countries & trade and study the strategic implications of climate agreements and the optimal club design

▶ Preview of the result:

- With enough policy instruments, the "coalitional Nash" climate agreement reproduces the world optimal policy: high carbon tax, high tariffs, participation of the entire world

▶ Literature:

- Nordhaus (2015), Iverson (2024), Old theoretical literature on Climate Agreements
- Trade Policy: Farrokhi, Lashkaripour (2021), Kortum, Weisbach (2022), Böhringer et al.
- Public finance / Heterogeneous agents macro / spatial

Model – Household & Firms

- Static and deterministic Neoclassical economy
  - countries $i \in \mathbb{I}$, heterogeneous in productivity z_i, temperature T_i, energy extraction cost $\mathcal{C}_i$
  - In each country, four agents:

1. Representative household problem $\mathcal{V}_i = \max_{c_{ij}} u(c_i)$

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

2. Competitive final good firm:

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

   - Externality: Damage function $\mathcal{D}(T_i)$, Inequality from z_i, Fossil energy tax: t_i^f

3. Renewable energy firm: elastic supply e_i^r at price $q_i^r = z^r \mathbb{P}_i$

Model – Energy markets & Emissions

4. Competitive fossil fuels energy 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

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

- Climate system: effect on local temperature in i

$$T_i = \bar{T}_{i0} + \underbrace{\Delta_i}_{\text{pattern scaling}} \underbrace{\textstyle\sum_{\mathbb{I}} e_i^f}_{\text{GHG emission}}$$

- Market clearing for goods: (in expenditure)

$$\mathrm{p}_i \underbrace{y_i}_{\substack{\text{output}\\ =\mathcal{D}(T_i) z_i f(\cdot)}} = \sum_{k \in \mathbb{I}} \frac{s_{ki}}{1+\mathrm{t}_{ki}^b} \left(\mathrm{p}_k y_k + q^f (e_k^x - e_k^f) + \mathrm{t}_k^{ls}\right)$$

Model – Equilibrium

- Given policies $\{\mathrm{t}_i^f, \mathrm{t}_{ij}^b, \mathrm{t}_i^{ls}\}_i$, a **competitive equilibrium** is a set of decisions $\{c_{ij}, e_i^f, e_i^x\}_{ij}$, states $\{T_i\}_i$ and prices $\{\mathrm{p}_i, w_i\}_i, q^f$ such that:
  - Households choose $\{c_{ij}\}_{ij}$ to max. utility s.t. budget constraint
  - Firm choose inputs $\{e_i^f, e_i^r\}_i$ to max. profit
  - Fossil firms extract/produce $\{e_i^x\}_i$ to max. profit. + Elastic renewable supply $\{e_i^r\}$
  - Emissions $\mathcal{E}$ affects climate $\{T_i\}_i$.
  - Government budget clear $\sum_i \mathrm{t}_i^{ls} = \sum_i \mathrm{t}_i^f e_i^f + \sum_{i,j} \mathrm{t}_{ij}^b c_{ij}\tau_{ij}\mathrm{p}_j$
  - 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

$$y_i := \mathcal{D}(T_i)\, z_i f(e_i^f) = \sum_{k\in\mathbb{I}} \tau_{ki}c_{ki} + \sum_{k\in\mathbb{I}} g_{ki}$$

with g_{ki} net export of good i to pay for costs of energy in k
In expenditure, with import shares $s_{ij} = \frac{c_{ij}\tau_{ij}\mathrm{p}_j}{c_i\mathbb{P}_i}$, it yields
$\mathrm{p}_i y_i = \sum_{k\in\mathbb{I}} \frac{s_{ki}}{1+\mathrm{t}_{ki}^b} \left(\mathrm{p}_k y_k + q^f(e_k^x - e_k^f) + \widetilde{\mathrm{t}}_k^{ls}\right)$

Benchmarks

- Two different benchmarks:
  - World's planner maximizing world's welfare without participation constraints
    - Single carbon and absence of cross country transfers $\mathbb{J} = \mathbb{I}$
    - Optimal carbon tax t^f accounts for:
      (i) Redistribution motive, G.E. effects on (ii) energy markets and (iii) through trade
      + optimal tariffs for terms-of-trade manipulations
  - Local planner in country i unilaterally choosing t_i^f and t_{ij}^b
    - Optimal unilateral carbon tax (subsidy!) and tariffs for terms-of-trade manipulations
    - Nash equilibrium of I agents choosing individually unilateral policies
  - Climate club $\mathbb{J} \subsetneq \mathbb{I}$

Benchmark: Optimal world policy – Summary of results

- Consider a social planner maximizing the world's welfare:
  - Choose a single carbon tax t^f for the world $\mathbb{J} = \mathbb{I}$

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

  - Optimal climate policy depends on the availability of redistribution instruments (i.e. lump-sum transfers t_i^{ls} across countries)
  - Without redistribution motives, optimal Pigouvian carbon tax: $\mathrm{t}^f = SCC$

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  - Optimal climate policy depends on the availability of redistribution instruments (i.e. lump-sum transfers t_i^{ls} across countries)
  - Without redistribution motives, optimal Pigouvian carbon tax: $\mathrm{t}^f = SCC$
  - Otherwise, the optimal carbon tax should account for the distribution of (i) Local Damage LCC_i, (ii) energy supply terms-of-trade effects, (iii) energy demand distortions, (iv) all of them weighted by an index $\phi_i \propto \omega_i u'(c_i)$

$$\mathrm{t}^f = \underbrace{\sum_i \phi_i \, LCC_i}_{=SCC} + \sum_i \phi_i \, \text{Supply Distortion}_i + \sum_i \phi_i \, \text{Demand Distortion}_i$$

- Details:

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

Ramsey Problem with participation constraints

- Consider that countries can "exit" climate agreement.

- ***Definition*** A climate agreement is a set $\{\mathbb{J}, \mathfrak{t}^f, \mathfrak{t}^b\}$, with $\mathbb{J} \subseteq \mathbb{I}$ countries and a C.E. $\{\boldsymbol{c}, \boldsymbol{e}, \boldsymbol{q}\}$ such that:
  - Countries $i \in \mathbb{J}$ are subject to a carbon tax $\mathfrak{t}^f$ on fossil energy
  - Countries can leave:
    If j exits the agreement, club members $i \in \mathbb{J}$ pay uniform tariffs $\mathfrak{t}^b_{ij} = \mathfrak{t}^b$ on goods from j.
    They still trade with club members in energy at price q^f
    Extension 1: The club $\mathbb{J}$ can also impose a tax $\mathfrak{t}^{bf}$ on energy.
  - Exit decision:
    Subcoalition exit: only $\hat{\mathbb{J}}$ stay in the agreement, "Coalitional-Nash" / "Core"

- Participation constraints, indirect utility $U_i(\mathbb{J}, \mathfrak{t}^f, \mathfrak{t}^b) \equiv u(c_{i(\mathbb{J}, \mathfrak{t}^f, \mathfrak{t}^b)})$

$$U_i(\mathbb{J}, \mathfrak{t}^f, \mathfrak{t}^b) \geq U_i(\hat{\mathbb{J}}, \mathfrak{t}^f, \mathfrak{t}^b) \qquad \forall\, \hat{\mathbb{J}} \subseteq \mathbb{J} \backslash \{i\} \qquad \text{[Coalition-Nash equilibrium]}$$

