Climate Change, Inequality, and the Optimal Climate Policy

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- Indeed, energy taxation and climate policy have strong distributional consequences:
  (i) between higher income countries and developing economies
  (ii) between warm and cold countries, and differential exposure to climate change
  (iii) between energy importer and exporters, and dependence on energy consumption and rents

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$\Rightarrow$ What is the optimal carbon policy in the presence of climate externality and inequality?

- The optimal design of Pigouvian taxation crucially depends on redistribution instruments i.e. lump-sum transfers across countries

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- Study an Integrated Assessment Model (IAM) with heterogeneous countries to:
  - Evaluate the welfare costs of global warming and the Social Cost of Carbon
  - Solve for general *optimal Ramsey policies* for carbon taxation
  - Provide a novel numerical methodology for IAMs with *heterogeneity*

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- Preview of the results:
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  $\Rightarrow$ ***Theoretically:*** effect *ambiguous*. ***Quantitative:*** carbon tax should be *lower* with inequality

  - Country-specific taxes: poorer countries should pay relatively lower taxes

Roadmap

- Simplified set-up: Toy example
- First-best carbon taxation: all instruments available
- Second-best carbon taxation: Constrained efficient without lump-sum transfers
  - Uniform carbon taxation
  - Heterogeneous carbon prices across countries
- Quantitative model: Dynamic IAMs with heterogeneity & Extensions
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Toy Model – Household & Firms

Static 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, five agents:

(i) Rep. household, (ii) final good firm, (iii-v) oil-gas (fossil), coal and renewable energy producers

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1. Representative household problem in each country i (passive):

$$\mathcal{V}_i = u(c_i) \qquad\qquad c_i = \underbrace{w_i \ell_i}_{\text{labor income}} + \underbrace{\pi_i^f}_{\text{fossil firm profit}} + \underbrace{\mathrm{t}_i^{ls}}_{\text{lump-sum transfers}}$$

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2. Competitive final good producer in country i

$$\max_{\ell_i, e_i^f, e_i^c, e_i^r} \underbrace{\mathcal{D}(T_i)}_{\text{climate damage}} \underbrace{z_i}_{TFP} f(\ell_i, e_i^f, e_i^c, e_i^r) - w_i \ell_i - \underbrace{(q^f + \mathrm{t}_i^{\varepsilon}) e_i^f}_{\text{fossil (oil-gas)}} - \underbrace{(q_i^c + \mathrm{t}_i^{\varepsilon}) e_i^c}_{\text{coal}} - \underbrace{q_i^r e_i^r}_{\text{non-carbon energy}}$$

- Climate policy: Carbon tax $\mathrm{t}_i^{\varepsilon}$

Model – Energy markets & Emissions

3. Competitive fossil fuels energy producer, selling on international fossil market:
   - Supply of fossil energy e_i^x by extraction at cost $\mathcal{C}_i^f$

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

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

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4. Coal energy firm: elastic supply e_i^c at price $q_i^c = z_i^c$
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- Climate system:
  - GHGs from oil-gas and coal affect temperatures:

$$T_i = \bar{T}_{i0} + \Delta_i \mathcal{E} = \bar{T}_{i0} + \underbrace{\Delta_i}_{\text{pattern scaling}} \sum_{\mathbb{I}} \underbrace{(e_i^f + e_i^c)}_{\text{GHG from energy}}$$

Model – Equilibrium

- Given policies $\{\mathrm{t}_i^f, \mathrm{t}_i^{ls}\}_i$, a **competitive equilibrium** is a set of decisions $\{c_i, e_i^f, e_i^r, e_i^x\}_i$, states $\{T_i\}_i$ and prices $\{q^f, q_i^c, q_i^r, w_i\}_i$ such that:

  - Households choose $\{c_i\}_i$ 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 $\{T_i\}_i$.
  - Government budget clear $\sum_i \mathrm{t}_i^{ls} = \sum_i \mathrm{t}_i^{\varepsilon}(e_i^f + e_i^c)$
  - Prices $\{q^f, q_i^c, q_i^r\}$ adjust to clear the markets for energy $\sum_{\mathbb{I}} e_i^x = \sum_{\mathbb{I}} e_i^f$, and e_i^c, e_i^r
    The good market clearing holds by Walras law.

Optimal world policy – Summary of results

- Competitive equilibrium Details eq 0
  - Passive policies $t^f = 0$, and large cost of climate change

- First-Best, with unlimited instruments Details eq 1
  - Welfare: $\mathcal{W} = \max_{\{\mathbf{t}, \boldsymbol{c}, \boldsymbol{e}\}_i} \sum_{i \in \mathbb{I}} \omega_i \, u(c_i) = \sum_{\mathbb{I}} \omega_i \mathcal{V}_i$
  - Social Planner redistribute across countries with lump-sum transfers t_i^{ls}
  - Set the optimal Pigouvian carbon tax to $t^f = SCC$

- Second-best Ramsey policy, with limited instruments Details eq 2
  - Optimal carbon tax accounts for (i) inequality and local climate damage, (ii) energy supply elasticities, (iv) energy demand distortions

- Endogenous Participation? If countries can exit climate agreements Details eq 3
  - All formulas corrected for participation constraints (multipliers affect distribution weights)
  - Optimal design of climate agreements / climate clubs $\Rightarrow$ JMP

Competitive equilibrium

- Key objects:
  - Marginal value of wealth $\lambda_i = u'(c_i)$
  - Marginal value of carbon ψ_i^{ε} for country i
  - "Local social cost of carbon" (LCC) for region i:

$$LCC_i := -\frac{\partial \mathcal{V}_i / \partial \mathcal{S}}{\partial \mathcal{V}_i / \partial c_i} = \frac{\psi_i^{\varepsilon}}{\lambda_i} = \Delta_i \, \gamma \, (T_i - T_i^{\star}) \, y_i > 0$$

    - w/ Nordhaus-style damage $\mathcal{D}_i(T) = e^{-\gamma (T - T_i^{\star})^2}$
    - Stationary eqbm closed-form formula, as in GHKT (2014) Closed Form Solution

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First-Best, Optimal policy with transfers

- First-Best, Maximizing welfare of the Social Planner:

$$\mathcal{W} = \max_{\{\mathbf{t},\boldsymbol{x},\boldsymbol{c},\boldsymbol{q}\}_i} \sum_{\mathbb{I}} \omega_i \, u(c_i) = \sum_{\mathbb{I}} \omega_i \mathcal{V}_i$$

  - Full set of instruments $\mathbf{t} = \{\mathrm{t}_i^{\varepsilon}, \mathrm{t}_i^{ls}\}$, including transfers *across countries*

