

# The Inequality of Climate Change

WORK IN PROGRESS

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*EPIC lunch*

May 2023

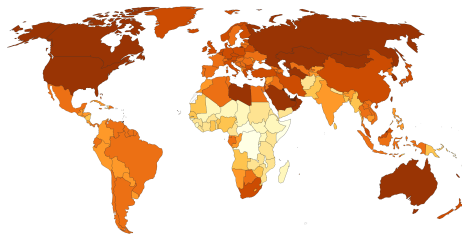
## Introduction – Motivation

Global warming is caused by greenhouse gas emissions (GHG) generated by human economic activity :

- ***Unequal causes*** : Developed economies account for over 65% of cumulative GHG emissions ( $\sim 25\%$  each for the EU and the US)
- ***Unequal consequences*** : Increase in temperatures disproportionately affects developing countries where the climate is already warm

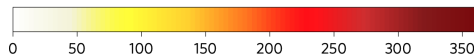
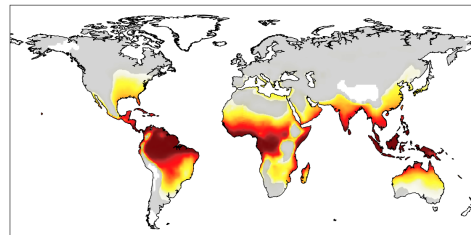
Per capita CO<sub>2</sub> emissions, 2021

Carbon dioxide (CO<sub>2</sub>) emissions from fossil fuels and industry<sup>1</sup>. Land use change is not included.



Thomas Bourany (UChicago)

RCP 8.5



Number of days per year above deadly threshold

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## Introduction – this project

- ▶ Marginal damages of climate & temperature varies across countries
- ▶ What is the optimal taxation of energy in the presence of climate externality *and* inequality?
  - In a context, where fossil fuels taxation and climate policy redistributes across countries

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- ▶ Marginal damages of climate & temperature varies across countries
- ▶ What is the optimal taxation of energy in the presence of climate externality *and* inequality?
  - In a context, where fossil fuels taxation and climate policy redistributes across countries
- ▶ Develop a simple and flexible model of climate economics
  - Standard IAM model with heterogeneous regions
  - Normative implications : Ramsey policy + possibility to study uncertainty

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- ▶ Marginal damages of climate & temperature varies across countries
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- ▶ Develop a simple and flexible model of climate economics
  - Standard IAM model with heterogeneous regions
  - Normative implications : Ramsey policy + possibility to study uncertainty
- Evaluate the heterogeneous welfare costs of global warming
- Provide analytical formulas and a numerical methodology to compute the cost of carbon
  - Heterogeneity increases the welfare cost of carbon
- Solve world optimal carbon policy with heterogeneous regions
  - Does the optimal carbon tax coincide with the social cost of carbon ?
  - ⇒ Maybe not, depending on transfer policy : need to adjust for inequality level
  - What are the welfare gains of suboptimal policies ?

## Toy model

- ▶ Consider two countries  $i = N, S$ , (North/South)
  - HH consuming good  $c_i$  and producing with energy  $e_i$  and productivity  $z_i$
  - Energy producer with profit  $\pi(E)$  owned by country  $i$  with share  $\theta_i$
- ▶ Household problem :

$$\mathcal{V}_i = \max_{c_i, e_i} U(c_i)$$

$$c_i + q^e e_i = \mathcal{D}_i(\mathcal{S}) z_i F(e_i) + \theta_i \pi(E) \quad [\lambda_i^k]$$

- ▶ Subject to damage  $\mathcal{D}_i(\mathcal{S})$  and climate externalities :

$$\mathcal{S} = \mathcal{S}_0 + \overbrace{\xi_N e_N + \xi_S e_S}^{\text{=GHG emissions}}$$

- ▶ And consuming energy in a single energy market with price  $q^e$

$$E = e_N + e_S \qquad q^e = c'(E) \qquad \pi(E) = q^e E - c(E)$$

## Toy model – Competitive equilibrium

► Three dimensions of heterogeneity :

1. Different levels of productivity  $z_i : z_N > z_S$
  2. Different climate damage  $\gamma_i = -\frac{\mathcal{D}'_i(S)}{S\mathcal{D}_i(S)}$ ,  $\gamma_S > \gamma_N$
  3. Different energy rent  $\theta_i : \theta_N > \theta_S$
- ⇒ Yields heterogeneity in consumption  $c_N > c_S$

► Competitive equilibrium Result :

- Marginal Product of Energy = Energy Cost

$$MPe_i = q^e = c'(E) \quad \text{with} \quad MPe_i := \mathcal{D}_i(\mathcal{S})z_iF'(\mathbf{e}_i)$$

- Inequality

$$\lambda_i^k = U'(c_i) \quad c_i = \mathcal{D}_i(\mathcal{S})z_iF(\mathbf{e}_i) + \theta_i\pi(E) - q^e e_i$$

## Toy model – First Best and Decentralization

- Comparison with Social planner with full transfers (First Best)

$$\begin{aligned}\mathbb{W} &= \max_{\{c_i, e_i\}_i} \sum_{i=N,S} \omega_i U(c_i) \\ \sum_{i=N,S} c_i + c(E) &= \sum_{i=N,S} \mathcal{D}_i(\mathcal{S}) z_i F(e_i) \quad [\lambda] \\ \mathcal{S} &:= \mathcal{S}_0 + \xi_N e_N + \xi_S e_S \quad E := e_N + e_S\end{aligned}$$



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- Marginal Product of Energy = Energy Cost + Social Cost of Carbon

$$MPe_i = c'(E) + \xi_i \underbrace{\overline{SCC}}_{=\mathbf{t}^e} \quad \text{with} \quad \overline{SCC} := - \sum_{i=N,S} \mathcal{D}'_i(\mathcal{S}) z_i F(e_i)$$

- Redistribution

$$\omega_S U'(c_S) = \omega_N U'(c_N) = \lambda$$

- Decentralization, needs to redistribute with *lump-sum transfers*  $T_S = -T_N$

$$\Rightarrow c_i + (q^e + \mathbf{t}^e) e_i = \mathcal{D}_i(\mathcal{S}) z_i F(e_i) + \theta_i \pi(E) + T_i$$

- Are lump-sum transfers feasible?

