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Linking Computable General Equilibrium Model with Power Sector Optimization Model to Evaluate Net-Zero Scenarios for Korea

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Abstract

This study investigates the economic impacts of implementing a net-zero carbon pricing policy in Korea through an integrated modeling framework that combines a top-down computable general equilibrium (CGE) model with a bottom-up power sector optimization model. The integration addresses the limitations of conventional CGE models in representing the technological nuances of carbon-free energy sources such as wind, solar, and energy storage systems (ESS). Using an iterative decomposition algorithm, the models exchange information on energy demand, prices, and technology deployment until convergence is achieved. The simulation spans from 2020 to 2050, evaluating four scenarios: two baselines with conservative and advanced technological assumptions, and two corresponding net-zero scenarios. The results reveal that achieving net-zero emissions through economy-wide carbon pricing may reduce real GDP by 4.24–7.39% and real income (GDI) by 3.40–6.58% by 2050, with lower economic costs under advanced technological development. Carbon prices required for net-zero range from KRW 1.36 to 2.98 million (USD 950–2,100) per ton CO_2, while renewable energy's share in power generation is projected to reach up to 87.2%. Methodological improvements include a refined convergence algorithm, calibration techniques to maintain model consistency, and the incorporation of hydrogen learning curves and detailed dispatch feasibility analysis.

1. Introduction

This study examines the economic implications of implementing a net zero carbon pricing policy in Korea, employing an integrated model that combines a computable general equilibrium (CGE) model with a power sector optimization model. By incorporating different assumptions regarding the role of technologies, we assess various net zero scenarios and their economic consequences.

While CGE models are widely used to evaluate the economic effects of economy-wide carbon pricing, they often overlook the detailed characteristics of carbon-free technologies, such as wind, solar, and energy storage systems (ESS). This limitation may lead to unrealistic outcomes from a technological standpoint. To address this issue, we develop an integrated model that combines a CGE model and a power sector optimization model using an iterative decomposition algorithm.

2. Literature Review

Approaches to integrating the TD and BU models vary in terms of methodological structure (soft vs. hard) and the direction of information flow (one-way vs. two-way) (Delzeit et al., 2020). Soft-linking methods maintain the independence of each model with exchanging data manually. This approach allows for flexible model coupling and can be effective in scenario analysis, as demonstrated by Fujimori et al. (2024) and Nishiura et al. (2024). However, ensuring internal consistency and solution convergence can be challenging, particularly when economic and technological responses interact dynamically. On the other hand, hard-linking methods integrate CGE and sector models within a unified optimization framework, aligning decision-making across both models. Böhringer and Rutherford (2009) applied a mixed complementarity problem (MCP) formulation to simultaneously solve economic and energy system equations. Helgesen and Tomasgard (2018) further refined these methods, incorporating detailed electricity sector constraints into a CGE-based optimization framework. Hard-linking usually offers a more internally consistent representation of interactions but requires significant computational resources and careful model calibration.

The direction of information exchange between models also influences outcomes. One-way linking methods, as employed by Havlik et al. (2014) and Chateau et al. (2014), treat sectoral model outputs as exogenous inputs to CGE models. While this approach simplifies computation, it fails to capture mutual interaction. Two-way linking overcomes this limitation by incorporating iterative feedback between models, enabling adjustments in energy investments and operations based on macroeconomic variables. Ringler et al. (2016) applied this approach to analyze the interaction between energy price changes, technological adoption, and economic growth, while Waisman et al. (2012) showed its importance in assessing the effects of carbon pricing.

