Dynamics of Global Emission Permit Prices and Regional Social Cost of Carbon under Noncooperation

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Background: Paris Agreement in 2015

Photo Source: https://www.un.org/

- Paris Agreement (2015)
  - Emission mitigation targets to limit temperature rise to 2°C
  - Nationally Determined Contributions (NDCs)
- Glasgow Climate Pact (2021)
  - Revisiting emission target to limit temperature rise to 1.5°C

Background: Emission Trading System

- Market-based approach to reduce emissions
  1. Carbon Tax
     - Tax for each unit of emission production
     - Carbon tax = Global Social cost of carbon (SCC)
  2. Emission Trading System (ETS)
     - Fixed emission cap
     - Sell and purchase emission permits

Background: Emission Trading System

- Regional ETS in practice
  - The first ETS: EU ETS in 2005 (70 euros per ton of CO2 as of 2025 June)
  - Other regional ETS: Canada, China, Japan, Korea, US, etc.
- Potential for **Global ETS**
  - Kyoto Protocol (1997) Article 17
  - **Paris Agreement (2015) Article 6**

    "Parties shall, where engaging on a voluntary basis in cooperative approaches that involve the use of internationally transferred mitigation outcomes towards nationally determined contributions, promote sustainable development and ensure environmental integrity and transparency, ..."

This paper

Objective: With multi-region IAM with **Global ETS**, we solve for

- Emission permit prices and trade pattern
- Regional Social Cost of Carbon (SCC)

Key Contributions

1. Solve market-clearing permit price in **dynamic noncooperative Nash Eq**. ($923 per ton of carbon, by 2050)
2. Theoretically & numerically show the relationship:
   - Regional SCC = Regional MAC $-$ m, where m is permit price
   - **Complementarity** of **global ETS** and **regional carbon tax**
3. Newly calibrated parameters and regional emission cap pathways
4. Comprehensive analysis on **global/partial ETS** and **emission cap scenarios**

Relevant Studies

- ETS in general equilibrium
  - Endogenous participation in ETS and allocation of emission permits (Carbone et al., 2009)
  - Comparing emission caps (without trade) and taxes in a dynamic stochastic GE (Fischer and Springborn, 2011)
  - Efficiency gains from integrating regional ETS (e.g., Doda et al., 2019; Holtsmark and Midttømme, 2021)
- Regional Integrated Assessment Models (IAMs)
  - Multi-region dynamic model of climate and economy
  - RICE (Nordhaus and Yang, 1996; Nordhaus, 2010)
  - North and Tropic/South (Cai et al., 2023)
  - WITCH (Massetti and Tavoni, 2012; De Cian and Tavoni, 2012)
- **This study**: IAM with global ETS,
  with fully endogenous market permit prices in dynamic IAM
  & complementarity between ETS and carbon tax

A Static Framework

A Static Framework

- Setup
  - A world consists of multiple regions $i \in \mathcal{I}$
  - Each region has an exogenous emission cap $\bar{E}_i$
  - To comply with emission cap, each region's social planner can either (i) purchase or sell emission permits in the global emission market, or (ii) undertake costly abatement efforts

- The emission cap constraint for each region i

$$E_i \leq \overline{E}_i + E_i^P$$

  - E_i: Emissions net of abatement
  - E_i^P: Emission permit purchases (if positive) or sales (if negative)

A Static Framework

- Regional social planner's problem

$$\min_{0 \leq E_i \leq \overline{E}_i + E_i^P} \underbrace{D_i\left(\sum_{j \in \mathcal{I}} E_j\right)}_{\text{Climate Damages}} + \underbrace{mE_i^P}_{\text{ETS Costs/Revenue}} + \underbrace{\int_{E_i}^{E_i^{\text{Gross}}} \text{MAC}_i(E)dE}_{\text{Emission Abatement Cost}}$$

- Karush-Kuhn-Tucker conditions implies

$$\underbrace{\frac{\partial D_i(\sum_{j \in \mathcal{I}} E_j)}{\partial E_i}}_{\text{Regional SCC}} = \underbrace{\text{MAC}_i(E_i) - m}_{\text{Deviation from Market Equilibrium}}$$

  - m: market emission permit price

Interpretation

$$\mathrm{SCC}_i = \mathrm{MAC}_i(E_i) - m$$

- $\mathrm{SCC}_i > 0$ implies $\mathrm{MAC}_i(E_i) > m$
- A region experiencing climate damages has an incentive to abate emissions to a level where the marginal abatement cost exceeds the market price of emission permits

$$\mathrm{MAC}_i(E_i) = m$$

- Equilibrium condition under ETS in a decentralized economy does not hold when the regional social planner accounts for marginal climate damages

Policy Instrument Complementarity

$$\mathrm{SCC}_i = \mathrm{MAC}_i(E_i) - m$$

- Necessary condition for optimal regional emission abatement from the *regional social planner's perspective*
- Uniform global carbon price alone may not achieve regionally optimal carbon pricing
  - Climate damages are region-specific
- Optimal regional carbon tax $= SCC_i$
  - Complementarity between global ETS and carbon tax

A Dynamic Model

Model – Main Features

- 12 aggregated regions
  - US, EU, Japan, Russia, Eurasia, China, India, MidEast, LatAm, Other High Income (OHI), OtherAsia
- Assumption:
  - Strict enforcement of emission caps pathways (Paris Agreement, and revised under the Glasgow Pact)
- Main feature of model
  - **Ramsey-type growth model**: intertemporal choice between current and future consumption (consumption smoothing)
  - **Negative externality of emissions**: current production increases global temperature, affecting other regions' climate damages
  - **Global ETS**: Choice between permit purchase and own abatement

