Linking Top-down and Bottom-up Models for Macroeconomic Analysis of Decarbonization in Northeast Asia

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BACKGROUND

Computable general equilibrium (CGE) models capture macroeconomic interactions and responses to policy shocks, including sectoral feedbacks, but often oversimplify sectoral representations. In contrast, bottom-up (BU) power sector models offer detailed technology assessments and cost-optimized investment decisions but operate independently of macroeconomic dynamics. Integrating the two approaches helps overcome the limitations of each type of model, particularly for evaluating carbon pricing and power sector policies.

The unique characteristics of the power sector (such as non-storability, grid dependence, and real-time balancing) make its linking with the broader economic system essential. Prior studies show that linked models improve the accuracy of mitigation cost estimates compared to standalone CGE model estimations (Britz and Hertel, 2011; Fujimori et al., 2019). The linking approach also makes it possible to capture investment and trade effects that are not captured in isolated BU models.

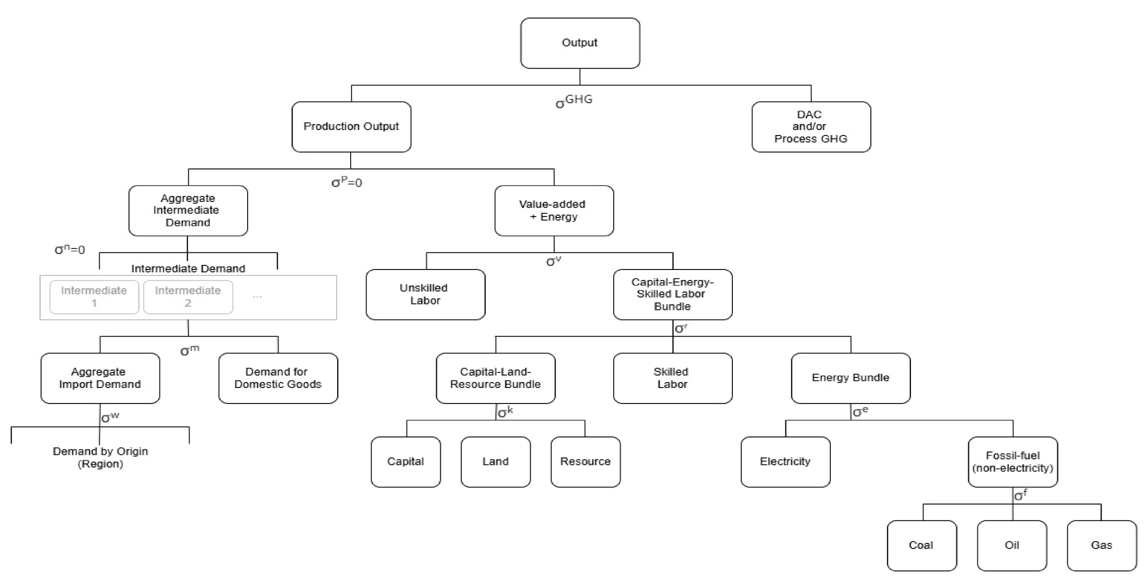
OBJECTIVES

- We develop an integrated assessment model, "UNICON-IAM," which fully integrates economic, climate, and damage function components. Develop "UNICON-G-Power", a two-way hard-linked model that integrates a CGE model and a power sector model
- Using UNICON-G-Power, examine (i) how carbon price differentials shape electricity trade patterns, (ii)how economic impacts are distributed across countries and sectors, and (iii) whether market integration supports regional decarbonization
  - Power market trade is well documented in Europe but remains understudied in Northeast Asia. We therefore focus on China, Japan, and South Korea, which together account for up to 35% of global CO2 emissions. These countries differ in renewable energy endowments, technology cost competitiveness, fossil fuel dependencies, which offers potential gains from electricity market integration

MODEL: TOP-DOWN

Global CGE Model

UNICON-G is a multi-regional, multi-sectoral dynamic recursive CGE model that provides a structured representation of the economy and its interactions, using a system of simultaneous equations. Production technologies are modeled using a nested CES structure, as illustrated below.



