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Analyzing the economic impacts of Low–Energy Demand pathways based on CGE analysis

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PART I Introduction

Research Background

Greater attention to demand-side approaches

- Importance of understanding changes in energy demand and their impacts on achieving NDC and Net Zero:
    - Extensive impacts of changes in energy demand, such as electrification, efficient use of resources, behavioral changes across key sectors, such as building, industry, and transport
    - Accelerating mitigation actions while alleviating the burden on supply-side responses
    - Limited research and modeling on the demand-side approaches

- Increasing emphasis on demand-side responses for achieving mitigation targets, alongside supply-side efforts
    - IMP-LD pathway illustrates demand-side responses, including a reduction in resource consumption through efficient use of resources and shifts in consumption while maintaining high levels of services and satisfying basic needs

Research Background

Analyzing the impacts of mitigation policies and demand changes: Global CGE

- The increasing importance of using global integrated assessment models for analyzing the economic impacts of various global pathways and climate policies
- Improving the global CGE model with consideration of energy demand drivers, which can be reflected in the model
- Analyzing the economic impacts of existing mitigation policies, such as carbon pricing, and their impacts under low-energy demand scenarios
- Ensuring model credibility through research collaboration and networking with leading research groups on top-down and bottom-up models

- Limited research and modeling exercises that reflect demand-side responses
- Limited top-down/bottom-up modeling exercises on demand-side changes, with the exception of a few sectors (the power sector incorporates demand changes by considering various scenarios changing the aggregate electricity demand, peak load, or different load patterns)

Research Framework

Discussions on Low-Energy Demand Scenarios

- Discussions on Low-Energy Demand Scenarios, incl. EDITS
- Literature review on energy demand changes and their impacts
- Review low-energy demand scenarios for modeling analysis

Literature review on energy demand change scenarios with CGE analysis

- Review energy demand change scenarios in national and global CGE models
- Review approaches on incorporating the energy demand changes in CGE model

Develop and Update Global CGE Model

- Most up-to-date database (SSP-update, GTAP 11)
- Update approaches to include energy demand changes in the CGE model based on the literature review
- Update CGE model structure for scenario analysis.

Analysis on Low-energy Demand Scenario

- Pilot study for analyzing the economic impacts of low-energy demand scenarios
- Pilot study for the economic impacts of achieving global mitigation targets under energy-demand changes

From Literature ...

- IPCC 6th Assessment Report WG3 (IPCC, 2022) suggested five Illustrative Mitigation Pathways (IMPs), and the IMP-LD scenario focuses on demand reductions through efficient use of resources, including energy, and transition of consumption patterns.
    - Demand-side approaches can achieve significant reductions in greenhouse gas emissions through socio-cultural aspects, infrastructure planning and use, and application of end-use technologies by 2050. Each component's mitigation potentials vary by sectors
- Grubler et al. (2018) established the narrative of low-energy demand scenarios and suggested the changes in activity levels and energy intensity of Global North and Global South.
    - Applied a bottom-up approach and analyzed the activity level, energy intensity, and energy demand of four final end-use sectors (thermal comfort, consumer goods, mobility, and contingency reserve) and five upstream sectors (public and commercial buildings, industry, freight transport, international aviation, and shipping)
- Ruijven et al. (2019) analyzed the energy demand changes due to climate change and estimated the relationship between temperature change and per capita demand of the three final energy carriers (electricity, oil products, and natural gas) associated with four sectors (agriculture, industry, residential, and commercial) → Indicating the importance of incorporating cooling and heating energy demand changes due to climate change
- Huang et al. (2023) indicated energy efficiency can reduce energy consumption, but at the same time, the rebound effects can occur partially or even greater than the reductions. Generally, the exogenous EEI setting leads to some positive rebound effects, and relatively few studies indicate over 100% of rebound effects.

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PART Ⅱ

Methodology

Methodology: Global CGE Model

Structure

- The recursive dynamic computable general equilibrium (CGE) model with **GTAP 11 Power DB** & **non-CO2 greenhouse gases** are aggregated into six GHGs (N2O, CH4, NF3, SF6, PFCs, HFCs)

- **The updated SSP 2 scenario from the EU Navigate project** (Leimbach et al. 2021) for calibration: The GDP and population projections with consideration of the impacts of COVID-19.