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  - Full set of instruments $\mathbf{t} = \{\mathrm{t}_i^{\varepsilon}, \mathrm{t}_i^{ls}\}$, including transfers *across countries*
  - Key objects: Local vs. Global Social Cost of Carbon,

$$SCC^{fb} := -\frac{\partial \mathcal{W}/\partial \mathcal{S}}{\partial \mathcal{W}/\partial \bar{c}} = \frac{\psi^{\varepsilon}}{\bar{\lambda}} = \frac{\sum_{\mathbb{I}} \psi_i^{\varepsilon}}{\frac{1}{I}\sum_{\mathbb{I}} \lambda_i} \qquad LCC_i := \frac{\partial \mathcal{V}_i/\partial \mathcal{S}}{\partial \mathcal{V}_i/\partial c_i} = \frac{\psi_i^{\varepsilon}}{\lambda_i}$$

First-Best, Optimal policy with transfers

- *Proposition 1:* Optimal carbon tax:

$$\mathrm{t}^{\varepsilon} = SCC^{fb}$$

  - Result as in Representative Agent economy, c.f. Nordhaus DICE (1996), GHKT (2014)

$$SCC^{fb} = \frac{\psi^{\varepsilon}}{\bar{\lambda}} = \sum_{\mathbb{I}} \frac{\psi_i^{\varepsilon}}{\lambda_i} = \textstyle\sum_{\mathbb{I}} LCC_i$$

- Lump-sum transfers redistribute across countries, s.t.

$$\omega_i u'(c_i) = \lambda_i = \bar{\lambda} = \lambda_j = \omega_j u'(c_j) \quad \forall i,j \in \mathbb{I}$$

  - Imply cross-countries lump-sum transfers $\exists\, i \;\; s.t.\; \mathrm{t}_i^{ls} \geq 0$ or $\exists\, j \;\; s.t.\; \mathrm{t}_j^{ls} \leq 0$

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Ramsey policy with limited transfers

- Second best without access to lump-sum transfers: choice of a carbon tax $\{\mathrm{t}^{\varepsilon}, \mathrm{t}^{r}\}$
  - Tax receipts redistributed lump-sum: $\mathrm{t}_i^{ls} = \mathrm{t}^{\varepsilon} e_i^f$
  - Inequality across regions:

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

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

  - Social Cost of Carbon integrates these inequalities:

$$SCC^{sb} = \sum_{\mathbb{I}} \widehat{\lambda}_i LCC_i$$

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

Ramsey Problem – Optimal Carbon and Energy Policy

- Tax on fossil energy has redistributive effects:
  1. Redistributes rent through energy markets: lowers eq. fossil price, hurts exporters
  2. Distorts energy demand, esp. countries that depend more on energy

$$\text{Supply Redistribution}^{sb} + \text{Demand Distortion}^{sb} = \underbrace{\mathcal{C}^f_{EE}}_{\text{agg. supply elasticity}} \underbrace{\mathbb{C}\text{ov}_i\left(\widehat{\lambda}_i, e^f_i - e^x_i\right)}_{\text{terms-of-trade redistribution}} - \underbrace{\mathbb{C}\text{ov}_i\left(\widehat{\upsilon}_i, \frac{q^f(1-s^f_i)}{\sigma_i e_i}\right)}_{\text{demand distortion}}$$

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

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- *Proposition 2:* Optimal fossil energy tax:

$$\Rightarrow \qquad \mathrm{t}^{\varepsilon} = SCC^{sb} + \text{Supply Redistribution}^{sb} + \text{Demand Distortion}^{sb}$$

  – Reexpressing demand terms:

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

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Ramsey Problem – Country-specific carbon tax

- Suppose the planner has access to a *distribution* of carbon price.
- *Proposition 3:* Optimal country-specific fossil energy tax:

$$\Rightarrow \qquad \mathrm{t}_i^{\varepsilon} = \frac{1}{\widehat{\lambda}_i}\left[SCC^{sb} + \text{Supply Redistribution}^{sb}\right] \propto \frac{1}{\omega_i u'(c_i)}$$

  - Social cost of carbon: $SCC^{sb} = \sum_{\mathbb{I}} \widehat{\lambda}_i \, LCC_i$
  - Supply Redistribution$^{sb} = \mathcal{C}^{f}_{EE} \mathbb{C}\mathrm{ov}_i\left(\widehat{\lambda}_i, e_i^f - e_i^x\right)$

$\Rightarrow$ Reduce the tax burden for poorer/more “valuable” countries

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Quantitative Dynamic Model

1. Climate system $\mathcal{S}_t = \mathcal{E} - \delta_s \mathcal{S}$, (multi-box climate system (WIP))

2. Firms:
   - Include capital to produce $f(\ell, k, e^f, e^c, e^r)$
   - Separate oil+gas e^f and coal e^c: coal rent $= 0$ vs. oil rent $\pi^f > 0$, higher emissions $\xi^c e^c$
   - Match the energy mix of each country $\{e^f, e^c, e^r\}$

3. Households:
   - Consumption / saving + capital $\Rightarrow$ Keynes-Ramsey rule

4. Energy markets
   - Fossil energy extraction/depleting reserves $\dot{\mathcal{R}}_{it} = -e^x_{it}$, $\Rightarrow$ Hotelling problem (WIP)
   - Price of clean energy q^r_{it} trending down

5. Population $\dot{\mathcal{P}}_i / \mathcal{P}_i = n$ and TFP growth dynamics $\dot{z}_i / z_i = \bar{g}$

6. Energy-augmenting Directed TC (WIP)

Ramsey Problem – Theoretical extensions (in the papers)

- Trade: redistributive effect through leakage effect
  - Trade model à la Armington Details trade
  - Additional trade-off: account for distortions on goods central in trade networks

- Uncertainty:
  - Stochastic climate impact, e.g. climate sensitivity Δ_i or damage curvature γ_i, Details uncertainty
  - Interaction in SCC between uncertainty and inequalities: covariance between cost of climate change and social welfare weights

- Dynamic considerations
  - Reserves values ψ_{it}^R = Hotelling rent: carbon tax changes intertemp. subst° of fossil prod.
    c.f. Heal, Schlenker (2019), Asker, Collard-Wexler, De Loecker (2019-2024),
  - Curb capital demand + distort consumption/saving decision
    c.f. optimal fiscal instruments in H.A. models, BEGS/LG-R/D-S

Dynamic models using the Pontryagin Max. Principle

- Every dynamic model can be expressed as a Forward Backward system of ODEs: states $\{k_{it}, \mathcal{S}_t\}$ and costates $\{\lambda^k_{it}, \psi^{\mathcal{S}}_t\}$. Ex NCG:

$$\begin{cases} \dot{k}_{it} & = f(k_{it}, e_{it}) - \delta k_{it} - q^e_{it} e_{it} - c_{it} \\ \dot{\lambda}^k_{it} & = -\big(f_k(k_{it}, e_{it}) - \delta - \rho\big)\lambda^k_{it} \end{cases}$$

