The Optimal design of Climate Agreements Inequality and incentives for carbon policy

WORK IN PROGRESS

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Capital theory

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Introduction

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Introduction – this project

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▶ Trade-off between intensive margins and extensive margin :
  – Climate club with a small number of countries with (i) a tax higher/closer to the *first-best*, (ii) large emissions reductions but (iii) potentially large carbon "leakage" effects
  – Extensive climate agreements with a large number of countries but lower optimal tax to accommodate participation constraints

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  – Extensive climate agreements with a large number of countries but lower optimal tax to accommodate participation constraints

▶ Develop an Integrated Assessment Model (IAM) with heterogeneous countries to :
  ○ Evaluate the welfare costs of global warming
  ○ Solve optimal carbon policy of climate clubs
  ○ Analyze the strategic implications of joining climate agreements
  ○ Design to optimal size of the climate club

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)
  - ⇒ *Optimal and constrained policy with heterogeneous countries*

- ▶ 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)
  - ⇒ *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*

Model – Household

▶ Deterministic Neoclassical economy, in continuous time

– countries $i \in \mathbb{I}$, heterogeneous in productivity z_i/wealth w_{it}, temperature τ_{it}, energy cost/reserves $\mathcal{R}_{it}$

• In each country, 4 agents : (i) household, (ii) homogeneous good firm, (iii) fossil and (iv) renewable energy producers.

▶ Representative household problem in each country i :

$$\mathcal{V}_{i0} = \max_{\{c_{it}, k_{it}, b_{it}\}} \int_0^\infty e^{-\rho t} \, u(c_{it}) dt$$

▶ Dynamics of wealth of country i, $w_{it} = b_{it} + k_{it}$ More details

$$\dot{w}_{it} := \dot{k}_{it} + \dot{b}_{it} = w_{it}\ell_{it} + \pi_{it}^f + r_t b_{it} + (r_t - \delta)k_{it} - c_{it} + \mathsf{t}_{it}^{ls}$$

• Labor income $w_{it}\ell_{it}$ from homogeneous good firm, profit π_{it}^f from fossil firm

Model – Representative Firm

▶ Competitive homogeneous good producer in country i

$$\max_{k_{it}, e_{it}^f, e_{it}^r} \mathcal{D}^y(\tau_{it}) z_i f(k_{it}, e_{it}^f, e_{it}^r) - w_{it}\ell_{it} - r_t k_{it} - (q_t^f + \mathfrak{t}_{it}^f)e_{it}^f - (q_t^r + \mathfrak{t}_{it}^r)e_{it}^r$$

- Energy mix with fossil e_{it}^f – emitting carbon – subject to price q_t^f and tax/subsidy $\mathfrak{t}_{it}^f$. Similarly "clean" renewable e_{it}^r, at price q_t^r and tax $\mathfrak{t}_{it}^r$.

- Climate externality : effect of temperature on damage/TFP, $\mathcal{D}_i^y(\tau) \in (0,1)$

Model – Energy markets

▶ Competitive fossil fuels energy producer :

- Extraction of fossil energy e_{it}^x depleting reserves $\mathcal{R}_{it} \Rightarrow$ Hotelling problem

$$\pi_{it}^f = \max_{e_{it}^x} q_t^f e_{it}^x - \mathcal{C}^f(e_{it}^x, \mathcal{R}_{it})$$

$$\dot{\mathcal{R}}_{it} = -e_{it}^x \qquad\qquad \mathcal{R}_{i0} = \bar{\mathcal{R}}_i$$

- Fossil energy traded in international markets :

$$\sum_{\mathbb{I}} e_{it}^f = \sum_{\mathbb{I}} e_{it}^x$$

   – Unique fossil price q_t^f clearing the market (More details)

Model – Energy markets

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- ▶ Renewable energy in each country i with exogenous price q_{it}^r

Climate system

▶ Fossil energy input e_t^f causes climate externality

$$\mathcal{E}_t = \sum_{\mathbb{I}} e_{it}^f$$

▶ Cumulative GHG in atmosphere $\mathcal{S}_t$ increases temperature

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

▶ Country's local temperature :

$$\tau_{it} = \bar{\tau}_{i0} + \Delta_i \, \mathcal{S}_t$$

• Linear model : Climate sensitivity/pattern scaling factor Δ_i, Carbon exit from atmosphere δ_s

Model – Solution

▶ Step 0 : Competitive equilibrium / Business as usual : No policy $t_{it} = 0$

▶ Step 1 : First Best, All instruments available $\{t_{it}^f, t_{it}^r, t_{it}^{ls}\}_{it}$ including transfers across countries

▶ Step 2 : Second best, Optimal (Ramsey) policy for a given climate club $\mathbb{J}$

▶ Step 3 : Countries decide whether to join the climate club : participation constraints

▶ Step 4 : Optimal design of size $\mathbb{J}$ and countries $j \in \mathbb{J}$ in the climate agreement