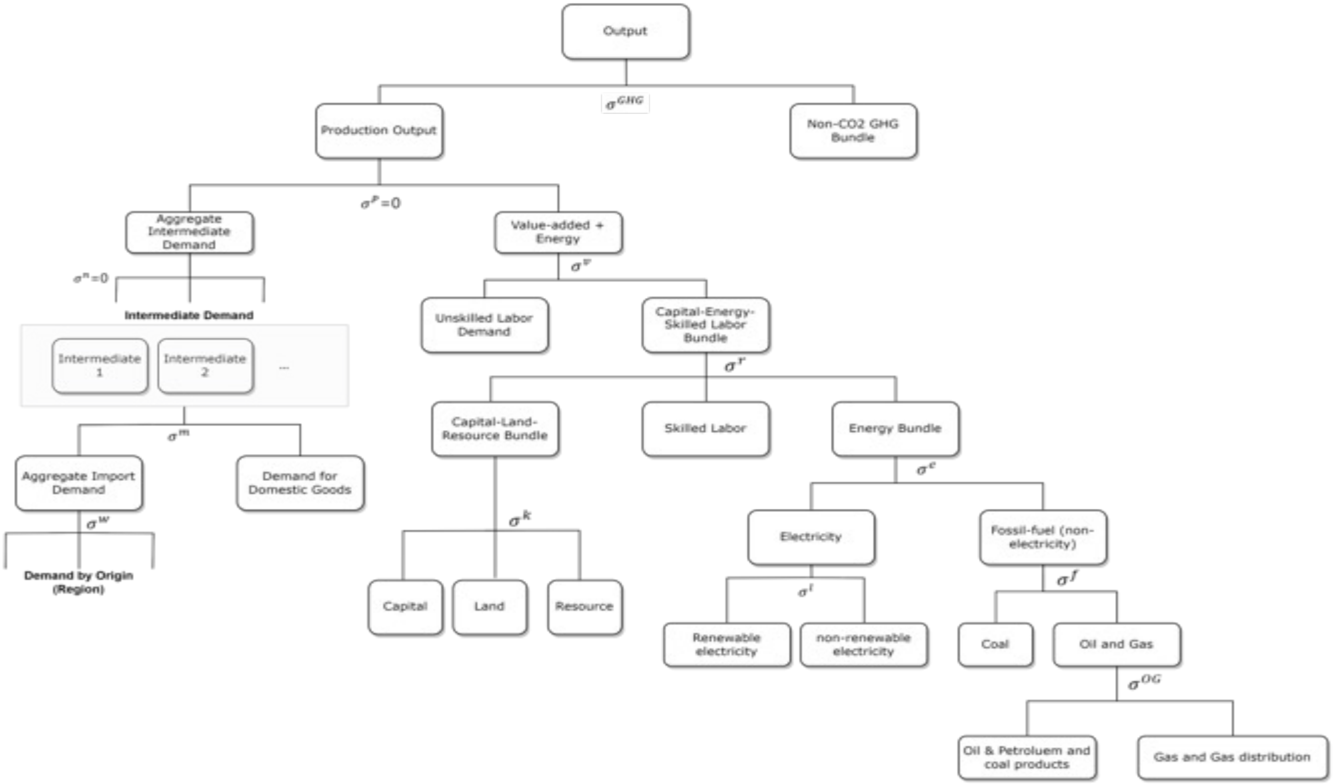
- GTAP 11 Power Database (Aguiar et al. 2022) with 160 aggregate regions (141 individual countries and 19 aggregate regions) and 76 products and services.
    - Total Factor Productivity is calibrated to replicate the updated SSP 2's GDP pathway
    - Constant Elasticity of Substitution (CES) functions are applied to the production function
    - Armington specification is considered for international trade, and a two-level nested CES structure is employed
        - Top-nest: Optimal composite of domestic and imported goods by the domestic agent
        - Bottom-nest: the aggregate import demand is distributed across the trade partners

- **A 15% learning rate to the productivity of renewable energy technologies.**

- **Vintage capital** (old and new capital) with differentiated elasticities of substitution across production inputs

Methodology: Global CGE Model

Production Nesting Structure



<u>Set of Equilibrium conditions for all regions and commodities:</u>
(1) Market Equilibrium, (2) Consumption demand functions, (3) Current account balance, budget constraints, and capital stock dynamic equations, (4) zero-profit conditions, (5) factor supply function (Jung et al. 2021; Kim et al, 2023)

Methodology: Global CGE Model

Regional and Sectoral Classification

- A climate module from the FUND model is applied
- The climate parameters of the FUND model are adopted in the model
    - Assumes that Korea and Japan have the same parameter values for the climate module
- 76 sectors in the GTAP Power Database are aggregated into 21 sectors

Label	Description
KOR	Republic of Korea
JPN	Japan
EAS	China, Hong Kong, Macau, North Korea, Mongolia
USA	United States of America
CAN	Canada
WEU	Western Europe
ANZ	Australia and New Zealand
CEE	Central and Eastern Europe
FSU	Former Soviet Union
MDE	Middle East
CAM	Central America
SAM	South America
SAS	South Asia
SEA	Southeast Asia
NAF	North Africa
SSA	Sub-Saharan Africa
SIS	Small Island States

21 Sector	
Coal	Paper
Oil	Chemical
Gas	Metal
Petroleum and Coal Product	ICT
Non-renewable Electricity	Vehicle
Renewable Electricity	Machine
Nuclear Electricity	Construction
Agriculture	Service
Mineral	Transport
Cloth	Dwelling
Food	

Integrating demand changes in global CGE model

Keywords from literature review

National Policy

- Energy Efficiency Improvement in major sectors (industry, transport, buildings)
- Awareness Raising
- Lifestyle Changes (for instance, dietary changes)
- ICT-based transformation

Literature

- Energy Efficiency improvement
- Energy consumption changes due to climate change
- Electrification and Digitalization
- Sharing Economy
- Circular Economy (resource efficiency)
- Lifestyle change
- Impact of COVID-19

What can be done in CGE analysis

- Autonomous Energy Efficiency Improvement (AEEI) in industry and household consumption
- Energy Consumption changes due to climate change
- Some Lifestyle Change
- Carbon Pricing
- Impact of COVID-19