Design climate agreements 1 – Tax schedule + stability

- Consider a climate agreement $\{\mathbb{J}, \mathfrak{t}^f, \mathfrak{t}^b\}$
  - Coalitional Nash eq. (or "core") $\mathbb{C}(\mathfrak{t}^f, \mathfrak{t}^b)$: robust to deviation of sub-coalitions:
    - No country i would be better off than in the current agreement $\mathbb{J}$
    - note: the "core" $\mathbb{C}(\mathfrak{t}^f, \mathfrak{t}^b)$ can be empty
- Objective: search for the optimal climate agreement

$$\max_{\mathbb{J}, \mathfrak{t}^f, \mathfrak{t}^b} \mathcal{W}(\mathbb{J}, \mathfrak{t}^f, \mathfrak{t}^b) = \max_{\mathfrak{t}^f, \mathfrak{t}^b} \max_{\mathbb{J}} \mathcal{W}(\mathbb{J}, \mathfrak{t}^f, \mathfrak{t}^b)$$

$$s.t. \qquad \mathbb{J} \in \mathbb{C}(\mathfrak{t}^f, \mathfrak{t}^b) = \left\{ \mathcal{J} \mid U_i(\mathbb{J}, \mathfrak{t}^f, \mathfrak{t}^b) \geq U_i(\hat{\mathbb{J}}, \mathfrak{t}^f, \mathfrak{t}^b) \ \forall i \in \mathcal{J} \ \& \ \forall \ \hat{\mathbb{J}} \subseteq \mathcal{J} \setminus \{i\} \right\}$$

  - Welfare, for coalition $\mathbb{J}$, weighting all countries $i \in \mathbb{I}$

$$\mathcal{W}(\mathbb{J}, \mathfrak{t}^f, \mathfrak{t}^b) = \sum_{i \in \mathbb{I}} \omega_i \, U_i(\mathbb{J}, \mathfrak{t}^f, \mathfrak{t}^b)$$

  - Current design: (i) choose taxes $\{\mathfrak{t}^f, \mathfrak{t}^b\}$,
    (ii) choose the coalition $\mathbb{J}$ s.t. participation constraints hold

Design climate agreements 2 – Coalition-dependent taxes

- Search for an optimal climate agreement $\{\mathbb{J}, \mathfrak{t}^f, \mathfrak{t}^b\}$

$$\max_{\mathbb{J}, \mathfrak{t}^f, \mathfrak{t}^b} \mathcal{W}(\mathbb{J}, \mathfrak{t}^f, \mathfrak{t}^b) = \max_{\mathbb{J}} \max_{\mathfrak{t}^f(\mathbb{J}), \mathfrak{t}^b(\mathbb{J})} \mathcal{W}(\mathbb{J}, \mathfrak{t}^f(\mathbb{J}), \mathfrak{t}^b(\mathbb{J}))$$

$$s.t. \qquad \mathfrak{t}^f(\mathbb{J}), \mathfrak{t}^b(\mathbb{J}) \in \mathbb{C}(\mathbb{J}) = \left\{ \mathfrak{t}^f, \mathfrak{t}^b \mid U_i(\mathbb{J}, \mathfrak{t}^f, \mathfrak{t}^b) \geq U_i(\mathbb{J} \backslash \{i\}, \mathfrak{t}^f(\mathbb{J} \backslash \{i\}), \mathfrak{t}^b(\mathbb{J} \backslash \{i\}))\ \ \forall i \in \mathcal{J} \right\}$$

  - Unilateral Nash eq. $\mathbb{C}$: robust to unilateral deviation
  - Welfare, for coalition $\mathbb{J}$, weighting all countries $i \in \mathbb{I}$

$$\mathcal{W}(\mathbb{J}, \mathfrak{t}^f, \mathfrak{t}^b) = \sum_{i \in \mathbb{I}} \omega_i\, U_i(\mathbb{J}, \mathfrak{t}^f, \mathfrak{t}^b)$$

  - Potential design: (i) choose the coalition $\mathbb{J}$
    (ii) choose the policies $\{\mathfrak{t}^f(\mathbb{J}), \mathfrak{t}^b(\mathbb{J})\}$ s.t. participation constraints hold
  - Differences:
    - Approach 1: current implementation (brute force), allow to study the coalition-Nash, computationally intensive
    - Approach 2: more flexible, but have to restrict to unilateral Nash

Quantification

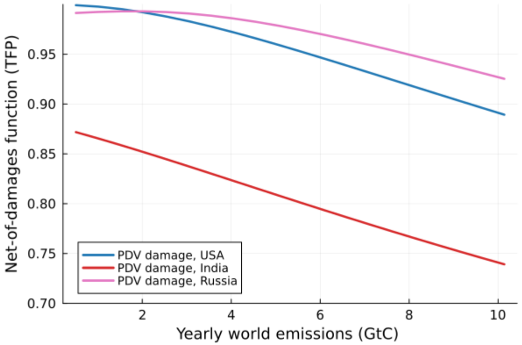
- Energy parameters to match production/reserves,
  - Isoelastic cost function $\mathcal{C}_i(e_i^x) = \bar{\nu}_i \left(e_i^x/\mathcal{R}_i\right)^{1+\nu_i} \mathcal{R}_i$
  - Use $\bar{\nu}_i, \nu_i$ to match e_i^x and π_i^f , ***In practice, can not match both e_i^x and π_i^f***
- Armington model,
  - Iceberg cost τ_{ij} projected on distance and preferences a_{ij} to match import shares $s_{ij} = \frac{c_{ij}\tau_{ij}\mathrm{p}_j}{c_i\mathbb{P}_i}$
- Production $\bar{y} = zf\left(\ell_i, k_i, e_i^f, e_i^r\right)$
  - Nested CES energy vs. labor-capital Cobb-Douglas bundle $k_i^{\alpha}\ell_i^{1-\alpha}$ (elasticity $\sigma_y < 1$), and fossil/renewable $\sigma_e > 1$, $CES(e_i^f, e_i^r)$
  - TFP, and DTC, z_i, z_i^e, calibrated to match GDP / energy shares data.
- Pareto weights ω_i:
  - Imply no redistribution motive, $\bar{c}_i$ consumption in initial equilibrium $t = 2000$

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

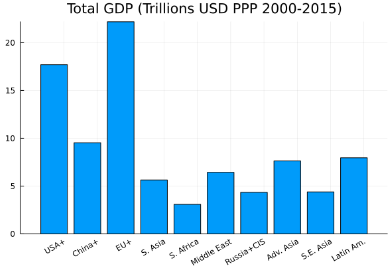
- Details More details

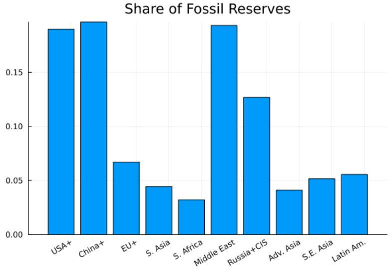
Quantification – Climate system and damage