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- *Novelty*:
  - *Heterogeneity*: exante, *arbitrary*, expost: *number of state/costate*
  - Large state space: as a *sequential* approach, no need for grid, just follow the agents
  - *Optimal* Ramsey (climate) policy:
    policies usually expressed as fct of multipliers $\Leftrightarrow$ costates: $\mathrm{t}^{\varepsilon} = SCC = -\psi^{\mathcal{S}}_t / \lambda^k_t$

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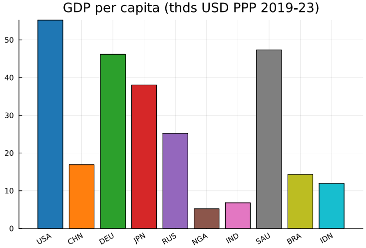
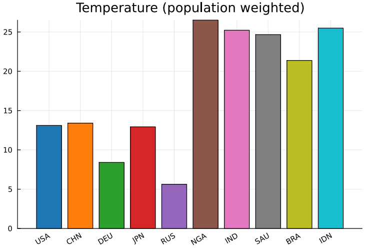
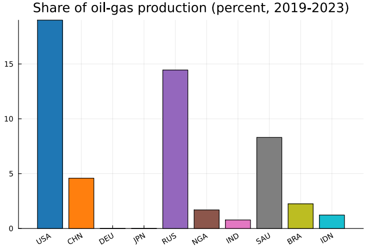
  - *Global* method $\rightarrow$ eqbm potentially far from steady state: non-linearity/tipping points?
  - *Caveat:* Rely (for now) on non-linear solvers.

Quantification

- Parameters matching country-level data (avg. 2018-2023) Details Quantification
- TFP $z_i \Rightarrow$ GDP y_i, Population $\mathcal{P}_i$, Temperature T_{it_0}, Pattern scaling Δ_i
- Mix: oil-gas e_i^f, Coal e_i^c, Low-carbon e_i^r, energy share ε_i, oil-gas prod° e_i^x, reserves $\mathcal{R}_i$, rents π_i^f







Inequality and Pareto weights

- Recall welfare objective: $\mathcal{W}_t = \sum_{i \in \mathbb{I}} \mathcal{P}_i \omega_i \mathcal{V}_{it}$
- ***Crucial:*** how to chose ω_i ?

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- ***Two benchmarks:***

▷ Uniform Pareto weights $\omega_i = 1$

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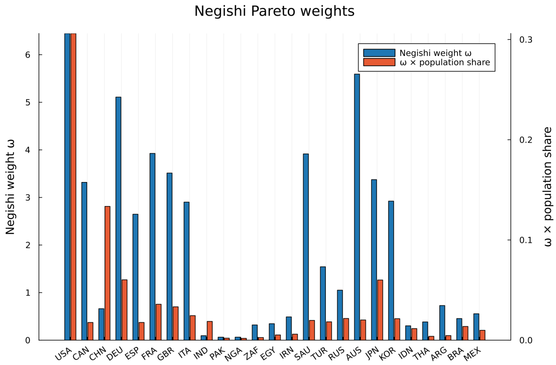
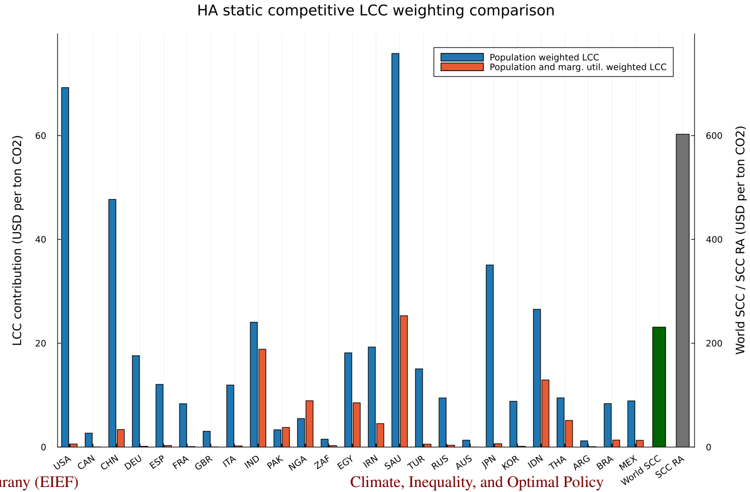
- ***Two benchmarks:***
  - Uniform Pareto weights $\omega_i = 1$
  - Negishi weights $\omega_i = \frac{1}{u'(\bar{c}_i)}$
    - with $\bar{c}_i$ conso in initial eqbm 2018-23 *without climate change*
    - implies no redistribution motive: $\omega_i u'(\bar{c}_i) = \omega_j u'(\bar{c}_j) \qquad \forall i,j \in \mathbb{I}$
    - Climate change + carbon tax have redistributive effects $\Rightarrow$ change allocation c_i



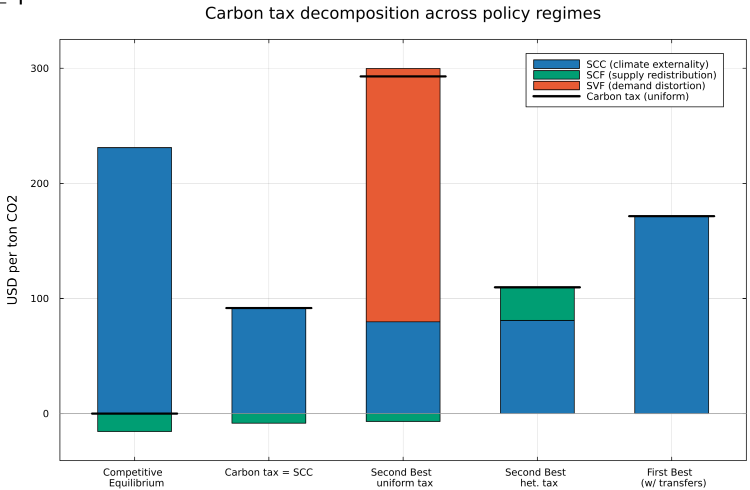
Local Cost of Carbon & Social Cost of Carbon

- Recall: $SCC = \sum_{\mathbb{I}} \widehat{\lambda}_i \, LCC_i$
- Difference: $LCC_i = \frac{\psi_i^S}{\lambda_i}$ (blue, left bars) vs. $\widehat{\lambda}_i LCC_i = \frac{\psi_i^S}{\bar{\lambda}}$ (red, right bars)



The Carbon Tax is not (only) the Social Cost of Carbon!