- The emphasis on reducing energy demand is well recognized, yet there has been limited quantitative analysis of its potential contribution towards achieving Net Zero goals
- It is necessary to understand the economic impacts of these efforts in the context of the Net Zero transition

Integrating demand changes in global CGE model

Various energy demand changes are considered in energy demand scenario

Energy Efficiency Improvement

- Improving energy efficiency ⬄ The existence of rebound effects in energy efficiency gains

Changes in Heating and cooling energy consumptions due to Climate Change

- Changes in heating and cooling energy consumptions, including climate-induced energy demand changes

Accelerated deployment of renewables

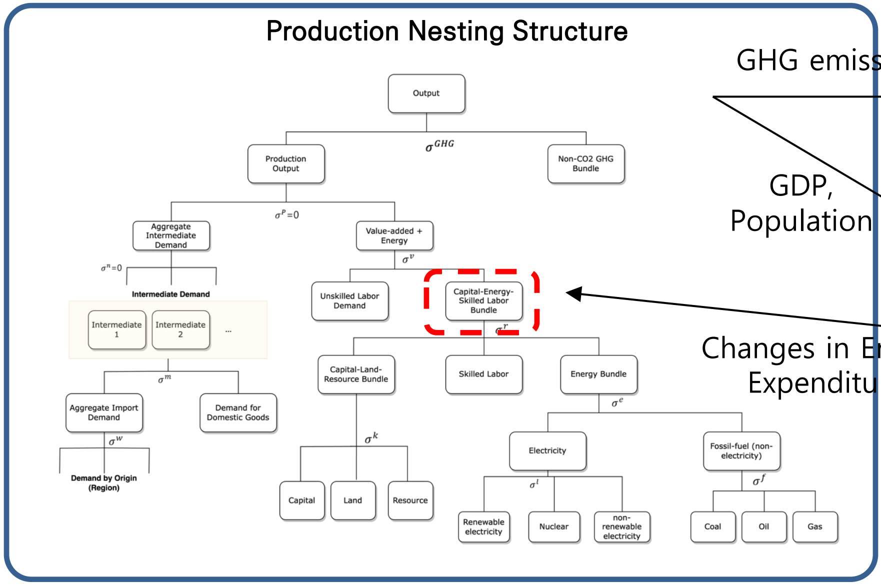
- Electrification may not unilaterally and directly reduce energy consumption
- Electrification with renewable transition ➔ opportunities to reduce greenhouse gas emissions from fossil fuel consumption

Constraints on household energy consumption

- Behavioral changes in households, such as limiting excess consumption, altering energy-consuming habits, and adopting a new, less energy-consuming lifestyle
- Technological improvements or advanced technologies leading to lower industrial energy use
- The application of those changes to a global CGE model is quite limited, so this study considers such changes as exogenous shocks

Integrating demand changes in global CGE model

Global CGE model for analyzing the energy demand changes



GHG emissions

GDP, Population

Changes in Energy Expenditure

Climate module from FUND

- Carbon Cycle, Radiative Forcing, Temperature Response, Sea Level Rise
- Heating and cooling energy expenditure changes

Integrating demand changes in global CGE model

Various energy demand changes are considered in low energy demand scenario

Changes in Heating and cooling energy consumptions

- First, Apply FUND models' Climate Module to calculate the global and regional temperature change

(Concentration)

$$C_t = C_{t-1} + aE_t - \beta(C_{t-1} - C_{pre})$$

$$BOX_{i,t} = \rho_i BOX_{i,t-1} + 0.000471 a_i E_t$$

$$C_t = \sum_{i=1}^{5} a_i BOX_{i,t}$$

C (Concentration), E (Emissions), t (Time), pre (Pre-industrial level); ρ (decay rate);

* Initial CO2 concentration from FUND model was 310.75 ppm, but this value was outdated. Thus, the study updated this value to 405.22 in 2017 from Lan, Tans, and Thoning(2024.1.5). "Trends in Atmospheric Carbon Dioxide", accessed on January 10, 2024.

(Radiative Forcing)

$$\begin{aligned} RF_t = {} & 5.35 \ln\left(\frac{CO2_t}{275}\right) + 0.036 * 1.4\left(\sqrt{CH4_t} - \sqrt{790}\right) + 0.12\left(\sqrt{N2O_t} - \sqrt{285}\right) \\ & - 0.47\ln(1+2.01*10^{-5} CH4_t^{0.75} 285^{0.75} + 5.31 * 10^{-15} CH4_t^{2.52} 285^{1.52}) \\ & - 0.47\ln(1+2.01*10^{-5} N2O_t^{0.75} 790^{0.75} + 5.31 * 10^{-15} N2O_t^{1.52} 790^{2.52}) \\ & + 2 * 0.47\ln(1+2.01*10^{-5} 790^{0.75} 285^{0.75} + 5.31 * 10^{-15} 790^{2.52} 285^{1.52}) \\ & + 0.00052(SF6_t - 0.04) + rfSO2_t \end{aligned}$$

(Temperature)

$$T_t = \left(1 - \frac{1}{\varphi}\right) T_{t-1} + \frac{1}{\varphi} \frac{CS}{5.35\, ln2} RF_t$$