Model – Equilibrium

- ► Equilibrium
  - Given, initial conditions $\{w_{i0}, \tau_{i0}, \mathcal{R}_{i0}, \mathcal{S}_{i0}\}$ and country-specific policies $\{t^f_{it}, t^r_{it}, t^{ls}_{it}\}$, a **competitive equilibrium** is a continuum of sequences of states $\{\mathbf{x}\} = \{w_{it}, \tau_{it}, \mathcal{R}_{it}, \mathcal{S}_t\}_{it}$, controls $\{\mathbf{c}\} = \{c_{it}, b_{it}, k_{it}, e^f_{it}, e^r_{it}, e^x_{it}\}_{it}$ and price sequences $\{\mathbf{q}\} = \{r^\star_t, q^f_t, q^r_t\}$ such that :

  - ○ Households choose policies $\{c_{it}, b_{it}\}_{it}$ to max utility s.t. budget constraint, giving $\dot{w}_{it}$

  - ○ Firm choose policies $\{k_{it}, e^f_{it}, e^r_{it}\}_{it}$ to max profit

  - ○ Fossil and renewables firms extract/produce $\{e^x_{it}, \bar{e}^r_{it}\}_{it}$ to max static profit, yielding $\dot{\mathcal{R}}_t$

  - ○ Emissions $\mathcal{E}_t$ affects climate $\{\mathcal{S}_t\}_t$, & $\{\tau_{it}\}_{it}$.

  - ○ Prices $\{r^\star_t, q^f_t, q^r_{it}\}$ adjust to clear the markets : $\sum_{\mathbb{I}} e^x_{it} = \sum_{\mathbb{I}} e^f_{it}$ and $e^r_{it} = \bar{e}^r_{it}$, and $\sum_{\mathbb{I}} b_{it} = 0$, with bonds $b_{it} = w_{it} - k_{it}$

  - Pontryagin Max. Principle : costates $\{\psi\} = \{\lambda^w_{it}, \psi^\tau_{it}, \psi^s_{it}\} \Rightarrow$ system of coupled ODEs
    More details

Step 0 : Competitive equilibrium

▶ Key objects :

- Marginal value of wealth $\lambda_{it}^w = u'(c_{it})$

- Marginal value of carbon ψ_{it}^S for country i

- "Local social cost of carbon" (LCC) for region i :

$$LCC_{it} := -\frac{\partial \mathcal{V}_{it}/\partial \mathcal{S}_t}{\partial \mathcal{V}_{it}/\partial c_{it}} = -\frac{\psi_{it}^S}{\lambda_{it}^w}$$

– Stationary equilibrium closed-form formula, analogous to GHKT (2014) (Here)

Step 1 : First-Best, Optimal policy with transfers

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

$$\mathcal{W}_0 = \max_{\{\mathbf{t}, \boldsymbol{x}, \boldsymbol{c}, \boldsymbol{q}\}_{it}} \sum_{\mathbb{I}} \int_0^\infty e^{-\rho t} \, \omega_i \, u(c_{it}) \, dt = \sum_{\mathbb{I}} \mathcal{W}_{i0}$$

- Full set of instruments $\mathbf{t} = \{t_{it}^f, t_{it}^r, t_{it}^{ls}\}$, including transfers *across countries*

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- Full set of instruments $\mathbf{t} = \{t_{it}^f, t_{it}^r, t_{it}^{ls}\}$, including transfers *across countries*

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

$$SCC_t^{fb} := -\frac{\partial \mathcal{W}_t / \partial \mathcal{S}_t}{\partial \mathcal{W}_t / \partial c_t} = -\frac{\psi_t^S}{\lambda_t^w} = -\frac{\sum_{\mathbb{I}} \psi_{it}^S di}{\frac{1}{I} \sum_{\mathbb{I}} \lambda_{it}^w di} \qquad\qquad LCC_{it} := -\frac{\partial \mathcal{W}_{it} / \partial \mathcal{S}_t}{\partial \mathcal{W}_{it} / \partial c_{it}} = -\frac{\psi_{it}^S}{\lambda_{it}^w}$$

Step 1 : First-Best, Optimal policy with transfers

▶ *Proposition 1 :* Optimal carbon tax :

$$t_t^S = SCC_t^{fb}$$

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

$$SCC_t^{fb} = -\frac{\psi_t^S}{\lambda_t^w} = -\sum_{\mathbb{I}} \frac{\psi_{it}^S}{\lambda_{it}^w} = \sum_{\mathbb{I}} LCC_{it}$$

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

$$\omega_i u'(c_{it}) = \lambda_{it}^w = \lambda_t^w = \lambda_{jt}^w = \omega_j u'(c_{jt}) \ \ \forall i,j \in \mathbb{I}$$

• Imply cross-countries lump-sum transfers $\exists \ i \ s.t. \ T_i \geq 0$ or $\exists j \ s.t. \ T_j \leq 0$

• There exist Pareto weights $\{\omega_i\}$ shutting down redistribution $T_i = 0$, e.g. $\omega_i = 1/u'(c_{it})$

Design of a Climate Agreement
└─ Optimal Policy
  └─ Ramsey policy without transfers

Step 2 : Ramsey policy with limited transfers

▶ Second best without access to lump-sum transfers : choice of a carbon tax $\{t_t^f, t_t^r\}$

- Tax receipts redistributed lump-sum : $t_{it}^{ls} = t_t^f e_{it}^f + t_t^r e_{it}^r$

- Inequality across regions :

$$\widehat{\lambda}_{it}^w = \frac{\lambda_{it}^w}{\lambda_t^w} = \frac{\omega_i u'(c_{it})}{\frac{1}{I}\sum_{\mathbb{I}}\omega_j u'(c_{jt})} \lesseqgtr 1$$