Model: Emissions

- Industrial Emission

$$E_{i,t}^{\text{Total}} = \sigma_{i,t} Q_{i,t}$$

- Emission Cap Constraint

$$\underbrace{E_{i,t}^{\text{Total}} - \underbrace{E_{i,t}^{A}}_{\text{abatement}}}_{\text{net emission } (E_{i,t}^{*})} - \underbrace{E_{i,t}^{P}}_{\text{permit purchase}} \leq \underbrace{\bar{E}_{i,t}}_{\text{Emission cap}}$$

- Emission Market Clearing

$$\sum_{i \in \mathcal{I}} E_{i,t}^{P} = 0, \quad \forall t$$

Model: Economic System

- Emission abatement cost

$$\Phi_{i,t} = b_{1,i,t}\mu_{i,t}^{b_{2,}} Q_{i,t}$$

  - $\mu_{i,t} = E_{i,t}^{A}/E_{i,t}^{\text{Total}} \in [0,1]$: emission control rate
  - $b_{1,i,t} = (b_{1,i} + b_{3,i}\exp(-b_{4,i}t))\sigma_{i,t}$

- Balance (total consumption)

$$c_{i,t}L_{i,t} = Y_{i,t} - I_{i,t} - \underbrace{\Phi_{i,t}}_{\text{Abatement Cost}} - \underbrace{\underbrace{m_t}_{\text{Permit price}} E_{i,t}^{P}}_{\text{Permit cost (or revenue)}}$$

Model: Climate System

- **Transient Climate Response to Emissions (TCRE)**
  - Global temperature rise is approx. linear to cumulative carbon emissions (Matthews et al., 2009)

- Global mean temperature (above preindustrial level)

$$T_t = \zeta \mathcal{E}_t$$

- Cumulative global emission

$$\mathcal{E}_{t+1} = \mathcal{E}_t + \sum_{i \in \mathcal{I}} E_{i,t}$$

Equilibrium

- Dynamic Noncooperative Nash Equilibrium

$$\max_{c_{i,t}, E^P_{i,t}, \mu_{i,t}} \sum_{t=0}^{\infty} \beta^t u(c_{i,t}) L_{i,t}$$

  - Dynamic Nash equilibrium for the noncooperative model solves UMP of each region simultaneously, including emission market clearing
    ▶ Solution Algorithm
  - Open-Loop Nash equilibrium (OLNE): regions commit to the strategies over time, with solution path depending on the initial state

Regional SCC and MAC

- **Regional Social Cost of Carbon (SCC)**

$$\mathrm{SCC}_{i,t}^{\mathrm{OLNE}} = \frac{-1,000(\partial V_{i,t}^{\mathrm{OLNE}}/\partial \mathcal{E}_t)}{\partial V_{i,t}^{\mathrm{OLNE}}/\partial K_{i,t}}$$

  - where $V_{i,t}^{\mathrm{OLNE}} = \max_{c_{i,s}, E_{i,s}^P, \mu_{i,s}} \sum_{s=t}^{\infty} \beta^t u(c_{i,s}) L_{i,s}$
  - Marginal rate of substitution between global emissions and regional capital

  $=$ PV of regional climate damages from additional unit of global emissions

- **Regional Marginal Abatement Cost (MAC)**

$$\mathrm{MAC}_{i,t} = 1,000 \left(\frac{\partial \mathrm{TAC}_{i,t}}{\partial E_{i,t}^A} \right) = 1,000 \left(\frac{b_{1,i,t} b_{2,i} \mu_{i,t}^{b_{2,i}-1}}{\sigma_{i,t}} \right)$$