# Toy model – Second Best - Ramsey Problem

- Assume now that *lump-sum transfers across countries* are prohibited

- Allow for carbon tax  $\mathbf{t}_i^e$  and lump-sum rebate  $T_i = \mathbf{t}_i^e e_i$

$$\begin{aligned} \mathcal{W} &= \max_{\{c_i, e_i\}_i} \sum_{i=N, S} \omega_i U(c_i) \\ s.t \quad c_i + (q^e + \mathbf{t}_i^e) e_i &= \mathcal{D}_i(\mathcal{S}) z_i F(e_i) + \theta_i \pi(E) + T^i \quad [\phi_i] \\ \mathcal{S} &:= \mathcal{S}_0 + \xi_N e_N + \xi_S e_S \quad E := e_N + e_S \quad q^e = c'(E) \end{aligned}$$

- Ramsey policy result :
  - Planner's marginal value of wealth

$$\phi_i = \omega_i U'(c_i)$$

- Energy decision :

$$\phi_i [M P e_i - c'(E)] + \underbrace{\xi_i \sum_j \phi_j \mathcal{D}'_j(\mathcal{S}) z_j F(e_j)}_{\propto -\text{SCC}} + \underbrace{\pi'(E) \sum_j \phi_j \theta_j}_{= \text{rent redistribution}} - \underbrace{c''(E) \sum_j \phi_j^k e_j}_{= \text{cost redistribution}} = 0$$

## Social Cost of Carbon with inequality

- Measure of inequality

$$\hat{\phi}_i = \frac{\phi_i}{\bar{\phi}} = \frac{\omega_i U'(c_i)}{\frac{1}{2} \sum_j \omega_j U'(c_j)} \leq 1 \qquad \bar{\phi} = \frac{1}{2} (\omega_N U'(c_N) + \omega_S U'(c_S))$$

- The SCC is exacerbated by heterogeneity

$$\begin{aligned} SCC &= - \sum_j \hat{\phi}_j \mathcal{D}'_j(\mathcal{S}) y_j \\ &= -\text{Cov}_j \left( \frac{\omega_j U'(c_j)}{\frac{1}{2} \sum_j \omega_j U'(c_j)}, \mathcal{D}'_j(\mathcal{S}) y_j \right) - \mathbb{E}_j[\mathcal{D}'_j(\mathcal{S}) y_j] > -\mathbb{E}_j[\mathcal{D}'_j(\mathcal{S}) y_j] = \overline{SCC} \end{aligned}$$

- Why? Low-income countries tend to be warmer/more vulnerable to climate change

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- Why? Low-income countries tend to be warmer/more vulnerable to climate change

- For the social value of rent (exporters) and energy cost (importer), it's the contrary !

$$SVR = \mathbb{Cov}_j \left( \frac{\omega_j U'(c_j)}{\frac{1}{2} \sum_j \omega_j U'(c_j)}, \theta_j \pi'_j(E) \right) + \pi'(E) < \pi'(E)$$

$$SCE = \mathbb{Cov}_j \left( \frac{\omega_j U'(c_j)}{\frac{1}{2} \sum_j \omega_j U'(c_j)}, e_j c''(E) \right) + c''(E) < c''(E) = \pi'(E)$$

## Optimal energy policy

► Energy taxation :

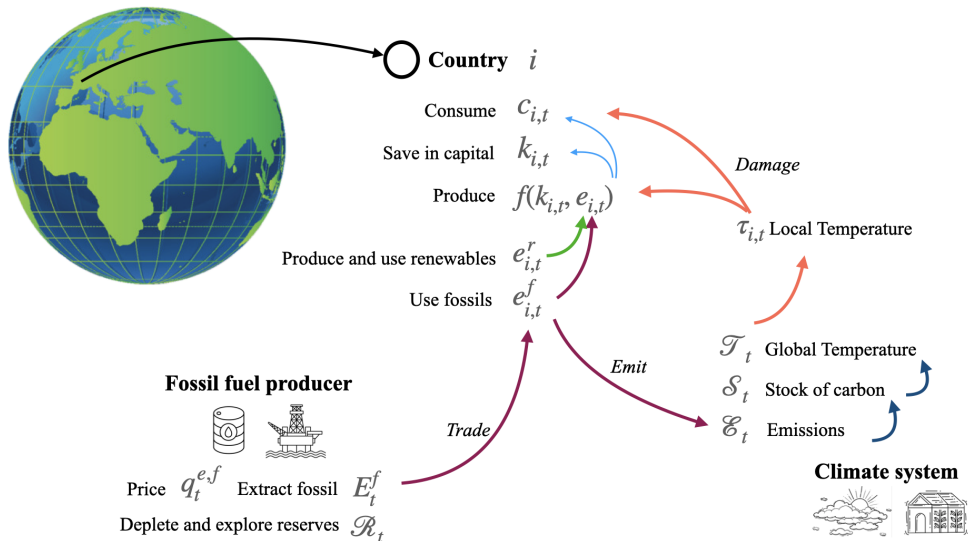
$$MPe_i = c'(E) + \xi_i \mathbf{t}_i^e$$

$$\mathbf{t}_i^e = \frac{\frac{1}{2} \sum_j \omega_j U'(c_j)}{\omega_i U'(c_i)} [\textcolor{green}{SCC} - \textcolor{brown}{SVR} + \textcolor{red}{SCE}]$$

► Four motives with a single tax and lump-sum rebate

- Distribution : Tax is higher for poorer countries  $\omega_S U'(c_S) > \omega_N U'(c_N) \Rightarrow \mathbf{t}_S^e > \mathbf{t}_N^e$
- Optimal tax level : Depends on
  - Distribution of climate damage in  $\textcolor{green}{SCC}$
  - Distribution of energy rent in  $\textcolor{brown}{SVR}$
  - Distribution of energy spending in  $\textcolor{red}{SCE}$

## Summary of the quantitative dynamic model



## Summary of the Model Environment

1. Households in individual countries  $i \in \mathbb{I}$  consuming  $c_{it}$  Household/Firms HH Solution
    - Markets : borrow/save on world bond markets  $b_{it}$  / invest in productive capital  $k_{it}$
    - Energy spending : fossil energy  $e_{it}^f$  and renewable  $e_{it}^r$
    - Taxation, fossil,  $t_{it}^f$  and renewable  $t_{it}^r$
  2. Energy markets Energy
    - Representative (Competitive) Fossil Fuel producer making profit  $\pi_t^f(q_t^f, E_t^f, \mathcal{R}_t)$
    - Extended Hotelling problem : Extraction  $E_t^f$  vs. Exploration  $\mathcal{I}_t$
    - Redistribute share  $\theta_i$  to household of country  $i$
    - Renewables with price  $q_t^r$
  3. Climate system Climate
    - Linear dynamics : emissions  $\mathcal{E}_t$  to atm. carbon  $\mathcal{S}_t$  to temperature  $\mathcal{T}$ , cf Dietz Venmans (19)
    - Damage function on TFP (c.f. DICE)  $\mathcal{D}_i(\tau_{it})$  and utility  $u(c_{it}, \tau_{it}) = U(\mathcal{D}_i(\tau_{it})c_{it})$ ,  $U$  CRRA
- Heterogeneity :
1. Productivity  $z_i$
  2. Population  $p_i$
  3. Temperature scaling  $\Delta_i$
  4. Fossil energy rent  $\theta_i$
  5. Carbon intensity of energy mix  $\xi_i$
  6. Local damage  $\gamma_i$
  7. Capital stock  $k_{it}$
  8. Local temperature  $\tau_{it}$
- ⇒ Yield inequality in consumption  $c_{it}$

## Model – Solution

### ► Main model equations and equilibrium Equilibrium

1. Household problem  $\mathcal{V}_i(w_{it_0}, \tau_{it_0}) = \max_{\{c, k, e^f, e^r\}} \int e^{-\rho t} u(c_{it}, \tau_{it}) dt$