MODEL: BOTTOM-UP

Power Sector Optimization Model : Capacity Expansion Model (LP)

- Objective function

$$\min \sum_{c,n,ts} \delta_{ts} \cdot \Bigg[\sum_{tech,t} \big((c_{ia}(n,tech,t) + f_c(n,tech,t)) \cdot capacity_{hist}(n,tech,t)\big) + \sum_{tech,t} \big((c_{ia}(n,tech,t) + f_c(n,tech,t)) \cdot CAP_{new}(n,tech,t)\big) + \sum_{tech,lr} v_c(n,tech,t) \cdot GEN(n,tech,ts,lr) \cdot time(lr) + \sum_{l}\sum_{t} (trans_{ci}(l) + trans_{vc}(l)) \cdot TRANS(l,t) \Bigg]$$

- Supply-demand balance

$$\sum_{tech} GEN(n,tech,ts,lr) \cdot (1 - selg(tech,n)) - \sum_{str} STORE(n,str,ts,lr) - CURtailCPM(n,ts,lr) + \sum_{l} inc(l,n) \cdot FL(l,ts,lr) \cdot eff_{trans} = \frac{demandR(lr,n,ts)}{1 - TransLoss(n)}$$

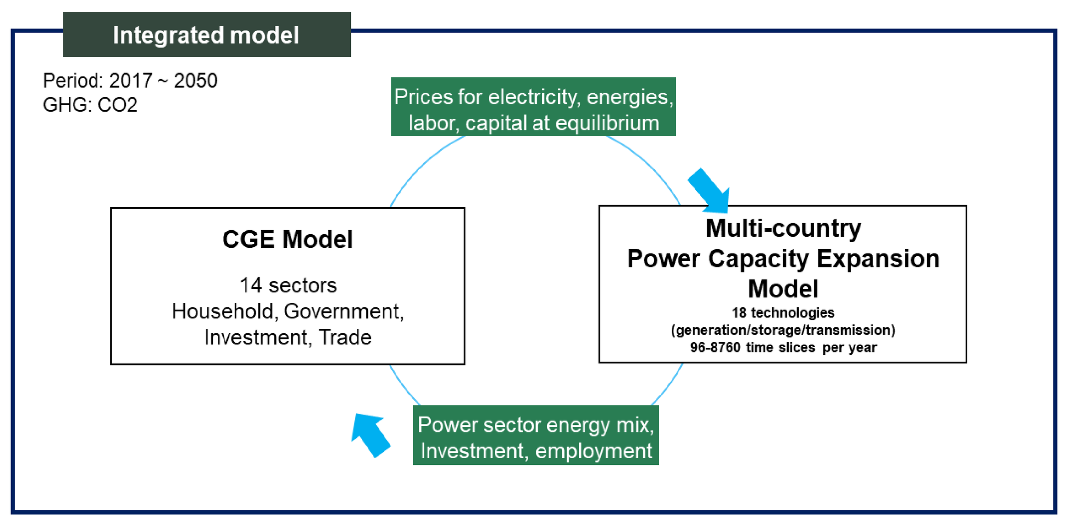
- Generation Capacity Constraint

$$GEN(n,tech,ts,lr) \le mxr(n,tech,ts,lr) \times \left(\sum_{t} capacity_{hist}(n,tech,t) + \sum_{t} CAP_{NEW}(n,tech,t) \right)$$

- Reserve margin, ramping constraint
- Storage constraint
- Emission constraint
- Renewable capacity constraint (hourly output, technical potential)
- Interstate transmission (maximum trade flows between countries)

INTEGRATION: DECOMPOSITION ALGORITHM

Following Böhringer & Rutherford (2009), we utilize a decomposition algorithm that ensures computational efficiency through iterative refinement of economic and energy system interactions. The BU model's objective function transforms into QP formulation, and the demand constraint is modified. The solution algorithm operates recursively on annual timesteps, beginning with power sector optimization and followed by parameter updates from the TD model.