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

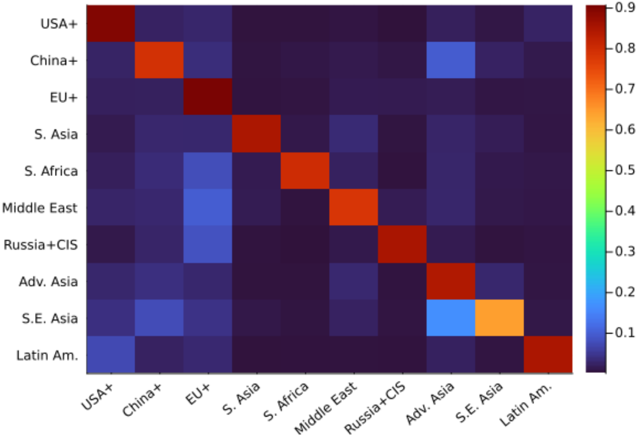


Numerical Application - Sample of "10 regions"





- Data on trade shares $s_{ij} = \frac{c_{ij}\tau_{ij}\mathrm{p}_j}{c_i\mathbb{P}_i}$, 10 regions, 2015



Theoretical investigation: decomposing the welfare effects

- Experiment:
  - Start from the equilibrium where carbon tax $\mathrm{t}_j^f = 0, \mathrm{t}_{jk}^b = 0, \forall j,$
  - Change in welfare: Linear approximation around that point $\Rightarrow$ small changes in carbon tax $d\mathrm{t}_j^f, \forall j$ and tariffs $d\mathrm{t}_{j,k}^b, \forall j, k$

$$\frac{d\mathcal{V}_i}{u'(c_i)} = \eta_i^c \frac{d\mathrm{p}_i}{\mathrm{p}_i} + \left[\eta_i^c \gamma_i \frac{1}{\bar{\nu}} - \eta_i^c s_i^e + \eta_i^\pi \left(1 + \frac{1}{\bar{\nu}}\right)\right] \frac{dq^f}{q^f} + \dots$$

  - Difference in the GE effect on energy markets $\frac{dq^f}{q^f} \approx \bar{\nu} \frac{dE^f}{E^f} + \dots$, due to taxation

$$\frac{dq^f}{q^f} = -\sum_j \nu_j^f \frac{d\mathrm{t}_j^f}{\mathrm{t}_j^f} + \sum_i \nu_j^{p,R} \frac{d\mathrm{p}_j}{\mathrm{p}_j} + \sum_{j,k} \nu_j^{R,f,z,qr} s_{j,k} \frac{d\mathrm{t}_{jk}^b}{\mathrm{t}_{jk}^b}$$

    - Trade and leakage effect: GE impact of t_j^f and $\mathrm{t}_{j,}^b$ on y_i and p_i
    - Simplifying assumption: no renewable

∘ Params: σ energy demand elast^y, s^e energy cost share, $\bar{\nu}$ energy supply inverse elas^y, Climate damage γ_i

Decomposing the welfare effects: gains from trade

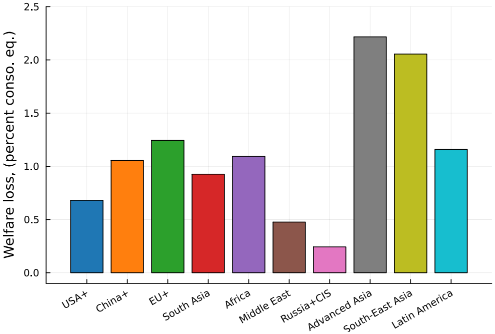
- Start from the equilibrium where carbon tax $t_j^f = 0, t_{jk}^b = 0, \forall j,$
- Change in welfare: Linear approximation around that point $\Rightarrow$ small changes in carbon tax $dt_j^f, \forall j$ and tariffs $dt_{j,k}^b, \forall j, k$

$$\frac{d\mathrm{p}}{\mathrm{p}} = \Big[\mathbf{I}-\mathbf{T}-(\theta-1)\big[\mathbf{T}\odot\mathbf{S}-(\mathbf{T}\odot\mathbf{I})'\big]\Big]^{-1}\left((\mathbf{T}-\mathbf{I})\frac{dy}{y} + \left(\mathbf{T}[(\theta-1)\mathbf{I}-\theta\mathbf{S}]\odot\frac{dt^b}{t^b}\right)\mathbb{1}\right)$$

$$\frac{dy_i}{y_i} = \alpha_i^{p,qr}\frac{d\mathrm{p}_i}{\mathrm{p}_i} - \alpha_i^{qf}\frac{dt_i^f}{t_i^f} + \dots$$

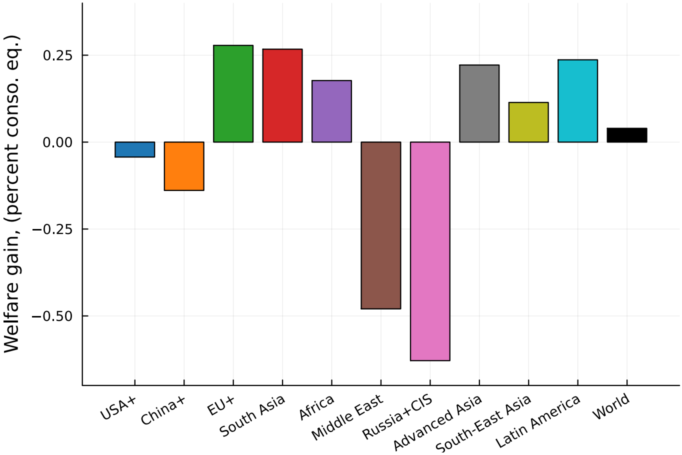
∘ Params: **S** Trade share matrix, **T** income flow matrix, θ, Armington CES

– Loss from trade from large tariffs / autarky:



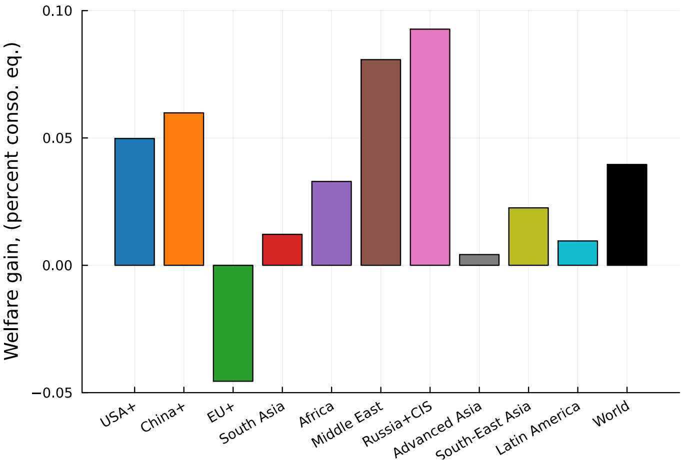
Gains from cooperation – Second Best

- Optimal carbon tax, Second Best: $\sim \$15/tCO_2 \ \ (\sim \$55/tC)$
- Reduce fossil fuels / CO_2 emissions by 4% compared to Business as Usual (BAU)
- Small welfare difference between World Second-Best Policy and BAU (Comp. Eq.)