  $\Rightarrow$ ceteris paribus, poorer countries have higher $\widehat{\lambda}_{it}^w$

- Social Cost of Carbon integrates these inequalities :

$$SCC_t^{sb} = \sum_{\mathbb{I}} \widehat{\lambda}_{it}^w LCC_{it}$$

$$SCC_t^{sb} = \sum_{\mathbb{I}} LCC_{it} + \mathbb{C}\text{ov}_i(\widehat{\lambda}_{it}^w, LCC_{it})$$

Design of a Climate Agreement
└─Optimal Policy
  └─Ramsey policy without transfers

Step 2 : Ramsey Problem – Optimal Carbon & Energy Policy

▶ Taxing fossil energy has additional redistributive effects :

- Lower eq. fossil fuels price benefit importers and hurt exporters
- New measure : Social Cost of Fossil (SCF)

$$SCF_t^{sb} := \frac{\partial \mathcal{W}_t / \partial E_t^f}{\partial \mathcal{W}_t / \partial c_t} = \mathcal{C}_{EE}^f \, \mathbb{C}\text{ov}_i\left(\widehat{\lambda}_{it}^w, e_{it}^f - e_{it}^x\right) \qquad \mathcal{C}_{EE}^f = \left(\sum_{i\in\mathbb{I}} (\mathcal{C}_{i,e^x e^x}^f)^{-1}\right)^{-1}$$

– with $\mathcal{C}_{EE}^f$ and $\mathcal{C}_{i,e^x e^x}^f \propto$ fossil energy supply elasticity

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▶ *Proposition 2 :* Optimal fossil energy tax :

$$\Rightarrow \quad t_t^f = SCC_t^{sb} + SCF_t^{sb}$$

  – Social cost of carbon : $SCC_t^{sb} = \sum_{\mathbb{I}} \widehat{\lambda}_{it}^w \, LCC_{it}$

▶ Tax on renewable energy e_t^r, no externality + constant return to scale : $t_{it}^r = 0$

Step 3 : Ramsey Problem with participation constraints

► Assume countries can exit climate agreements + lump-sum transfers prohibited

  • Participation constraint, with $\bar{c}_i$ autarky consumption (no trade in energy/assets)

$$u(c_{it}) \geq u(\bar{c}_{it}) \qquad [\nu_{it}]$$

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▶ *Proposition 3 :* Second-Best without transfers & participation constraints

- Participation incentive change our measure of inequality

$$\widetilde{\lambda}_{it}^w = \frac{\omega_i u'(c_{it}) + \nu_{it} u'(c_{it})}{\frac{1}{I} \sum_{\mathbb{I}} (\omega_j + \nu_{jt}) u'(c_{jt})} \neq \widehat{\lambda}_{it}^w$$

- Optimal fossil energy tax :

$$\Rightarrow \quad \mathfrak{t}_t^f = SCC_t^{pc} + SCF_t^{pc}$$

$$= \sum_{i \in \mathbb{I}} \widetilde{\lambda}_{it}^w \, LCC_{it} + \mathcal{C}_{EE}^f \sum_{i \in \mathbb{I}} \widetilde{\lambda}_{it}^w (e_{it}^f - e_{it}^x)$$

Design of a Climate Agreement
└─ Optimal Policy
  └─ Climate agreement design

Step 4 : the Design of a Climate agreement

▶ Climate Agreement planner maximizes :

$$\mathcal{W}_0(\mathbb{J}) = \max_{\{\mathbf{t},...\}_{it}} \frac{1}{\mathbb{J}} \sum_{\mathbb{J}} \int_0^\infty e^{-\rho t} \, \omega_i \, u(c_{it}) \, dt$$

$$s.t. \qquad u(c_{it}) \geq u(\bar{c}_i) \qquad \forall t, i \in \mathbb{J}$$

▶ Choice of countries $\mathbb{J} \subset \mathbb{I}$ to maximize welfare
  • Other countries $\mathbb{I} \backslash \mathbb{J}$ in autarky : own bond $\tilde{r}$/energy $\tilde{q}^f$ market
  • Alternative : Optimal trade tax/tariffs ⇒ *work in progress*

▶ Adding country j to $\mathbb{J}$
  • Changes the optimal tax :

$$\mathbf{t}_t^f(\mathbb{J}) = SCC_t^{ca}(\mathbb{J}) + SCF_t^{ca}(\mathbb{J}) = \sum_{i \in \mathbb{J}} \widetilde{\lambda}_{it}^w \, LCC_{it} + \mathcal{C}_{EE}^f \sum_{i \in \mathbb{J}} \widetilde{\lambda}_{it}^w (e_{it}^f - e_{it}^x)$$

  • Change the equilibrium on energy markets :

$$\text{price } q_t^f \qquad s.t. \qquad \sum_{j \in \mathbb{J}} e_{it}^f = \sum_{j \in \mathbb{J}} e_{it}^f$$