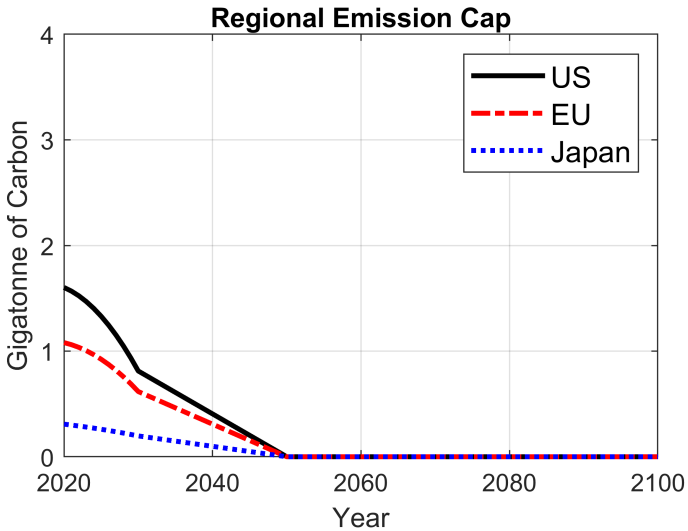
Data and Calibration

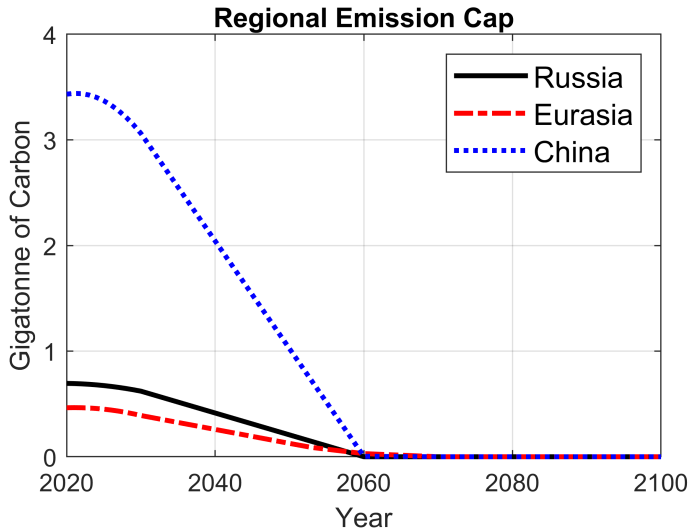
Data and Calibration

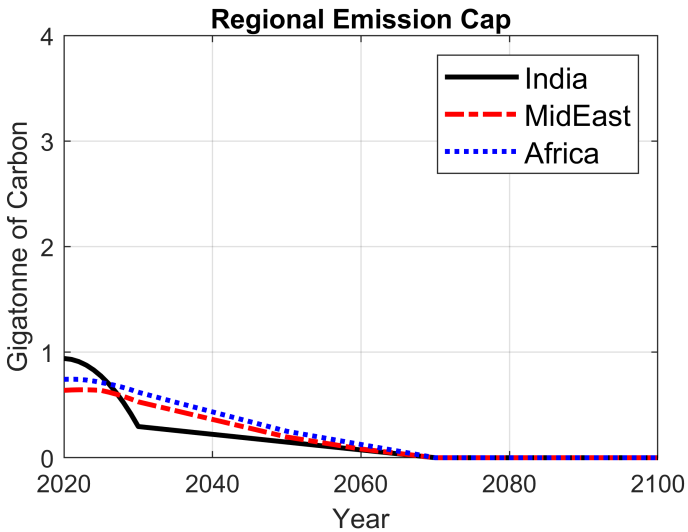
1. Emission Cap Pathways
2. Total Factor Productivity ▶ TFP calibration
   - using Burke et al. (2018) projections
3. Carbon Intensity ▶ Carbon intensity calibration
   - using Ueckerdt et al. (2019) projections
4. Abatement Cost Parameters ▶ Abatement cost calibration
   - using Burke et al. (2018) projections
5. Climate Damage Parameters ▶ Damage calibration
   - using Kahn et al. (2021) projections

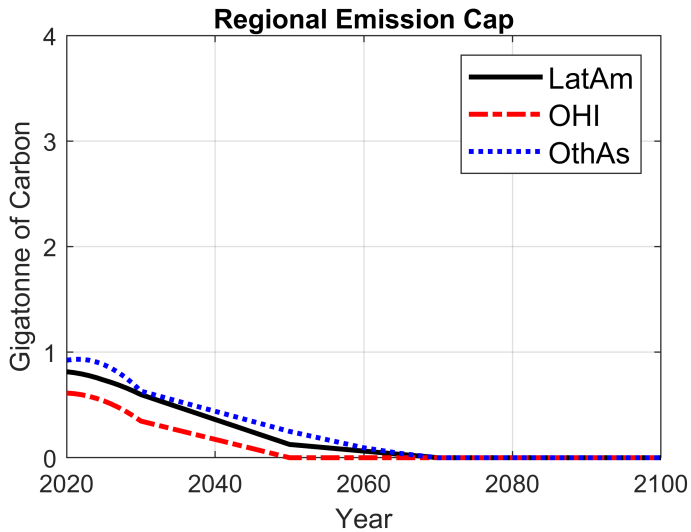
Emission Cap Pathways (baseline scenario)