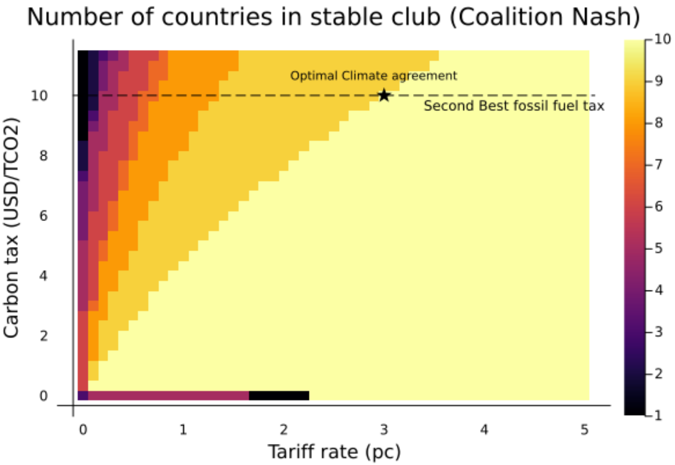
Gains from free-riding / unilateral deviation

- Free-riding: benefit from leaving the cooperative agreement
  - Country i sets tax $t^f = 0$ while countries j still set $t^f = t^{f\star}$
  - No retaliatory tariffs from country j for now
  - Gain from reduction in energy taxation distortion e_i
  - Gain from energy rent π_i^f: taxation $\downarrow \Rightarrow$ energy price $q^f \uparrow$
  - Loss from higher emissions $\mathcal{E} \uparrow \Rightarrow T_i \uparrow$
  - Loss from terms-of-trade: $e_i \uparrow, y_i \uparrow, p_i \downarrow$

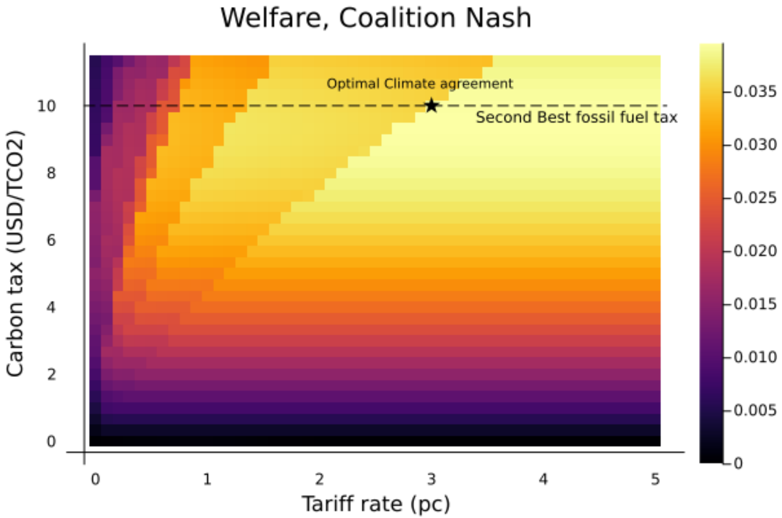


Optimal coalition

- With this set of $(t^f, t^b) \Rightarrow$ can sustain any coalition
- Large tariffs $\Rightarrow$ full participation
- Result (i.e. $\{t^{f\star}, t^{b\star}\}$) sensitive to Pareto weights



Taxes combination can recover any climate coalition



General - unanswered - question

- Current "equilibrium": $\mathrm{t}_i^f = 0$, $\mathrm{t}_{ij}^b = 0$
- Optimal club equilibrium $\mathrm{t}_i^f = \mathrm{t}^{f\star}$, $\mathrm{t}_{ij}^b = \mathrm{t}^{b\star}\mathbb{1}\{i \in \mathbb{J}, j \notin \mathbb{J}\}$
- Idea: optimal club follows the world social planner and optimal participation decision:

$$\mathbb{J}^\star = \mathbb{J}\left(\mathrm{t}^{f\star}, \mathrm{t}^{b\star}\right)$$

▶ What is driving the coordination failure?

- Possible explanation: coalition building may never reach such equilibrium in finite time

$$\bar{\mathbb{J}}_{t_0}(0,0) = \mathbb{I} \quad \xrightarrow[t \to T]{?} \quad \bar{\mathbb{J}}_T\left(\mathrm{t}^{f\star}, \mathrm{t}^{b\star}\right) = \mathbb{I}$$

- Can we find a sequence $\mathbb{J}_t, \mathrm{t}_t^f, \mathrm{t}_t^b$ such that

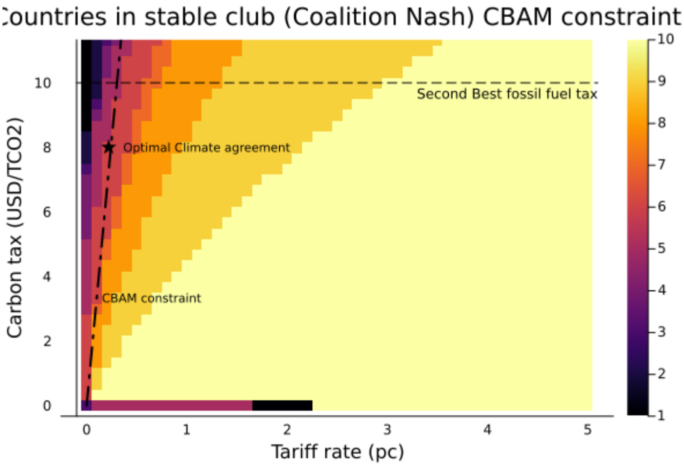
$$\{\mathbb{J}_{t_0}, \mathrm{t}_{t_0}^f, \mathrm{t}_{t_0}^b\} = \{\bar{\mathbb{J}}_{t_0}, 0, 0\} \qquad \{\mathbb{J}_T, \mathrm{t}_T^f, \mathrm{t}_T^b\} = \{\bar{\mathbb{J}}_T, \mathrm{t}^{f\star}, \mathrm{t}^{b\star}\}$$

Extensions

- Unilateral policy outside of the club, c.f. Farrokhi Lashkaripour (2021)
  - Instead of passive policy $\mathrm{t}_i^f = 0, \mathrm{t}_{ij}^b = 0$ if $i \notin \mathbb{J}$
- Retaliatory tariffs from outsiders
  - Ad-hoc rule: tit-for-tat, $\mathrm{t}_{ij}^b = \mathrm{t}_{ji}^b$
- Policy constraint and Carbon Border Adjustment Mechanism
  - Need $\mathrm{t}_{ij}^b = \frac{e_j}{y_j}\mathrm{t}_i^f$
- Trembling-Hand equilibrium
  - Account for off-equilibrium path: ε_i probability, country i does not apply optimal decision
- Lack-of-commitment
  - Country $i \in \mathbb{J}$ deviate on their policies $\{\mathrm{t}^{f\star}, \mathrm{t}^{b\star}\}$

