

# The Optimal Design of Climate Agreements

## Inequality, Trade, and Incentives for Carbon Policy

*Thomas Bourany*

THE UNIVERSITY OF CHICAGO

*E-axes Forum – Young Scholars Webinar  
on Climate Economics*

September 2024

# Motivation

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

# Motivation

- ▶ Fighting climate change requires implementing ambitious carbon reduction policies
  - The “free-riding problem” causes climate inaction:  
costs of taxation are local but climate benefits are global
  - Climate policy redistributes across countries through:  
(i) change in climate (ii) energy markets, and (iii) reallocation of activity through trade
- ▶ One proposal against climate inaction: “Climate club” – Nordhaus (2015)
  - Trade sanctions need to be imposed on non-participants to sustain a “club” and reduce emissions meaningfully

# Motivation

- ▶ Fighting climate change requires implementing ambitious carbon reduction policies
    - The “free-riding problem” causes climate inaction:  
costs of taxation are local but climate benefits are global
    - Climate policy redistributes across countries through:  
(i) change in climate (ii) energy markets, and (iii) reallocation of activity through trade
  - ▶ One proposal against climate inaction: “Climate club” – Nordhaus (2015)
    - Trade sanctions need to be imposed on non-participants to sustain a “club” and reduce emissions meaningfully
- ⇒ How can we design a climate agreement that implements the optimal energy taxation in the presence of inequality and policy constraints?

# Introduction

- ⇒ How can we design a 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
  - Trade-off:  
*Intensive margin*: a “climate club” with few countries and large emission reductions  
vs. *Extensive margin*: a larger set of countries, at the cost of lowering the carbon tax

# Introduction

- ⇒ How can we design a 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
  - Trade-off:  
*Intensive margin*: a “climate club” with few countries and large emission reductions  
vs. *Extensive margin*: a larger set of countries, at the cost of lowering the carbon tax
  - Build a Climate-Macro model (IAM) with heterogeneous countries and trade to study the strategic implications of climate agreements and the optimal club design

# Introduction

⇒ How can we design a 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
- Trade-off:  
*Intensive margin*: a “climate club” with few countries and large emission reductions  
vs. *Extensive margin*: a larger set of countries, at the cost of lowering the carbon tax
- Build a Climate-Macro model (IAM) with heterogeneous countries and trade to study the strategic implications of climate agreements and the optimal club design

► Preview of the results:

- Despite complete freedom of policy instruments, **impossible** to achieve the world’s optimal policy with complete participation
- Beneficial to **leave several fossil fuels producing countries** outside of the climate agreement
- Welfare improvement with transfers, c.f. UN COP27’s “loss and damage” fund

# Literature

## ► Climate change & optimal carbon taxation

- RA model: Nordhaus DICE (1996-), Weitzman (2014), Golosov et al (2014)
- HA model: Krusell Smith (2022), Kotlikoff, Kubler, Polbin, Scheidegger (2021)
- Spatial models: Cruz, Rossi-Hansberg (2022, 2023) among others

⇒ *Optimal and constrained policy with heterogeneous countries & trade*

## ► Unilateral vs. climate club policies:

- Climate clubs: Nordhaus (2015), Non-cooperative taxation: Chari, Kehoe (1990), Suboptimal policy: Hassler, Krusell, Olovsson (2019)
- Trade policy: Kortum, Weisbach (2023), Farrokhi, Lashkaripour (2021), Hsiao (2022), Costinot, Donalson, Vogel, Werning (2015), Adao, Costinot (2022), Antras, Fort, Gutierrez, Tintelnot (2022)

⇒ *Climate cooperation and optimal design of climate club*

## ► Optimal policy in heterogeneous agents models

- Policy with limited instruments: Diamond (1973), Davila, Walther (2022)
- Bhandari et al (2021), Le Grand, Ragot (2022), Davila, Schaab (2022) ...

⇒ *Application to climate and carbon taxation policy*



# Literature

## ► Climate change & optimal carbon taxation

- RA model: Nordhaus DICE (1996-), Weitzman (2014), Golosov et al (2014)
- HA model: Krusell Smith (2022), Kotlikoff, Kubler, Polbin, Scheidegger (2021)
- Spatial models: Cruz, Rossi-Hansberg (2022, 2023) among others

⇒ *Optimal and constrained policy with heterogeneous countries & trade*

## ► Unilateral vs. climate club policies:

- Climate clubs: Nordhaus (2015), Non-cooperative taxation: Chari, Kehoe (1990), Suboptimal policy: Hassler, Krusell, Olovsson (2019)
- Trade policy: Kortum, Weisbach (2023), Farrokhi, Lashkaripour (2021), Hsiao (2022), Costinot, Donalson, Vogel, Werning (2015), Adao, Costinot (2022), Antras, Fort, Gutierrez, Tintelnot (2022)

⇒ *Climate cooperation and optimal design of climate club*

## ► Optimal policy in heterogeneous agents models

- Policy with limited instruments: Diamond (1973), Davila, Walther (2022)
- Bhandari et al (2021), Le Grand, Ragot (2022), Davila, Schaab (2022) ...

⇒ *Application to climate and carbon taxation policy*

# Literature

- ▶ Nordhaus (2015)
  - Examine "stable climate coalitions" (club imposing carbon tax) in a simple model
  - Abstract from General Equilibrium and distributional effects
  - Results: Penalty tariffs necessary to enforce a climate club
- ▶ Farrokhi, Lashkaripour (2021)
  - Study and characterize the optimal trade policy with climate externality
  - General static trade model. Results: unilateral tariffs not effective
  - Sequential search for one stable climate club if EU or US join.
- ▶ Main contribution:
  - Search for the *optimal* climate agreement
  - GE on good and energy market and redistribution effects are first-order
  - Cost of climate change is endogenous to policy (damages are non-linear)
  - Possibility of analyzing other distributional policies (transfers, *loss and damage funds*)
  - General framework for analyzing macrodynamics

## Model – Household & Firms

### ► 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:

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

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

# Model – Household & Firms

## ► Deterministic Neoclassical economy

- countries  $i \in \mathbb{I}$ , heterogeneous in productivity  $z_i$ , temperature  $T_i$ , energy extraction cost  $C_i$
- In each country, five agents:

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

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

### 2. Competitive final good firm:

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

- Externality: Damage function  $\mathcal{D}_i(\mathcal{E})$ , Income inequality from  $z_i$ , Carbon tax:  $t_i^\varepsilon$
- Trade, à la Armington

## Model – Energy markets & Emissions

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

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

- Energy traded in international markets, at price  $q^f$

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

## Model – Energy markets & Emissions

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

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

- Energy traded in international markets, at price  $q^f$

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

4. Coal energy firm: elastic supply  $e_i^c$  at price  $q_i^c = z_i^c \mathbb{P}_i$

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

## Model – Energy markets & Emissions

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

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

- Energy traded in international markets, at price  $q^f$

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

4. Coal energy firm: elastic supply  $e_i^c$  at price  $q_i^c = z_i^c \mathbb{P}_i$
5. Renewable energy firm: elastic supply  $e_i^r$  at price  $q_i^r = z_i^r \mathbb{P}_i$
- Climate system: mapping from emission  $\mathcal{E} = \sum_{\mathbb{I}} e_i^f + e_i^c$  to damage  $\mathcal{D}_i(\mathcal{E})$