- Paris Agreement/Glasgow Pact (NDCs;2030) + Net Zero emission targets



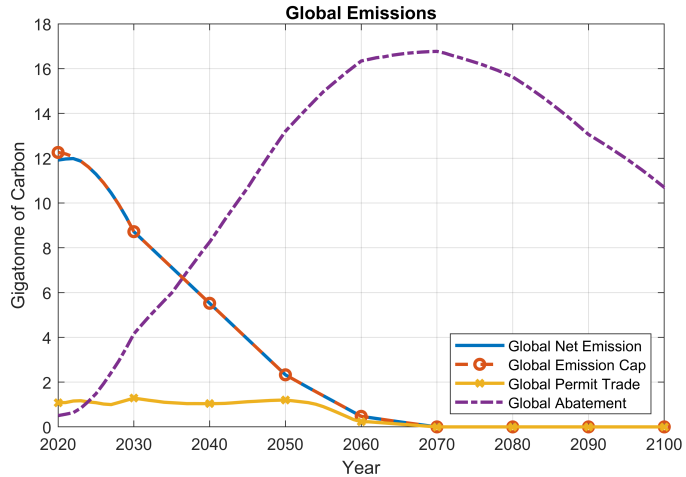


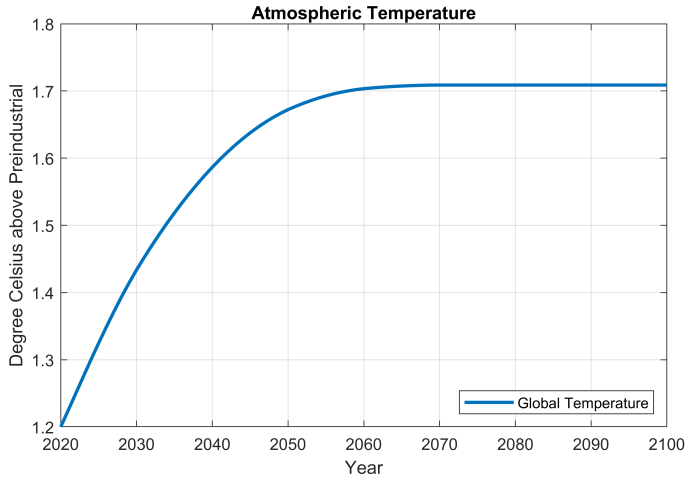


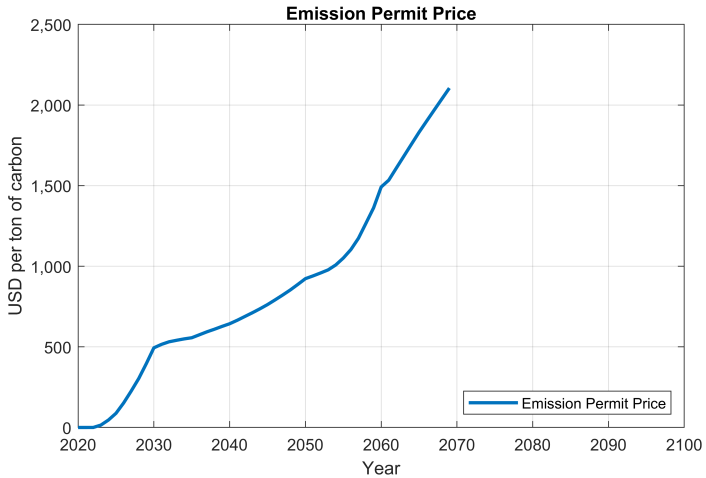


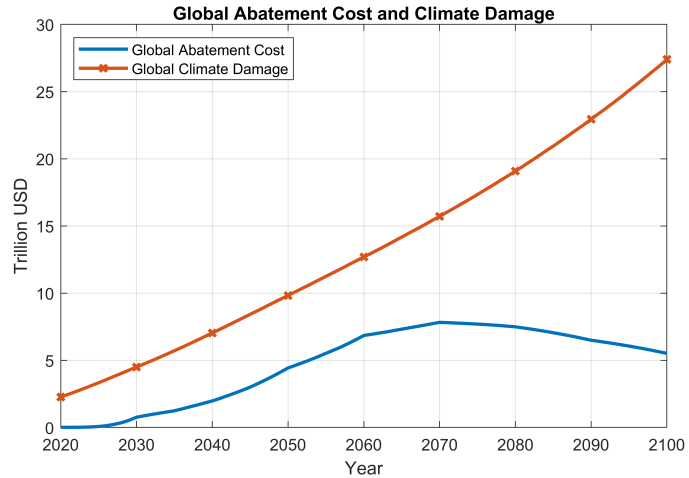
Simulation Results

Noncooperative model with CAP & ETS



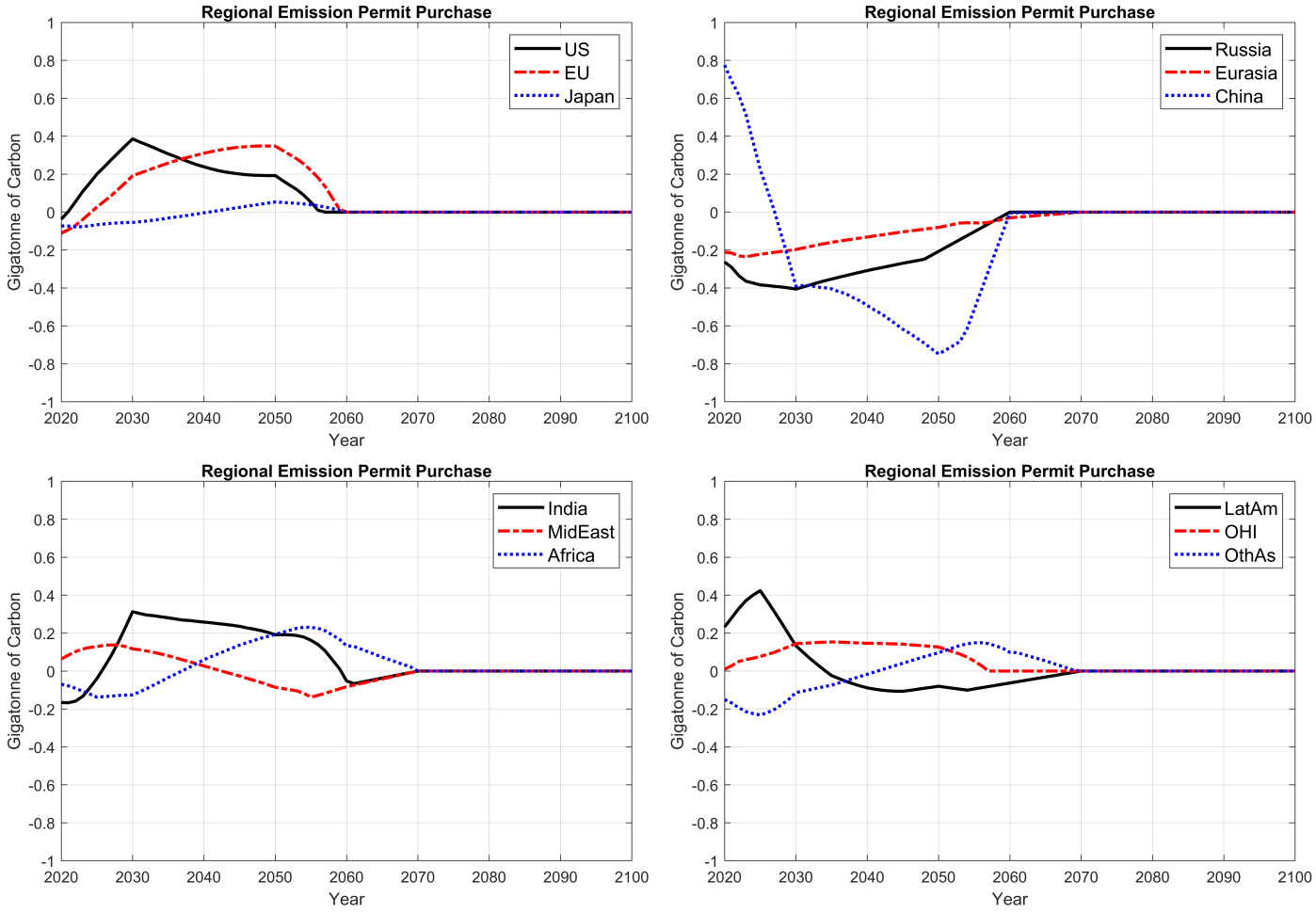