CBAM and policy constraint

- Policy constraint: tax inside and outside the club the same way:
  - Country i sets tax $t^f = t^{f\star}$ and CBAM $t^b_{ij} = \frac{e_j}{y_j} t^{f\star}$
  - Extension: Countries j outside can change optimally t^f_j to change $\frac{e_j}{y_j}$
  - Can not impose (too) large tariffs t^b
  - Optimal club might be smaller: extensive/intensive margin tradeoff



Two extensions: climate agreements, retaliation and lack of commitment

- Consider a climate agreement $\{\mathbb{J}, \mathrm{t}^f, \mathrm{t}^b\}$
  - Coalitional Nash eq. (or "core") $\mathbb{C}(\mathrm{t}^f, \mathrm{t}^b)$: robust to deviation of sub-coalitions

1. Countries outside the club decide on a retaliation trade policy t^r
   - General approach: search for optimal agreement in $\mathbb{I}-\mathbb{J}+1$ players continuous Nash games

$$\max_{\mathbb{J}, \mathrm{t}^f, \mathrm{t}^b} \mathcal{W}(\mathbb{J}, \mathrm{t}^f, \mathrm{t}^b, \mathrm{t}^r) \qquad s.t. \qquad \mathbb{J} \in \mathbb{C}(\mathrm{t}^f, \mathrm{t}^b, \mathrm{t}^r)$$

$$\max_{\mathrm{t}^r} \mathcal{V}_i(\mathbb{J}, \mathrm{t}^f, \mathrm{t}^b, \mathrm{t}^r) \qquad \forall\, i \in \mathbb{I} \backslash \mathbb{J}$$

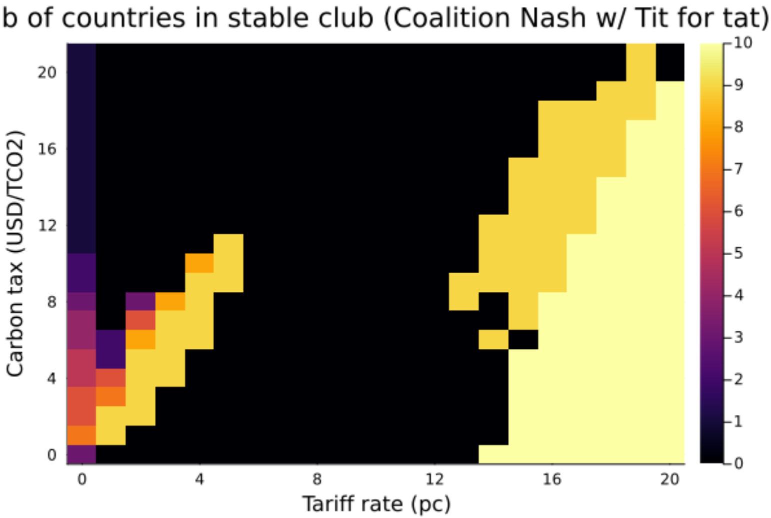
   - Simple experiment: tit-for-tat: $\mathrm{t}^r = \mathrm{t}^b$ equal retaliation

2. Countries within the club deviate from applying a retaliation trade policy t^b
   - Individual / unilateral policy $\tilde{\mathrm{t}}^f_i, \tilde{\mathrm{t}}^b_{ij}$

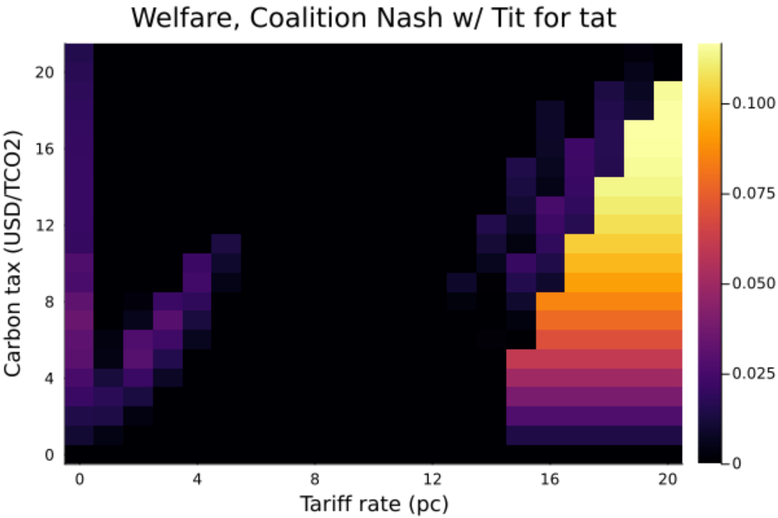
$$\max_{\tilde{\mathrm{t}}^f_i, \tilde{\mathrm{t}}^b_{ij}} \mathcal{V}_i(\tilde{\mathrm{t}}^f_i, \tilde{\mathrm{t}}^b_{ij}, \mathbb{J}, \mathrm{t}^f, \mathrm{t}^b) \qquad \forall\, i \in \mathbb{J}$$

   - Additional participation constraint for the climate agreement: $U_i(\mathbb{J}, \mathrm{t}^f, \mathrm{t}^b) \geq \mathcal{V}_i(\tilde{\mathrm{t}}^f_i, \tilde{\mathrm{t}}^b_{ij}, \mathbb{J}, \mathrm{t}^f, \mathrm{t}^b)$

Retaliation break climate coalition



Retaliation break climate coalition



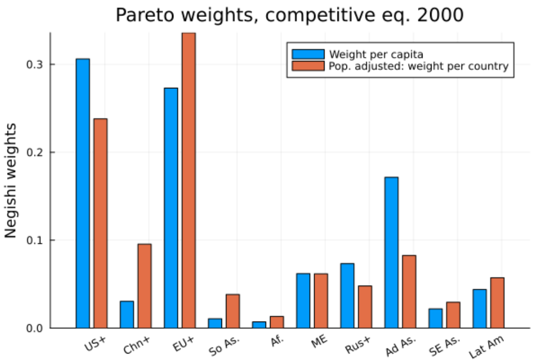
Conclusion

- In this project, I solve for the optimal climate policy
  - Accounting for inequality as it depends on the availability of transfer mechanisms
  - Redistributing through GE effects on energy and good markets $\Rightarrow$ terms-of-trade effects
- Climate agreement design jointly solves for:
  - The optimal choice of countries participating
  - The carbon tax level, both for correcting externality & respecting participation constraints
- Optimal coalition: strong result, with enough freedom of instruments, can replicate any coalition
  - Positive G.E effet on energy market and large(r) welfare cost of tariffs compared to cost of carbon taxation
- Extensions:
  - More intricate game-theoretical considerations
  - Extend this to dynamic settings: intertemporal tradeoffs

Appendices

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 $= 2000$
- Imply no redistribution motive in $t = 2000$
$$\omega_i u'(\bar{c}_i) = \omega_j u'(\bar{c}_j) \qquad \forall i, j \in \mathbb{I}$$
- Climate change, taxation, and climate agreement (tax + tariffs) have redistributive effects $\Rightarrow$ change distribution of c_i.