T (Global Mean Temperature); CS (Climate Sensitivity = 3); φ (e-folding time)

$$\varphi = \max\left(a + \beta^l CS + \beta^q CS^2, 1\right)$$

β^l = 29.1; β^q=0.001

$$RT_t = REG * T_t$$

RT (Regional Temperature); REG (Fixed Factor)

Integrating demand changes in global CGE model

Various energy demand changes are considered in low energy demand scenario

Changes in Heating and cooling energy consumptions

- Then, apply damage function (additional energy consumption for cooling and heating)

(Heating and Cooling)

$$X_{t,r}^{heating} = \alpha_r^{heating} Y_{1990,r} \left(\frac{atan(Temp_{t,r} - Temp_{1990,r})}{atan\ 1.0}\right) \cdot \left(\frac{y_{t,r}}{y_{1909,r}}\right)^{\epsilon_h} \left(\frac{Pop_{t,r}}{Pop_{1990,r}}\right) /\ cumAEEI_{t,r}^{1990}$$

$$X_{t,r}^{cooling} = \alpha_r^{cooling} Y_{1990,r} \left(\frac{Temp_{t,r} - Temp_{1990,r}}{1.0}\right)^{\gamma} \left(\frac{y_{t,r}}{y_{1990,r}}\right)^{\epsilon_c} \left(\frac{Pop_{t,r}}{Pop_{1990,r}}\right) /\ cumAEEI_{t,r}^{1990}$$

X (additional expenditure for space heating and cooling); a (parameter, impact of climate change on expenditure for heating and cooling); ϵ_h(parameter, impact of economic growth for heating); ϵ_c(parameter, impact of economic growth for cooling); $cumAEEI_{t,r}^{1990}$(cumulative value of AEEI since 1990); γ (parameter, impact of global temperature change on cooling expense)

* For cumulative AEEI, this study applies FUND model's initial AEEI and cumAEEI values for calculating the changes in heating and cooling impacts until 2017. Afterwards, the rate of energy efficiency changes assumed in this study is applied to calculate cumAEEI.

(CGE Model)

$$TQENL_r = \sum_{i,v} QENL_{r,i,v} + \sum_{i \in ely} QC_{r,i} + \sum_{i \in e} QC_{r,i}$$

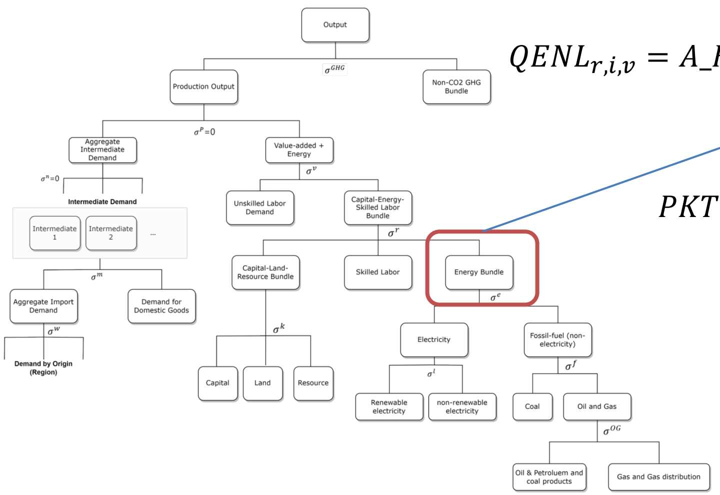
$$A\_KTRE_{ENL,r,i,v} = A\_KTRE0_{ENL,r,i,v}\left(1 - \left(\frac{(X_{t,r}^{heating} - X_{2017,r}^{heating} + X_{t,r}^{cooling} - X_{2017,r}^{cooling})}{TQENL_r}\right)\right)$$

$$A\_KTRE_{LB,r,i,v} = A\_KTRE_{LB,r,i,v} + (A\_KTRE0_{ENL,r,i,v} - A\_KTRE_{ENL,r,i,v})$$

* Heating and Cooling impacts change the share parameter of Energy Bundle. To make the sum of all share parameters equal to one, the changes are adjusted by share of skilled-labor

Integrating demand changes in global CGE model

Global CGE model for analyzing the energy demand changes



$$QENL_{r,i,v} = A\_KTRE_{ENL,r,i,v}\boxed{\lambda^{\sigma-1}_{r,i,v}}\left(\frac{PKTRE0_{r,i,v}}{PENL0_{r,i,v}*(1+PTENL0_{r,i,v})}\right)^{1-\sigma}\left(\frac{PKTRE_{r,i,v}}{PENL_{r,i,v}*(1+PTENL_{r,i,v})}\right)^{\sigma} QKTRE_{r,i,v}$$