## Model – Equilibrium

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

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

with  $x_{ki}$  export of good  $i$  as input in energy production in  $k$

In expenditure, with import shares  $s_{ij} = \frac{c_{ij} \tau_{ij} p_j}{c_i p_i}$ , it yields

$$p_i y_i = \sum_{k \in \mathbb{I}} \frac{s_{ki}}{1 + t_{ki}^b} (p_k y_k + q^f (e_k^x - e_k^f) + \tilde{t}_k^{ls})$$



## Ramsey Problem with endogenous participation

- **Definition:** A climate agreement is a set  $\{\mathbb{J}, \mathbf{t}^\varepsilon, \mathbf{t}^b\}$  of  $\mathbb{J} \subseteq \mathbb{I}$  countries and a C.E. s.t.:
  - Countries  $i \in \mathbb{J}$  pay carbon tax  $\mathbf{t}^\varepsilon$
  - If  $j$  **exits** the agreement, club members  $i \in \mathbb{J}$  impose uniform tariffs  $t_{ij}^b = \mathbf{t}^b$  on goods from  $j$   
They still trade with club members in oil-gas at price  $q^f$
  - Exit: unilateral deviation  $\mathbb{J} \setminus \{j\}, \Rightarrow$  **Nash equilibrium**
- Participation constraints, given indirect utility  $U_i(\mathbb{J}, \mathbf{t}^\varepsilon, \mathbf{t}^b) \equiv u(c_i(\mathbb{J}, \mathbf{t}^\varepsilon, \mathbf{t}^b))$

$$U_i(\mathbb{J}, \mathbf{t}^\varepsilon, \mathbf{t}^b) \geq U_i(\mathbb{J} \setminus \{i\}, \mathbf{t}^\varepsilon, \mathbf{t}^b) \quad [\text{Nash equilibrium}]$$

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

$$\begin{aligned} \max_{\mathbb{J}, \mathbf{t}^\varepsilon, \mathbf{t}^b} \mathcal{W}(\mathbb{J}, \mathbf{t}^\varepsilon, \mathbf{t}^b) &= \max_{\mathbf{t}^\varepsilon, \mathbf{t}^b} \max_{\mathbb{J}} \sum_{i \in \mathbb{I}} \omega_i U_i(\mathbb{J}, \mathbf{t}^\varepsilon, \mathbf{t}^b) \\ \text{s.t.} \quad \mathbb{J} \in \mathbb{S}(\mathbf{t}^\varepsilon, \mathbf{t}^b) &= \left\{ \mathbb{J} \mid U_i(\mathbb{J}, \mathbf{t}^\varepsilon, \mathbf{t}^b) \geq U_i(\mathbb{J} \setminus \{i\}, \mathbf{t}^\varepsilon, \mathbf{t}^b) \ \forall i \in \mathbb{J} \right\} \end{aligned}$$

## Ramsey Problem with endogenous participation

- **Objective:** optimal *and stable* climate agreement  $\{\mathbb{J}, t^e, t^b\}$

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

$$s.t. \quad \mathbb{J} \in \mathbb{S}(t^e, t^b) = \left\{ \mathcal{J} \mid U_i(\mathbb{J}, t^e, t^b) \geq U_i(\mathbb{J} \setminus \{i\}, t^e, t^b) \quad \forall i \in \mathcal{J} \right\}$$

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

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

## Ramsey Problem with endogenous participation

- **Objective:** optimal and stable climate agreement  $\{\mathbb{J}, t^e, t^b\}$

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

$$s.t. \quad \mathbb{J} \in \mathbb{S}(t^e, t^b) = \left\{ \mathcal{J} \mid U_i(\mathbb{J}, t^e, t^b) \geq U_i(\mathbb{J} \setminus \{i\}, t^e, t^b) \quad \forall i \in \mathcal{J} \right\}$$

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

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

- No country  $i$  and subcoalition  $\hat{\mathbb{J}}$  would be better off than in the current agreement  $\mathbb{J}$

- Current design: (i) choose taxes  $\{t^f, t^b\}$ ,  
(ii) choose the coalition  $\mathbb{J}$  s.t. participation constraints hold
- Solution method (Nash equilibrium):
  - relies on the complementarity of the combinatorial discrete choice problem and use a “squeezing procedure”, c.f. Jia (2008), Arkolakis, Eckert, Shi (2023), to handle the problem

# Quantification

- ▶ Energy parameters to match production/reserves,
  - Isoelastic cost function  $C_i(e_i^x) = \bar{\nu}_i (e_i^x / \mathcal{R}_i)^{1+\nu_i} \mathcal{R}_i$
  - Use  $\bar{\nu}_i, \nu_i$  to match  $e_i^x$  and  $\pi_i^f$ ,
- ▶ Armington model,
  - Iceberg cost  $\tau_{ij}$  projected on distance and preferences  $a_{ij}$  to match import shares  $s_{ij} = \frac{c_{ij} \tau_{ij} p_j}{c_i \mathbb{P}_i}$
- ▶ Production  $\bar{y} = z f(\ell_i, k_i, e_i^f, e_i^r)$ 
  - 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  $\omega_i$ :
  - Imply no redistribution motive,  $\bar{c}_i$  consumption in initial equilibrium  $t = 2020$

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

- ▶ Details [More details](#) [Details Pareto weights](#)

## 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:

$$\dot{S}_t = \mathcal{E} - \delta_s S_t$$

$$T_{it} = \bar{T}_{i0} + \Delta_i S_t$$

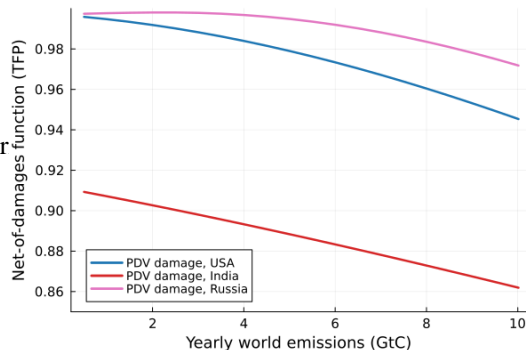
- Path of period damages heterogeneous across countries  
Quadratic (c.f. Nordhaus-DICE)

$$\mathcal{D}_i(T_{it}) = e^{-\gamma(T_{it} - T_i^*)^2}$$

- Economic feedback in Present discounted value

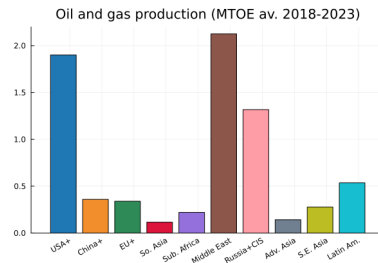
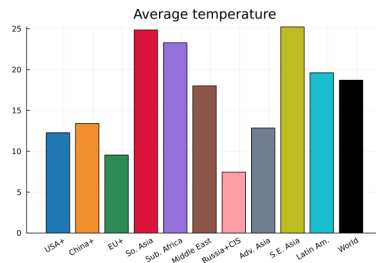
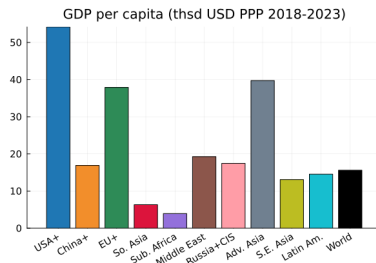
$$\mathcal{D}_i(\mathcal{E}) = \int_0^\infty e^{-\rho t} \mathcal{D}(T_{it}) dt$$