Step 0: Competitive equilibrium & Trade

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

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

  - 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

$$LCC_i = \frac{\partial \mathcal{W}_i / \partial \mathcal{E}}{\partial \mathcal{W}_i / \partial w_i} = \frac{\psi_i^{\mathcal{E}}}{\lambda_i} = -\Delta_i \mathcal{D}'(T_i) z_i f(e_i^f) \frac{\mathrm{p}_i}{\mathbb{P}_i} \qquad (> 0 \text{ if heat causes losses})$$

back

Step 1: World First-best policy

- Maximizing welfare of the world Social Planner:

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

  - Full array of instruments: cross-countries lump-sum transfers t_i^{ls}, individual carbon taxes t_i^f on energy e_i^f, 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:

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

  - Energy use:

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

  - Social cost of carbon:

$$SCC = -\frac{\sum_j \Delta_j \omega_j \mu_j \mathcal{D}_j'(T_j)\bar{y}_j}{\frac{1}{I}\sum_j \omega_j \mu_j}$$

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 $\mathrm{t}_i^{ls} = \mathrm{t}^f e_i^f$

- 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 & supply, etc.
  - Trade-off faced by the planner:
    - (i) Correcting externality, (ii) Redistributive effect, (iii) Distort energy demand and supply

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:

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

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

- Relative welfare weights, representing inequality

$$\text{w/o trade:} \qquad \widehat{\lambda}_i = \frac{\omega_i \lambda_i}{\bar{\lambda}} = \frac{\omega_i u'(c_i)}{\frac{1}{I} \sum_{\mathbb{I}} \omega_j u'(c_j)} \lesseqgtr 1 \qquad \Rightarrow$$

ceteris paribus, poorer countries have higher $\widehat{\lambda}_i$

$$\text{vs. w/ trade:} \qquad \widehat{\lambda}_i = \frac{\omega_i (\lambda_i + \mu_i)}{\frac{1}{I} \sum_{\mathbb{I}} \omega_i (\lambda_i + \mu_i)} \lesseqgtr 1$$

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:

$$LCC_i := \frac{\partial \mathcal{W}_i / \partial \mathcal{E}}{\partial \mathcal{W}_i / \partial w_i} = \frac{\psi_i^{\mathcal{E}}}{\lambda_i} = -\Delta_i \mathcal{D}'(T_i) z_i f(e_i^f) \mathrm{p}_i \qquad (> 0 \text{ if heat causes losses})$$

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  - Social Cost of Carbon for the planner:

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

  - Social Cost of Carbon integrates these inequalities:

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

Step 2: Optimal policy – Other motives

- Taxing fossil energy has additional redistributive effects:
  1. Through energy markets: distort supply, lowers eq. fossil price, benefit net importers
  2. Distort energy demand, of countries that need more or less energy
- New measure: Social Value of Fossil (SVF)

$$SVF := \frac{\partial \mathcal{W}/\partial E}{\partial \mathcal{W}/\partial w} = \mathcal{C}^f_{EE}\, \mathbb{C}\mathrm{ov}_i\left(\widehat{\lambda}_i, e^f_i - e^x_i\right) - \mathbb{C}\mathrm{ov}_i\left(\widehat{\lambda}_i, \frac{q^f(1-s^f_i)}{\sigma}\right)$$

∘ Params: $\mathcal{C}^f_{EE}$ agg. fossil supply elasticity, s^f_i energy cost share and σ energy demand elasticity

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- New measure: Social Value of Fossil (SVF)

$$SVF := \frac{\partial \mathcal{W}/\partial E}{\partial \mathcal{W}/\partial w} = \underbrace{\mathcal{C}^f_{EE}}_{\text{agg. supply distortion}} \underbrace{\mathbb{C}\text{ov}_i\left(\widehat{\lambda}_i, e^f_i - e^x_i\right)}_{\text{terms-of-trade redistribution}} - \underbrace{\mathbb{C}\text{ov}_i\left(\widehat{\lambda}_i, \frac{q^f(1-s^f_i)}{\sigma}\right)}_{\text{demand distortion}}$$

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∘ Params: $\mathcal{C}^f_{EE}$ agg. fossil supply elasticity, s^f_i energy cost share and σ energy demand elasticity

- *Proposition 2:* Optimal fossil energy tax:

$$\Rightarrow \qquad t^f = SCC + SVF$$

  – Social cost of carbon: $SCC = \sum_{\mathbb{I}} \widehat{\lambda}_i \, LCC_i$

back

Step 3: Ramsey Problem with participation constraints

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

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

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

- Welfare:

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

Step 3: Ramsey Problem with participation constraints

- Participation constraints
$$u(c_i) \geq u(\tilde{c}_i) \quad [\nu_i]$$
- *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 $\mathrm{t}^f(\mathbb{J})$:

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

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

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

back

Countries' incentives – Model w/o trade in goods

- Experiment: Model with trade in energy but not in "goods"
  - Start from the equilibrium where carbon tax $\mathrm{t}^f(\mathbb{J}) = 0$,
    $\Rightarrow$ country i is indifferent to join the club $\mathbb{J}$ or not
  - Linear approximation around that point $\Rightarrow$ small changes in carbon tax $d\mathrm{t}^f$

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  - Change in welfare if $i \in \mathbb{J}$ vs. $i \notin \mathbb{J}$

$$\frac{d\mathcal{W}_{i|i\in\mathbb{J}}}{u'(c_i^{i\in\mathbb{J}})} - \frac{d\mathcal{W}_{i|i\notin\mathbb{J}}}{u'(c_i^{i\notin\mathbb{J}})} = -e_i d\mathfrak{t}^f - \gamma_i (T_i - T_{i0})^\delta y_i \Delta_i (dE_{i\in\mathbb{J}} - dE_{i\notin\mathbb{J}})$$
$$- e_i \frac{q^f \nu}{E_{\mathbb{I}}} (dE_{i\in\mathbb{J}} - dE_{i\notin\mathbb{J}}) + \pi_i \frac{(1+\nu)}{E} (dE_{i\in\mathbb{J}} - dE_{i\notin\mathbb{J}})$$

  - Difference in the GE effect on energy markets, for $\sigma \approx 1$

$$dE_{i\in\mathbb{J}} - dE_{i\notin\mathbb{J}} = -\Big(E_{\mathbb{J}} - E_{\mathbb{J}\setminus\{i\}}\Big) \frac{\sigma \, d\mathfrak{t}^f}{q^f(1-s^f)} \frac{1}{1 + \frac{\nu\sigma}{(1-s^f)}}$$

∘ Params: σ energy demand elast^y, s^f energy cost share, ν energy supply elas^y, Climate damage γ_i and curv. δ

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∘ Params: σ energy demand elast^y, s^f energy cost share, ν energy supply elas^y, Climate damage γ_i and curv. δ