Design of a Climate Agreement
└─ Optimal Policy
  └─ Climate agreement design

Step 4 : the Design of a Climate agreement

▶ Tradeoff extensive/intensive margin

▶ Reduction in emissions $\mathcal{E} = \sum_{i \in \mathbb{I}} e_i^f$ depends both on :
  • The level of tax t^f, since high $t^f \Leftrightarrow$ large change in emissions $\Delta\mathcal{E}(\mathbb{J})$
  • The *number* of countries $\mathbb{J}$ in a stable coalition

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▶ Naive approach :
  - Combinatorial problem : $\mathcal{P}(\mathbb{I})$ with $2^{|\mathbb{I}|}$ choices

$$\max_{\mathbb{J} \in \mathcal{P}(\mathbb{I})} \mathcal{W}_0(\mathbb{J})$$

  - Search for complementarity

$$\Delta W(\mathbb{J}', j) := W(\mathbb{J}' \cup j) - W(\mathbb{J}') > \Delta W(\mathbb{J}, j) \qquad \text{when } \mathbb{J}' \supset \mathbb{J} \qquad \text{for all } j \in \mathbb{I}$$

  - Choice of countries $\mathbb{J}$ yields optimal tax $t^f(\mathbb{J})$

Design of a Climate Agreement
└─ Optimal Policy
  └─ Climate agreement design

Step 4 : the Design of a Climate agreement

▶ Tradeoff extensive/intensive margin

▶ Alternative approach :

- From the level of the tax $t^f(\mathbb{J})$ imposed on club $\mathbb{J}$, we can deduce the number of countries $\widetilde{\mathbb{J}}$ with binding participation constraints

$$\widetilde{\mathbb{J}} \quad s.t. \quad u(c_i) \geq u(\bar{c}_i) \quad \forall i \in \widetilde{\mathbb{J}}$$

- Find a fixed point of function $\widetilde{\mathbb{J}} = f(\mathbb{J}, t^f)$
- Sequential approach :
  - Start from $\mathbb{J} = \mathbb{I}$
  - Search for t^f that yield $\mathbb{J} = f(\mathbb{J}, t^f)$
  - If $Im(f(\mathbb{J}, t^f) \subsetneq \mathbb{J}$ remove countries one-by-one.
  - Repeat (2-3) until convergence or unraveling

Quantification and numerical method

▶ Quantification More details

- Production $\bar{y} = zf(k, e^f, e^r)$ with Nested CES capital/energy $\sigma_y < 0$ and fossil/renewable $\sigma_e > 1$. Calibrate parameters to match GDP / energy shares data.

- Quadratic damage as in Nordhaus DICE $y = \mathcal{D}_i(\tau)\bar{y}$ with $\mathcal{D}_i(\tau) = e^{-\gamma(\tau - \tau_i)^2}$

- Energy parameters to match production/reserves

▶ Numerical method More details

- Sequential approach : rely on Pontryagin Maximum Principle
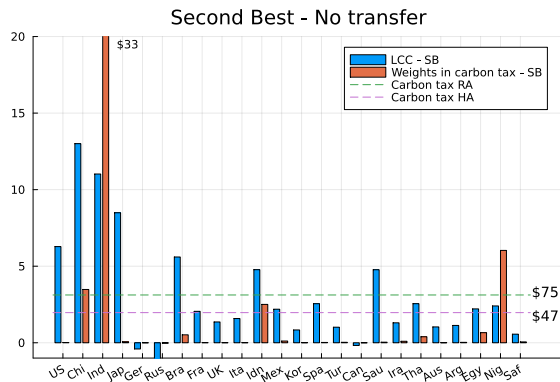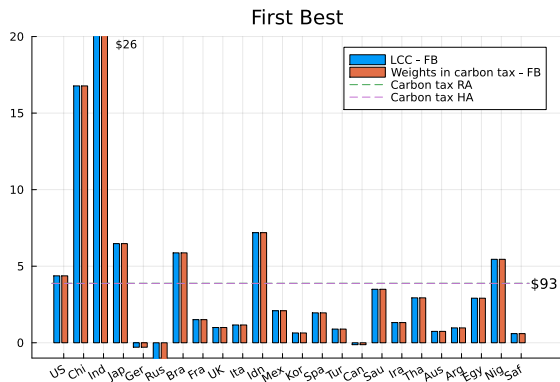- Can simulate models with arbitrary numbers of dimensions of heterogeneity

Numerical Application – Competitive equilibrium

▶ Data : 24 countries, (G20+4 large countries)

Damage from climate change
Competitive Equilibrium
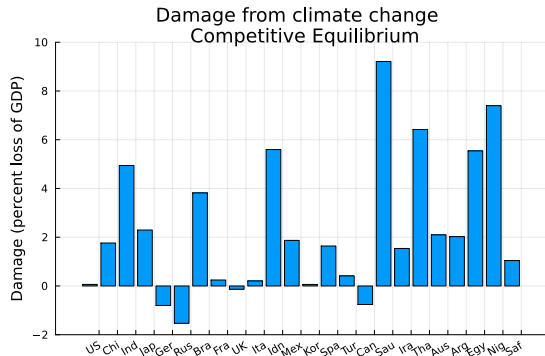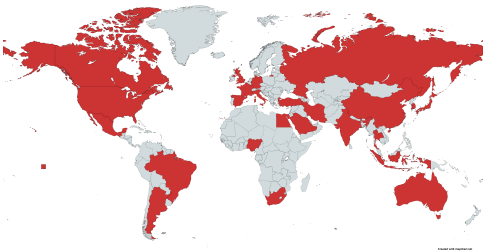
Local Cost of Carbon & Carbon Tax – First and Second Best