- Similarly for  $LCC_i, SCC_i \dots$



## Quantitative application – Sample of 10 “regions”

- ▶ Sample of 10 “regions”: (i) US+Canada, (ii) China+HK, (iii) UE+UK+Schengen, (iv) South Asia, (v) Sub-saharian Africa, (vi) Middle-East+Maghreb, (vii) Russia+CIS, (viii) Japan+Korean+Australia+Asian Dragons, (ix) South-East Asia (Asean), (x) Latin America **WIP: 25 countries + 5 regions**
- ▶ Data (Avg. 2018-2023) on macro variables, energy markets, trade shares  $s_{ij} = \frac{c_{ij}\tau_{ij}p_j}{c_i p_i}$ , etc.



### Details Trade shares – details

## Optimal policy : benchmarks

- ▶ Three policy benchmarks, c.f. Bourany (2024), without endogenous participation
  - ***First-Best***, Social planner maximizing global welfare with unlimited instruments
    - Pigouvian result: Carbon tax = Social Cost of Carbon
    - Relies heavily on cross-country transfers to offset redistributive effects

## Optimal policy : benchmarks

► Three policy benchmarks, c.f. Bourany (2024), without endogenous participation

- **First-Best**, Social planner maximizing global welfare with unlimited instruments
  - Pigouvian result: Carbon tax = Social Cost of Carbon
  - Relies heavily on cross-country transfers to offset redistributive effects
- **Second-Best**: Social planner, single carbon tax without transfers
  - Optimal carbon tax  $t^e$  correct climate externality, but also accounts for:
    - (i) Redistribution motives, G.E. effects on (ii) energy markets and (iii) trade leakage

$$t^e = \underbrace{\sum_i \phi_i LCC_i}_{=SCC} + \sum_i \phi_i \text{Supply Redistribution}_i + \sum_i \phi_i \text{Demand Distortion}_i \quad \phi_i \propto \omega_i(u'(c_i) + \mu_i)$$

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



## Optimal policy : benchmarks

► Three policy benchmarks, c.f. Bourany (2024), without endogenous participation

- **First-Best**, Social planner maximizing global welfare with unlimited instruments
  - Pigouvian result: Carbon tax = Social Cost of Carbon
  - Relies heavily on cross-country transfers to offset redistributive effects

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

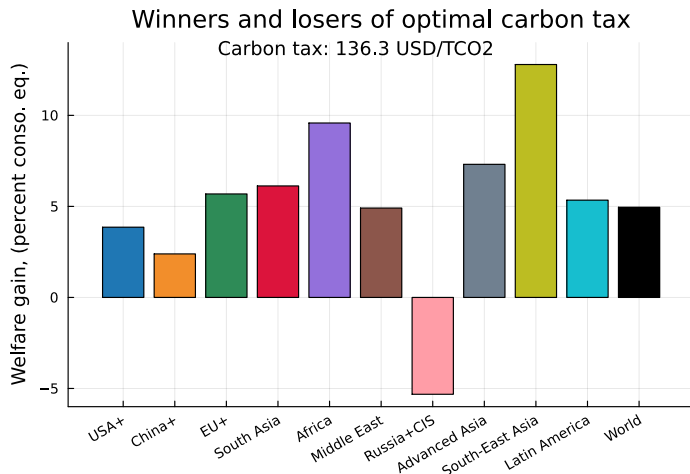
$$t^\varepsilon = \underbrace{\sum_i \phi_i LCC_i}_{=SCC} + \sum_i \phi_i \text{Supply Redistribution}_i + \sum_i \phi_i \text{Demand Distortion}_i \quad \phi_i \propto \omega_i(u'(c_i) + \mu_i)$$

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

- **Unilateral policy**: Local planner in country  $i$  unilaterally choosing  $t_i^\varepsilon$  and  $t_{ij}^b$ 
  - Optimal unilateral carbon tax (subsidy!) and tariffs for terms-of-trade manipulations
  - Nash equilibrium of  $\mathbb{I}$  countries choosing individually unilateral policies

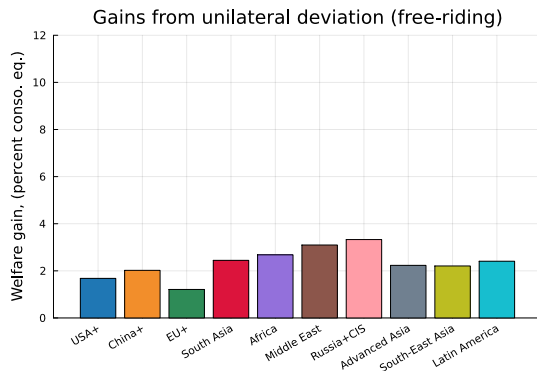
## Gains from cooperation – World Optimal policy

- ▶ Optimal carbon tax  
(Second Best):  $\sim \$136/tCO_2$
- ▶ Reduce fossil fuels /  $CO_2$  emissions by 40% compared to Business as Usual (BAU)
- ▶ Welfare difference btw world optimal policy w/o participation constraints vs BAU (Comp. Eq.)



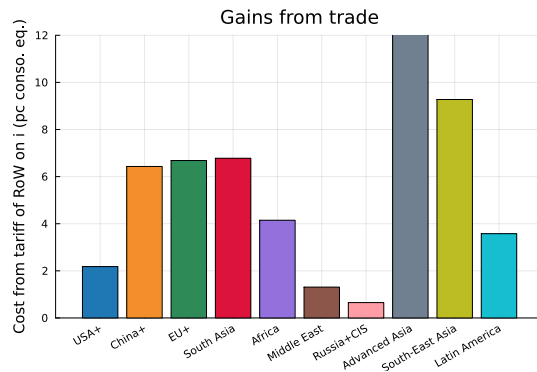
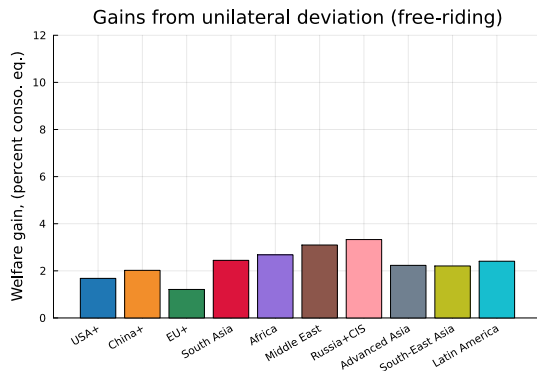
## Trade-off – Cost of Carbon Taxation vs. Gains from trade

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



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

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



## Theoretical investigation: decomposing the welfare effects

### ► Experiment:

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

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

- 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

$$\frac{dq^f}{q^f} = -\sum_j \nu_j^f \frac{dt_j^f}{t_j^f} + \sum_i \nu_j^{p,R} \frac{dp_j}{p_j} + \sum_{j,k} \nu_j^{R,f,z,q^r} s_{j,k} \frac{dt_{jk}^b}{t_{jk}^b}$$