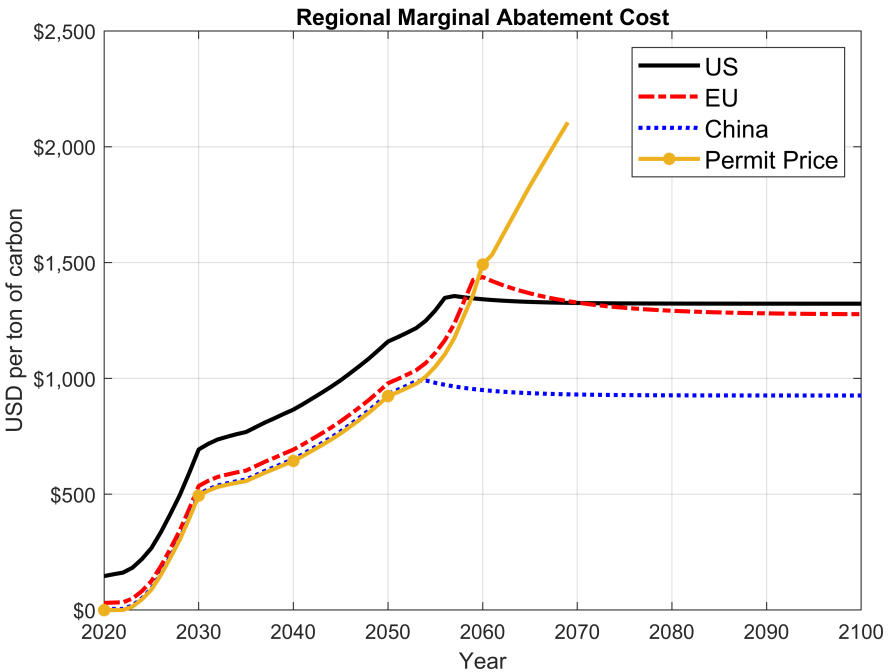
- Zero price until 2024 due to excessive global emission permit supply
- Permit price rises to \$923 (2050) and \$2,105 (2069)

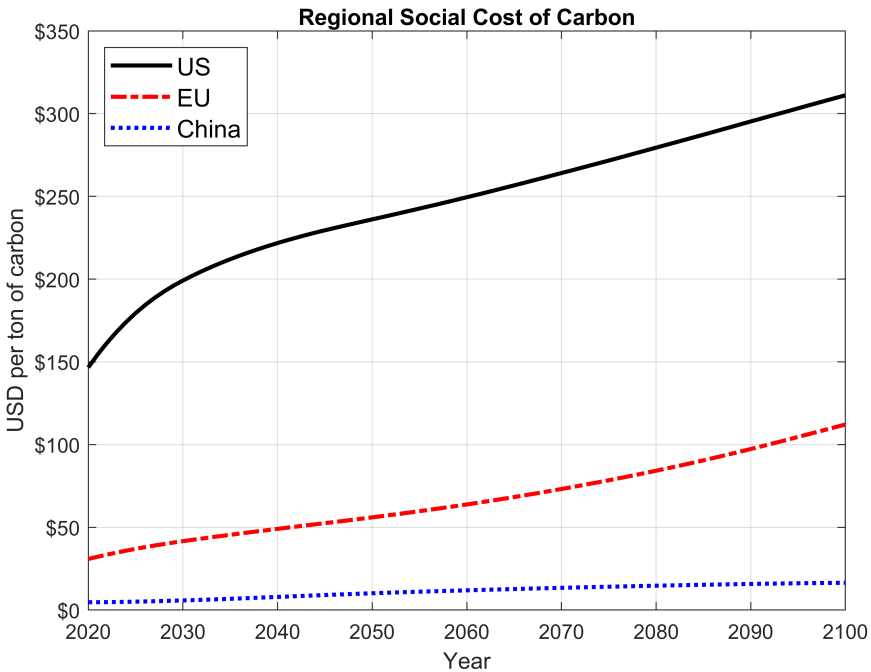
Emission Permit Trade (Purchase)



- Permit buyer: US, EU, India, Africa, OHI
- Permit seller: Russia, Eurasia, China, OthAs, LatAm