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



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2. Energy Markets

$$E_t^f = \int_{\mathbb{I}} e_{it}^f di \qquad q_t^{ef} = C_E^f(E_t^f, \mathcal{R}_t) + \lambda_t^R \qquad \dot{\mathcal{R}}_t = -E_t^f + \delta_R \mathcal{I}_t$$

$$\pi_t^f = q_t^{ef} E_t^f - \nu(E_t^f, \mathcal{R}_t) - \mu(\mathcal{I}_t, \mathcal{R}_t)$$

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3. Climate system

$$\mathcal{E}_t = \int_{\mathbb{I}} \xi_i e_{it}^f di$$

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

$$\dot{\tau}_{it} = \zeta(\Delta_i \chi \mathcal{S}_t - (\tau_{it} - \bar{\tau}_{it_0}))$$

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4. Household Decisions, consumption/saving, and energy

$$\dot{c}_{it} = c_{it} \frac{1}{\eta} (r_t^* - \rho) \quad MPk_{it} - \bar{\delta} = r_t^* \quad MPe_{it} = \mathcal{Q}(q_t^f + \mathbf{t}_{it}^f, q_{it}^r + \mathbf{t}_{it}^r)$$

$$\Rightarrow \quad e_{it}^f = \mathcal{Q}_{q^f}(q_t^f + \mathbf{t}_{it}^f, q_{it}^r + \mathbf{t}_{it}^r) e_{it} \quad e_{it}^r = \mathcal{Q}_{q^r}(q_t^f + \mathbf{t}_{it}^f, q_{it}^r + \mathbf{t}_{it}^r) e_{it}$$

## Optimal policy

- ▶ Social planner, First best with a full set of instruments :
  - Solves world's inequality, using lump-sum transfers such that
$$\lambda_t = \omega_i u'(c_{it}) = \omega_j u'(c_{jt}) \quad \forall i, j \in \mathbb{I}$$
  - Pigouvian tax in RA economy with  $\mathbf{t}_t^f = -\frac{\lambda_t^S}{\lambda_t^k} =: SCC_t$ , c.f. GHKT (2014)
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- ▶ Second best / Ramsey planner :
  - Doesn't have access to redistribution / lump-sum transfers
  - Can only use region- $i$ -specific distortive energy taxes :  $\{\mathbf{t}_{it}^f, \mathbf{t}_{it}^r\}$
  - Redistribute lump sum the tax revenues :  $\mathbf{t}_{it}^{ls} = \mathbf{t}_{it}^f e_{it}^f + \mathbf{t}_{it}^r e_{it}^r$

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- ▶ Questions :
  - Is the level of energy tax regions specific ?
    - ⇒ Yes ! depends on the distribution of wealth/consumption
  - What is the level of the Pigouvian tax ?
    - ⇒  $\propto$  Welfare cost/climate damage : “social costate” for carbon  $S$ , i.e.  $\psi^S$
    - ⇒ Inequality/Heterogeneity in damage change the *level* of this tax

# The Ramsey Problem

- Consider a Social Planner that care about aggregate welfare :

$$\mathcal{W}_{t_0} = \max_{\{\mathbf{t}_{it}^f, \mathbf{t}_{it}^r, c_{it}, e_{it}^f, e_{it}^r, k_{it}, \lambda_{it}^k, \tau_{it}, \mathcal{S}_t, \mathcal{R}_t, \mathcal{I}_t, \lambda_t^{\mathcal{R}}\}_{it}} \int_{t_0}^{\infty} \int_{\mathbb{I}} e^{-\bar{\rho}t} \omega_i u(c_{it}, \tau_{it}) di dt$$

subject to

- Optimality conditions of households, for  $c_i$ ,  $e_i^f$ ,  $e_i^r$  and  $k_i$
- Optimality conditions of the Fossil firm, for  $E^f$ ,  $\mathcal{I}$  and  $\mathcal{R}$
- Optimality condition of the renewable firm, for  $e_i^r$
- Climate and temperature dynamics  $\tau_i$  and  $\mathcal{S}$
- Given Pareto weights  $\omega_i$

⇒ Large scale system of ODE More details - Hamiltonian

- A Ramsey plan is a set  $\{\mathbf{t}_{it}^f, \mathbf{t}_{it}^r, \mathbf{t}_{it}^{ls}\}_{it}$  s.t. the competitive equilibrium is maximizing welfare
- States  $\{w_{it}, \tau_{it}, c_{it}, k_{it}, e_{it}^f, e_{it}^r, E_t^f, \mathcal{E}_t, \mathcal{S}_t, \mathcal{R}_t\}$
- Costates  $\{\psi_{it}^w, \psi_{it}^{\tau}, \psi_{it}^{\mathcal{S}}, \psi_t^{\mathcal{R}}\}$

# The Ramsey Problem – Solution 1

- Measure of inequality : given by the shadow value of wealth

$$\widehat{\psi}_{it}^w = \frac{\psi_{it}^w}{\overline{\psi}_t^w} = \frac{\omega_i u_c(c_i, \tau_{it}) p_i}{\int_{j \in \mathbb{I}} \omega_j u_c(c_{jt}, \tau_{jt}) p_j dj} \leq 1 \quad \text{low } z_i, k_i / \text{high } \tau_{it} \Rightarrow \text{low } c_i, \text{ high } \psi_{it}^w \propto \omega_i u'(c_i) p_i$$



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- **SCC** : Shadow values of carbon  $\psi_{it}^S$  give measures for local/global cost of carbon SCC

$$\psi_t^S = \frac{\partial \mathcal{W}_t}{\partial \mathcal{S}_t} = \int_{j \in \mathbb{I}} \psi_{jt}^S dj \quad \text{LSCC}_{it}^{sp} := - \frac{\psi_{it}^S}{\psi_{it}^w}$$

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- Expression for the social cost of carbon  $SCC_t$

$$SCC_t = - \frac{\psi_t^S}{\psi_t^w} = \text{Cov}_j \left( \widehat{\psi}_{it}^w, LSCC_{j,t}^{sp} \right) + \mathbb{E}_j [LSCC_{j,t}^{sp}] > \mathbb{E}_j [LSCC_{j,t}^{sp}] = \overline{SCC}_t$$

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$$\psi_t^S = \frac{\partial \mathcal{W}_t}{\partial \mathcal{S}_t} = \int_{j \in \mathbb{I}} \psi_{jt}^S dj \quad \text{LSCC}_{it}^{sp} := -\frac{\psi_{it}^S}{\psi_{it}^w}$$

- Expression for the social cost of carbon  $SCC_t$

$$SCC_t = -\frac{\psi_t^S}{\psi_t^w} = \text{Cov}_j \left( \widehat{\psi}_{it}^w, \text{LSCC}_{j,t}^{sp} \right) + \mathbb{E}_j [\text{LSCC}_{j,t}^{sp}] > \mathbb{E}_j [\text{LSCC}_{j,t}^{sp}] = \overline{SCC}_t$$

- **SVF** : Energy taxation redistribution

$$SVF_t = \frac{\phi_t^{Ef}}{\psi_t^k} = \int_{\mathbb{I}} \widehat{\psi}_{jt}^k e_{jt}^f dj - \partial_{q^f} \pi^f \int_{\mathbb{I}} \widehat{\psi}_{jt}^k \theta_j dj = \text{Cov}_j \left( \widehat{\psi}_{jt}^k, e_{jt}^f \right) - E_t^f \text{Cov}_j \left( \widehat{\psi}_{jt}^k, \theta_{jt}^f \right)$$