- Trade and leakage effect: GE impact of  $t_j^f$  and  $t_{jk}^b$  on  $y_i$  and  $p_i$
- Simplifying assumption: no renewable

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

## 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  $dt_{j,k}^b, \forall j, k$

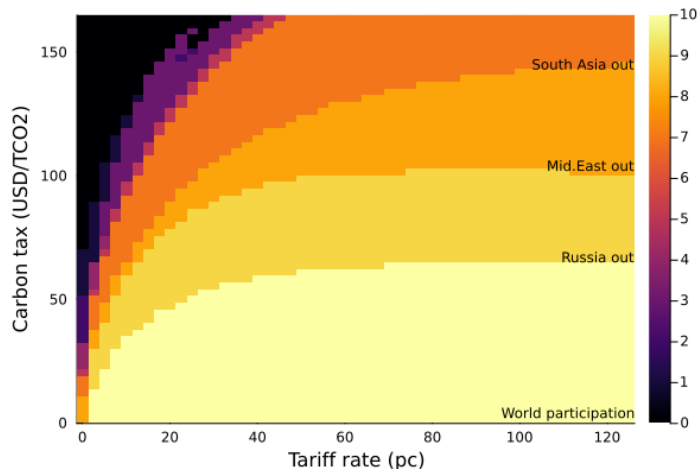
$$\frac{dp}{p} = \left[ \mathbf{I} - \mathbf{T} - (\theta - 1) [\mathbf{T} \odot \mathbf{S} - (\mathbf{T} \odot \mathbf{I})'] \right]^{-1} \left( (\mathbf{T} - \mathbf{I}) \frac{dy}{y} + (\mathbf{T} [(\theta - 1) \mathbf{I} - \theta \mathbf{S}] \odot \frac{dt^b}{t^b}) \mathbf{1} \right)$$

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

- Params:  $\mathbf{S}$  Trade share matrix,  $\mathbf{T}$  income flow matrix,  $\theta$ , Armington CES

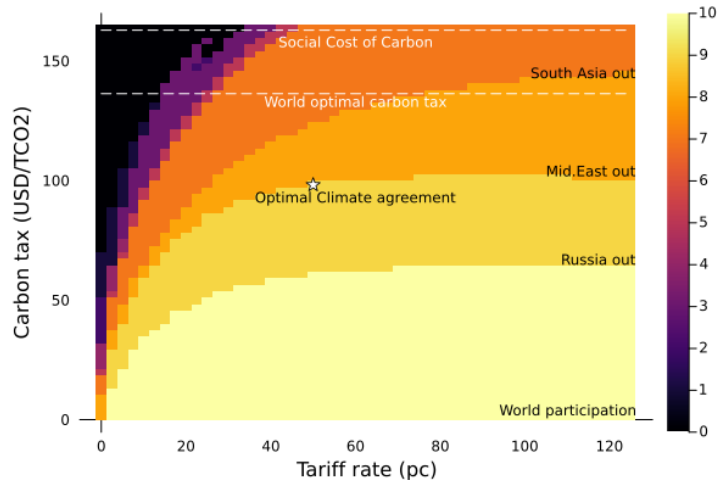
# Climate Agreements: Intensive vs. Extensive Margin

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



# Optimal Climate Agreement

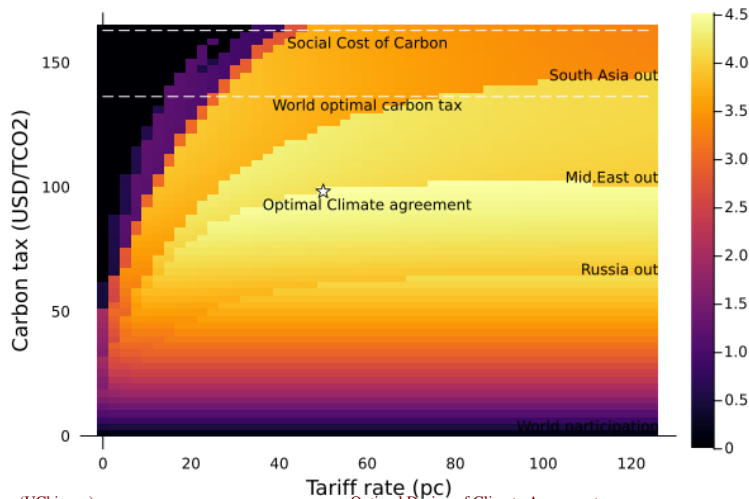
- ▶ Despite full freedom of instruments ( $t^e, t^b$ )  
 ⇒ can not sustain an agreement with Russia & Middle East  
 ⇒ need to reduce carbon tax from \$136 to \$98
- ▶ Intuition:  
 relatively cold and closed economy, and fossil-fuel producers





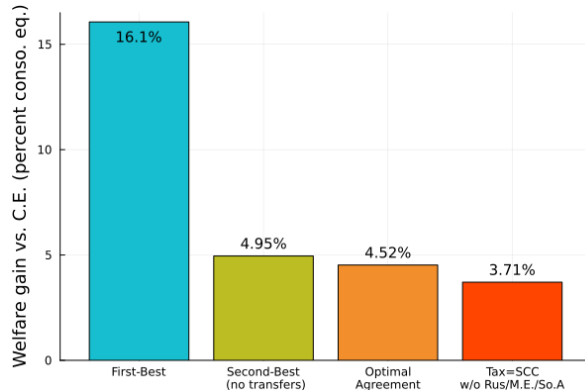
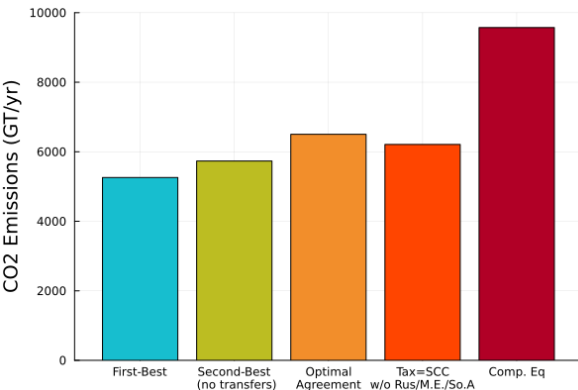
# Climate agreement and welfare

Recover 91% of welfare gains, i.e. 4.5% out of 5% conso equivalent.