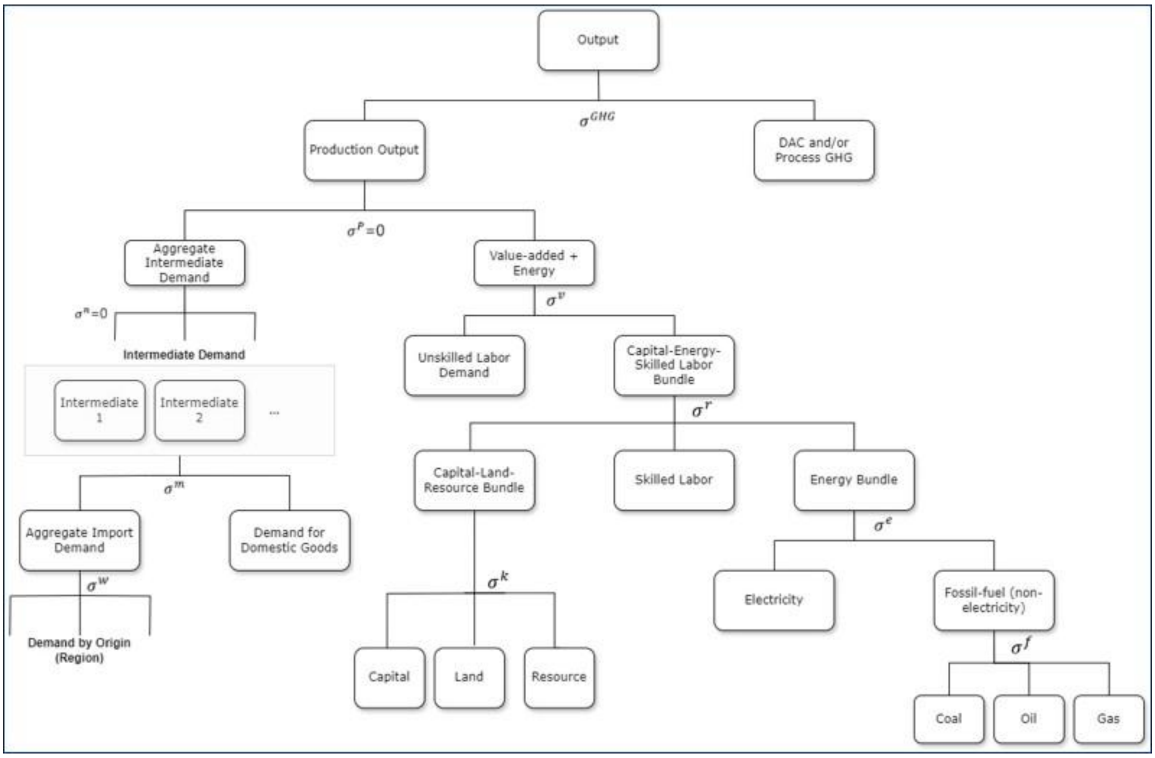
Our methodological approach builds on existing developments by conducting a two-way hard-linking framework that facilitates consistency between macroeconomic and sectoral models through iterative adjustments (Helgeson and Tomasgard, 2018). This approach complements existing integrated assessment models (IAMs) in the field. While AIM/CGE provides comprehensive economy-wide analysis with energy system representation, and GCAM offers detailed technological pathways, our model specifically focuses on electricity market dynamics in Korea. Models such as TEA/COFFEE and ETH-NEXUS have made valuable contributions to integrating electricity and economic systems analysis, particularly at broader regional scales. Our model adds to this literature by incorporating detailed electricity market characteristics.

3. Model

We model a two-way hard-linking framework that combines bottom-up electricity sector optimization with top-down CGE modeling using the General Algebraic Modeling System (GAMS). The framework extends the UNICON-K-v1 model, originally developed for Korea's electricity market analysis, to encompass multiple countries. Following Böhringer and Rutherford (2009), our integration methodology implements a decomposition algorithm that ensures computational efficiency through iterative refinement of economic and energy system interactions. The solution algorithm operates recursively on annual timesteps, beginning with power sector optimization and followed by parameter updates from the top-down model.

The CGE model employed in this study as a top-down (TD) model is a small open-economy multisector recursive dynamic model based on Korean Input-Output Table 2020 (Bank of Korea). It evaluates the macroeconomic impact of a policy shock by considering optimizing behavior of firms and consumers. On the other hand, the power sector optimization model is a bottom-up (BU) model that examines the micro-behavior of the power sector and its response to relevant policy shocks. The BU models determine the technology combination that minimizes costs based on energy demands and prices. However, they do not account for the fact that a new technology combination can change energy prices and demands, consequently affecting the optimal technology mix. In our integrated model, the power sector optimization model considers around 300 existing generators, 20 new technologies, and factors in hourly demand and availability of supplies. It calculates the energy supply and input demands using the economy-wide electricity demand and various commodity prices provided by the CGE model (TD model), which in turn uses the input profile from the BU model to compute market clearing commodity prices and demands.

Figure 1. Nesting Structure of the CGE Model



The integrated model, including both the CGE and power sector models, is designed to start from 2020 as a base year and to run every 5 years to finish in 2050 as the final simulation year. Once the values from the integrated model converge, the model reveals the macro and micro effects of policy options, including emissions, GDP, employment, energy mix, and the details of hourly dispatches of power generation. The convergence criterion is set to reach sufficiently small difference between the two consecutive iterations, where the difference is the sum of squares of all the energy and factor prices and quantities of both the CGE and power sector models.

Several methodological improvements have been made. First, we developed a more sophisticated decomposition algorithm to improve the convergence performance of the integrated TD/BU model, where both the CGE and power sector models accommodate not only endogenous carbon prices in TD models but also shadow price of constraints in BU models. This guarantees a convergence between the top-down and the bottom-up models under the emission cap scenarios, while the decomposition algorithm based on carbon price transfer only, as suggested by Bohringer & Rutherford (2009), fails to converge and tends to oscillate. Secondly, a new subroutine has been constructed to make the consistency of TD and BU models, where the new penalty term was introduced for the BU model, being calibrated to guarantee that the electricity demands given by exogenous assumptions do not change even after the integration of TD and BU models. This helps prevent the deviation of the base year equilibrium from the base year data after linking with BU models, while it needs to be kept as an equilibrium in the starting year. Thirdly, the learning curve has been introduced to reflect the economies of scale for the hydrogen.