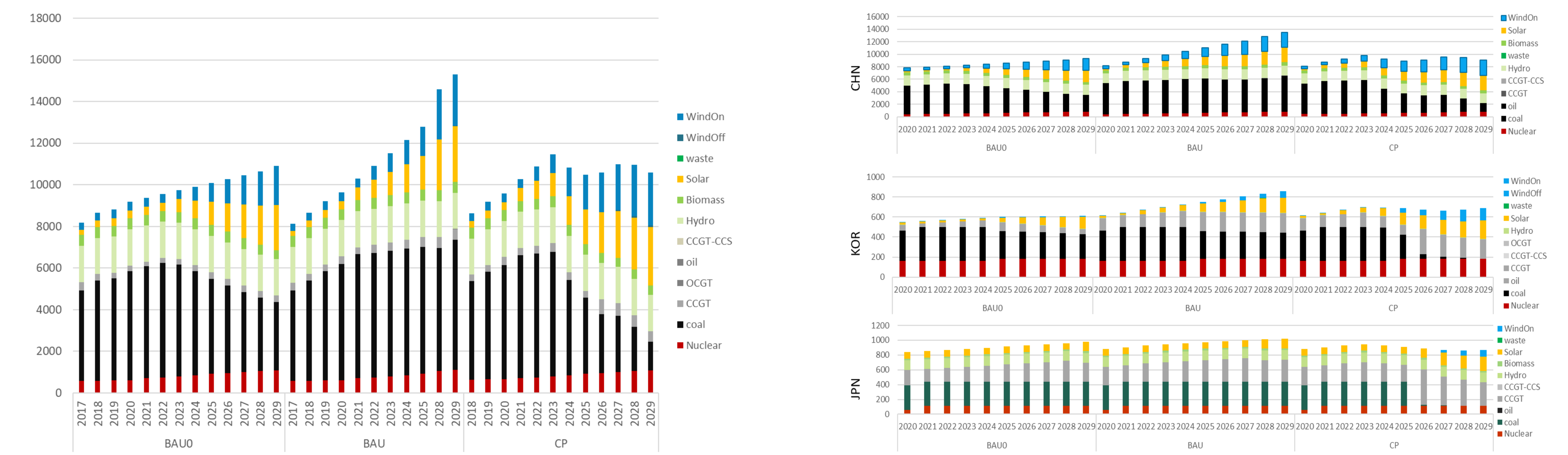


SCENARIOS & ASSUMPTIONS

- **BAU0:** baseline BU run as a standalone model
- **BAU :** baseline with CGE-BU linking
- **CP:** baseline + linear interpolation of carbon price between 2023 and 2050 from 0 to 300 USD/mtCO2 (CHN) or 350 USD/mtCO2 (KOR, JPN)
  - * For baseline: Total Factor Productivity (TPF)is calibrated to reproduce real GDP projection from SSP2 scenario
  - \+ with and without a Power Trade option