## Welfare and emission reduction: Different metrics!

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

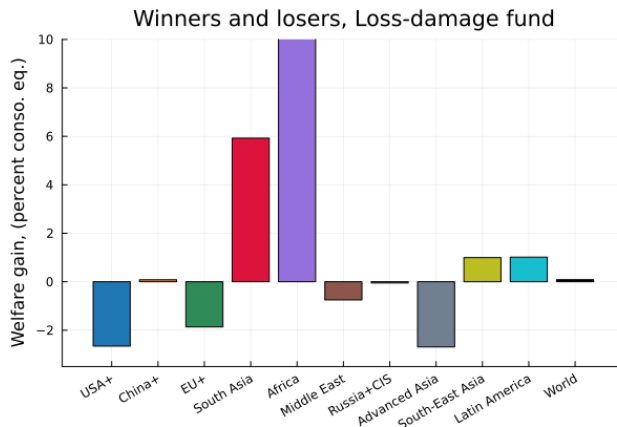


## Transfers – Loss and damage funds

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

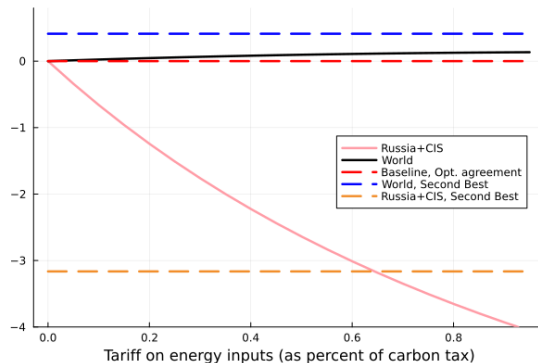
$$t_i^{ls} = (1 - \alpha)t^\varepsilon \varepsilon_i + \alpha \frac{1}{P} \sum_j t^\varepsilon \varepsilon_j$$

- ▶ In practice: transfers from large emitters to low emitters



## Taxation of fossil fuels energy inputs

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



## Dynamic coalition formation

- Current “equilibrium”:  $t_i^\varepsilon = 0, t_{ij}^b = 0$
- Optimal club equilibrium  $t_i^\varepsilon = t^{\varepsilon*}, t_{ij}^b = t^{b*} \mathbb{1}\{i \in \mathbb{J}, j \notin \mathbb{J}\}$
- Optimal agreement follows the planner taxes and participation decision:

$$\mathbb{J}^* = \mathbb{J}(t^{\varepsilon*}, t^{b*})$$

### ► What is driving the coordination failure?

- Possible explanation: coalition building and *bargaining* may never reach such equilibrium:

$$\bar{\mathbb{J}}_{t_0}(0, 0) = \mathbb{I} \quad \xrightarrow[t \rightarrow T]{?} \quad \bar{\mathbb{J}}_T(t^{\varepsilon*}, t^{b*}) = \mathbb{J}^*$$

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

$$\{\mathbb{J}_{t_0}, t_{t_0}^f, t_{t_0}^b\} = \{\bar{\mathbb{J}}_{t_0}, 0, 0\} \qquad \{\mathbb{J}_T, t_T^\varepsilon, t_T^b\} = \{\bar{\mathbb{J}}_T, t^{f*}, t^{b*}\}$$

- Instruments used by leader countries (e.g. E.U., U.S. or China?) to reach such agreement?

# Conclusion

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

⇒ Need a large coalition and a carbon at 70% of the world optimum
- ▶ Extensions:
  - Extend this to dynamic settings: coalition building
  - Explore additional policy proposal to improve the optimal agreement

# Conclusion

**Thank you!**

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

# Appendices



# Welfare and Pareto weights

- Welfare:

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

- Pareto weights  $\omega_i$ :

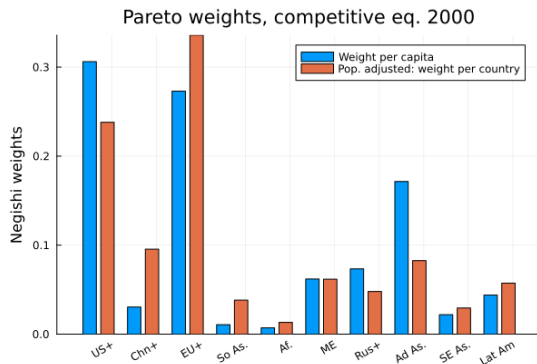
$$\omega_i = \frac{1}{u'(\bar{c}_i)}$$

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

- Imply no redistribution motive in  $t = 2020$

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

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



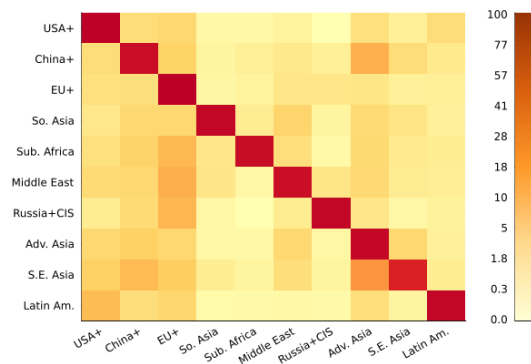
back

# Quantification – Trade model

- Armington Trade model:

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

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


[back](#)

## Step 0: Competitive equilibrium & Trade

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

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

- Energy consumption doesn't internalize climate damage:

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

- Inequality, as measured in local welfare units:

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

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

$$LCC_i = \frac{\partial W_i / \partial \mathcal{E}}{\partial W_i / \partial w_i} = \frac{\psi_i^{\mathcal{E}}}{\lambda_i} = -\Delta_i \mathcal{D}'(T_i) z_{if}(e_i^f) \frac{p_i}{p_i} \quad (> 0 \text{ if heat causes losses})$$

## Step 1: World First-best policy

- Maximizing welfare of the world Social Planner:

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

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

back

## Step 1: World First-best policy

### ► Social planner results:

- Consumption:

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

- 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:

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

- One single instrument: uniform carbon tax  $\mathbf{t}^f$  on energy  $e_i^f$
  - Rebate tax lump-sum to HHs  $\mathbf{t}_i^{ls} = \mathbf{t}^f e_i^f$
- 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**  $\lambda_i$
  - (ii) the **shadow value of good  $i$** , from market clearing,  $\mu_i$ :

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

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

- Relative welfare weights, representing inequality

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

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

## 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  $i$ :

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



## 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  $i$ :

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

- 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:

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

## Step 2: Optimal policy – Other motives

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

$$SVF := \frac{\partial \mathcal{W} / \partial E}{\partial \mathcal{W} / \partial w} = \mathcal{C}_{EE}^f \mathbb{Cov}_i \left( \hat{\lambda}_i, e_i^f - e_i^x \right) - \mathbb{Cov}_i \left( \hat{\lambda}_i, \frac{q^f (1 - s_i^f)}{\sigma} \right)$$

- Params:  $\mathcal{C}_{EE}^f$  agg. fossil supply elasticity,  $s_i^f$  energy cost share and  $\sigma$  energy demand elasticity

## 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)

$$SVF := \frac{\partial \mathcal{W} / \partial E}{\partial \mathcal{W} / \partial w} = \underbrace{\mathcal{C}_{EE}^f}_{\text{agg. supply distortion}} \underbrace{\mathbb{Cov}_i(\hat{\lambda}_i, e_i^f - e_i^x)}_{\text{terms-of-trade redistribution}} - \underbrace{\mathbb{Cov}_i\left(\hat{\lambda}_i, \frac{q^f(1-s_i^f)}{\sigma}\right)}_{\text{demand distortion}}$$

- Params:  $\mathcal{C}_{EE}^f$  agg. fossil supply elasticity,  $s_i^f$  energy cost share and  $\sigma$  energy demand elasticity

## 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)

$$SVF := \frac{\partial \mathcal{W} / \partial E}{\partial \mathcal{W} / \partial w} = \mathcal{C}_{EE}^f \text{Cov}_i \left( \hat{\lambda}_i, e_i^f - e_i^x \right) - \text{Cov}_i \left( \hat{\lambda}_i, \frac{q^f (1 - s_i^f)}{\sigma} \right)$$