Finally, the more detailed power dispatch optimization model based on mixed integer formulation has been developed and applied to check the feasibility of the solutions of power sector capacity planning model, which is employed as the bottom-up model in this research.

4. Scenarios and Simulation Results

We construct 4 scenarios: 2 baseline scenarios with different technological developments and 2 net zero scenarios for the two different technological assumptions. The first baseline scenario, named BAU_cons, describes a conservative technological development where the future cost reduction and the potential magnitude of renewable energy is low, the nuclear capacity expansion is limited, the maximum potential storage of captured carbon is low (1 $GtCO_2$), the import price and maximum available supply of hydrogen is low. Another baseline scenario for the advanced technological development, named BAU_adv, assumes the opposite situation with optimistic assumptions on renewable energies, nuclear energy, CCS and hydrogen. The two net zero scenarios, NZ_cons and NZ_adv, are corresponding the two different baseline scenarios with the same trajectory of CO_2 limitations.

The baseline scenarios are constructed to follow the economic growth and electricity consumption forecasts of the Net-Zero scenario the Carbon Neutral Green Growth (CNGG) Commission (2021). CO_2 emissions are projected to increase from 593.7 $MtCO_2$ in 2020 to 512.3~576.7 $MtCO_2$ by 2050, while the real GDP increases by 56.1% during the 30 years.

The net-zero scenarios are designed as an economy-wide carbon pricing to achieve the net-zero target in 2050 via linearly decreasing from 2020 level. The 2050 net-zero target is described as a remaining emission of carbon dioxide by 28 $MtCO_2$, reflecting negative emissions in AFOLU (from the Net-Zero Scenario by CNGG Commission).

The simulation results show that the net zero transition via carbon pricing could lead to changes of -4.24~-7.39 % of real GDP in 2050, compared to the baseline scenarios, while the real income (GDI) changes by -3.40~ -6.58%. The advanced technological development scenario provides the lower loss of real GDP and GDI. The carbon price required to meet the net-zero emission trajectories are expected to increase gradually toward around 1.36~2.98 million Korean Won (roughly 950~2,100 USD) per ton of CO_2 by 2050. The required carbon price is much lower under the advanced technology scenario compared with the conservative one.

The share of renewable energies (solar and wind) in power generation is expected to reach 71.8~87.2 % in 2050 under the net-zero scenarios, leapfrogging from 12.1~32.1% under the baseline scenarios. The advanced technology scenario leads to much higher portion of renewables not only in the net-zero but also in the baseline scenario.

Figure 2. Real GDP Impacts of Net-Zero Scenarios

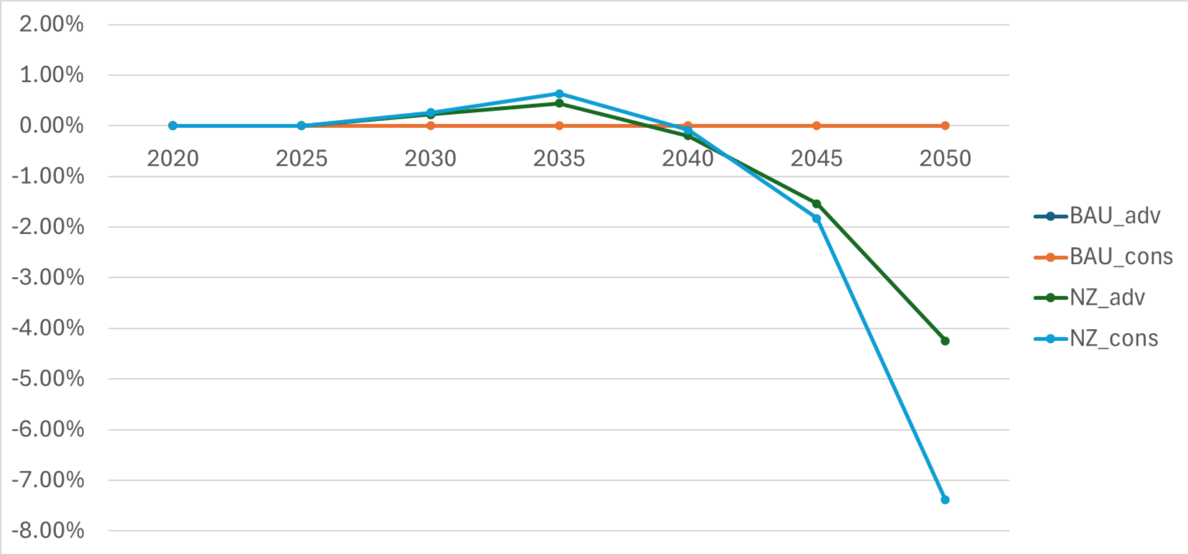


Figure 3. Power Generation Mixes by Scenarios