$$PKTRE_{r,i,v} = A\_KTRE_{ENL,r,i,v}\boxed{\lambda^{\sigma-1}_{ENL,r,i,v}}\left(\frac{PENL_{r,i,v} * (1 + PTENL_{r,i,v})}{PENL0_{r,i,v} * (1 + PTENL0_{r,i,v})}\right)^{1-\sigma}$$
$$+A\_KTRE_{LB,r,i,v}\lambda^{\sigma-1}_{LB,r,i,v}\left(\frac{PLB_{r,i,v}*(1+PLB_{r,i,v})}{PLB0_{r,i,v}*(1+PTLB0_{r,i,v})}\right)^{1-\sigma}$$
$$+ A\_KTRE_{KTR,r,i,v}\lambda^{\sigma-1}_{KTR,r,i,v}\left(\frac{PKTR_{r,i,v}*(1+PTKTR_{r,i,v})}{PKTR0_{r,i,v}*(1+PTKTR0_{r,i,v})}\right)^{1-\sigma}$$

r (Region), i (Sector), v (Vintage), P (Price), Q (Quantity);
ENL (Energy Bundle); KTRE (Capital–Energy–Skilled Labor Bundle);
$A\_KTRE_{ENL,r,i,v}$(Share parameter), σ (elasticity)

- Adjusting the Share Parameter of Consumption composite for reducing energy consumption (household) by 1.25% (Global South) and 1.5% (Global North) per year (Household)
- Energy efficiency improvements (autonomous energy efficiency improvement; AEEI) in all sectors (Adjusting efficiency parameter by 1.5% per year in Global South and by 1% per year in Global North

Low Energy Demand and Carbon Pricing Scenarios

Scenario Setting

Scenario	Description
Business-as-Usual (BAU)	• Baseline scenario without energy expenditure changes
Energy Expenditure (E_EXP)	• BAU scenario with changes in cooling and heating energy demand changes due to temperature changes
Low Energy Demand in Industry (LED_ind)	• In addition to the E_EXP Scenario, energy efficiency improvements in industrial sectors are considered • Energy efficiency improvements in all sectors by 1% per year in Global North and 1.5% per year in Global South
Carbon Pricing (CP)	• E_EXP scenario with GCAM Below 2-degree carbon pricing
Low Energy Demand in Industry with CP (LED_ind_CP)	• Follows Carbon Pricing scenario's emissions pathways • In addition to E_EXP Scenario, energy efficiency improvements in industrial sectors are considered • Energy efficiency improvements in all sectors by 1% per year in Global North and by 1.5% per year in Global South
Low Energy Demand in Industry and Household with CP (LED_all_CP)	• Follows CP scenario's emissions pathways • In addition to the LED_ind_CP Scenario, efficiency improvements to household energy consumption households, reductions in household energy consumption, and reductions in transport sector energy consumption are considered. 1.25% energy and 1.5% energy consumption reductions in Global South and Global North, respectively

Low Energy Demand and Carbon Pricing Scenarios

Scenario Setting

NGFS Below 2-degree Carbon Prices (from GCAM)

	CPZ30	CPZ40	CPZ50
ANZ	45.0	213.0	528.1
SIS	59.1	185.2	346.5
CHI	52.1	112.9	230.1
JPK	80.3	165.7	414.8
KOR	121.7	265.2	651.3
SEA	66.0	207.0	387.2
SAS	83.4	180.7	390.0
CAN	87.8	227.6	510.6
USA	65.9	179.9	430.8
CAM	66.0	207.0	387.2
SAM	103.4	262.6	537.4
WEU	51.1	165.0	406.7
CEE	56.4	181.8	446.7
FSU	65.8	206.3	388.8
MDE	66.0	207.0	387.2
NAF	66.0	207.0	387.2
SSA	58.3	188.4	424.2

Note: The study utilized the NGFS Below 2-degree (GCAM) Carbon Prices by Region and Year
Source: Richters et al. (2023.11.7), “NGFS Climate Scenario Dataset (4.1)”, accessed on November 15, 2023.