- Params:  $\mathcal{C}_{EE}^f$  agg. fossil supply elasticity,  $s_i^f$  energy cost share and  $\sigma$  energy demand elasticity
- ▶ Proposition 2: Optimal fossil energy tax:

$$\Rightarrow \quad \tau^f = SCC + SVF$$

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

## 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  $\tau^f$
  - Countries  $i \in \mathbb{J}$  can unilaterally leave, subject to retaliation tariff  $\tau^{b,r}$  on goods and get consumption  $\tilde{c}_i$
  - Countries  $i \notin \mathbb{J}$  trade in goods subject to tariff  $\tau^b$  with club members and countries outside the club. They still trade with the club members in energy at price  $q^f$

## Step 3: Ramsey Problem with participation constraints

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

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

- ▶ Welfare:

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

## Step 3: Ramsey Problem with participation constraints

### ► Participation constraints

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

### ► Proposition 3.1: Second-Best social valuation with participation constraints

- Participation incentives change our measure of inequality

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

$$\Rightarrow \quad \hat{\tilde{\lambda}}_i = \frac{\omega_i(\tilde{\lambda}_i + \tilde{\mu}_i)}{\frac{1}{J} \sum_{j \in \mathbb{J}} \omega_i(\tilde{\lambda}_i + \tilde{\mu}_i)} \neq \hat{\lambda}_i$$

$$\text{vs. w/o trade} \quad \hat{\tilde{\lambda}}_i = \frac{\omega_i(1+\nu_i)u'(c_i)}{\frac{1}{J} \sum_{j \in \mathbb{J}} \omega_j(1+\nu_j)u'(c_j)} \neq \hat{\lambda}_i$$

- Similarly, the “effective Pareto weights” are  $\alpha\omega_i$  for countries outside the club  $i \notin \mathbb{J}$  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  $\nu$  fossil supply elasticity,  $\sigma$  energy demand elasticity and  $s^f$  energy cost share.
- Optimal fossil energy tax  $t^f(\mathbb{J})$ :

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

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

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



## 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  $\tau^f(\mathbb{J}) = 0$ ,  
 $\Rightarrow$  country  $i$  is indifferent to join the club  $\mathbb{J}$  or not
  - Linear approximation around that point  $\Rightarrow$  small changes in carbon tax  $d\tau^f$

## 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  $t^f(\mathbb{J}) = 0$ ,  
 $\Rightarrow$  country  $i$  is indifferent to join the club  $\mathbb{J}$  or not
- Linear approximation around that point  $\Rightarrow$  small changes in carbon tax  $dt^f$
- Change in welfare if  $i \in \mathbb{J}$  vs.  $i \notin \mathbb{J}$

$$\frac{d\mathcal{W}_{i|i \in \mathbb{J}}}{u'(c_i^{i \in \mathbb{J}})} - \frac{d\mathcal{W}_{i|i \notin \mathbb{J}}}{u'(c_i^{i \notin \mathbb{J}})} = -e_i dt^f - \gamma_i (T_i - T_{i0})^\delta y_i \Delta_i (dE_{i \in \mathbb{J}} - dE_{i \notin \mathbb{J}}) \\ - e_i \frac{q^f \nu}{E_{\mathbb{I}}} (dE_{i \in \mathbb{J}} - dE_{i \notin \mathbb{J}}) + \pi_i \frac{(1+\nu)}{E} (dE_{i \in \mathbb{J}} - dE_{i \notin \mathbb{J}})$$

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

$$dE_{i \in \mathbb{J}} - dE_{i \notin \mathbb{J}} = - \left( E_{\mathbb{J}} - E_{\mathbb{J} \setminus \{i\}} \right) \frac{\sigma dt^f}{q^f (1 - s^f)} \frac{1}{1 + \frac{\nu \sigma}{(1 - s^f)}}$$

◦ Params:  $\sigma$  energy demand elast<sup>y</sup>,  $s^f$  energy cost share,  $\nu$  energy supply elas<sup>y</sup>, Climate damage  $\gamma_i$  and curv.  $\delta$

## 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  $t^f(\mathbb{J}) = 0$ ,  
 $\Rightarrow$  country  $i$  is indifferent to join the club  $\mathbb{J}$  or not
  - Linear approximation around that point  $\Rightarrow$  small changes in carbon tax  $dt^f$
  - Change in welfare if  $i \in \mathbb{J}$  vs.  $i \notin \mathbb{J}$

$$\frac{d\mathcal{W}_{i|i \in \mathbb{J}}}{u'(c_i^{i \in \mathbb{J}})} - \frac{d\mathcal{W}_{i|i \notin \mathbb{J}}}{u'(c_i^{i \notin \mathbb{J}})} = -e_i dt^f - \gamma_i (T_i - T_{i0})^\delta y_i \Delta_i (dE_{i \in \mathbb{J}} - dE_{i \notin \mathbb{J}}) \\ - e_i \frac{q^f \nu}{E_{\mathbb{J}}} (dE_{i \in \mathbb{J}} - dE_{i \notin \mathbb{J}}) + \pi_i \frac{(1+\nu)}{E} (dE_{i \in \mathbb{J}} - dE_{i \notin \mathbb{J}})$$

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

$$dE_{i \in \mathbb{J}} - dE_{i \notin \mathbb{J}} = - \left( E_{\mathbb{J}} - E_{\mathbb{J} \setminus \{i\}} \right) \frac{\sigma dt^f}{q^f (1 - s^f)} \frac{1}{1 + \frac{\nu \sigma}{(1 - s^f)}}$$

◦ Params:  $\sigma$  energy demand elast<sup>y</sup>,  $s^f$  energy cost share,  $\nu$  energy supply elas<sup>y</sup>, Climate damage  $\gamma_i$  and curv.  $\delta$

## Countries' incentives – Armington Model with trade in goods

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

$$\begin{aligned} \frac{d\mathcal{W}_{i|i \in \mathbb{J}}}{u'(c_i^{i \in \mathbb{J}})c_i} - \frac{d\mathcal{W}_{i|i \notin \mathbb{J}}}{u'(c_i^{i \notin \mathbb{J}})c_i} = & -e_i dt^f - \gamma_i (T_i - T_{i0})^\delta \eta_i^y \Delta_i (dE_{i \in \mathbb{J}} - dE_{i \notin \mathbb{J}}) \\ & - e_i \frac{q^f \nu}{E_{\mathbb{J}}} (dE_{i \in \mathbb{J}} - dE_{i \notin \mathbb{J}}) + \eta_i^f \frac{(1+\nu)}{E} (dE_{i \in \mathbb{J}} - dE_{i \notin \mathbb{J}}) \\ & + \eta_i^y \left( \frac{dp_i}{p_i} \Big|_{i \in \mathbb{J}} - \frac{dp_i}{p_i} \Big|_{i \notin \mathbb{J}} \right) - s_{i\mathbb{J}^c} dt^b - \sum_{j \in \mathbb{J}} s_{ij} \left( \frac{dp_j}{p_j} \Big|_{i \in \mathbb{J}} - \frac{dp_j}{p_j} \Big|_{i \notin \mathbb{J}} \right) \end{aligned}$$