▶ Difference $LCC_i = \frac{\psi_i^{\mathcal{S}}}{\lambda_i^w}$ vs. $\widehat{\lambda}_i^w LCC_i = \frac{\psi_i^{\mathcal{S}}}{\lambda^w}$ since $SCC = \sum_{\mathbb{I}} \widehat{\lambda}_i^w LCC_i$
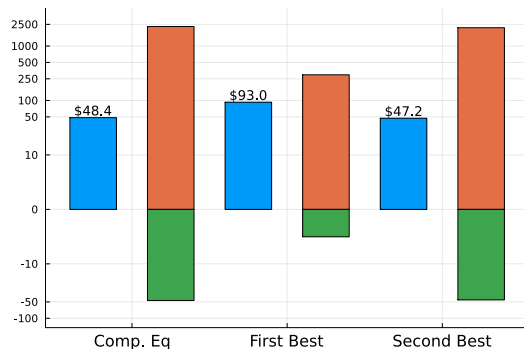
Comparison - Value of wealth vs. Social Cost of Carbon

▶ Social Cost of Carbon can be decomposed :

$$SCC_t := -\frac{\partial \mathcal{W}_t / \partial \mathcal{S}_t}{\partial \mathcal{W}_t / \partial c_t} = -\frac{\psi_t^S}{\lambda_t^w} = -\frac{\sum_{\mathbb{I}} \psi_{it}^S di}{\frac{1}{I} \sum_{\mathbb{I}} \lambda_{it}^w di}$$

▶ Here plot that decomposition :

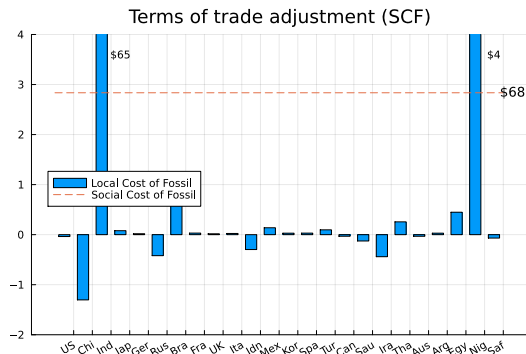$$\log(SCC_t) = \log(-\psi_t^S) - \log(\lambda_t^w)$$

Local Cost of Fossil and Terms of Trade Adjustment

▶ Social Cost of Fossil Energy :

$$SCF_t = \mathcal{C}_{EE}^f \sum_{\mathbb{I}} \widehat{\lambda}_{it}^w \big(e_{it}^f - e_{it}^x \big) \qquad \mathcal{C}_{EE}^{f\,-1} = \sum_{\mathbb{I}} \big(\mathcal{C}_{i,e^x e^x}^f \big)$$

▶ Here plotting local cost of fossil :

$$LCF_{it} = \widehat{\lambda}_{it}^w \big(e_{it}^f - e_{it}^x \big)$$

Terms of trade adjustment (SCF)

Climate club design and unraveling
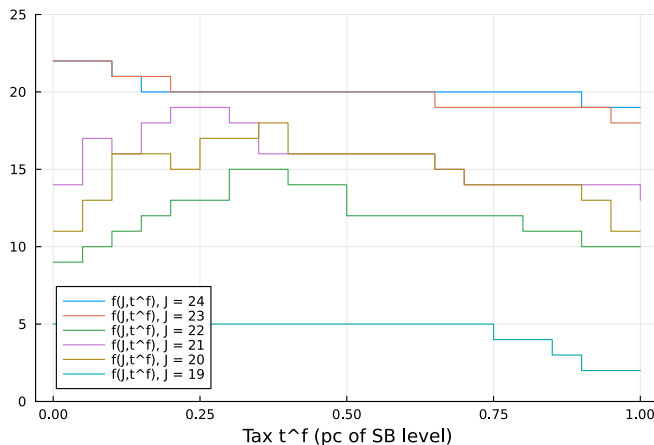
▶ Plot of fct $f(\mathbb{J}, t^f) = \widetilde{\mathbb{J}}$: for a club of size $\mathbb{J}$ and tax t^f, $\widetilde{\mathbb{J}}$ countries willing to participate

▶ Removing China $(23 \rightarrow 22)$ and the US $(20 \rightarrow 19)$ causes unraveling

Climate club design and unraveling

▶ Unraveling caused by lack of complementarity in this economy

▶ Trade in good (c.f. Nordhaus 2014)
  • Possibility to include tradable at a single price p and non-tradable only consumed domestically
  • Optimal tariff/trade tax – e.g. increasing in the number of countries outside the club – can change incentives and induce complementarity

▶ Long-run effects of climate
  • Benefit of increasing the size of the club for curbing emissions and future damages

▶ Dynamics in energy markets
  • Scarcity / fossil price increasing vs. Renewable getting cheaper change energy dependence

▶ Accounting for dynamic participation constraints
  • If countries can join/exit later, may reinforce/dampen the benefits of joining today

Conclusion

▶ Climate change has redistributive effects & heterogeneous impacts
▶ Optimal carbon policy takes into account inequality and redistribution