RESULTS

Power Generation Mix (GWh) – NEA Total & by Country



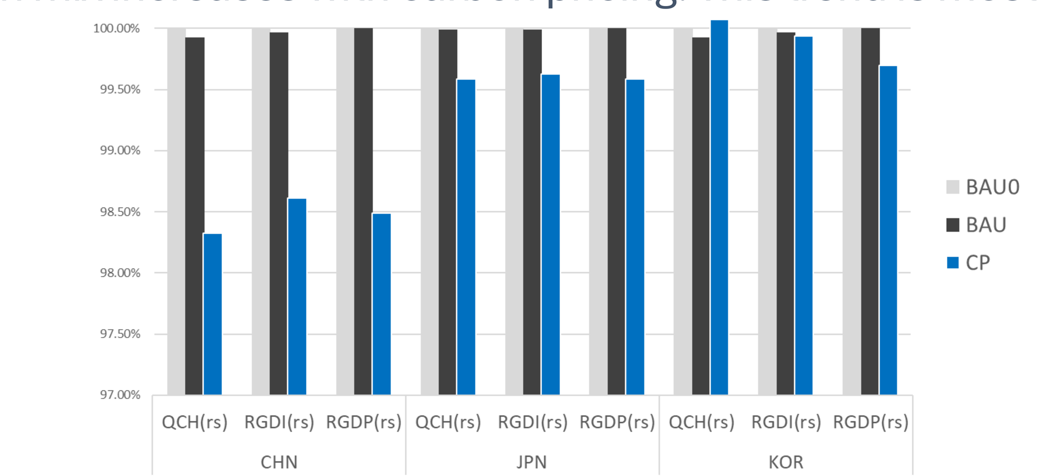
Over time, the share of renewable power in the generation mix increases with carbon pricing. This trend is most evident in the power generation mix of CHN.

Macroeconomic Impacts of Carbon Pricing in 2030

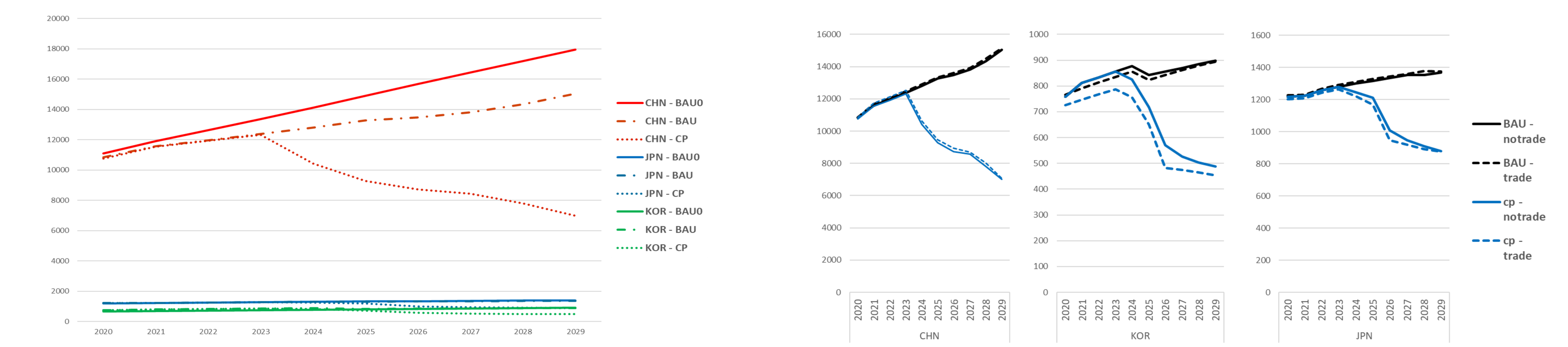
* Household consumption (QCH), Real Gross Domestic Income (RGDI), Real Gross Domestic Production (RGDP), % of Standalone CGE run (BAU0)

Carbon pricing brings negative GDP impact, with CHN expected to suffer the highest level of losses.

The income effect is less affected, due to improved terms of trade (ToT) in the three countries.



Economy-wide Total CO2 Emissions (GWh) & Grid Interconnection Impact on CO2



In all three countries, total CO_2 emissions decline substantially with the implementation of a carbon price in starting from 2023. Grid interconnections bring disparate emission impacts for exporters and importers (KOR with largest emission reduction with electricity import from CHN).

More detailed policy interventions are required to ensure emission reduction at all participating nodes.

CONCLUSION

- UNICON-G-Power integrates a multiregional CGE model with detailed power-sector optimization through hard-linked two-way coupling, enabling consistent and efficient assessment of energy-economy feedbacks.
- Focusing on Northeast Asia, an important yet understudied region, this study provides a detailed look at how carbon-price differentials and grid integration reshape electricity trade, regional efficiency, and CO_2 leakage, with uneven outcomes across countries.

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