## The Ramsey Problem – Solution 2

- Optimal policy for fossil energy, FOC of Ramsey planner :

$$\Rightarrow \hat{\psi}_{it}^w \mathbf{t}_{it}^f = \xi_i \text{SCC}_t + \text{SVF}_t \mathcal{C}_{EE}^f \quad \& \quad \mathbf{t}_{it}^r = 0$$

- Pigouvian tax :

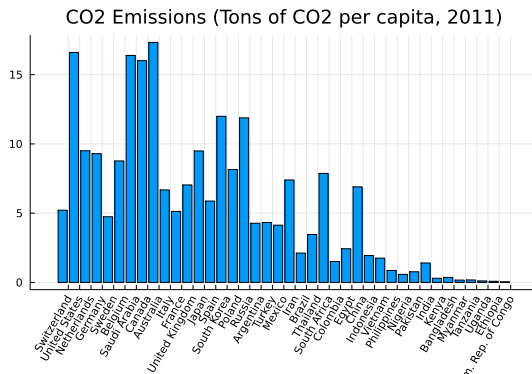
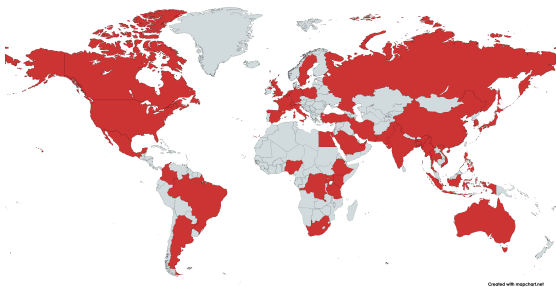
- Integrate several redistribution motives : Climate  $\text{SCC}_t$  & fossil price redistribution  $\text{SVF}$
- **Depends** on country's consumption level  $\hat{\psi}_{it}^w$  : lower tax on poorer/high  $\hat{\psi}_{it}^w$  countries

- Welfare costs of suboptimal taxes :

- Depends on the curvature of the production function  $f(k, e)$  and substitution  $e_{it}^f$  and  $e_{it}^r$

## Numerical Application

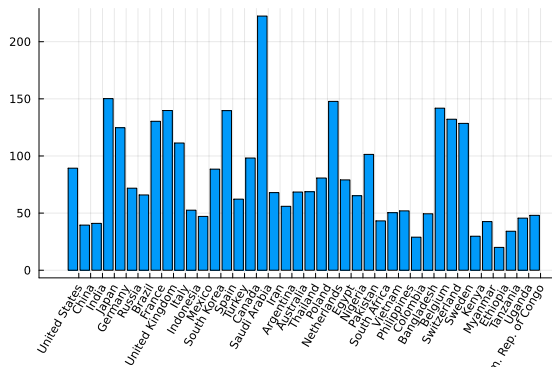
- ▶ Data : 40 countries
- ▶ Temperature (of the *largest city*), GDP, energy, population
- ▶ Calibrate  $z$  to match the distribution of output per capita at steady state



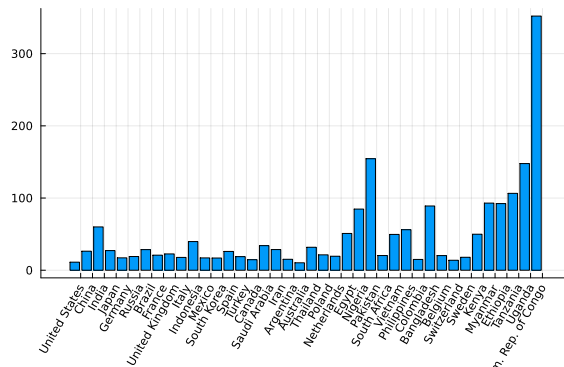
# Local Cost of Carbon

► Difference  $LSCC_i = \psi_{it}^S / \psi_{it}^k$  and  $LWCC_{it} = \hat{\psi}_{it}^k LSCC_{it} = \psi_{it}^S / \bar{\psi}_t^k$

LSCC (USD PPP 2011)



LWCC (USD PPP 2011)



## Conclusion

- ▶ Climate change has redistributive effects & heterogeneous impacts
- ▶ Redistributive effects of policy
  - Pigouvian tax that covers aggregate marginal damages
  - Can account for inequality both for heterogeneous welfare costs of climate and redistributive effects of energy price, for importers and exporters
- ▶ Study suboptimal policies
  - If carbon taxes are unfeasible : renewable subsidy ?
- ▶ Future plans
  - Dynamics on the capacity of renewable ?
  - Endogenous growth in TFP/energy saving technology  
Learning-by-doing : positive externality ?
  - Uncertainty : HA model with aggregate risk hard to solve

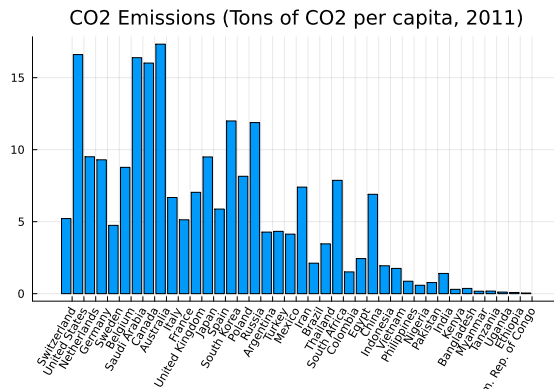
# Appendices



# Numerical Applications

# Numerical Application

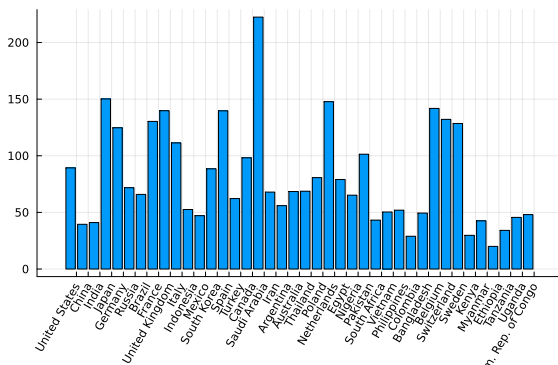
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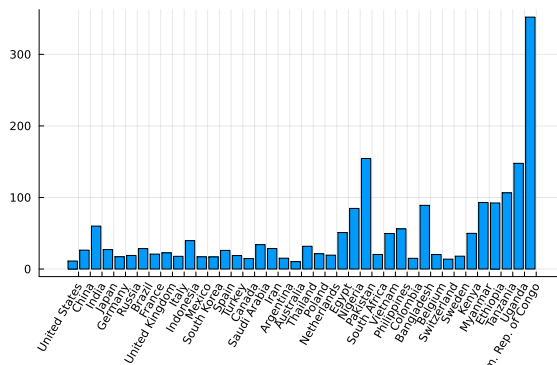
# Local Cost of Carbon