- First-best w/ transfers: $\Rightarrow \quad \mathrm{t}^{\varepsilon} = SCC^{fb}$, and $|\mathrm{t}_i^{ls}| \gg 0$
- Second-best carbon tax w/o transfers: $\Rightarrow \quad \mathrm{t}^{\varepsilon} = SCC^{sb}$+Supply Redistrib.+Demand Distort°
- Uniform weights $\omega_i = 1$



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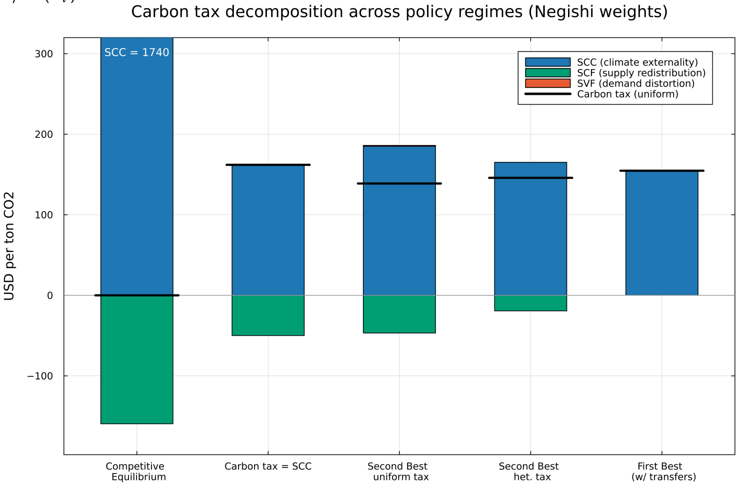
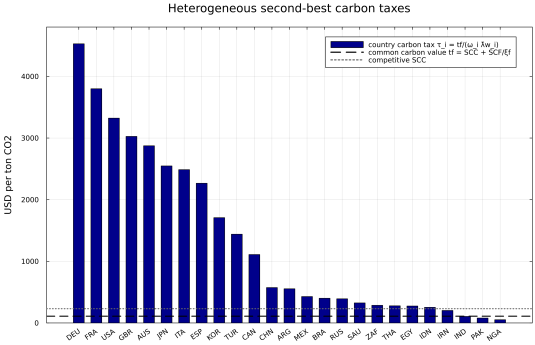
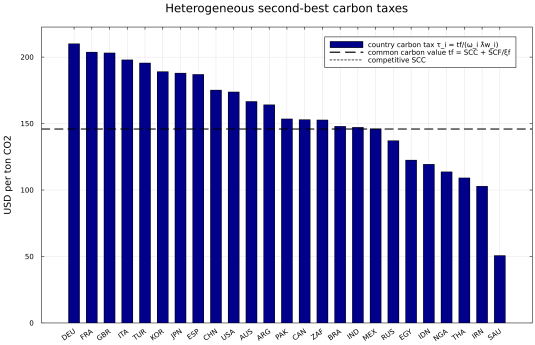
- Negishi weights $\omega_i \propto 1/u'(\bar{c}_i)$



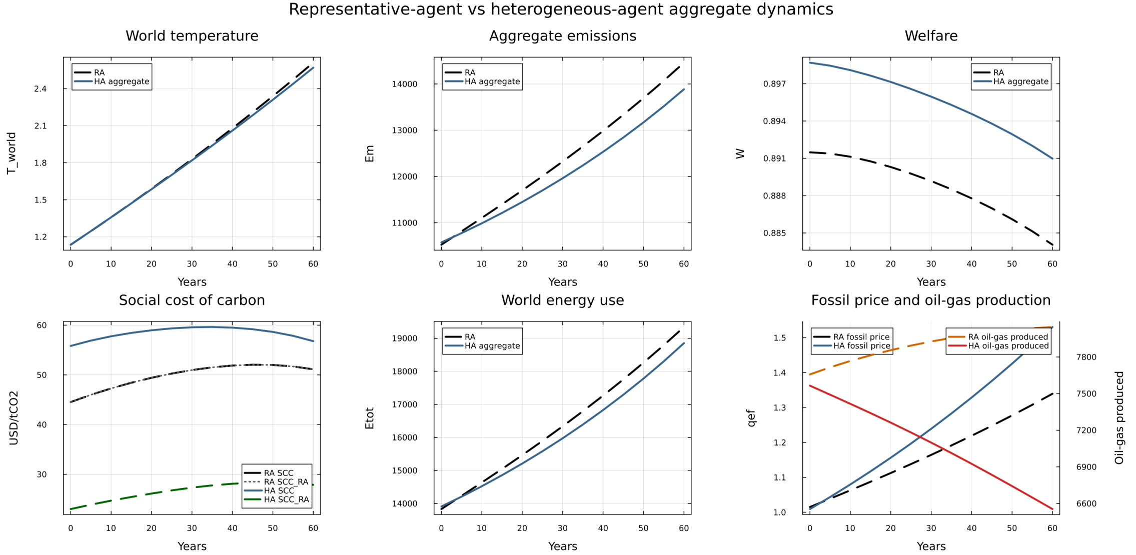
Heterogeneous Carbon taxes are not the Local Social Cost of Carbon!

- Het. carbon taxes: $t_i^{\varepsilon} \propto \frac{1}{\omega_i u'(c_i)} [SCC^{sb} + \text{Supply Redistrib.}] \neq LCC_i$
- More results: Details Aggregates





Climate dynamics (Business as Usual) with heterogeneity



Taking stocks + Going further?

- Optimal climate policy with inequality:
  - Requires sizeable transfers. Otherwise, need large change in carbon tax level / trajectory
  - Need to account for the distribution + reallocative/GE effects on energy and good markets

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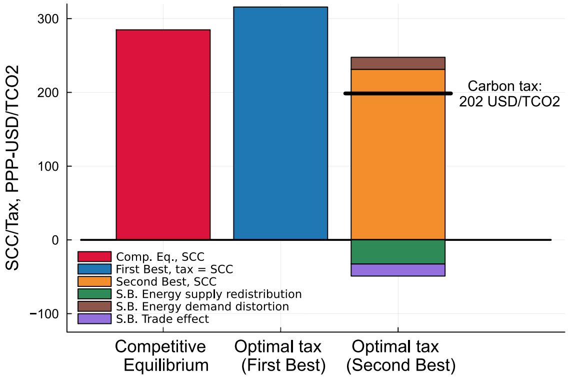
- Incentives and implementability:
  - What if some countries strategically deviate from applying the optimal carbon tax?
  - Game theoretical consideration ⇒ participation constraints
  - Implementation of "climate clubs":
    Penalty tariffs or CBAM to non-participants crucial for enforcing carbon policy

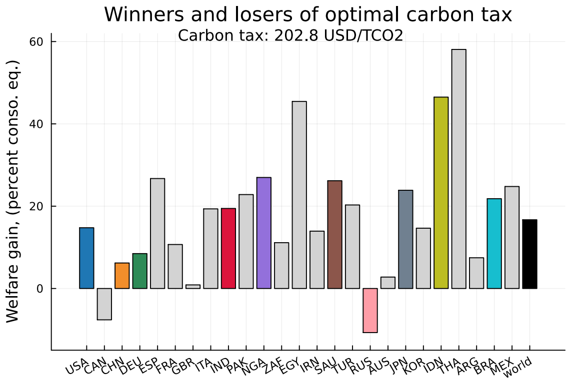
⇒ Job Market Paper: "The Optimal Design of Climate Agreements"