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PART III

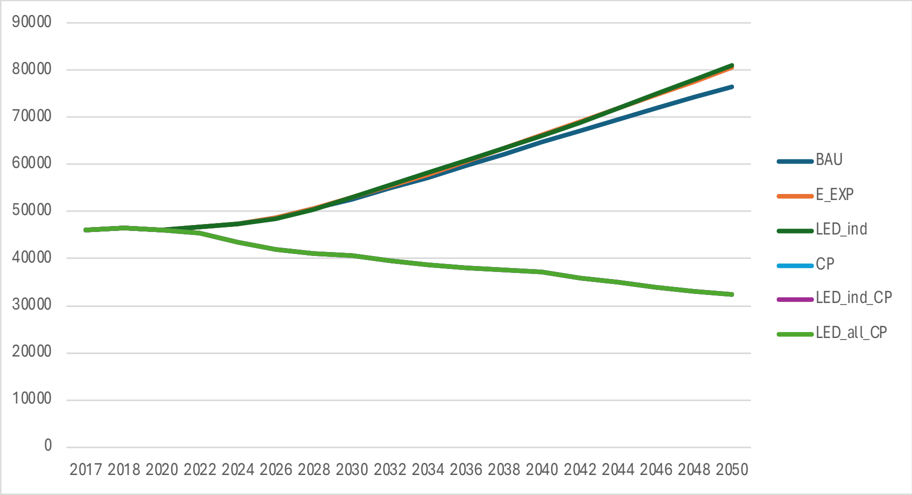
Results and Implication

Key Result

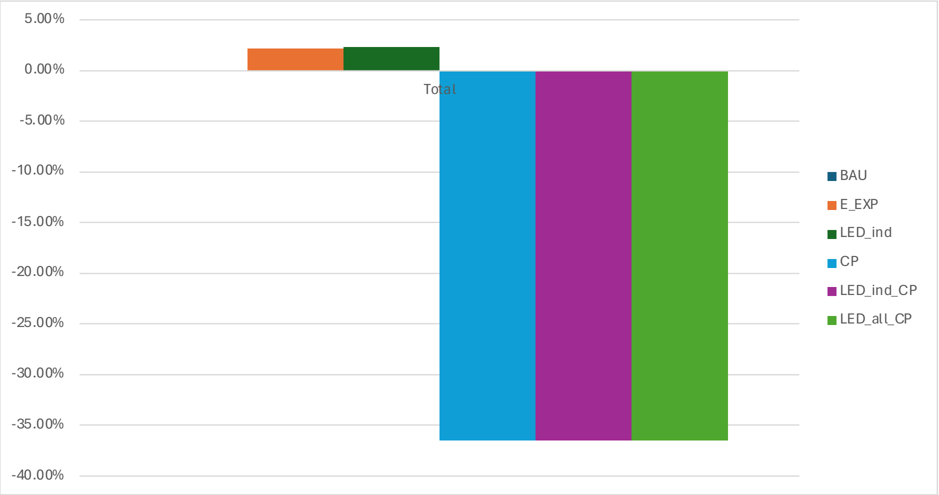
Global: Greenhouse Gas Emissions

- Changes in cooling and heating energy demand due to climate change can increase global GHG emissions slightly
- Global GHG emissions can decline rapidly with a net zero carbon price
- The global mean temperature increase could go beyond 2℃ in the next few decades
- The results suggest evidence of the rebound effects of energy efficiency improvement, similar to other CGE models (Huang et al, 2023).

Global Greenhouse Gas Emissions (unit: MtCO2eq)



Changes in Global GHG Emissions (2022~2050) (relative to BAU) (unit: %)

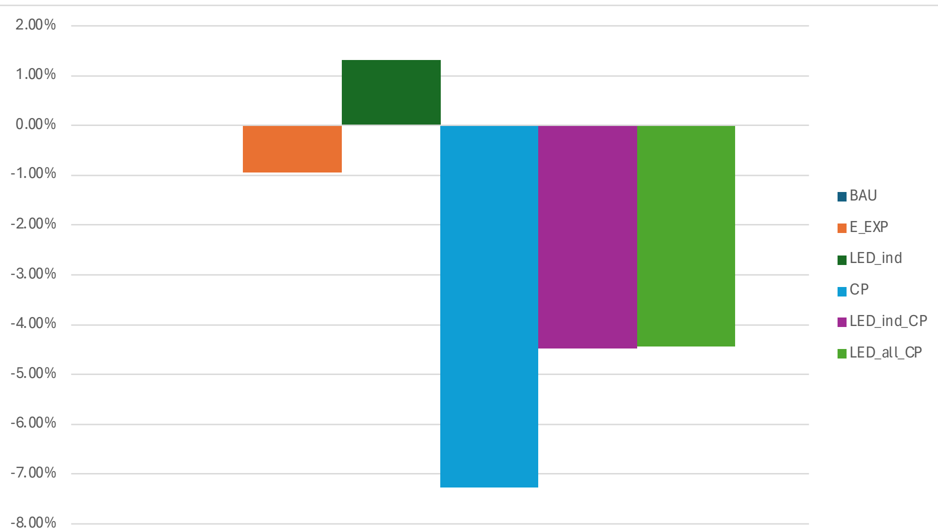


Key Result

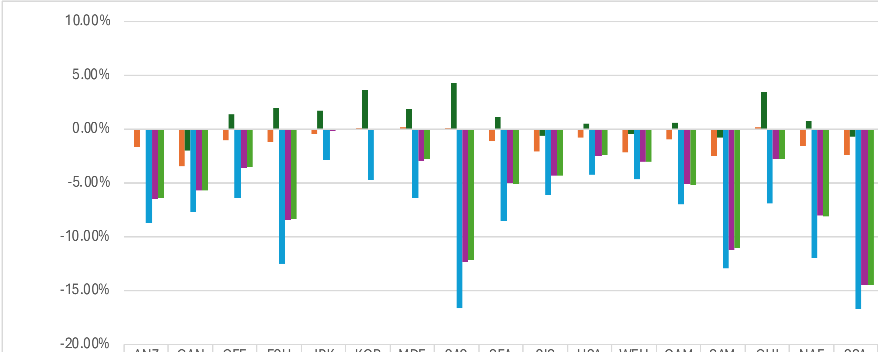
Global: Economic variable (Real GDP)

- For economic impacts, the introduction of carbon pricing leads to some economic losses globally
- low-energy demand measures, besides carbon pricing, could reduce the negative economic impacts compared with the CP scenario
- At the regional level, the results indicate that the economic impacts vary considerably by country, but low energy demand measures reduce the economic burden in all regions

Changes in Global real GDP (2022-2050) (relative to BAU) (unit: %)



Changes in Regional real GDP (2022-2050) (relative to BAU) (unit: %)