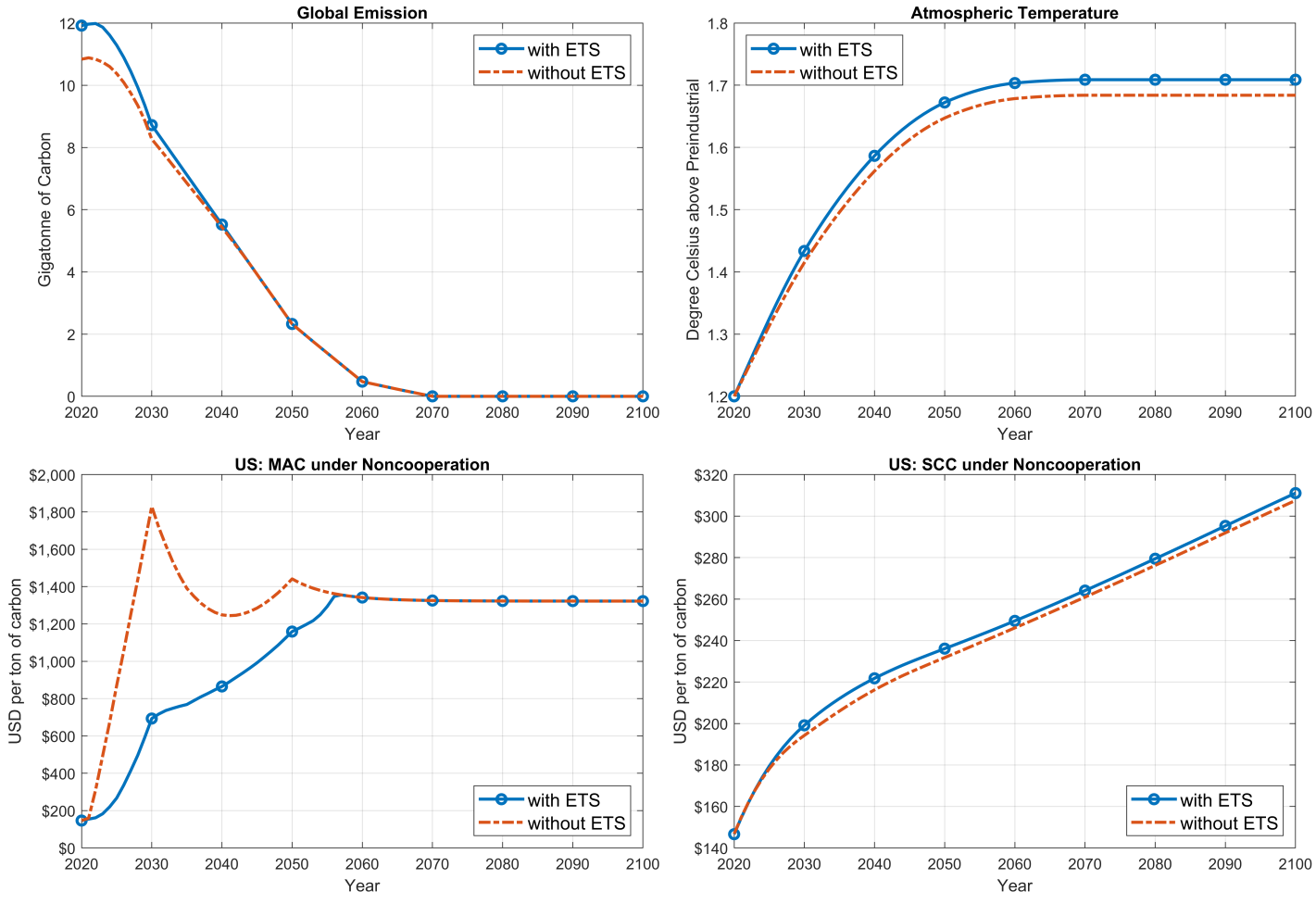
Regional MAC and SCC





- $(\text{MAC}_{i,t} - m_t) = \text{SCC}_{i,t}$, $\forall E^*_{i,t} > 0$
- Sizable regional heterogeneity in SCC: highest in the US ($236) in 2050
  - Optimal regional carbon tax

Effects of ETS Implementation



- ETS results in slightly higher emissions and temperature increases compared to the case without the ETS

Effects of ETS Implementation

- Welfare effects measured as compensating variation (CV) per capita
  - Comparing equilibrium with ETS vs. without ETS

Table: Welfare effects of the ETS implementation: pre-emission cap adjustment

	US	EU	Japan	Russia	Eurasia	China
CV per capita ($)	38.94	83.04	-0.03	552.75	53.18	42.90
CV per capita (%)	0.089	0.330	0.000	6.699	1.062	0.429
	India	MidEast	Africa	LatAm	OHI	OthAs
CV per capita ($)	22.94	-36.03	-5.40	66.68	109.69	-18.93
CV per capita (%)	1.469	-0.387	-0.354	1.001	0.317	-0.806

- Some regions with negative welfare effects
  - Note global net emissions and resulting climate damages differ across the two economies

Effects of ETS Implementation

- **Isolate** the effect of ETS: adjust emission cap
  - Comparing economy with ETS (adjusted emission cap) vs. without ETS

Table: Welfare effects of the ETS implementation: post-emission cap adjustment.