Countries' incentives – Armington Model with trade in goods

- Trade in energy and goods *à la* Armington, Linear approx. around $\mathrm{t}^f \approx 0$ and $\mathrm{t}^b \approx 0$
  - Change in welfare if $i \in \mathbb{J}$, vs. $i \notin \mathbb{J}$

$$
\begin{aligned}
\frac{d\mathcal{W}_{i|i\in\mathbb{J}}}{u'(c_i^{i\in\mathbb{J}})c_i} - \frac{d\mathcal{W}_{i|i\notin\mathbb{J}}}{u'(c_i^{i\notin\mathbb{J}})c_i} = & -e_i d\mathrm{t}^f - \gamma_i (T_i - T_{i0})^\delta \eta_i^y \Delta_i (dE_{i\in\mathbb{J}} - dE_{i\notin\mathbb{J}}) \\
& - e_i \frac{q^f \nu}{E_{\mathbb{I}}} (dE_{i\in\mathbb{J}} - dE_{i\notin\mathbb{J}}) \ + \ \eta_i^f \frac{(1+\nu)}{E} (dE_{i\in\mathbb{J}} - dE_{i\notin\mathbb{J}}) \\
& + \eta_i^y \Big(\frac{d\mathrm{p}_i}{\mathrm{p}_i}\Big|_{i\in\mathbb{J}} - \frac{d\mathrm{p}_i}{\mathrm{p}_i}\Big|_{i\notin\mathbb{J}} \Big) - s_{i\mathbb{J}^c} d\mathrm{t}^b - \sum_{j\in\mathbb{I}} s_{ij} \Big(\frac{d\mathrm{p}_j}{\mathrm{p}_j}\Big|_{i\in\mathbb{J}} - \frac{d\mathrm{p}_j}{\mathrm{p}_j}\Big|_{i\notin\mathbb{J}} \Big)
\end{aligned}
$$

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$$\frac{d\mathcal{W}_{i|i\in\mathbb{J}}}{u'(c_i^{i\in\mathbb{J}})c_i} - \frac{d\mathcal{W}_{i|i\notin\mathbb{J}}}{u'(c_i^{i\notin\mathbb{J}})c_i} = -e_i d\mathrm{t}^f - \gamma_i (T_i - T_{i0})^\delta \eta_i^y \Delta_i (dE_{i\in\mathbb{J}} - dE_{i\notin\mathbb{J}})$$
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$$+ \eta_i^y \Big(\frac{d\mathrm{p}_i}{\mathrm{p}_i}\Big|_{i\in\mathbb{J}} - \frac{d\mathrm{p}_i}{\mathrm{p}_i}\Big|_{i\notin\mathbb{J}} \Big) - s_{i\mathbb{J}^c} d\mathrm{t}^b - \sum_{j\in\mathbb{I}} s_{ij} \Big(\frac{d\mathrm{p}_j}{\mathrm{p}_j}\Big|_{i\in\mathbb{J}} - \frac{d\mathrm{p}_j}{\mathrm{p}_j}\Big|_{i\notin\mathbb{J}} \Big)$$

  - GE effect on energy markets, same as before
  - GE effect on goods markets, equilibrium on expenditure $v_i = \mathbb{P}_i c_i$, for $\theta \approx 1$

$$\frac{dv_i}{v_i} = \sum_{k\in\mathbb{I}} \mathcal{P}_k \alpha_{ki} \Big(\frac{dv_k}{v_k} - \theta \frac{d\mathrm{t}^b_{ki}}{1+\mathrm{t}^b_{ki}} \Big) \qquad \alpha_{ki} = \frac{c_{ki}\tau_{ki}\mathrm{p}_i}{\sum_\ell c_{k\ell}\tau_{k\ell}\mathrm{p}_\ell} \frac{v_k}{v_i} = s_{ki} \frac{v_k}{(1+\mathrm{t}^b_{ki})v_i}$$

    – Params: σ energy demand elasticity, s^f energy cost share, ν energy supply elasticity, share of output y in income $\eta_i^y = \frac{y_i \mathrm{p}_i}{v_i}$, fossil rent share $\eta_i^f = \frac{\pi_i}{v_i}$

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  - Change in welfare if $i \in \mathbb{J}$, vs. $i \notin \mathbb{J}$

$$\frac{d\mathcal{W}_{i|i\in\mathbb{J}}}{u'(c_i^{i\in\mathbb{J}})c_i} - \frac{d\mathcal{W}_{i|i\notin\mathbb{J}}}{u'(c_i^{i\notin\mathbb{J}})c_i} = -e_i d\mathrm{t}^f - \gamma_i(T_i - T_{i0})^\delta \eta_i^y \Delta_i(dE_{i\in\mathbb{J}} - dE_{i\notin\mathbb{J}})$$
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Complementarity in coalition formation – Model w/o trade in goods

- Is marginal gain $\Delta\mathcal{W}(\mathbb{J},j) := \mathcal{W}(\mathbb{J}\cup j) - \mathcal{W}(\mathbb{J})$ "growing" in $\mathbb{J}$?
  - Linear approximation for small $\{\mathrm{t}^f,\mathrm{t}^b\}$

$$\Delta\mathcal{W}(\mathbb{J},j) = -\omega_j u'(c_j) e_j d\mathrm{t}^f + \Big[\sum_{i\in\mathbb{I}} \omega_i u'(c_i)\Delta_i \gamma_i (T_i - T_{i0})^{\delta} y_i\Big] \frac{\sigma\, e_j d\mathrm{t}^f}{q^f(1-s^f+\nu\sigma)}$$
$$+ \Big[\sum_{i\in\mathbb{I}} \omega_i u'(c_i) e_i\Big] \frac{1}{1+\frac{1-s^f}{\nu\sigma}} \frac{e_j d\mathrm{t}^f}{E_{\mathbb{I}}} - \Big[\sum_{i\in\mathbb{I}} \omega_i u'(c_i)\pi_i\Big] \frac{(1+\nu)}{E_{\mathbb{I}}} \frac{\sigma\, e_j d\mathrm{t}^f}{q^f(1-s^f+\nu\sigma)}$$

  - Free-riding problem: $\Delta\mathcal{W}(\mathbb{J},j)$ could be negative
  - If $\Delta\mathcal{W}(\mathbb{J},j) > 0$, what effects does $\mathbb{J}$ have on marginal gain?
    - Marginal climate benefit decreases in $\mathbb{J}$, since temperature T_i declines!
    - G.E. effect on energy price: $E_{\mathbb{I}}$, q and π^f decreases with $\mathbb{J}$, effect on demand ambiguous
    - Similar formula for the case with trade tariffs: Work in progress.