► Difference  $LSCC_i = \psi_{it}^S / \psi_{it}^k$  and  $LWCC_{it} = \hat{\psi}_{it}^k LSCC_{it} = \psi_{it}^S / \bar{\psi}_{it}^k$

LSCC (USD PPP 2011)



LWCC (USD PPP 2011)



# Model 1

- ▶ Neoclassical economy, in continuous time Back
  - countries/regions  $i \in \mathbb{I}$  : ex-ante heterogeneous : productivity  $z_i$  and more
  - ex-post heterogeneity in capital and temperature  $\{k_i, \tau_i\}$
- ▶ Representative household problem in each country  $i$  :

$$\mathcal{V}_{it_0} = \max_{\{c_{it}, e_{it}^f, e_{it}^r\}} \int_{t_0}^{\infty} e^{-\rho t} u(c_{it}, \tau_{it}) dt$$

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

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

- Damage  $\mathcal{D}^y(\tau_{it})$  affect country's production and consumption  $u(\cdot, \tau_{it})$
- Energy mix :  $e_{it} = \mathcal{E}(e_{it}^f, e_{it}^r | \sigma_e)$  with fossil  $e_{it}^f$  – emitting carbon – vs. renewable  $e_{it}^r$
- Energy **rents** redistributed : share  $\theta_i$  for fossils / fully for local renew. firm.
- Prices, fossil  $q_t^f$  and non-carbon  $q_t^r$  (c.f. next slides)

## Model 2 – Energy markets

### ► Fossil fuels energy producer :

- Extended-Hotelling problem (depleting reserves with stock effects and exploration)

$$\max_{\{E_t^f, \mathcal{I}_t\}_t} \int_0^\infty e^{-\rho t} \pi_t^f(q_t^f, E_t^f, \mathcal{R}_t) dt \quad \text{with } \pi_t(E_t^f, \mathcal{R}_t) = q_t^{ef} E_t^f - \mathcal{C}^f(E_t^f, \mathcal{R}_t) - \mathcal{C}^i(\mathcal{I}_t, \mathcal{R}_t)$$

$$s.t. \quad E_t^f = \int_{\mathbb{I}} e_{it}^f di \quad \dot{\mathcal{R}}_t = -E_t^f + \delta_R \mathcal{I}_t$$

- Optimal pricing with finite-resources rents [More details](#)

$$q_t^{ef} = \mathcal{C}_E^f(E_t^f, \mathcal{R}_t) + \lambda_t^R \quad \mathcal{C}_{\mathcal{I}}^i(\mathcal{I}_t, \mathcal{R}_t) = \delta_R \lambda_t^R$$

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### ► Renewable energy as a substitute technology *for each country i* (Static problem)

$$\pi_{it}^r = \max_{\{e_{it}^r\}} q_{it}^r e_{it}^r - \mathcal{C}^r(e_{it}^r) \quad \Rightarrow \quad q_{it}^r = \mathcal{C}_E^r(e_{it}^r)$$

[Back](#)

## Model 3 - Climate model :

- ▶ Fossil energy input  $e_t^f$  causes climate externality

$$\mathcal{E}_t = \int_{\mathbb{I}} \xi_i e_{it}^f di$$

- ▶ World climate – cumulative GHG in atmosphere  $\mathcal{S}_t$  leads to increase in temperature

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

- ▶ Impact of climate on country's local temperature :

$$\dot{\tau}_{it} = \zeta \left( \Delta_i \chi \mathcal{S}_t - (\tau_{it} - \bar{\tau}_{it_0}) \right)$$

- Simple model : Climate sensitivity to carbon  $\chi$ , Climate reaction/inertia  $\zeta$ , Carbon content of fossils  $\xi$ , Country scaling factor  $\Delta_i$ , Carbon exit for atmosphere  $\delta_s$

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## Model 4 – Household Solution

- ▶ Household solves a consumption/saving/energy decision, as in the NCG [More details](#)
  - Using Pontryagin (PMP), we obtain a system of coupled ODEs [More details](#)



## Model 4 – Household Solution

- Household solves a consumption/saving/energy decision, as in the NCG [More details](#)

- Using Pontryagin (PMP), we obtain a system of coupled ODEs [More details](#)
- Consumption/Saving Euler equation (financial integration) :

$$\dot{c}_{it} = c_{it} \frac{1}{\eta} (r_t^* - \rho) \qquad MPk_{it} - \bar{\delta} = r_t^*$$

- Energy decisions :

Static demand for the two sources of energy : fossil  $e_{it}^f$  and renewable  $e_{it}^r$  for every  $i$ , taking prices  $\{q^f, q^r\}$  as given

$$\begin{aligned} MPe_{it} &= \mathcal{Q}(q_t^f + \mathbf{t}_{it}^f, q_{it}^r + \mathbf{t}_{it}^r) \\ \Rightarrow \quad e_{it}^f &= \mathcal{Q}_{q^f}(q_t^f + \mathbf{t}_{it}^f, q_{it}^r + \mathbf{t}_{it}^r) e_{it} \qquad e_{it}^r = \mathcal{Q}_{q^r}(q_t^f + \mathbf{t}_{it}^f, q_{it}^r + \mathbf{t}_{it}^r) e_{it} \end{aligned}$$

- with  $MPk_{it} = \mathcal{D}(\tau_{it}) z_{ifk,it}$  and  $MPe_{it} = \mathcal{D}^y(\tau_{it}) z_{ife}(k_{it}, e_{it})$ , and  $\mathcal{Q}(\cdot)$  are aggregators functions (e.g. CES) and  $\mathcal{Q}_{q^f}(\cdot)$  demand for fossil.

## Model – Equilibrium

- ▶ Three types of interactions Equilibrium
  - On climate (externality) + heterogeneous effects of temperatures
  - On bonds markets + capital constraints
  - On energy market + redistribution effects of energy rent
  - No bilateral flows (eq. doesn't exist with continuum and trade or migration)

## Model – Equilibrium

### ► Three types of interactions Equilibrium

- On climate (externality) + heterogeneous effects of temperatures
- On bonds markets + capital constraints
- On energy market + redistribution effects of energy rent
- No bilateral flows (eq. doesn't exist with continuum and trade or migration)

### ► Equilibrium

- Given, initial conditions  $\{k_0, \tau_0\}$  and country-specific policies  $\{\mathbf{t}_{it}^f, \mathbf{t}_{it}^r, \mathbf{t}_{it}^{ls}\}$ , a competitive equilibrium is a continuum of sequences of states  $\{k_{it}, \tau_{it}\}_{it}$  and  $\{\mathcal{S}_t, \mathcal{T}_t, \mathcal{R}_t\}_t$  and policies  $\{c_{it}, e_{it}^f, e_{it}^r\}_{it}$  and  $\{E_t^f, \mathcal{E}_t, \mathcal{I}_t\}_t$ , and price sequences  $\{q_t^f, q_t^r\}$  such that :
  - Households choose policies  $\{c_{it}, e_{it}^f, e_{it}^r\}_{it}$  to max utility s.t. budget constraint, giving  $\dot{k}_{it}$
  - Renewable energy firm produce  $\{e_{it}^r\}$  to max static profit
  - Fossil fuel firm extract and explore  $\{E_t^f, \mathcal{I}_t\}$  to max profit, yielding  $\dot{\mathcal{R}}_t$
  - Emissions  $\mathcal{E}_t$  affects climate  $\{\mathcal{S}_t, \mathcal{T}_t\}_t$ , &  $\{\tau_{it}\}_{it}$ .
  - Prices  $\{q_t^f, q_{it}^r, r_t^*\}$  adjust to clear the markets :  $E_t^f = \int_{\mathbb{I}} e_{it}^f di$  and  $e_{it}^r = e_{it}^r$ , and  $\int_{i \in \mathbb{I}} b_{it} di = 0$