	US	EU	Japan	Russia	Eurasia	China
CV per capita ($)	116.18	100.26	38.60	235.17	57.49	34.62
CV per capita (%)	0.267	0.399	0.136	2.850	1.148	0.346
	India	MidEast	Africa	LatAm	OHI	OthAs
CV per capita ($)	33.34	42.73	16.82	75.30	100.63	12.40
CV per capita (%)	2.135	0.459	1.103	1.130	0.291	0.529

- Under the same pathways of global net emissions and temperature, economy with ETS results in positive welfare for all regions
  - **Gains from trade**: efficiency gains achieved through the reallocation of emission abatement efforts across regions

Partial ETS

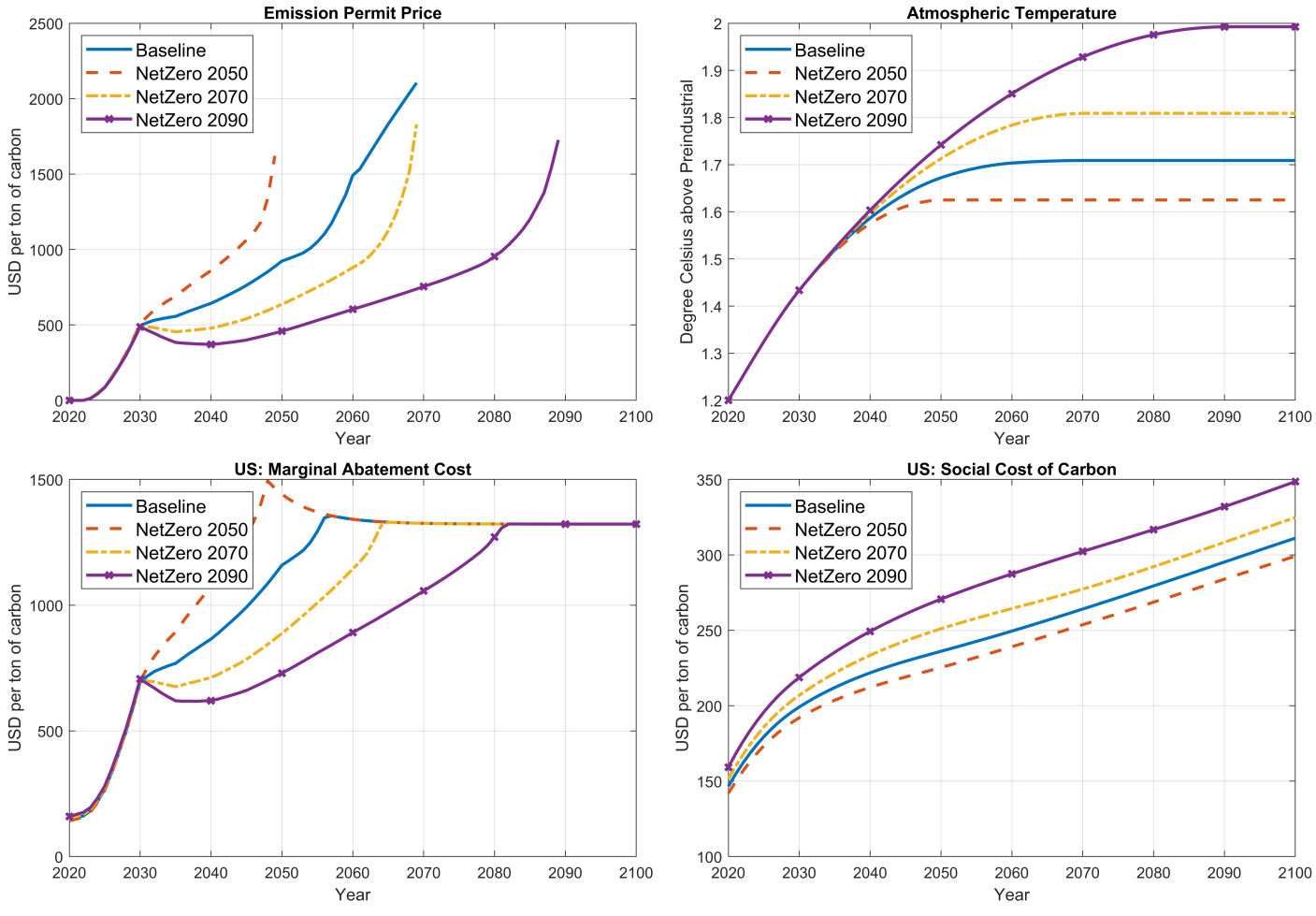
- Achieving international commitment to climate policies is challenging
  - Scenario: US does not adopt an emission cap or participate in the ETS

Table: Welfare effects of US non-participation in the global ETS

	US	EU	Japan	Russia	Eurasia	China
CV per capita ($)	564.96	-54.00	-115.07	105.06	-129.73	-10.15
CV per capita (%)	1.309	-0.215	-0.404	1.226	-2.561	-0.103
	India	MidEast	Africa	LatAm	OHI	OthAs
CV per capita ($)	-28.94	-327.27	-52.56	-121.99	-3.23	-79.91
CV per capita (%)	-1.867	-3.793	-3.409	-1.966	-0.009	-3.378

- Strong **free-riding** incentive under noncooperation

Alternative Net Zero Scenarios



- Net zero 2050: \$1,621 per ton of carbon by 2049, 1.62°C by 2100
- Net zero 2090: \$446 per ton of carbon by 2049, 1.99°C by 2100

Conclusion

- Under global ETS with baseline emission cap (Paris Agreement)
  - Global permit price can rise up to $923 by 2050 under global ETS
  - Temperature rise up to 1.7°C by 2100
- Regional SCC = MAC - m
  - Necessary condition for regional social planner
- Policy implications
  - Meeting global target of 1.5°C requires stronger mitigation policies
  - Effective global ETS requires stricter caps to avoid excessive supply
  - Complementarity between the global ETS and emisison tax

Thank You

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Algorithm for Noncooperative Model