Roadmap

- Simplified set-up: Toy example
- First-best carbon taxation: all instruments available
- Second-best carbon taxation: Constrained efficient without lump-sum transfers
  - Uniform carbon taxation
  - Heterogeneous carbon prices across countries
- Quantitative model: Dynamic IAMs with heterogeneity & Extensions
- **Optimal Climate Agreements**

Second-Best climate policy and Gains from cooperation





Main result and Intuition

- The optimal climate agreement navigates the intensive and extensive margin tradeoff:
  - ***Participation:*** most countries in the world with the exception of: *Russia, former Soviet countries, Saudi Arabia, Gulf countries, Egypt, Iran, Nigeria*
  - ***Carbon tax:*** reduce carbon tax from \$200 to \$120$/tCO_2$
  - ***Trade tariffs:*** impose substantial tariff 90% on the goods from non-members

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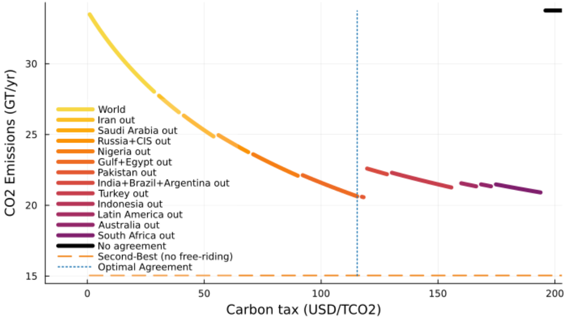
  - ***Trade tariffs:*** impose substantial tariff 90% on the goods from non-members

- Mechanism:
  - Countries participate depending on $\begin{cases} \text{(i) the cost of distortionary carbon taxation} \\ \text{(ii) the cost of tariffs (= the gains from trade)} \end{cases}$
  - Russia/Middle East/South Asia do not join the club for high carbon tax *for any tariffs* when cost of taxing fossil-fuels $\gg$ cost of tariffs / autarky

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

Laffer curve for carbon taxation

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

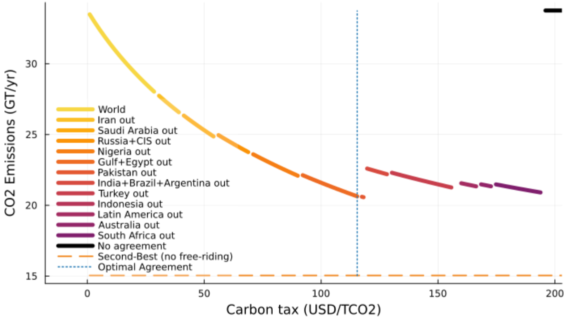


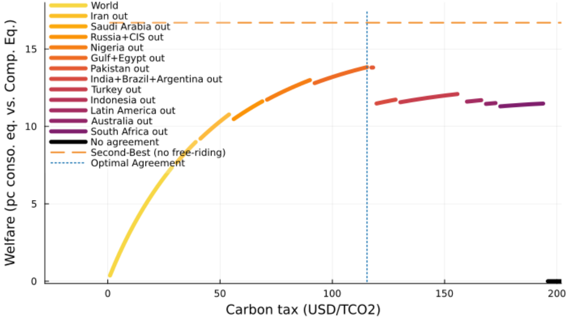
Emissions $\mathcal{E}$ (in $GtCO_2/yr$) and welfare $\mathcal{W}$ as function of the carbon tax t^{ε}, with tariff $t^b = 90\%$.

Laffer curve for carbon taxation

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

– Need to lower the carbon tax to \$120 to increase participation:
Improve welfare by sharing the costs of carbon mitigation with *more countries*





Emissions $\mathcal{E}$ (in $GtCO_2/yr$) and welfare $\mathcal{W}$ as function of the carbon tax t^{ε}, with tariff $t^{b} = 90\%$.

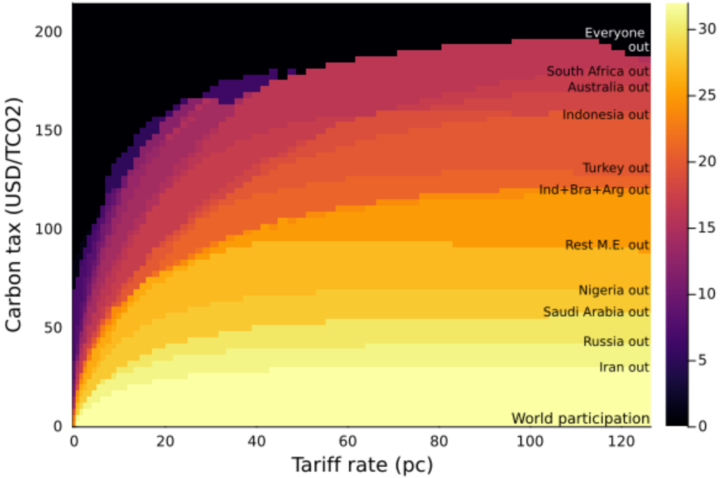
Climate Agreements: Intensive vs. Extensive Margin

- **Intensive margin:**

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

- **Extensive margin:**

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



Optimal Climate Agreement

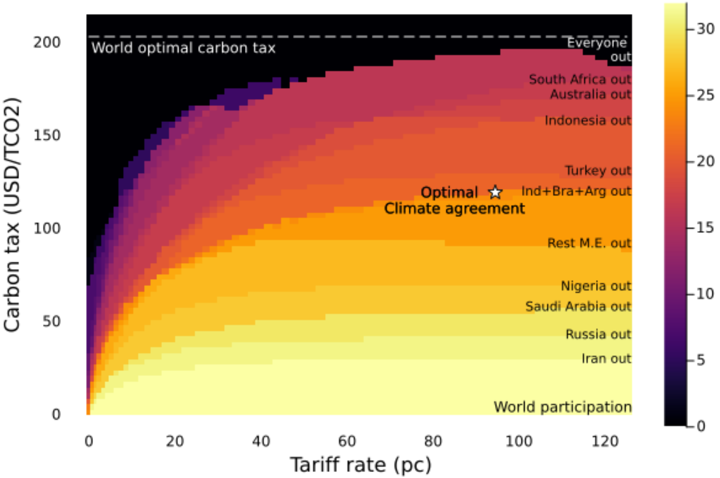
- Despite full discretion of instruments (t^{ε}, t^{b}), we cannot sustain an agreement with Russia, Middle East, South-Asia & South America