## Impact of increase in temperature

- Using Damage fct  $\mathcal{D}^y(\tau_{it}) = e^{-\frac{1}{2}\gamma_i(\tau_{it}-\tau_i^*)^2}$  and  $u(c, \tau) = u(\mathcal{D}^u(\tau_{it})c)$ , w/  $u(\hat{c}) = \frac{c^{1-\eta}}{1-\eta}$
- Marginal values of the climate variables :  $\lambda_{it}^S$  and  $\lambda_{it}^\tau$

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

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

- Costate  $\lambda_{it}^S$  : marg. cost of 1Mt carbon in atmosphere, for country  $i$ . Increases with :
  - Temperature gaps  $\tau_{it} - \tau_i^*$  & damage sensitivity of TFP  $\gamma_i$  and utility  $\phi_i$
  - Development level  $f(k_{it}, e_{it})$  and  $c_{it}$
  - Climate params :  $\chi$  climate sensitivity,  $\Delta_i$  “catching up” of  $\tau_i$  and  $\zeta$  reaction speed
  - [back](#)

## Local Social cost of carbon

- The marginal “externality damage” or “local social cost of carbon” (SCC) for region  $i$  :

$$LSCC_{it} := -\frac{\partial \mathcal{V}_{it} / \partial \mathcal{S}_t}{\partial \mathcal{V}_{it} / \partial c_{it}} = -\frac{\lambda_{it}^S}{\lambda_{it}^k}$$

- Ratio of marg. cost of carbon vs. the marg. value of consumption/capital
- Theorem : **Stationary LSCC** :

When  $t \rightarrow \infty$  and for a BGP with  $\mathcal{E}_t = \delta_s \mathcal{S}_t$  and  $\tau_t \rightarrow \tau_\infty$ , the LSCC is *proportional* to climate sensitivity  $\chi$ , **marg. damage  $\gamma$** ,  **$\phi$** , **temperature**, and **output, consumption**.

$$LSCC_{it} \equiv \frac{\chi \Delta_i}{\tilde{\rho} + \delta^s} (\tau_{i,\infty} - \tau_i^*) [\gamma_i y_{i,\infty} + \phi_i c_{i,\infty}]$$

- More general formula : [Here](#) , Proof : [Here](#) + What determine temperatures ? [Details Temperature](#)

## More details – Capital market

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

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

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

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

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

- Two polar cases :

- $\vartheta \rightarrow 0$ , full autarky (no trade), and  $w_{it} = k_{it}$
- $\vartheta \rightarrow 1$ , full financial integration :

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

## More details – Energy market

- Fossil fuel producer : price the Hotelling rent with the maximum principle :

$$\mathcal{H}^m(\mathcal{R}_t, \lambda_t^R, E_t, \mathcal{I}_t^e) = \pi_t(E_t^f, \mathcal{I}_t^f, \mathcal{R}_t) + \lambda_t^R(\delta^R \mathcal{I}_t^e - E_t)$$

- Rent  $\lambda_t^R$  grows with interest  $\rho$  and with the marginal gain of increasing reserves

$$\begin{aligned}\dot{\lambda}_t^R &= \rho \lambda_t^R - \partial_R \mathcal{C}(E_t^f, \mathcal{I}_t^f, \mathcal{R}_t) \\ &= \rho \lambda_t^R + \frac{\bar{\nu} \nu}{1 + \nu} \left( \frac{E_t^*}{\mathcal{R}_t} \right)^{1+\nu} + \frac{\bar{\mu} \mu}{1 + \mu} \left( \frac{I_t^*}{\mathcal{R}_t} \right)^{1+\mu} \\ \dot{\lambda}_t^R &= \rho \lambda_t^R + \frac{\bar{\nu}^{-1/\nu} \nu}{1 + \nu} (q^{ef} - \lambda_t^R)^{1+1/\nu} + \frac{\bar{\mu}^{-1/\mu} \mu}{1 + \mu} (\delta^R \lambda_t^R)^{1+1/\mu}\end{aligned}$$

- Because of decreasing return to scale and Hotelling rents : profits are  $> 0$

$$\pi_t(E_t^f, \mathcal{R}_t, \lambda_t^R) = \frac{1 + \nu - \bar{\nu}}{1 + \nu} \left( \frac{E_t^f}{\mathcal{R}_t} \right)^{1+\nu} \mathcal{R}_t + \lambda_t^R E_t^f - \frac{\bar{\mu}^{-1/\mu}}{1 + \mu} (\delta^R \lambda_t^R)^{1+1/\mu}$$

## More details – PMP – Competitive equilibrium

- Household problem : State variables  $s_{it} = (k_{it}, \tau_{it}, z_{it}, p_{it}, \Delta_{it})$
- Pontryagin Maximum Principle

[Back](#)

$$\mathcal{H}^{hh}(s, \{c\}, \{e^f\}, \{e^r\}, \{\lambda\}) = u(c_{it}, \tau_{it}) + \lambda_{it}^k \left( \mathcal{D}(\tau_{it}) f(k_{it}, e_{it}) - (n + \bar{g} + \delta) k_{it} - q_{it}^f e_{it}^f - q_{it}^r e_{it}^r - c_{it} \right) + \lambda_{it}^\tau \zeta \left( \Delta_{it} \chi \mathcal{S}_t - (\tau_{it} - \tau_{i0}) \right) + \lambda_{it}^S \left( \mathcal{E}_t - \delta^S \mathcal{S}_t \right)$$

$$[c_t] \quad u'(c_{it}) = \lambda_{it}^k$$

$$[e_t^f] \quad MPE_{it}^f = \mathcal{D}(\tau_{it}) z \partial_e f(k_{it}, e_{it}) \left( \frac{e_{it}^f}{\omega e_{it}} \right)^{-\frac{1}{\sigma_e}} = q_{it}^f$$

$$[e_t^r] \quad MPE_{it}^r = \mathcal{D}(\tau_{it}) z \partial_e f(k_{it}, e_{it}) \left( \frac{e_{it}^r}{(1 - \omega) e_{it}} \right)^{-\frac{1}{\sigma_e}} = q_{it}^r$$

$$[k_t] \quad \dot{\lambda}_{it}^k = -\lambda_{it}^k \left( \mathcal{D}(\tau_{it}) \partial_k f(k_{it}, e_{it}) - \delta - \bar{g} - n - \rho \right)$$