- Depends on the availability of transfer mechanisms
- Pigouvian tax & Social Cost of Carbon change with inequality and terms-of-trade effects

▶ Climate agreement design accounts jointly for

- The optimal choice of countries participating
- The level of tax, chosen for correcting externality & respecting participation constraints

Appendices

More details – Capital market

▶ In each countries, the agent can save in two assets, capital k_{it} and bonds b_{it} :

$$\begin{cases} \dot{k}_{it} & = \mathcal{D}_i^y(\tau_{it})z_i f(k_{it}, e_{it}) - (\delta + n + \bar{g})k_{it} + \iota_{it} \\ \dot{b}_{it} & = r^\star b_{it} + \theta_i \pi_t^f + \pi_{it}^r - (q_t^f + t_{it}^f)e_{it}^f - (q_t^r + t_{it}^r)e_{it}^r - \iota_{it} - c_{it} + t_{it}^{ls} \\ b_{it} & \geq -\vartheta k_{it} \end{cases}$$

▶ Combining, substituting ι_{it} and defining wealth $w_{it} = k_{it} + b_{it}$, we obtain the main equation

$$\dot{w}_{it} = r^\star w_{it} + \mathcal{D}^y(\tau_{it})z_{it}f(k_{it}, e_{it}) - (\bar{\delta} + r_t^\star)k_{it} + \theta_i \pi_t^f + \pi_{it}^r - (q_t^f + t_{it}^f)e_{it}^f - (q_t^r + t_{it}^r)e_{it}^r - c_{it} + t_{it}^{ls}$$

$$k_{it} \leq \frac{1}{1 - \vartheta}w_{it}$$

▶ Two polar cases :
  • $\vartheta \to 0$, full autarky (no trade), and $w_{it} = k_{it}$
  • $\vartheta \to 1$, full financial integration :

$$k_{it} \qquad s.t. \qquad MPk_{it} - \bar{\delta} = \mathcal{D}_i^y(\tau_{it})z_i \partial_k f(k_{it}, e_{it}) - (\delta + n + \bar{g}) = r_t^\star$$

back

Impact of increase in temperature

▶ Marginal values of the climate variables : λ_{it}^s and λ_{it}^τ

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

$$\dot{\lambda}_{it}^S = \lambda_{it}^S(\rho + \delta^s) - \zeta\,\chi\,\Delta_i\,\lambda_{it}^\tau$$

▶ Costate λ_{it}^S : marg. cost of $1Mt$ carbon in atmosphere, for country i. Increases with :
  - Temperature gaps $\tau_{it} - \tau_i^\star$ & damage sensitivity of TFP γ_i^y and utility γ_i^u
  - 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

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

$$\dot{\lambda}_t^S = \lambda_t^S(\widetilde{\rho} + \delta^s) - \int_\mathbb{I}\Delta_i\zeta\chi\lambda_{it}^\tau$$

▶ Solving for λ_t^τ and $\lambda_t^\mathcal{S}$, in stationary equilibrium $\dot{\lambda}_t^S = \dot{\lambda}_t^\tau = 0$

$$\lambda_{it}^\tau = -\int_t^\infty e^{-(\widetilde{\rho}+\zeta)u}(\tau_u - \tau^\star)\Big(\gamma\mathcal{D}^y(\tau_u)y_\tau\lambda_u^k + \phi\mathcal{D}^u(\tau_u)u(c_u)\Big)du$$

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

$$\lambda_t^S = -\int_t^\infty e^{-(\widetilde{\rho}+\delta^s)u}\zeta\chi\int_\mathbb{I}\Delta_j\lambda_{j,u}^\tau dj\,du$$

$$= \frac{1}{\widetilde{\rho}+\delta^s}\zeta\chi\int_\mathbb{I}\Delta_j\lambda_{j,\infty}^\tau$$

$$= -\frac{\chi}{\widetilde{\rho}+\delta^s}\frac{\zeta}{\widetilde{\rho}+\zeta}\int_\mathbb{I}\Delta_j(\tau_{j,\infty}-\tau^\star)\Big(\gamma\mathcal{D}^y(\tau_{j,\infty})y_\infty\lambda_{j,\infty}^k + \phi\mathcal{D}^u(\tau_{j,\infty})u(c_{j,\infty})\Big)dj$$

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

Cost of carbon / Marginal value of temperature

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

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

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

Social cost of carbon & temperature

► Cost of carbon depends only on final temperatures and path of emissions :

$$\tau_T - \tau_{t_0} = \Delta\,\chi\,\xi\,\omega \int_{t_0}^{T} e^{(n+\bar{g})t-\delta_s(T-t)} q_t^{f\,-\sigma_e} \int_{j\in\mathbb{I}} \left(z_j z_{j,t}^e \mathcal{D}(\tau_{j,t})\right)^{\sigma-1} y_{j,t}\, q_{j,t}^{\sigma_e-\sigma} dj\, dt$$

- Geographical factors determining warming Δ_i
- Climate sensitivity χ & carbon exit from atmosphere δ_s
- Growth of population n, aggregate productivity $\bar{g}$
- Deviation of output from trend y_i & relative TFP z_j
- Directed technical change z_t^e, elasticity of energy in output σ
- Fossil energy price $q^{e,f}$ and Hotelling rent $g^{q^f} \approx \dot{\lambda}_t^R/\lambda_t^R = \rho$
- Change in energy mix, renewable share ω, price q_t^r & elasticity of source σ_e