$\Rightarrow$ need to reduce carbon tax from \$200 to \$120

$\Rightarrow$ Beneficial to leave several fossil-fuel producers outside the agreement

e.g. no incentive for Russia to join: cold, closed to trade, large fossil-fuel producer

Graph welfare Mechanisms



Conclusion

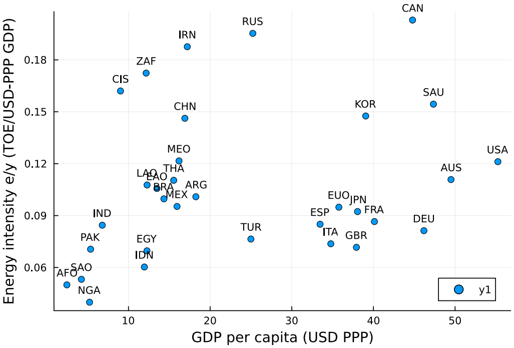
- In these projects, I solve for the optimal climate policy
  - Accounting for ***inequality*** + GE effects through energy markets and trade leakage
  - ... and strategic ***free-riding incentives***
- Additionaly climate agreements design jointly solve for:
  - The optimal choice of countries participating
  - The carbon tax and tariff levels, accounting for participation constraints
- The optimal climate club:
  - ***trade-off:*** gains of cooperation / free-riding incentives vs. gains from trade, i.e. cost of retaliation tariffs

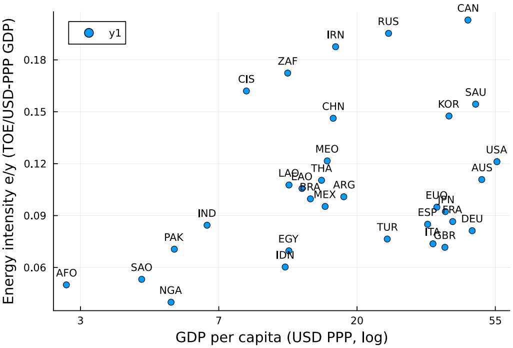
  $\Rightarrow$ large coalition, lower the carbon tax from \$250 to \$200 to \$120

Appendices

Energy intensity

- Energy intensity e_i/y_i vs. GDP per capita y_i





Step 0: Competitive equilibrium & Trade

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

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

  - 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

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

back

Step 1: World First-best policy

- Maximizing welfare of the world Social Planner:

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

  - Full array of instruments: cross-countries lump-sum transfers t_i^{ls}, individual carbon taxes $\mathrm{t}_i^{\varepsilon}$ on energy e_i^f, bilateral tariffs t_{ij}^b
  - Budget constraint: $\sum_i \mathrm{t}_i^{ls} = \sum_i \mathrm{t}_i^f e_i^f + \sum_{i,j} \mathrm{t}_{ij}^b c_{ij} d_{ij} \mathrm{p}_j$

- 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:

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

  - 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:

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

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

- 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:

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

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

- Relative welfare weights, representing inequality

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

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

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

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:

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

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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:

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

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
- New measure: Social Value of Fossil (SVF)

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

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

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- *Proposition 2:* Optimal fossil energy tax:

$$\Rightarrow \qquad \mathrm{t}^{\varepsilon} = SCC + SVF$$

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

back

Step 2: Optimal policy – Details

- Taxing fossil energy has additional redistributive effects:
  1. Through energy markets: distort supply, lowers eq. fossil price, benefit net importers

$$\text{Supply Redistribution} = \left(\sum_i \frac{1}{C^i_{ee}(e^x_i)}\right)^{-1} \sum_i \widehat{\lambda}_i (e^f_i - e^x_i)$$
$$= q^f \left(\sum_i \frac{e^x_i}{\nu_i}\right)^{-1} \sum_i \widehat{\lambda}_i (e^f_i - e^x_i)$$

  2. Distort energy demand, of countries that need more or less energy:
     FOC $MPe^f_i = q^f$, multiplier $\propto \widehat{\upsilon}^f_i$

$$\text{Demand Distortion} = \frac{1}{I}\sum_i \widehat{\upsilon}^f_i \partial_{e^f} MPe^f_i + \widehat{\upsilon}^r_i \partial_{e^f} MPe^f_i$$
$$= -(q^f + t^f)\frac{1}{I}\sum_i \widehat{\upsilon}^f_i \frac{1}{e^f_i}\left[\frac{1-s^f_i}{\sigma^e} + s^f_i \frac{1-s^e_i}{\sigma^y}\right] + \frac{1}{I}\sum_i \widehat{\upsilon}^r_i \frac{q^r_i}{e^f_i} s^f_i \left[\frac{1}{\sigma^e} - \frac{1-s^e_i}{\sigma^y}\right]$$

Step 2: Optimal policy – Details

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- *Proposition 2:* Optimal fossil energy tax: back

$$\Rightarrow \qquad \mathrm{t}^{\varepsilon} = SCC + \text{Supply Redistrib.} + \text{Demand Distortion}$$

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

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^{ε}
  - 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

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

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

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

  - Result: $\omega_i(1+\nu_i)$ are the "endogenous Pareto weights"

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

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

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

  - 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

Climate uncertainty and the Cost of Carbon:

- Stochastics: for any shock ϵ with distribution $\epsilon \sim \varphi(\epsilon)$
- New measure for inequalities:

$$\widehat{\lambda}^{w}_{it}(\epsilon) = \frac{\lambda^{k}_{it}(\epsilon)}{\mathbb{E}_{i,\epsilon}[\lambda^{w}_{it}(\epsilon)]} = \frac{\omega_i u'(c_{it}(\epsilon))}{\int_{\epsilon}\int_{j} \omega_j u'(c_{j,t}(\epsilon))\, dj\, d\varphi(\epsilon)}$$

- Uncertainty-adjusted SCC writes:

$$\begin{aligned}\mathbb{E}_{\epsilon}[SCC] &= \int_{\mathcal{E}}\int_{\mathbb{I}} \widehat{\lambda}^{w}_{it}(\epsilon) LCC_{it}(\epsilon) d\varphi(\epsilon) \\ &= \mathbb{E}_j\Big[\underbrace{\mathbb{C}\mathrm{ov}_{\epsilon}\Big(\widehat{\lambda}^{w}_{it}(\epsilon), LCC_{jt}(\epsilon)\Big)\Big]}_{=\text{effect of aggregate risk } \epsilon} + \underbrace{\mathbb{C}\mathrm{ov}_j\Big[\mathbb{E}_{\epsilon}\big(\widehat{\lambda}^{w}_{it}(\epsilon)\big), \mathbb{E}_{\epsilon}\big(LCC_{jt}(\epsilon)\big)\Big]}_{=\text{effect of heterogeneity across } j} + \underbrace{\mathbb{E}_{j,\epsilon}[LCC_{jt}(\epsilon)]}_{=\text{average exp. damage}} \\ &> \mathbb{E}_{\epsilon}[\overline{SCC}(\epsilon)] \qquad \& \qquad > SCC_t\end{aligned}$$