Quantification – Firms

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

$$f_i(k, \ell, \varepsilon(e^f, e^r)) = \left[(1-\epsilon_i)^{\frac{1}{\sigma_y}} \left(k^\alpha \ell^{1-\alpha}\right)^{\frac{\sigma_y - 1}{\sigma_y}} + \epsilon_i^{\frac{1}{\sigma_y}} \left(z_i^e \; \varepsilon_i(e^f, e^r)\right)^{\frac{\sigma_y-1}{\sigma_y}}\right]^{\frac{\sigma_y}{\sigma_y - 1}}$$

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

  - Calibrate TFP z_i to match $y_i = GDP_i$ per capita in 2011 (PPP).
  - Today: $\omega_i = \bar{\omega} = 85\%$ and $\epsilon_i = \bar{\epsilon} = 12\%$ for all i
  - Future: $(z_i^e, \omega_i, \epsilon_i)$ to match Energy/GDP $(e_i^f + e_i^r)/y_i$ and energy mix (e_i^f, e_i^r)

- 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)

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  - Future: Choose $(\bar{\nu}_i, \nu_i, \mathcal{R}_i)$ to match marginal cost $\mathcal{C}_e$ & extraction data e^x_i (BP, IEA)

- Renewable: Production $\bar{e}^r_{it}$ and price q^r_{it}
  - Now: $q^r_{it} = z^r e^{-g_r t}$, with g_r growth rate in renewable energy price decreases.
  - Future: Choose z^r_i to match the energy mix (e^f_i, e^r_i)

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Quantification – Future Extensions:

- Damage parameters:
  - $\gamma_i^{\pm,y}$ depends on daily temperature distribution $T \sim \mathcal{T}_i(\bar{T}, \sigma^T)$ following Rudik et al. (2022)
  - Use Climate Lab's (Greenstone et al) estimates for damage γ_i ?
- Fossil Energy markets:
  - Divide fossils e^f_{it}/e^x_{it} into oil/gas/coal
  - Match the production/cost/reserves data across countries
  - Use a dynamic model: extraction/exploration a la Hotelling
- Renewables Energy markets:
  - Make the problem dynamic with investment in capacity C^r_{it}
- Population dynamics
  - Match UN forecast for growth rate / fertility

Calibration

Table: Baseline calibration ($\star$ = subject to future changes)

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 2020)
ω	0.8	Fossil energy share in $e(\cdot)$	Fossil/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
g_e	$0.01^\star$	Long run energy directed technical change	Conservative / Acemoglu et al (2012)
g_r	$-0.01^\star$	Long run renewable price decrease	Conservative / Match price fall in R.E.
ν	$2^\star$	Extraction elasticity of fossil energy	Cubic extraction cost
Preferences & Time horizon			
ρ	0.03	HH Discount factor	Long term interest rate & usual calib. in IAMs
η	2.5	Risk aversion	
n	$0.01^\star$	Long run population growth	Conservative estimate for growth
ω_i	1	Pareto weights	Uniforms / Utilitarian Social Planner
T	90	Time horizon	Horizon 2100 years since 2010

Calibration

Table: Baseline calibration ($\star$ = subject to future changes)

Climate parameters			
ξ	0.81	Emission factor	Conversion 1 $MTOE \;\Rightarrow\; 1\, MT\ CO_2$
ζ	0.3	Inverse climate persistence / inertia	Sluggishness of temperature $\sim 11-15$ years
χ	$2.1/1e6$	Climate sensitivity	Pulse experiment: $100\, GtC \equiv 0.21^\circ C$ medium-term warming
δ_s	0.0014	Carbon exit from atmosphere	Pulse experiment: $100\, GtC \equiv 0.16^\circ C$ long-term warming
$\gamma^{\oplus}$	$0.00234^{\star}$	Damage sensitivity	Nordhaus' DICE
$\gamma^{\ominus}$	$0.2 \times \gamma^{\oplus\ \star}$	Damage sensitivity	Nordhaus' DICE & Rudik et al (2022)
α^T	$0.2^{\star}$	Weight historical climate for optimal temp.	Marginal damage decorrelated with initial temp.
$T^{\star}$	15.5	Optimal yearly temperature	Average spring temperature / Developed economies
Parameters calibrated to match data			
p_i		Population	Data – World Bank 2011
z_i		TFP	To match GDP Data – World Bank 2011
T_i		Local Temperature	To match temperature of largest city
$\mathcal{R}_i$		Local Fossil reserves	To match data from BP Energy review

Sequential solution method

- Summary of the model:
  - ODEs for states $\{\boldsymbol{x}\} = \{w_{it}, T_{it}, \mathcal{R}_{it}, \mathcal{S}_t\}_{it}$
  - Backward ODE for the costates $\{\boldsymbol{\lambda}\} = \{\lambda^w_{it}, \lambda^T_{it}, \lambda^{\mathcal{S}}_t, \lambda^{\mathcal{R}}_{it}\}_{it}$
  - Non-linear equations (FOCs) for household controls $\{\boldsymbol{c_1}\} = \{c_{it}, b_{it}, k_{it}\}_{it}$ and static demands for energy/capital $\{\boldsymbol{c_2}\} = \{e^f_{it}, e^r_{it}, k_{it}\}_{it}$ and static supplies $\{\boldsymbol{c_3}\} = \{e^x_{it}, \bar{e}^r_{it}\}_{it}$.
  - Market clearing as equation for prices $\{\boldsymbol{q}\} = \{q^f_t, r^\star_t\}_t$
  - Existence and Uniqueness, c.f. Mean Field Game theory (Carmona-Delarue)

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  - Market clearing as equation for prices $\{\boldsymbol{q}\} = \{q^f_t, r^\star_t\}_t$
  - Existence and Uniqueness, c.f. Mean Field Game theory (Carmona-Delarue)
- Global Numerical solution:
  - Discretize agents (countries) space $i \in \mathbb{I}$ with M and time-space $t \in [t_0, t_T]$ with T periods
  - Express as a large vector $\boldsymbol{y} = \{\boldsymbol{x}, \boldsymbol{\lambda}, \boldsymbol{c}, \boldsymbol{q}\}$ in a large non-linear function

$$F(\boldsymbol{y}) = \boldsymbol{0}$$

  - Solve for the large system with $N = (N_{ind,vars} \times M + N_{agg,vars}) \times T$ unknowns and N equations with gradient-descent – Newton-Raphson methods.

Sequential method: Pros and Cons

- Why use a sequential approach?
  - *Global approach*: *Only* need to follow the trajectories for i agents:
    - Arbitrary (!) number of dimension of *ex-ante* heterogeneity:
      Productivity z_i Population p_i, Temperature scaling Δ_i, Fossil energy cost $\bar{\nu}_i$, Energy mix $\epsilon_i, \omega_i, z_i^r$, Local damage $\gamma_i^y, \gamma_i^u, T_i^\star$, Directed Technical Change z_i^e
    - Potentially large dimensions of *ex-post* heterogeneity and aggregate state variables:
      For now: Wealth w_{it}, temperature T_{it}, reserves $\mathcal{R}_{it}$, Carbon $\mathcal{S}_t$
      Extension with a large climate system as a proof of concept (e.g. Cai, Lontzek, Judd, 2013)
    - Newton method & Non-linear solvers very efficient

- Why not:
  - Numerical constraint to solve a large system of ODEs and non-linear equations:

  $\Rightarrow$ Constraint on $N = (N_{ind,vars} \times M + N_{agg,vars}) \times T$, so either M or T can't be too large

  - Relying on numerical solvers/structure of the problem can be opaque

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