► Approximations at $T \equiv$ Generalized Kaya (or $I = PAT$) identity (More details)

$$\frac{\dot{\tau}_T}{\tau_T} \propto\ n\,+\,\bar{g}^y\,-\,(1-\sigma)\big(g^{z^e}-\tilde{\gamma}\big)\,+\,(\sigma_e-\sigma)(1-\omega)g^{q^r}\,-\,(\sigma_e(1-\omega)+\sigma\omega)g^{q^f}$$

(Back)

Equilibrium – Mean Field Games

▶ Uniqueness : Lasry-Lions monotonicity on the function :

$$\int_{\mathbb{I}} [f(t, x, \mu', \alpha) - f(t, x, \mu, \alpha)] d(\mu' - \mu)(x) \geq 0 \qquad \mu, \mu' \in \mathcal{P}(\mathbb{X})$$

- Work in progress : checking such conditions along the transition

$$\sum_{i \in \mathbb{I}} \left(u(c^{\star}(w, \tau, p')) - u(c^{\star}(w, \tau, p)) \right) [p'(w, \tau) - p'(w, \tau)] \geq 0$$

  with $p'(w, \tau)$ empirical distribution $p'(w, \tau) = \frac{1}{\mathbb{I}} \sum_{i \in \mathbb{I}} \delta_{\{x_i = (w, \tau)\}} \equiv$ population distribution !

▶ Mean Field approximation & Carmona Delarue (2013)
  - Mean-Field is an ε-equilibrium of the N-player game when $N \to \infty$
  - Require symmetry and invariance under permutation
  - Back

Sequential solution method

► Summary of the model :

- ODEs for states $\{x\} = \{w_{it}, \tau_{it}, \mathcal{R}_{it}, \mathcal{S}_t\}_{it}$
- Backward ODE for the costates $\{\lambda\} = \{\lambda_{it}^w, \lambda_{it}^\tau, \lambda_{it}^s\}_{it}$
- Non-linear equations (FOCs) for household controls $\{c_1\} = \{c_{it}, b_{it}, k_{it}\}_{it}$ and static demands for energy/capital $\{c_2\} = \{e_{it}^f, e_{it}^r, k_{it}\}_{it}$ and static supplies $\{c_3\} = \{e_{it}^x, \bar{e}_{it}^r\}_{it}$.
- Market clearing as equation for prices $\{q\} = \{q_t^f, r_t^\star\}_t$
- Existence and Uniqueness More details

Sequential solution method

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   - Market clearing as equation for prices $\{\boldsymbol{q}\} = \{q_t^f, r_t^\star\}_t$
   - Existence and Uniqueness More details

▶ Global Numerical solution :
   - Discretize agents (countries) space $i \in \mathbb{I}$ with M and time-space $t \in [t_0, t_T]$ with T periods
   - Express as a large vector $\boldsymbol{y} = \{\boldsymbol{x}, \boldsymbol{\lambda}, \boldsymbol{c}, \boldsymbol{q}\}$ in a large non-linear function

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

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

Sequential method : Pros and Cons

▶ Why use a sequential approach ?

  • *Global approach* : *Only* need to follow the trajectories for *i* agents :

  – Arbitrary (!) number of dimension of *ex-ante* heterogeneity :
  Productivity z_i Population p_i, Temperature scaling Δ_i, Fossil energy cost $\bar{\nu}_i$, Energy mix $\epsilon_i, \omega_i, z_i^r$, Local damage $\gamma_i^y, \gamma_i^u, \tau_i^\star$, Directed Technical Change z_i^e

  – Potentially large dimensions of *ex-post* heterogeneity and aggregate state variables :
  For now : Wealth w_{it}, temperature τ_{it}, reserves $\mathcal{R}_{it}$, Carbon $\mathcal{S}_t$
  Extension with a large climate system as a proof of concept (e.g. Cai, Lontzek, Judd, 2013)

  – Newton method & Non-linear solvers very efficient

▶ Why not :

  • Numerical constraint to solve a large system of ODEs and non-linear equations :

  ⇒ 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

Quantification – Firms

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

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

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

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

▶ Damage functions in production function y :

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

- Asymmetry in damage to match empirics with $\gamma^y = \gamma^{+, y} \mathbb{1}_{\{\tau > \tau_i^\star\}} + \gamma^{-, y} \mathbb{1}_{\{\tau < \tau_i^\star\}}$
- Today $\gamma_i^{\pm, y} = \bar{\gamma}^{\pm, y}$ & $\tau_i^\star = \bar{\alpha} \tau_{it_0} + (1 - \bar{\alpha}) \tau^\star$

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. $\nu_i = \nu = 1$ quadratic extraction cost.

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

Quantification – Energy markets

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- 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. $\nu_i = \nu = 1$ quadratic extraction cost.