$\Rightarrow$ Climate uncertainty reinforces the unequal costs of climate change! back

Sequential solution method

- Summary of the dynamic model:
  - ODEs for states $\{\boldsymbol{x}\} = \{w_{it}, \tau_{it}, \mathcal{R}_{it}, \mathcal{S}_t\}_{it}$
  - Backward ODE for the costates $\{\boldsymbol{\lambda}\} = \{\lambda^w_{it}, \lambda^\tau_{it}, \lambda^{\mathcal{S}}_t, \lambda^{\mathcal{R}}_{it}\}_{it}$
  - 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)

Sequential solution method

- Summary of the dynamic model:
  - ODEs for states $\{\boldsymbol{x}\} = \{w_{it}, \tau_{it}, \mathcal{R}_{it}, \mathcal{S}_t\}_{it}$
  - Backward ODE for the costates $\{\boldsymbol{\lambda}\} = \{\lambda^w_{it}, \lambda^\tau_{it}, \lambda^{\mathcal{S}}_t, \lambda^{\mathcal{R}}_{it}\}_{it}$
  - 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)
- 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.

Impact of increase in temperature

- Marginal values of the climate variables: λ^s_{it} and λ^τ_{it}

$$\dot{\lambda}^\tau_{it} = \lambda^\tau_{it}(\rho+\zeta) + \overbrace{\gamma_i(\tau_{it}-\tau^\star_i)\mathcal{D}^y(\tau_{it})}^{-\partial_\tau \mathcal{D}^y(\tau_{it})} f(k_{it},e_{it})\lambda^k_{it} + \overbrace{\phi_i(\tau_{it}-\tau^\star_i)\mathcal{D}^u(\tau_{it})^{1-\eta} c_{it}^{1-\eta}}^{\partial_\tau u(c,\tau)}$$

$$\dot{\lambda}^S_{it} = \lambda^S_{it}(\rho+\delta^s) - \zeta\,\chi\,\Delta_i\,\lambda^\tau_{it}$$

- Costate λ^S_{it}: marg. cost of $1Mt$ carbon in atmosphere, for country i. Increases with:
  - Temperature gaps $\tau_{it}-\tau^\star_i$ & damage sensitivity of TFP γ^y_i and utility γ^u_i
  - Development level $f(k_{it},e_{it})$ and c_{it}
  - Climate params: χ climate sensitivity, Δ_i "catching up" of τ_i and ζ reaction speed
  - back

Cost of carbon / Marginal value of temperature

- Solving for the cost of carbon and temperature $\Leftrightarrow$ solving ODE

$$\dot{\lambda}^{\tau}_{it} = \lambda^{\tau}_{t}(\tilde{\rho} + \Delta\zeta) + \gamma(\tau - \tau^{\star})\mathcal{D}^{y}(\tau)f(k,e)\lambda^{k}_{t} + \phi(\tau - \tau^{\star})\mathcal{D}^{u}(\tau)u(c)$$

$$\dot{\lambda}^{S}_{t} = {\lambda^{S}}_{t}(\tilde{\rho} + \delta^{s}) - \int_{\mathbb{I}} \Delta_i \zeta \chi \lambda^{\tau}_{it}$$

- Solving for λ^{τ}_{t} and $\lambda^{\mathcal{S}}_{t}$, in stationary equilibrium $\dot{\lambda}^{S}_{t} = \dot{\lambda}^{\tau}_{t} = 0$

$$\lambda^{\tau}_{it} = -\int_{t}^{\infty} e^{-(\tilde{\rho}+\zeta)u}(\tau_u - \tau^{\star})\Big(\gamma\mathcal{D}^{y}(\tau_u)y_{\tau}\lambda^{k}_{u} + \phi\mathcal{D}^{u}(\tau_u)u(c_u)\Big)du$$

$$\lambda^{\tau}_{it} = -\frac{1}{\tilde{\rho} + \Delta\zeta}(\tau_{\infty} - \tau^{\star})\Big(\gamma\mathcal{D}^{y}(\tau_{\infty})y_{\infty}\lambda^{k}_{\infty} + \phi\mathcal{D}^{u}(\tau_{\infty})u(c_{\infty})\Big)$$

$$\begin{aligned}
\lambda^{S}_{t} &= -\int_{t}^{\infty} e^{-(\tilde{\rho}+\delta^{S})u}\zeta\chi\int_{\mathbb{I}}\Delta_j\lambda^{\tau}_{j,u}dj\,du \\
&= \frac{1}{\tilde{\rho} + \delta^{s}}\zeta\chi\int_{\mathbb{I}}\Delta_j\lambda^{\tau}_{j,\infty} \\
&= -\frac{\chi}{\tilde{\rho} + \delta^{s}}\frac{\zeta}{\tilde{\rho} + \zeta}\int_{\mathbb{I}}\Delta_j(\tau_{j,\infty} - \tau^{\star})\Big(\gamma\mathcal{D}^{y}(\tau_{j,\infty})y_{\infty}\lambda^{k}_{j,\infty} + \phi\mathcal{D}^{u}(\tau_{j,\infty})u(c_{j,\infty})\Big)dj
\end{aligned}$$

$$\lambda^{S}_{t} \xrightarrow[\zeta\to\infty]{} -\frac{\chi}{\tilde{\rho} + \delta^{s}}\int_{\mathbb{I}}\Delta_j(\tau_{j,\infty} - \tau^{\star})\Big(\gamma\mathcal{D}^{y}(\tau_{j,\infty})y_{j,\infty}\lambda^{k}_{j,\infty} + \mathcal{D}^{u}(\tau_{j,\infty})u(c_{j,\infty})\Big)dj$$

Cost of carbon / Marginal value of temperature

- ***Proposition (Stationary LCC)***:
  When $t \to \infty$ and for a BGP with $\mathcal{E}_t = \delta_s \mathcal{S}_t$ and $\tau_t \to \tau_\infty$, the LCC is *proportional* to climate sensitivity χ, marg. damage γ_i^y, γ_i^u, temperature, and output, consumption.

$$LCC_{it} \equiv \frac{\Delta_i \chi}{\rho - n + \bar{g}(\eta - 1) + \delta^s}(\tau_\infty - \tau^\star)\Big(\gamma \mathcal{D}^y(\tau_\infty) y_\infty + \phi \mathcal{D}^u(\tau_\infty) c_\infty\Big)$$

  - Stationary equilibrium: $\dot{\lambda}_t^S = \dot{\lambda}_t^T = 0$
  - Fast temperature adjustment $\zeta \to \infty$
  - Back