## Countries' incentives – Armington Model with trade in goods

- Trade in energy and goods *à la* Armington, Linear approx. around  $t^f \approx 0$  and  $t^b \approx 0$

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

$$\begin{aligned} \frac{d\mathcal{W}_{i|i \in \mathbb{J}}}{u'(c_i^{i \in \mathbb{J}})c_i} - \frac{d\mathcal{W}_{i|i \notin \mathbb{J}}}{u'(c_i^{i \notin \mathbb{J}})c_i} = & -e_i dt^f - \gamma_i (T_i - T_{i0})^\delta \eta_i^y \Delta_i (dE_{i \in \mathbb{J}} - dE_{i \notin \mathbb{J}}) \\ & - e_i \frac{q^f \nu}{E_{\mathbb{J}}} (dE_{i \in \mathbb{J}} - dE_{i \notin \mathbb{J}}) + \eta_i^f \frac{(1+\nu)}{E} (dE_{i \in \mathbb{J}} - dE_{i \notin \mathbb{J}}) \\ & + \eta_i^y \left( \frac{dp_i}{p_i} \Big|_{i \in \mathbb{J}} - \frac{dp_i}{p_i} \Big|_{i \notin \mathbb{J}} \right) - s_{i\mathbb{J}^c} dt^b - \sum_{j \in \mathbb{J}} s_{ij} \left( \frac{dp_j}{p_j} \Big|_{i \in \mathbb{J}} - \frac{dp_j}{p_j} \Big|_{i \notin \mathbb{J}} \right) \end{aligned}$$

- GE effect on energy markets, same as before
- GE effect on goods markets, equilibrium on expenditure  $v_i = p_i c_i$ , for  $\theta \approx 1$

$$\frac{dv_i}{v_i} = \sum_{k \in \mathbb{J}} \mathcal{P}_k \alpha_{ki} \left( \frac{dv_k}{v_k} - \theta \frac{dt_{ki}^b}{1+t_{ki}^b} \right) \quad \alpha_{ki} = \frac{c_{ki} \tau_{ki} p_i}{\sum_{\ell} c_{k\ell} \tau_{k\ell} p_{\ell}} \frac{v_k}{v_i} = s_{ki} \frac{v_k}{(1+t_{ki}^b) v_i}$$

- Params:  $\sigma$  energy demand elasticity,  $s^f$  energy cost share,  $\nu$  energy supply elasticity, share of output  $y$  in income  $\eta_i^y = \frac{y_i p_i}{v_i}$ , fossil rent share  $\eta_i^f = \frac{\pi_i}{v_i}$

## Countries' incentives – Armington Model with trade in goods

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

$$\begin{aligned} \frac{d\mathcal{W}_{i|i \in \mathbb{J}}}{u'(c_i^{i \in \mathbb{J}})c_i} - \frac{d\mathcal{W}_{i|i \notin \mathbb{J}}}{u'(c_i^{i \notin \mathbb{J}})c_i} = & -e_i dt^f - \gamma_i (T_i - T_{i0})^\delta \eta_i^y \Delta_i (dE_{i \in \mathbb{J}} - dE_{i \notin \mathbb{J}}) \\ & - e_i \frac{q^f \nu}{E_{\mathbb{J}}} (dE_{i \in \mathbb{J}} - dE_{i \notin \mathbb{J}}) + \eta_i^f \frac{(1+\nu)}{E} (dE_{i \in \mathbb{J}} - dE_{i \notin \mathbb{J}}) \\ & + \eta_i^y \left( \frac{dp_i}{p_i} \Big|_{i \in \mathbb{J}} - \frac{dp_i}{p_i} \Big|_{i \notin \mathbb{J}} \right) - s_{i\mathbb{J}^c} dt^b - \sum_{j \in \mathbb{J}} s_{ij} \left( \frac{dp_j}{p_j} \Big|_{i \in \mathbb{J}} - \frac{dp_j}{p_j} \Big|_{i \notin \mathbb{J}} \right) \end{aligned}$$

- GE effect on energy markets, same as before
- GE effect on goods markets, equilibrium on expenditure  $v_i = p_i c_i$ , for  $\theta \approx 1$

$$\frac{dv_i}{v_i} = \sum_{k \in \mathbb{J}} \mathcal{P}_k \alpha_{ki} \left( \frac{dv_k}{v_k} - \theta \frac{dt_{ki}^b}{1+t_{ki}^b} \right) \quad \alpha_{ki} = \frac{c_{ki} \tau_{ki} p_i}{\sum_{\ell} c_{k\ell} \tau_{k\ell} p_{\ell}} \frac{v_k}{v_i} = s_{ki} \frac{v_k}{(1+t_{ki}^b) v_i}$$

- Params:  $\sigma$  energy demand elasticity,  $s^f$  energy cost share,  $\nu$  energy supply elasticity, share of output y in income  $\eta_i^y = \frac{y_i p_i}{v_i}$ , fossil rent share  $\eta_i^f = \frac{\pi_i}{v_i}$

## 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  $\{t^f, t^b\}$

$$\begin{aligned} \Delta\mathcal{W}(\mathbb{J}, j) = & -\omega_j u'(c_j) e_j dt^f + \left[ \sum_{i \in \mathbb{I}} \omega_i u'(c_i) \Delta_i \gamma_i (T_i - T_{i0})^\delta y_i \right] \frac{\sigma e_j dt^f}{q^f (1 - s^f + \nu \sigma)} \\ & + \left[ \sum_{i \in \mathbb{I}} \omega_i u'(c_i) e_i \right] \frac{1}{1 + \frac{1-s^f}{\nu \sigma}} \frac{e_j dt^f}{E_{\mathbb{I}}} - \left[ \sum_{i \in \mathbb{I}} \omega_i u'(c_i) \pi_i \right] \frac{(1+\nu)}{E_{\mathbb{I}}} \frac{\sigma e_j dt^f}{q^f (1 - s^f + \nu \sigma)} \end{aligned}$$

- 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  $\pi^f$  decreases with  $\mathbb{J}$ , effect on demand ambiguous
  - Similar formula for the case with trade tariffs: Work in progress.