- 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 $\tau \sim \mathcal{T}_i(\bar{T}, \sigma^T)$ following Rudik et al. (2022)
  • Use Climate Lab's (Greenstone et al) estimates for damage γ_i ?
▶ Fossil Energy markets :
  • Divide fossils e_{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 ($\star$ = subject to future changes)

Technology & Energy markets

α	0.35	Capital share in $f(\cdot)$	Capital/Output ratio
ϵ	0.12	Energy share in $f(\cdot)$	Energy cost share (8.5%)
σ	0.3	Elasticity capital-labor vs. energy	Complementarity in production (c.f. Bourany 2020)
ω	0.8	Fossil energy share in $e(\cdot)$	Fossil/Energy ratio
σ_e	2.0	Elasticity fossil-renewable	Slight substitutability & Study by Stern
δ	0.06	Depreciation rate	Investment/Output ratio
$\bar{g}$	$0.01^\star$	Long run TFP growth	Conservative estimate for growth
g_e	$0.01^\star$	Long run energy directed technical change	Conservative / Acemoglu et al (2012)
g_r	$-0.01^\star$	Long run renewable price decrease	Conservative / Match price fall in R.E.
ν	$2^\star$	Extraction elasticity of fossil energy	Cubic extraction cost

Preferences & Time horizon

ρ	0.03	HH Discount factor	Long term interest rate & usual calib. in IAMs
η	2.5	Risk aversion	
n	$0.01^\star$	Long run population growth	Conservative estimate for growth
ω_i	1	Pareto weights	Uniforms / Utilitarian Social Planner
T	90	Time horizon	Horizon 2100 years since 2010

Calibration

TABLE – Baseline calibration ($\star$ = subject to future changes)

Climate parameters			
ξ	0.81	Emission factor	Conversion 1 $MTOE \Rightarrow$ 1 $MT\ CO_2$
ζ	0.3	Inverse climate persistence / inertia	Sluggishness of temperature $\sim 11-15$ years
χ	2.1/1e6	Climate sensitivity	Pulse experiment : 100 $GtC \equiv 0.21°C$ medium-term warming
δ_s	0.0014	Carbon exit from atmosphere	Pulse experiment : 100 $GtC \equiv 0.16°C$ long-term warming
$\gamma^{\oplus}$	$0.00234^{\star}$	Damage sensitivity	Nordhaus' DICE
$\gamma^{\ominus}$	$0.2 \times \gamma^{\oplus}$ *	Damage sensitivity	Nordhaus' DICE & Rudik et al (2022)
α^{τ}	$0.2^{\star}$	Weight historical climate for optimal temp.	Marginal damage decorrelated with initial temp.
$\tau^{\star}$	15.5	Optimal yearly temperature	Average spring temperature / Developed economies
Parameters calibrated to match data			
p_i		Population	Data – World Bank 2011
z_i		TFP	To match GDP Data – World Bank 2011
τ_i		Local Temperature	To match temperature of largest city
$\mathcal{R}_i$		Local Fossil reserves	To match data from BP Energy review

Step 4 : the Design of a Climate agreement

▶ Welfare effect : 1st order :

$$\delta(\mathbb{J},j) = \mathcal{W}_{t_0}(\mathbb{J} \cup \{j\}) - \mathcal{W}_{t_0}(\mathbb{J}) = \omega_j u(c_{jt}) + \sum_{i \in \mathbb{J}} \Delta \mathcal{W}_i$$

$$\Delta \mathcal{W}_i \approx d\mathcal{W}_i = \lambda_i^w (1-\theta_i) \Big(\underbrace{\epsilon_i^e + (1-\epsilon_i^e)\alpha\sigma_i^{k/e}}_{\text{production } f(k,e)} \Big) \Big(\underbrace{-\omega_i^f \sigma_i^f + (1-\omega_i^f)\sigma_i^{r/f}}_{\text{energy use } \varepsilon(e^f,e^r)} \Big) \Big(\underbrace{\frac{\mathfrak{t}^f}{q^f+\mathfrak{t}^f}\frac{d\mathfrak{t}^f}{\mathfrak{t}^f}}_{\text{tax change}} + \underbrace{\frac{q^f}{q^f+\mathfrak{t}^f}\frac{dq^f}{q^f}}_{\text{GE effect}} \Big)$$

$$+ \lambda_i^w \underbrace{\theta_i(1+\tfrac{1}{\nu_i})}_{\text{fossil rent/supply}} \underbrace{\frac{q^f}{q^f+\mathfrak{t}^f}\frac{dq^f}{q^f}}_{\text{GE effect}} + \underbrace{\psi_i^S}_{\substack{\tau_i \text{ damage climate} \\ \text{sens}^{ty}}} \Big[\underbrace{\chi \sum_{j \in \mathbb{I}} \varepsilon_i \sigma_j^f}_{} \Big] \Big(\underbrace{\frac{\mathfrak{t}^f}{q^f+\mathfrak{t}^f}\frac{d\mathfrak{t}^f}{\mathfrak{t}^f}}_{\text{tax change}} + \underbrace{\frac{q^f}{q^f+\mathfrak{t}^f}\frac{dq^f}{q^f}}_{\text{GE effect}} \Big)$$

- Direct effect on energy use on production and substitutability with renewable
  cost-share ϵ_e, fossil-share ω_i, elasticity σ_j^f & capital-energy cross elast^{ty}. $\sigma_{k,e}$, fossil-renewable cross elast^{ty}. $\sigma_i^{r/f}$
- Indirect effect through energy market fossil rent θ_i, supply elasticity ν_i
- Indirect climate effect of a reduction in world emissions