Quantification: Climate and parametrization

- Climate block: Climate System
  - Static economic model: decisions taken "once and for all", e.g. $\mathcal{E} = \sum_i e_i^f + e_i^c$.
  - "Dynamic" climate system: $\dot{\mathcal{S}}_t = \mathcal{E} - \delta_s \mathcal{S}_t, \quad T_{it} = \bar{T}_{i0} + \Delta_i \mathcal{S}_t$
  - Quadratic damage functions as in Nordhaus-DICE: $\mathcal{D}(T_{it} - T_i^\star) = e^{-\gamma(T_{it} - T_i^\star)^2}$
  - Feedback in Present discounted value: $\mathcal{D}_i^y(\mathcal{E}) = \bar{\rho} \int_0^\infty e^{-(\rho - n + (1-\eta)\bar{g})t} \mathcal{D}\left(T_{it} - T_i^\star\right) dt$

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  - Estimate γ from trade data (as Rudik, Lyn, Tan, and Ortiz-Bobea (2021)) Damage, Gravity

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

$$\Rightarrow \quad \gamma = 0.012 \approx 3 \times \gamma_{DICE}$$

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- Standard functional forms:
  - CRRA utility, Nested CES production, Iso-elastic fossil fuel extraction back

Quantification – Firms

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

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

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

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

- Damage functions in production function y:

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

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

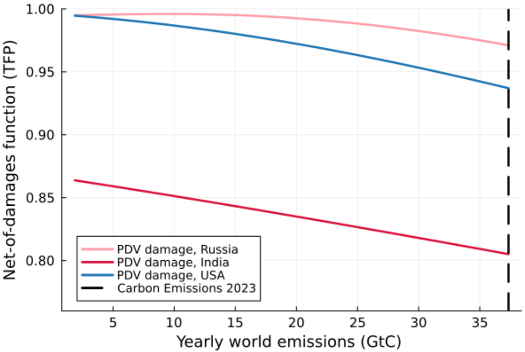
Quantification – Energy markets

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

back

Quantification – Climate system and damage

- Static economic model:
  decisions $e_i^f + e_i^c$ taken "once and for all", $\mathcal{E} = \sum_i e_i^f + e_i^c$
  - Climate system:
$$\dot{\mathcal{S}}_t = \mathcal{E} - \delta_s \mathcal{S}_t$$
$$T_{it} = \bar{T}_{i0} + \Delta_i \mathcal{S}_t$$
  - Path damages heterogeneous across countries
    Quadratic, c.f. Nordhaus-DICE / IAM
$$\mathcal{D}(T_{it} - T_i^\star) = e^{-\gamma (T_{it} - T_i^\star)^2}$$
  - Economic feedback in Present discounted value
$$\mathcal{D}_i^y(\mathcal{E}) = \bar{\rho} \int_0^\infty e^{-\overbrace{(\rho - n + (1-\eta)\bar{g})}^{\equiv \bar{\rho}} t} \mathcal{D}\big(T_{it} - T_i^\star\big) dt$$
  - Similarly for $\mathcal{D}_i^u(\mathcal{E})$, SCC and LCC_i ... 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 $GtC \equiv 0.23^\circ C$ medium-term warming
δ_s	0.0004	Carbon exit from atmosphere	Pulse experiment: 100 $GtC \equiv 0.15^\circ C$ 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

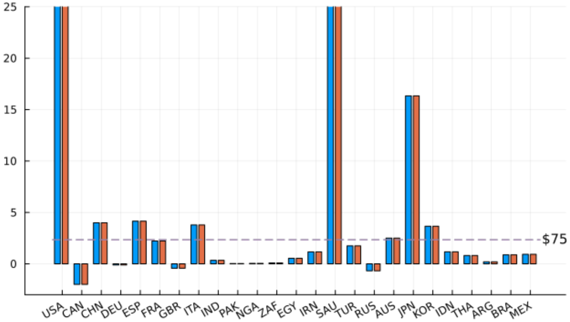
Table: Heterogeneity across countries

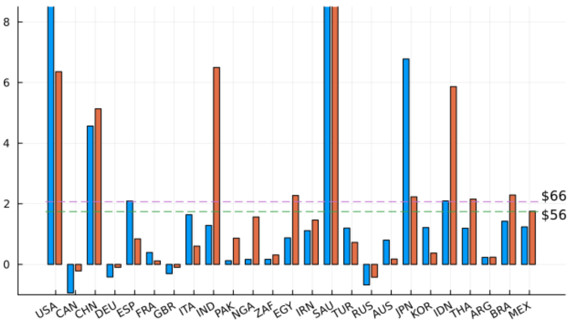
Dimension of heterogeneity	Model parameter	Matched variable from the data	Source
Population	Country size $\mathcal{P}_i$	Population	UN
TFP/technology/institutions	Firm productivity z_i	GDP per capita (2019-PPP)	WDI
Productivity in energy	Energy-augmenting productivity z_i^e	Energy cost share	SRE
Cost 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

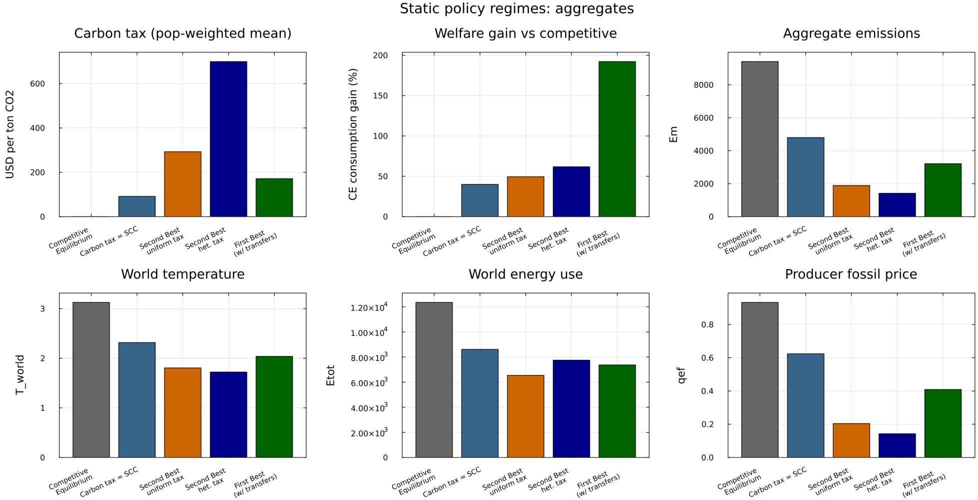
Local Cost of Carbon & Carbon Tax – First and Second Best

- Recall: $SCC = \sum_{\mathbb{I}} \widehat{\lambda}_i^w LCC_i$
- Difference: $LCC_i = \frac{\psi_i^{\mathcal{S}}}{\lambda_i^w}$ vs. $\widehat{\lambda}_i^w LCC_i = \frac{\psi_i^{\mathcal{S}}}{\bar{\lambda}^w}$





Allocations under different policy regimes



Allocations under different policy regimes