- Fossil Energy Monopoly :

$$\mathcal{H}^m(\mathcal{R}_t, \lambda_t^R, E_t^f, \mathcal{I}_t) = \pi_t(E_t^f, \mathcal{I}_t, \mathcal{R}_t) + \lambda_t^R (\delta^R \mathcal{I}_t - E_t^f)$$

$$[\mathcal{R}_t] \quad \dot{\lambda}_t^R = \rho \lambda_t^R + \frac{\bar{\nu} \nu}{1 + \nu} \left( \frac{E_t^*}{R_t} \right)^{1+\nu} + \frac{\bar{\mu} \mu}{1 + \mu} \left( \frac{I_t^*}{R_t} \right)^{1+\mu}$$

$$[E_t^f] \quad q_t^{ef} = \nu_E(E, \mathcal{R}) + \lambda_t^R = \bar{\nu} \left( \frac{E_t}{\mathcal{R}_t} \right)^\nu + \lambda_t^R$$

$$[\mathcal{I}_t] \quad \lambda_t^R \delta^R = \mu_I(I_t, R_t) = \bar{\mu} \left( \frac{\mathcal{I}_t}{\mathcal{R}_t} \right)^\mu \quad \mathcal{I}_t = R_t \left( \frac{\lambda_t^R \delta}{\bar{\mu}} \right)^{1/\mu}$$



## Cost of carbon / Marginal value of temperature

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

$$\begin{aligned}\dot{\lambda}_{it}^{\tau} &= \lambda_t^{\tau}(\tilde{\rho} + \Delta\zeta) + \gamma(\tau - \tau^*)\mathcal{D}^y(\tau)f(k, e)\lambda_t^k + \phi(\tau - \tau^*)\mathcal{D}^u(\tau)u(c) \\ \dot{\lambda}_t^S &= \lambda_t^S(\tilde{\rho} + \delta^s) - \int_{\mathbb{I}} \Delta_i \zeta \chi \lambda_{it}^{\tau}\end{aligned}$$

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

$$\begin{aligned}\lambda_{it}^{\tau} &= - \int_t^{\infty} e^{-(\tilde{\rho} + \zeta)u} (\tau_u - \tau^*) \left( \gamma \mathcal{D}^y(\tau_u) y_{\tau} \lambda_u^k + \phi \mathcal{D}^u(\tau_u) u(c_u) \right) du \\ \lambda_{it}^{\tau} &= - \frac{1}{\tilde{\rho} + \Delta\zeta} (\tau_{\infty} - \tau^*) \left( \gamma \mathcal{D}^y(\tau_{\infty}) y_{\infty} \lambda_{\infty}^k + \phi \mathcal{D}^u(\tau_{\infty}) u(c_{\infty}) \right) \\ \lambda_t^S &= - \int_t^{\infty} e^{-(\tilde{\rho} + \delta^s)u} \zeta \chi \int_{\mathbb{I}} \Delta_j \lambda_{j,u}^{\tau} dj du \\ &= \frac{1}{\tilde{\rho} + \delta^s} \zeta \chi \int_{\mathbb{I}} \Delta_j \lambda_{j,\infty}^{\tau} \\ &= - \frac{\chi}{\tilde{\rho} + \delta^s} \frac{\zeta}{\tilde{\rho} + \zeta} \int_{\mathbb{I}} \Delta_j (\tau_{j,\infty} - \tau^*) \left( \gamma \mathcal{D}^y(\tau_{j,\infty}) y_{\infty} \lambda_{j,\infty}^k + \phi \mathcal{D}^u(\tau_{j,\infty}) u(c_{j,\infty}) \right) dj \\ \lambda_t^S &\xrightarrow{\zeta \rightarrow \infty} - \frac{\chi}{\tilde{\rho} + \delta^s} \int_{\mathbb{I}} \Delta_j (\tau_{j,\infty} - \tau^*) \left( \gamma \mathcal{D}^y(\tau_{j,\infty}) y_{j,\infty} \lambda_{j,\infty}^k + \mathcal{D}^u(\tau_{j,\infty}) u(c_{j,\infty}) \right) dj\end{aligned}$$

## Cost of carbon / Marginal value of temperature

► Closed form solution for CC :

- In stationary equilibrium :  $\dot{\lambda}_t^S = \dot{\lambda}_t^T = 0$
- Fast temperature adjustment  $\zeta \rightarrow \infty$
- no internalization of externality (business as usual)

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

► Heterogeneity + uncertainty about models [Back](#)

## Social cost of carbon & temperature

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

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

- Geographical factors determining warming  $\Delta_i$
- Climate sensitivity  $\chi$  & carbon exit from atmosphere  $\delta_s$
- 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  $\sigma$
- Fossil energy price  $q^{ef}$  and Hotelling rent  $g^{qf} \approx \dot{\lambda}_t^R / \lambda_t^R = \rho$
- Change in energy mix, renewable share  $\omega$ , price  $q_t^r$  & elasticity of source  $\sigma_e$

- Approximations at  $T \equiv$  Generalized Kaya (or  $I = PAT$ ) identity [More details](#)

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

## More details – PMP – Ramsey Optimal Allocation

### ► Hamiltonian :

$$\begin{aligned}
 \mathcal{H}^{sp}(s, \{c\}, \{e^f\}, \{e^r\}, \{\lambda\}, \{\psi\}) = & \int_{\mathbb{I}} \omega_i u(c_i, \tau_i) p_i di \\
 & + \psi_{it}^k \left( \mathcal{D}(\tau_{it}) f(k_{it}, e_{it}) - (n + \bar{g} + \delta) k_t + \theta_i \pi(E_t^f, \mathcal{I}_t, \mathcal{R}_t) + \pi_{it}^r(e_{it}^r) - (q_t^f + \mathbf{t}_{it}^f) e_{it}^f - (q_{it}^r + \mathbf{t}_{it}^r) e_{it}^r - c_t + \mathbf{t}_t^{ls} \right) \\
 & + \psi_t^s \left( \mathcal{E}_t - \delta^s \mathcal{S}_t \right) + \psi_{it}^\tau \zeta \left( \Delta_i \chi \mathcal{S}_t - (\tau_{it} - \tau_{i0}) \right) + \psi_{it}^{\mathcal{R}} \left( -E_t^f + \delta^R \mathcal{I}_t \right) \\
 & + \psi_{it}^{\lambda k} \left( \lambda_t^k (\rho - r_t) \right) + \psi_t^{\lambda R} \left( \rho \lambda_t^R + \mathcal{C}_{\mathcal{R}}^f(E_t^f, \mathcal{I}_t, \mathcal{R}_t) \right) + \phi_{it}^c (u_c(c_i, \tau_{it}) - \lambda_{it}^k) \\
 & + \phi_{it}^{ef} \left( e_{it}^f - \mathcal{Q}_{q^f}(q_t^f + \mathbf{t}_{it}^f, q_t^r + \mathbf{t}_{it}^r) e_{it} \right) + \phi_{it}^{er} \left( e_{it}^r - \mathcal{Q}_{q^r}(q_t^f + \mathbf{t}_{it}^f, q_t^r + \mathbf{t}_{it}^r) e_{it} \right) \\
 & + \phi_{it}^e \left( f_e(k_{it}, e_{it}) - \mathcal{Q}(q_t^f + \mathbf{t}_{it}^f, q_t^r + \mathbf{t}_{it}^r) \right) + \phi_t^{Ef} (q_t^f - \mathcal{C}_E^f(\cdot) - \lambda_t^{\mathcal{R}}) + \phi_{it}^{Er} (q_{it}^r - \mathcal{C}_e^r(\cdot)) + \phi_t^{\mathcal{I}f} (\delta \lambda_t^{\mathcal{R}} - \mathcal{C}_{\mathcal{I}}^f(\cdot))
 \end{aligned}$$