	ANZ	CAN	CEE	FSU	JPK	KOR	MDE	SAS	SEA	SIS	USA	WEU	CAM	SAM	CHI	NAF	SSA
BAU																	
E_EXP	-1.59%	-3.44%	-1.03%	-1.23%	-0.41%	0.12%	0.19%	0.03%	-1.09%	-2.10%	-0.78%	-2.18%	-0.98%	-2.53%	0.14%	-1.56%	-2.38%
LED_ind	-0.02%	-1.94%	1.36%	1.98%	1.77%	3.63%	1.86%	4.30%	1.12%	-0.63%	0.53%	-0.44%	0.57%	-0.78%	3.47%	0.82%	-0.65%
CP	-8.74%	-7.63%	-6.39%	-12.52	-2.84%	-4.70%	-6.35%	-16.63	-8.54%	-6.10%	-4.23%	-4.69%	-6.97%	-12.89	-6.94%	-11.96	-16.72
LED_ind_CP	-6.46%	-5.67%	-3.58%	-8.48%	-0.17%	-0.08%	-2.89%	-12.30	-5.00%	-4.32%	-2.46%	-3.02%	-5.07%	-11.18	-2.75%	-8.02%	-14.46
LED_all_CP	-6.39%	-5.66%	-3.50%	-8.38%	-0.05%	-0.03%	-2.79%	-12.14	-5.05%	-4.34%	-2.42%	-3.02%	-5.19%	-11.07	-2.73%	-8.12%	-14.46

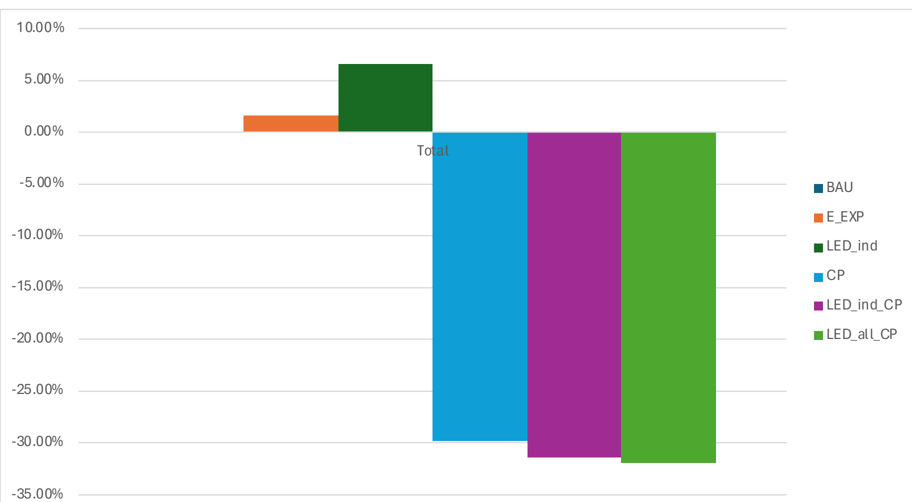
* Revenue recycling (carbon price): Lumpsum Transfer to Household

Key Result

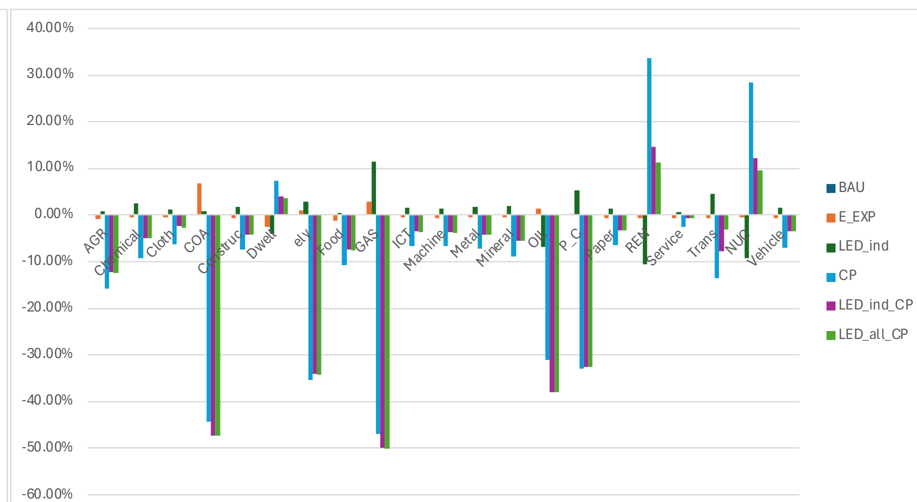
Global: Final Energy Demand and Production by Sector

- Net zero carbon pricing can reduce global production and investment in several sectors: Significant damages to fossil fuels and non-renewable electricity sectors ⇔ Substantial benefits to renewables and nuclear
- Energy efficiency improvements and efforts on energy consumption reductions could achieve greater reductions in final energy demand relative to the BAU scenario if sufficient carbon prices are accompanied by these measures

Changes in Final Energy Demand (2022-2050) (relative to BAU) (unit: %)



Changes in global Production by Sector (2022-2050) (relative to BAU) (unit: %)