## Quantification – Firms

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

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

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

- Calibrate TFP  $z_i$  to match  $y_i = GDP_i$  per capita in 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  $y$ :

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

- Asymmetry in damage to match empirics with  $\gamma^y = \gamma^{+,y} \mathbb{1}_{\{T > T_i^*\}} + \gamma^{-,y} \mathbb{1}_{\{T < T_i^*\}}$
- Today  $\gamma_i^{\pm,y} = \bar{\gamma}^{\pm,y}$  &  $T_i^* = \bar{\alpha} T_{it0} + (1 - \bar{\alpha}) T^*$



## Quantification – Energy markets

### ► Fossil production $e_{it}^x$ and reserve $\mathcal{R}_{it}$

- Cost  $\mathcal{C}_i(e^x, \mathcal{R}) = \frac{\bar{\nu}_i}{1+\nu_i} \left(\frac{e^x}{\mathcal{R}}\right)^{1+\nu_i} \mathcal{R}$
- Now:  $\bar{\nu}_i$  to match extraction data  $e_i^x$ ,  $\mathcal{R}_{it}$  calibrated to *proven reserves* data from BP.  $\nu_i$  extraction cost curvature to match profit  $\pi_i^f = \frac{\bar{\nu}_i \nu_i}{1+\nu_i} \left(\frac{e_i^x}{\mathcal{R}_i}\right)^{\nu_i} \mathcal{R}_i \mathbb{P}_i$
- Future: Choose  $(\bar{\nu}_i, \nu_i, \mathcal{R}_i)$  to match marginal cost  $\mathcal{C}_e$  & extraction data  $e_i^x$  (BP, IEA)

## Quantification – Energy markets

- ▶ Fossil production  $e_{it}^x$  and reserve  $\mathcal{R}_{it}$ 
  - Cost  $\mathcal{C}_i(e^x, \mathcal{R}) = \frac{\bar{\nu}_i}{1+\nu_i} \left( \frac{e^x}{\mathcal{R}} \right)^{1+\nu_i} \mathcal{R}$
  - Now:  $\bar{\nu}_i$  to match extraction data  $e_i^x$ ,  $\mathcal{R}_{it}$  calibrated to *proven reserves* data from BP.  $\nu_i$  extraction cost curvature to match profit  $\pi_i^f = \frac{\bar{\nu}_i \nu_i}{1+\nu_i} \left( \frac{e_i^x}{\mathcal{R}_i} \right)^{\nu_i} \mathcal{R}_i \mathbb{P}_i$
  - Future: Choose  $(\bar{\nu}_i, \nu_i, \mathcal{R}_i)$  to match marginal cost  $\mathcal{C}_e$  & extraction data  $e_i^x$  (BP, IEA)
  
- ▶ Renewable: Production  $\bar{e}_{it}^r$  and price  $q_{it}^r$ 
  - Now:  $q_{it}^r = z^r e^{-g_r t}$ , with  $g_r$  growth rate in renewable energy price decreases.
  - Future: Choose  $z_i^r$  to match the energy mix  $(e_i^f, e_i^r)$

back

## 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  $\gamma_i$  ?
- ▶ Fossil Energy markets:
  - Divide fossils  $e_{it}^f / e_{it}^x$  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  $C_{it}^r$
- ▶ Population dynamics
  - Match UN forecast for growth rate / fertility

# Calibration

**Table:** Baseline calibration (★ = subject to future changes)

<i>Technology &amp; Energy markets</i>				
$\alpha$	0.35	Capital share in $f(\cdot)$		Capital/Output ratio
$\epsilon$	0.12	Energy share in $f(\cdot)$		Energy cost share (8.5%)
$\sigma$	0.3	Elasticity capital-labor vs. energy		Complementarity in production (c.f. Bourany 2020)
$\omega$	0.8	Fossil energy share in $e(\cdot)$		Fossil/Energy ratio
$\sigma_e$	2.0	Elasticity fossil-renewable		Slight substitutability & Study by Stern
$\delta$	0.06	Depreciation rate		Investment/Output ratio
$\bar{g}$	0.01★	Long run TFP growth		Conservative estimate for growth
$g_e$	0.01★	Long run energy directed technical change		Conservative / Acemoglu et al (2012)
$g_r$	-0.01★	Long run renewable price decrease		Conservative / Match price fall in R.E.
$\nu$	2★	Extraction elasticity of fossil energy		Cubic extraction cost
<i>Preferences &amp; Time horizon</i>				
$\rho$	0.03	HH Discount factor		Long term interest rate & usual calib. in IAMs
$\eta$	2.5	Risk aversion		
$n$	0.01★	Long run population growth		Conservative estimate for growth
$\omega_i$	1	Pareto weights		Uniforms / Utilitarian Social Planner
$T$	90	Time horizon		Horizon 2100 years since 2010

# Calibration

**Table:** Baseline calibration (★ = subject to future changes)

<i>Climate parameters</i>			
$\xi$	0.81	Emission factor	Conversion $1 \text{ MTOE} \Rightarrow 1 \text{ MT } CO_2$
$\zeta$	0.3	Inverse climate persistence / inertia	Sluggishness of temperature $\sim 11-15$ years
$\chi$	$2.1/1e6$	Climate sensitivity	Pulse experiment: $100 \text{ GtC} \equiv 0.21^\circ\text{C}$ medium-term warming
$\delta_s$	0.0014	Carbon exit from atmosphere	Pulse experiment: $100 \text{ GtC} \equiv 0.16^\circ\text{C}$ 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)
$\alpha^T$	$0.2^\star$	Weight historical climate for optimal temp.	Marginal damage decorrelated with initial temp.
$T^\star$	15.5	Optimal yearly temperature	Average spring temperature / Developed economies
<i>Parameters calibrated to match data</i>			
$p_i$		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  $\{\mathbf{x}\} = \{w_{it}, T_{it}, \mathcal{R}_{it}, \mathcal{S}_t\}_{it}$
- Backward ODE for the costates  $\{\boldsymbol{\lambda}\} = \{\lambda_{it}^w, \lambda_{it}^T, \lambda_t^S, \lambda_{it}^{\mathcal{R}}\}_{it}$
- Non-linear equations (FOCs) for household controls  $\{\mathbf{c}_1\} = \{c_{it}, b_{it}, k_{it}\}_{it}$  and static demands for energy/capital  $\{\mathbf{c}_2\} = \{e_{it}^f, e_{it}^r, k_{it}\}_{it}$  and static supplies  $\{\mathbf{c}_3\} = \{e_{it}^x, \bar{e}_{it}^r\}_{it}$ .
- Market clearing as equation for prices  $\{\mathbf{q}\} = \{q_t^f, r_t^*\}_t$
- Existence and Uniqueness, c.f. Mean Field Game theory (Carmona-Delarue)

## Sequential solution method

### ► Summary of the model:

- ODEs for states  $\{\mathbf{x}\} = \{w_{it}, T_{it}, \mathcal{R}_{it}, \mathcal{S}_t\}_{it}$
- Backward ODE for the costates  $\{\boldsymbol{\lambda}\} = \{\lambda_{it}^w, \lambda_{it}^T, \lambda_t^S, \lambda_{it}^{\mathcal{R}}\}_{it}$
- Non-linear equations (FOCs) for household controls  $\{\mathbf{c}_1\} = \{c_{it}, b_{it}, k_{it}\}_{it}$  and static demands for energy/capital  $\{\mathbf{c}_2\} = \{e_{it}^f, e_{it}^r, k_{it}\}_{it}$  and static supplies  $\{\mathbf{c}_3\} = \{e_{it}^x, \bar{e}_{it}^r\}_{it}$ .
- Market clearing as equation for prices  $\{\mathbf{q}\} = \{q_t^f, r_t^*\}_t$
- 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  $\mathbf{y} = \{\mathbf{x}, \boldsymbol{\lambda}, \mathbf{c}, \mathbf{q}\}$  in a large non-linear function

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

- 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  $\Delta_i$ , Fossil energy cost  $\bar{\nu}_i$ , Energy mix  $\epsilon_i, \omega_i, z_i^r$ ,  
 Local damage  $\gamma_i^y, \gamma_i^u, T_i^*$ , 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  $S_t$*   
*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:
  - ⇒ 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

back