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## Ramsey Optimal Allocation - FOCs

► FOCs w.r.t.  $\{c_{it}, e_{it}, e_{it}^f, e_{it}^r, \mathcal{I}_t\}$ , prices  $\{q_t^f, q_t^r\}$  and taxes, denoting  $\tilde{q}_{it} = q_t + \mathbf{t}_{it}$

$$[c_{it}] \quad \psi_{it}^k = \underbrace{\omega_i u_c(c_i, \tau_{it}) p_i}_{=\text{direct effect}} + \underbrace{\phi_{it}^c u_{cc}(c_i, \tau_{it})}_{=\text{effect on savings}}$$

$$[e_{it}] \quad \psi_{it}^k f_{e,it} + \phi_{it}^e f_{ee,it} - \phi_{it}^{ef} \mathcal{Q}_{q^f} - \phi_{it}^{er} \mathcal{Q}_{q^r} = 0 \quad \Rightarrow \quad \phi_{it}^e = \frac{1}{f_{ee,it}} (\phi_{it}^{ef} \mathcal{Q}_{q^f} + \phi_{it}^{er} \mathcal{Q}_{q^r} - \psi_{it}^k f_{e,it})$$

$$[e_{it}^f] \quad \phi_{it}^{ef} = \psi_{it}^k \tilde{q}_t^f - \psi_{it}^k \mathbf{t}_{it}^f - \xi \psi_t^S p_i + \phi_t^{Ef} \mathcal{C}_{EE}^f(\cdot) \quad [e_{it}^r] \quad \phi_{it}^{er} = \psi_{it}^k \tilde{q}_t^r - \psi_{it}^k \mathbf{t}_{it}^r + \phi_{it}^{Er} \mathcal{C}_{er}^r(\cdot)$$

$$[\tilde{q}_{it}^f] \quad \phi_{it}^e \mathcal{Q}_{q^f} + \phi_{it}^{ef} \mathcal{Q}_{q^f q^f} + \phi_{it}^{er} \mathcal{Q}_{q^r q^f} = 0$$

$$\Rightarrow \quad \left( \frac{\mathcal{Q}_{q^f}^2}{f_{ee,it}} + \mathcal{Q}_{q^f q^f} \right) [-\xi \psi_t^S p_i + \phi_t^{Ef} \mathcal{C}_{EE}^f(\cdot) - \psi_{it}^k \mathbf{t}_{it}^f] + \left( \frac{\mathcal{Q}_{q^f} \mathcal{Q}_{q^r}}{f_{ee,it}} + \mathcal{Q}_{q^r q^f} \right) [\phi_{it}^{Er} \mathcal{C}_{er}^r(\cdot) - \psi_{it}^k \mathbf{t}_{it}^r]$$

$$[\tilde{q}_{it}^r] \quad \phi_{it}^e \mathcal{Q}_{q^r} + \phi_{it}^{ef} \mathcal{Q}_{q^f q^r} + \phi_{it}^{er} \mathcal{Q}_{q^r q^r} = 0$$

$$\Rightarrow \quad \left( \frac{\mathcal{Q}_{q^f} \mathcal{Q}_{q^r}}{f_{ee,it}} + \mathcal{Q}_{q^f q^r} \right) [-\xi \psi_t^S p_i + \phi_t^{Ef} \mathcal{C}_{EE}^f(\cdot) - \psi_{it}^k \mathbf{t}_{it}^f] + \left( \frac{\mathcal{Q}_{q^r}^2}{f_{ee,it}} + \mathcal{Q}_{q^r q^r} \right) [\phi_{it}^{Er} \mathcal{C}_{er}^r(\cdot) - \psi_{it}^k \mathbf{t}_{it}^r] = 0$$

$$[q_t^f] \quad \phi_t^{Ef} = \int_{\mathbb{I}} \psi_{jt}^k e_{jt}^f dj - \partial_{q^f} \pi^f(\cdot) \int_{\mathbb{I}} \theta_j \psi_{jt}^k dj \quad [q_t^r] \quad \phi_{it}^{Er} = \psi_{it}^k e_{it}^r - \psi_{it}^k \partial_{q^r} \pi_{it}^r = 0$$

$$[\mathcal{I}_t] \quad \delta \psi_t^{\mathcal{R}} + \partial_{\mathcal{R}\mathcal{I}}^2 \mathcal{C}(\cdot) \psi_t^{\lambda, \mathcal{R}} - \phi_t^{\mathcal{I}} \partial_{\mathcal{I}\mathcal{I}}^2 \mathcal{C}(\cdot) = 0$$

## Ramsey Optimal Allocation - FOCs

### ► Backward equations for planner's costates

$$[k_i] \quad \dot{\psi}_{it}^k = \psi_{it}^k (\tilde{\rho} - r_{it}) + \psi_{it}^{\lambda k} \lambda_{it}^k \partial_k MPk_i + \frac{f_{ek,it}}{f_{ee,it}} \left[ -\xi \psi_t^S p_i + \phi_t^{Ef} C_{EE}^f(\cdot) - \psi_{it}^k \mathbf{t}_{it}^f \right]$$

$$[S_i] \quad \dot{\psi}_t^S = (\tilde{\rho} + \delta^s) \psi_t^S - \int_{\mathbb{I}} \Delta_j \zeta \chi \psi_{jt}^\tau dj$$

$$[\tau_i] \quad \dot{\psi}_t^\tau = (\tilde{\rho} + \zeta) \psi_t^\tau - \left( \omega_i u_\tau(c_{it}, \tau_{it}) + \psi_{it}^k \mathcal{D}'(\tau_{it}) f(k_{it}, e_{it}) + \phi_{it}^c u_{c,\tau}(c_{it}, \tau_{it}) + \mathcal{D}'(\tau_{it}) f_e \phi_{it}^e \right)$$

$$[\mathcal{R}] \quad \dot{\psi}_t^{\mathcal{R}} = \psi_t^{\mathcal{R}} \left( \tilde{\rho} - \partial_{\mathcal{R}}^2 \mathcal{C}(\cdot) \right) - \phi_t^{Ef} \partial_{\mathcal{R}E}^2 \mathcal{C}(\cdot)$$

$$[\lambda_i^k] \quad \dot{\psi}_t^{\lambda,k} = \psi_t^{\lambda,k} [\tilde{\rho} - (\rho - r_{it})] + \phi_{it}^c$$

$$[\lambda_i^{\mathcal{R}}] \quad \dot{\psi}_t^{\lambda,\mathcal{R}} = \psi_t^{\lambda,\mathcal{R}} (\tilde{\rho} - \rho) + \phi_t^{Ef} - \delta \phi_t^{\mathcal{I}f}$$

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