Back

1. Initialization
   - Given initial guess of permit price $\{m_t^0 : \ t \geq 0\}$, solve the cooperative model
2. Maximization
   - Solve the maximization problem without market clearing conditions for each region, with other regions' net emissions fixed
3. Update permit price and net emissions
   - After solving the optimization problem of all regions, update

$$m_t^{j+1} = m_t^j \exp\left(\omega \sum_{i \in \mathcal{I}} E_{i,t}^{P,j+1}\right)$$

$$E_{i,t}^{j+1} = \omega E_{i,t}^* + (1-\omega) E_{i,t}^j, \quad \forall i \in \mathcal{I}$$

4. Check convergence criterion
   - Check if $m_t^{j+1} \simeq m_t^j$, $E_{i,t}^{j+1} \simeq E_{i,t}^j$, and $E_{i,t}^{P,j+1} \simeq E_{i,t}^{P,j}$
   - repeat steps 2-4 until convergence

Total Factor Productivity

Back

- Use GDP projections in Burke et al. (2018)
  - obtain regional TFP ($A_{i,t}$) under no climate impacts

$$A_{i,t+1} = A_{i,t} \exp\left(g_{i,t}\right)$$

$$g_{i,t} = g_{i,0} \exp\left(-d_i t\right)$$

- Structural Estimation for TFP parameters $(g_{i,0}, d_i)$

$$\min_{g_{i,0}, d_i, \pi_{1,i}, \pi_{2,i}} \sum_{t=0}^{79} \left(\frac{y_{i,t}^{\text{NoCC}}}{y_{i,0}^{\text{NoCC}}} - \frac{y_{i,t}^{\text{BDD,NoCC}}}{y_{i,0}^{\text{BDD,NoCC}}} \right)^2 + \sum_{t=0}^{29} \left(\frac{y_{i,t}}{y_{i,0}} - \frac{y_{i,t}^{\text{BDD}}}{y_{i,0}^{\text{BDD}}} \right)^2$$

where $y_{i,t}^{\text{NoCC}}$ is obtained by solving

$$\max_{c_{i,t}} \quad \sum_{t=0}^{\infty} \beta^t u(c_{i,t}) L_{i,t}$$

$$\text{s.t.} \quad K_{i,t+1} = (1-\delta) K_{i,t} + \left(y_{i,t}^{\text{NoCC}} - c_{i,t}\right) L_{i,t}$$

Total Factor Productivity

Back

and where $y_{i,t}$ is obtained by solving

$$\begin{aligned} \max_{c_{i,t}} \quad & \sum_{t=0}^{\infty} \beta^t u(c_{i,t}) L_{i,t} \\ \text{s.t.} \quad & K_{i,t+1} = (1-\delta) K_{i,t} + (y_{i,t} - c_{i,t})\, L_{i,t} \end{aligned}$$

with

$$y_{i,t} = \frac{1}{1 + \pi_{1,i}\, T_t^{\text{RCP4.5}} + \pi_{2,i} \left(T_t^{\text{RCP4.5}}\right)^2} A_{i,t} K_{i,t}^{\alpha} L_{i,t}^{-\alpha}$$

Carbon Intensity and Abatement Cost Parameters

Back

- Carbon Intensity ($\sigma_{i,t}$)
  - Use projections of GDP and emissions in Ueckerdt et al. (2019)
  - Based on zero-carbon tax scenario (FFrun211),

$$\sigma_{i,t} = E^{U}_{i,t,\mathrm{FFrun211}} / Q_{i,t,\mathrm{FFrun211}}$$

- Abatement Cost Parameter ($b_{1,i}, b_{2,i}, b_{3,i}, b_{4,i}$)
  - Use carbon tax and projected net emissions in Ueckerdt et al. (2019)
  - Step1) For carbon tax scenarios j, compute emission control rate

$$\mu^{U}_{i,t,j} = 1 - \frac{E^{U}_{i,t,j}}{E^{U}_{i,t,\mathrm{FFrun211}}}$$

  - Step2) Fit the data to the model, assuming "carbon tax = MAC"

$$\tau^{U}_{t,j} = MAC_{t,j} = 1,000 b_{2,i} \mu^{b_{2,i}-1}_{i,t,j} (b_{1,i} + b_{3,i} \exp(-b_{4,i} t))$$

Climate Damage Parameters

Back

- Use GDP loss projections in Kahn et al. (2021)
- Obtain climate damage parameters $(\pi_{1,i}, \pi_{2,i})$
  - Step1) Compute GDP loss in percentages

$$\Delta_{i,t}^{\text{RCP26}} = 1 - y_{i,t}^{\text{RCP26}} / y_{i,t}^{\text{base}}$$

$$\Delta_{i,t}^{\text{RCP85}} = 1 - y_{i,t}^{\text{RCP85}} / y_{i,t}^{\text{base}}$$

  - Step2) Fit the data to model,
    using ratio between scenarios RCP 2.6 and RCP 8.5

$$\min_{\pi_{1,i},\pi_{2,i}} \sum_{t=0}^{94} \left(\frac{1 + \pi_{1,i} T_t^{\text{RCP85}} + \pi_{2,i} \left(T_t^{\text{RCP85}}\right)^2}{1 + \pi_{1,i} T_t^{\text{RCP26}} + \pi_{2,i} \left(T_t^{\text{RCP26}}\right)^2} - \frac{1 - \Delta_{t,i}^{\text{RCP26}}}{1 - \Delta_{t,i}^{\text{RCP85}}} \right)^2$$