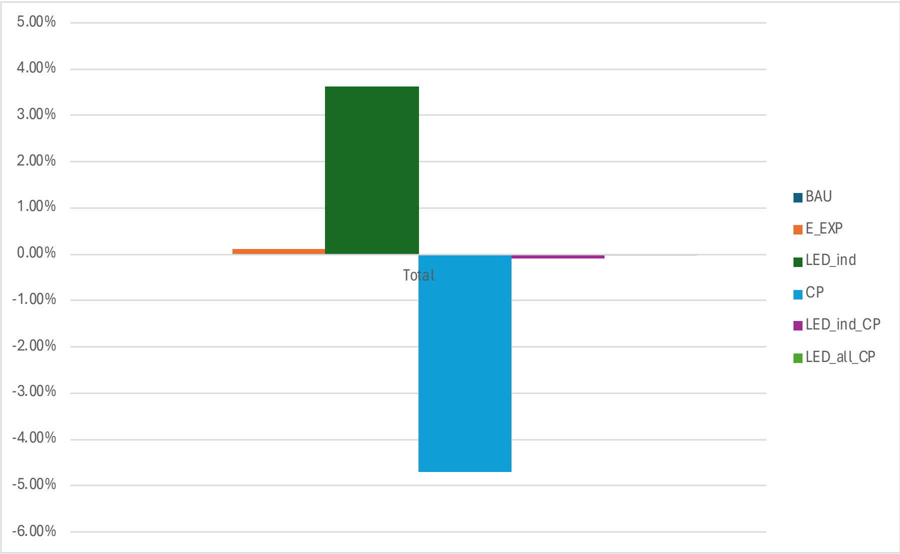


Key Result

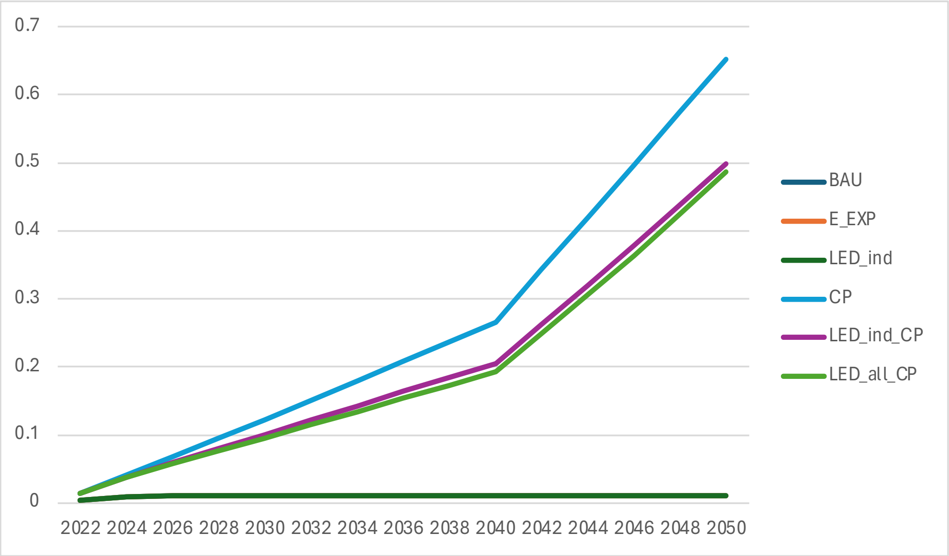
Korea: Greenhouse Gas Emissions and Carbon Price Trajectories

- Significant reductions in GHG emissions can be achieved if a carbon price is imposed
- Low-energy demand measures could lower the economy-wide carbon prices required to meet the same level of emission reduction in the Carbon Pricing scenario by 2050
- This implies the importance of policy measures for reducing the energy demand of industrial sectors, reducing GHG emissions, and meeting national mitigation targets

Changes in Korea's real GDP (2022–2050) (relative to BAU)



Korea's Carbon Price Trajectories by Scenario (unit: 1,000 USD)



Policy Implications

Potential of Low Energy Demand Measures

- Low energy demand measures accompanied by carbon pricing could bring synergy effects and achieve mitigation in more efficient and effective ways
  ➔ Some Benefits Even with Limited Application of such Measures
- The transition of industrial sectors with high energy use and GHG emissions is key for low-energy demand and net-zero transitions
  ➔ If other measures, such as shifts in design, circular economy, dematerialization, and technological advancements are considered, low energy demand measures could result in more significant benefits.

Support Just Transition

- Low energy demand measures can reduce expected economic losses and alleviate the economic burden on society
- The utilization of carbon revenue to support low-income or vulnerable groups could support a net-zero transition ➔ Policies and strategies for utilizing the revenue from carbon pricing should be designed to alleviate social costs in transition pathways.
- Reducing energy consumption and adopting low demand lifestyle could alleviate the economic burden of households by reducing expenditure on energy commodities

Further Study

Innovative Technologies and Circular Economy

- Innovative technologies, such as CCS and hydrogen, as well as circular economy and material demand, should be included to analyze the Net Zero transition

Top-down and Bottom-up Integrated Model

- To address both individual or group demand-side measures and their economy-wide potential, top-down and bottom-up integrated models
- Collecting behavioral information on individuals and households, such as real-time energy consumption data and social and economic drivers of energy consumption, will become increasingly important

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THANK YOU